Attenuation of Intensity for the Zemmouri Earthquake of 21 May 2003 (Mw 6.8): Insights for the Seismic Hazard and Historical Earthquake Sources in Northern Algeria

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Foreword On the basis of the detailed macroseismic study of the 21 May, 2003 Zemmouri earthquake (Mw $=$ 6.8), we measured the epicentral distance to about 600 intensity-observation localities and analysed the resulting dataset by regression procedures. The earthquake that is the most destructive event in Algeria since 1980 caused 2,280 casualties and the collapse and serious damage of more than 30,000 buildings. The coastal epicentre location makes the earthquake an important case study useful for a better understanding of the seismic hazard of the Algiers region. Different regression curves are calculated using various directions and the resulting attenuation distribution shows diverse behaviours related to the specific geological structures. Significant variations of intensity are related to the sedimentary versus basement and rocky areas. These results extend our knowledge on the interaction between the damage distribution and the local soil conditions. Moreover, the comparison of the Zemmouri earthquake with historical offshore and coastal seismic events, the 1856 Djidjelli earthquake to the east and the 1891 Villebourg earthquake to the west, allows us to infer new conclusions on the seismogenic sources along the Algerian coastal area.

1 Introduction

The Tell Atlas of Northern Algeria has been the site of several destructive earthquakes during the last seven centuries that cover the historical catalogue (Rothé 1950, Mokrane et al. 1994, Benouar 1994; Table 1, Fig. 1). This high rate of earthquake activity is due to the Tell Atlas location along the convergent domain at the plate boundary between Africa and Eurasia. The most recent Zemmouri earthquake of 21 May 2003 (Mw 6.8) allowed us to characterize a newly identified active zone

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J. Fréchet et al. (eds.), *Historical Seismology*,
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Table 1 The most damaging earthquakes in Algeria with estimated intensities (see also Fig. 1)

No	Earthquake	Damage and casualties	Intensity	References
1	Algiers 3.1.1365	Large number of dead; collapse of houses and palaces.	X EMS	Harbi et al. 2007a
2	Algiers 3.2.1716	Strong damage to buildings, half of them destroyed; 20,000 victims	IX EMS	Harbi et al. 2007a
3	Djidjelli 22.8.1856	Heavy damage to several traditional, dwellings, colonial houses and public buildings in at least 27 sites. The total of the damage had been estimated at about 443,000 FF.	VIII MSK	Harbi et al. 2003
4	Biskra 16.11.1869	30 dead and several injured. More than 245 housing units destroyed and several seriously damaged	VIII MSK	Harbi et al. 2003
5	M’sila 3.12.1885	33 dead, 17 injured; 75% of the village of M’sila destroyed and many others seriously damaged in the epicentral area	IX MSK	Harbi et al. 2003
6	Mansourah 8.1.1887	Destruction of 60 traditional houses and severe damage to many others	VIII MSK	Harbi et al. 2003
7	Villebourg 15.1.1891	39 dead, destruction of almost all the houses of Villebourg, destruction and serious damage at Gouraya	IX EMS	This study
8	Constantine 4.8.1908	Many deadly accidents; destruction of old houses; heavy damage to public buildings	VIII MSK	Benouar 1994
9	Aumale 24.6.1910	At least 81 dead and several injured; destruction or heavy damage to many traditional houses; colonial and public buildings	VIII MSK	Benouar 1994
10	Cavaignac 25.8.1922	At least 4 dead and several injured; destruction of about 80% of houses in Cavaignac and heavy damage to others in the epicentral area	VIII–IX MSK	Benouar 1994
11	Mac-Mahon 16.3.1924	At least 4 dead and several injured; destruction or heavy damage to many traditional houses; colonial and public buildings	VIII MSK	Benouar 1994
12	Douéra 5.11.1924	At least 4 dead and several injured, destruction or heavy damage to several housing units and colonial farms	VIII MSK	Benouar 1994
13	Inkerman 24.8.1928	At least 4 dead; destruction or heavy damage to many traditional houses and serious cracks to well built colonial constructions	VIII MSK	Benouar 1994
14	Guelma 10.2.1937	2 dead and at least 16 injured; destruction or heavy damage to several housing units and public buildings	VIII MSK	Benouar 1994
14	Guelma 10.2.1937	2 dead and at least 16 injured; destruction or heavy damage to several housing units and public buildings	VIII MSK	Benouar 1994

Table 1 (continued)

No	Earthquake	Damage and casualties	Intensity	References
15	Berhoum 12.2.1946	277 dead, 118 injured and 7,500 homeless; destruction or heavy damage to 1,000 housing units	VIII MSK	Benouar 1994
16	Orléansville 9.9.1954	1,409 dead, 5,000 injured and 50,000 homeless; destruction of more than 33,000 buildings	X MSK	Benouar 1994
17	Béni Rached 5.6.1955	No casualties but destruction of colonial and traditional houses	VIII MSK	Benouar 1994
18	Bou Medfaa 7.11.1959	2 injured and at least 500 homeless; destruction or heavy damage to 80% of the houses, farms and buildings	VIII MSK	Benouar 1994
19	Melouza 21.2.1960	47 dead, 129 injured and 4,900 homeless; destruction of about 600 housing units	VIII MSK	Benouar 1994
20	Bir Hadada 4.9.1963	1 dead and ∼ 100 injured; collapse of more than 50% of the traditional housing units of the city	VIII–IX EMS	Harbi 2006
21	M'sila 1.1.1965	5 dead, 25 injured and 25,000 homeless; destruction or serious damage to 3,145 housing units	VIII MSK	Benouar 1994
22	Mansourah 24.11.1973	4 dead, 43 injured, 14,922 homeless; Serious damage and destruction of∼ 2,000 housing units	VIII–IX EMS	Harbi 2006
23	Ouled Aissa 31.1.1979	15 dwellings seriously damaged without casualties	VII–VIII EMS	Harbi 2006
24	El Asnam 10.10.1980	3,000 dead, 8,500 injured and 400,000 homeless, destruction or serious damage to 60,000 housing units	X MSK	Benouar 1994
25	Ain Fekroun 5.10.1984	123 traditional houses seriously damaged with 13 shattered	VII–VIII EMS	Harbi 2006
26	Constantine 27.10.1985	10 dead, 300 injured; severe damage or destruction to old houses and farms	VIII MSK	Benouar 1994
27	Chenoua 29.10.1989	35 dead, more than 700 injured and 50,000 homeless; severe damage or destruction to 8,000 housing units and 500 public buildings	VIII MSK	Benouar 1994
28	Mascara 18.8.1994	171 dead, 654 injured, 12,500 homeless; serious damage or destruction to 2,000 housing units, farms and about 10 schools	VIII MSK	Benouar 1994
29	Ain Temouchent 1999	25 dead, 25,000 homeless; Serious damage to housing units and public buildings	VII MSK	Yelles et al. 2004
30	Zemmouri 21.5.2003	2,278 dead, 1,1450 injured and 250,000 homeless; destruction or serious damage to 6,000 buildings and 20,800 housing units	X MSK	Harbi et al. 2007b

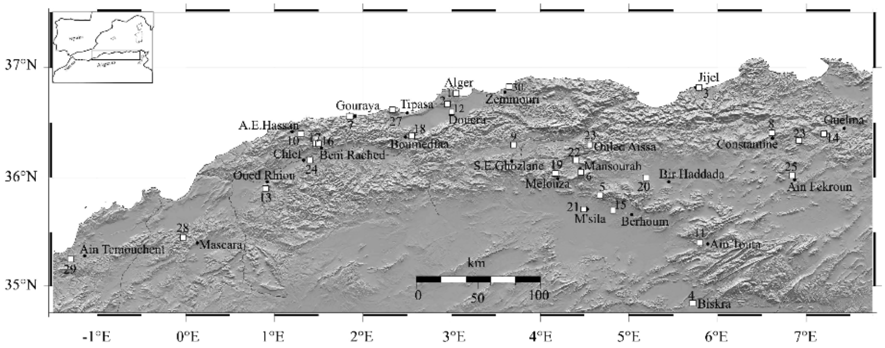


Fig. 1 The most damaging earthquakes in Algeria with estimated intensities (as cited in Table 1). *Circle*: city, *square*: seismic event

east of Algiers (Ayadi et al. 2003, Bounif et al. 2004). Therefore, it offers an opportunity to study in detail the spatial variation of damage distribution and evaluate the related attenuation of intensity necessary for the earthquake engineering and seismic hazard assessment near the capital city of Algeria. The macroseismic survey was carried out a few days after the 2003 mainshock by means of a thorough field investigation using a detailed questionnaire and official reports in the damaged area (Harbi et al. 2007b). The detailed macroseismic study has provided us with the most complete intensity dataset ever obtained from field investigations of previous earthquakes. For comparison, we revisited two destructive historical offshore seismic events, namely the Djidjelli earthquake of 22 August 1856 (Jijel, Io VIII MKS; Ambraseys 1982) and the Villebourg earthquake of 15 January 1891 (Larhat, Io X MM; Rothé 1950).

The crustal attenuation in northern Algeria has been poorly studied due to the lack of strong motion records. The damage distribution of moderate and large earthquakes along the Tell Atlas provides, however, a wealth of macroseismic information. The intensity distribution has been the subject of several studies that allowed determining an attenuation law in Europe (Ambraseys 1995). The decay of body waves may have a direct relationship with the source dimension as represented by the seismic moment and fault rupture size (Frankel 1991). The tsunamigenic 1856 Djidjelli earthquake was studied by Ambraseys and Vogt (1988) who prepared an isoseismals map, and by Harbi et al. (1999, 2003b) who discussed the possible seismic source from the interpretation of seismic profiles. The 1891 Villebourg earthquake presents favourable conditions for a comparison with the 2003 Zemmouri earthquake. Indeed, the coastal location between the seismogenic Cheliff and the Mitidja Plio-Quaternary basins confers to this seismic event and causative source a great interest for the understanding of the earthquake hazard in northern Algeria. These results, in connection with the soil conditions and the building vulnerability suggest that the coastal area, which extends along 1,200 km in the E–W direction, is exposed to a relatively high seismic risk sometimes caused by tsunamigenic sources.

This paper is two-fold: (1) Using the dataset of the isoseismal map produced by Harbi et al. (2007b) and taking into account previous field investigations and macroseismic distribution in the Algiers-Zemmouri region, we estimate the attenuation of intensity with distance from assigned European Macroseismic Scale intensity value to 600 localities; and (2) we compare the results to those obtained for the 1856 (Djidjelli) and 1891 (Villebourg) coastal earthquakes and show similarities from the damage distribution, seismological effects and geological structures viewpoints.

2 The 21 May 2003 Earthquake

The Mw 6.8 coastal mainshock generated strong and damaging effects within 150 km radius as well as significant ground deformation with uplifted marine terraces, liquefaction, minor landslides, rockfalls, ground fissures and anomalies in the flow of springs (Harbi et al. 2007b). The most impressive phenomenon induced by the earthquake corresponds to the large coastal uplift of marine terraces which implied an important continental deformation related to a SE dipping and 55-km-long thrust fault (Meghraoui et al. 2004). The seismic event has been a subject of several studies. Using a simple double difference method, Bounif et al. (2004) relocated the mainshock epicentre on the coastline (36.83°N, 3.65°E, Fig. 1) with 8–10 km hypocentral depth and analysed the distribution of the aftershocks sequence which shows a $\sim 40^\circ$–50° south dipping fault plane and two distinct clusters of seismic events along strike. From the inversion of the teleseismic body waves, joined with GPS and uplift data, Delouis et al. (2004) calculated the effective 12s rupture duration, the 2.86×10^{19} N-m seismic moment and pointed up that the Zemmouri earthquake involved a bilateral rupture propagation from the hypocentre: the south-westward slip with 11–2 km depth range, and the north-eastward slip zone that extends from 6 km depth to the surface. Meghraoui et al. (2004) measured coseismic shoreline changes of emerged algae jointly with kinematic GPS and conventional levelling lines. The obtained dataset allowed them to model the surface deformation along about 60 km coastline and suggest two rupture patches along a 50°SE dipping planar reverse fault geometry located between 5 and 10 km offshore. Using modelling GPS data from 5 stations located west of the epicentral area, Yelles et al. (2004) infer a uniform model on a plane dipping 42° to the south. Semmane et al. (2005) combined geodetic data and accelerograms to model the fault location at 15–22 km offshore and showed two large slip zones on the fault with the largest located west of the hypocenter. Alasset et al. (2006) modelled the initiation and propagation of the tsunami wave triggered by the earthquake and compared synthetic results with the 2 m high waves of tide gauge records of the Balearic Islands, whereas no similar effect was reported along the Algerian coast. Their analysis and modelling lead to the conclusion that an earthquake larger than Mw = 7 followed by tsunami could produce a possible run-up along the Algerian coast (the Zemmouri earthquake did not) and large wave-amplitudes (more than 3 m) could reach the Balearic Islands. Laouami et al. (2004) reconsidered the epicentre location and magnitude using the accelerograms and the accelerometric records, respectively, with the empirical formula of Betbeder-Matibet (1995); they also give details on the recorded acceleration at 12 stations. Harbi et al. (2007b) provided the results of the macroseismic survey conducted immediately after the earthquake and produced maps of damage and intensity of the Zemmouri earthquake. The NE–SW elongation of isoseismals well correlates with the fault direction identified from seismotectonic studies (Ayadi et al. 2003).

3 Soil Conditions

The geological and tectonic setting of the Mitidja basin was presented and discussed at length in previous works (Meghraoui 1988, 1991, Harbi et al. 2004, Maouche et al. 2004). In the 2003 earthquake area, the local geology shows that, the basement outcrops east of Boumerdes, North Thenia and west in the Blida Mountain. It is mainly composed of bedrock formed by schist, micaschist, gneiss and the Mesozoic calcareous units which constitute the eastern mountain chain of Djurdjura. To the west, the basement outcrops at Cap Matifou and Bouzareah (Algiers). The epicentral zone is covered essentially by Plio-Quaternary deposits. The recent Quaternary includes the alluvial deposits made of clay, silt and gravel within the basin area and marine terraces along the coast (Fig. 2). From Boumerdes to Algiers, crossing the Mitidja basin, the local geology is made of soft sediment such as sandy dunes with alluvial and marine deposits, mixed sandstone and clay (fill) and the

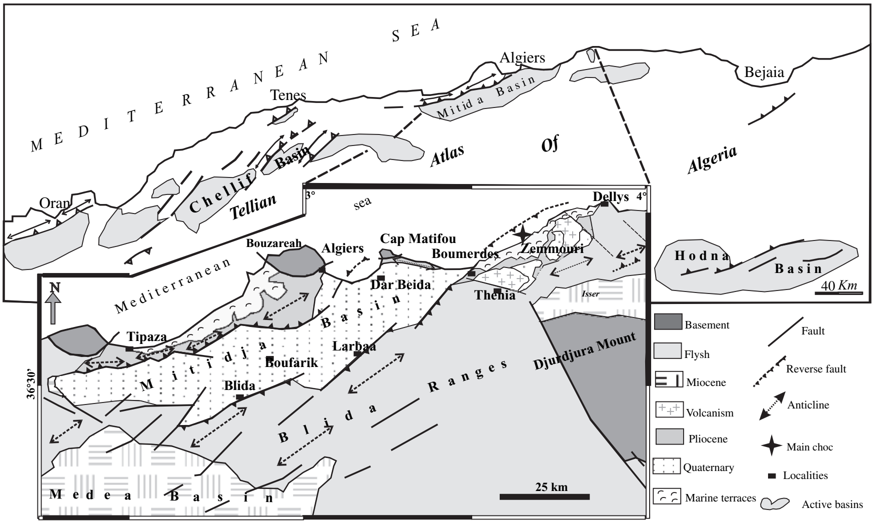


Fig. 2 Structural geological map of the Algiers region including the area affected by the 21 May 2003 Zemmouri earthquake

marshy deposits which extend over the most recent suburbs such as Bab Ezzouar and Dar El Beida in the Algiers province. The early Quaternary (Villafranchian) alluvial deposit made of sand or sand with other components (silt, clay, gravel, sandstone) and the recent landfill, represented by sandy, silty or argillous deposits, cover the area from Boumerdes to Zemmouri and Cap Djinet. To the south of the earthquake area, the Isser, Si Mustapha and Bordj Menaiel cities have the same soil conditions.

4 Damage Assessment and Interpretation

The detailed damage description and other ground effects as well as the intensity assessment are presented in a previous work by Harbi et al. (2007b). The results of the macroseismic study of the Zemmouri earthquake, conducted at about 600 locations, allowed drawing with good constraint the spatial distribution of damage in the form of an isoseismal map (Fig. 3). The NE-SW elongated isoseismals are accentuated along the Mitidja basin mainly because of the lithological and structural framework. It is worthwhile to note that the general shape of intensity distribution appears to be primarily controlled by this sedimentary basin and the isoseismals seems to be compressed in the SE direction. In some localities such as at Bordj Menaiel, Baghlia and Bouira the intensities are influenced by smaller scale basins

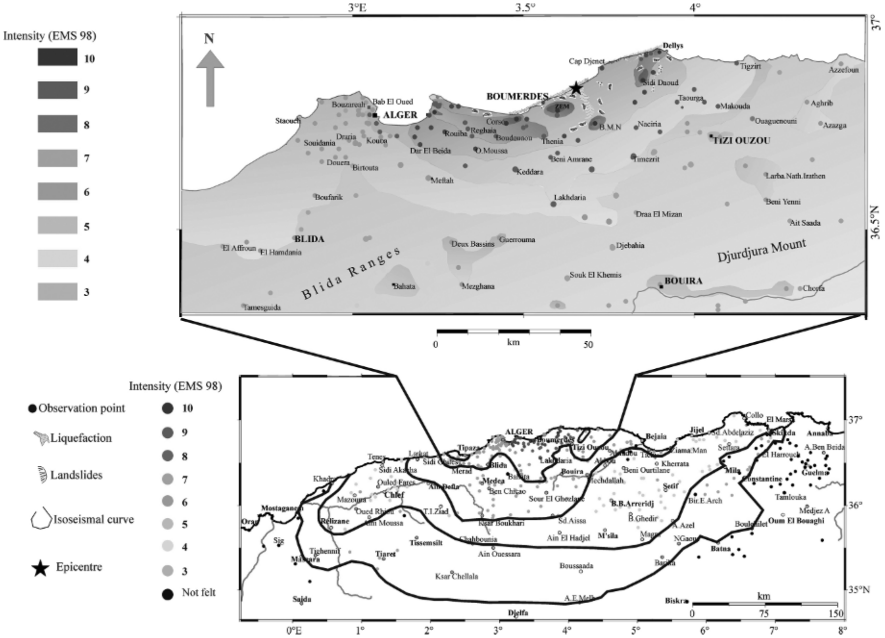


Fig. 3 Isoseismal map of the Zemmouri earthquake of 21 May 2003 (Mw 6.8, I_0 X EMS), modified from Harbi et al. (2007b) (Zem: Zemmouri, Z. Bah: Zemmouri Bahri, B. Kfane: Bordj El Kiffane, BMN: Bordj Menaïel)

containing soft sediments and related local lithological and topographic conditions. However, geology is not the only factor which explains the observed elongation of the intensity patterns. Directivity effects played an important role in the damage amplification particularly for intensities 8, 9 and 10. This is attested by the PGA records which show higher values for the E–W components than the N–S ones, independently from station azimuth, epicentral distance and site conditions (Laouami et al. 2006).

As the first step of analysis, we compared the damage distribution with the population density inside the provinces where the event was felt (Appendix 1). The 2003 epicentral area that includes a large section of the eastern suburb of Algiers city and related large population within the Mitidja basin is crossed by at least 3 macroseismic curves. The macroseismic field investigations also indicate that damage distribution is strongly conditioned by soil conditions and building vulnerability. In some zones, the separation of the isoseismals X and IX could not be achieved because of the large variation of the local geology and likely related site effects. The isoseismals are clearly asymmetric and elongated in the NE–SW direction which represents the fault rupture strike.

5 Attenuation

The assessment of seismic hazard at a given site requires an attenuation law for the peak ground acceleration (PGA). The intensity-attenuation relationship is obtained by deriving empirical correlations between intensity and epicentral distance for earthquakes for which isoseismal maps are available. Many authors developed attenuation relationships worldwide. Douglas (2001) presents a valuable summary of 121 published attenuation relations for PGA. Examples include the attenuation laws developed by Idriss (1978), Joyner and Boore (1981), Campbell (1985), Boore and Joyner (1982), Joyner and Boore (1988), Sadigh et al. (1993), Ambraseys and Boomer (1991) and Ambraseys (1995). In Algeria, generally when assessing the seismic hazard at a given site, authors (Benouar 1996, Naili and Benouar 2000, Laouami et al. 2004) adopt the PGA attenuation laws developed by Ambraseys and Boomer (1991) (Equation (1)) and Ambraseys (1995) (Equation (2)). The former has been derived from 529 accelerograms recorded mainly on soft rock or soil from 219 shallow seismic events (≤ 25 km) mainly in the Mediterranean region, which includes Algerian data, and the second is based after data correction on 1,260 accelerograms generated from 619 shallow seismic events of which 3% are Algerian data.

$$\log_{10}(a_h) = -0.87 + 0.217(Ms) - \log_{10}(r) - 0.00117(r) \pm 0.26P \tag{1}$$

$$\log_{10}(a_h) = -1.43 + 0.245(Ms) - 0.786\log_{10}(r) - 0.0010(r) \pm 0.24P \tag{2}$$

Where $r^2 = (d^2+h^2)$, h is the focal depth (taken at an optimum value of $h = 2.7$ km), d is the epicentral distance in km, Ms is the surface-wave magnitude, and a_h is the predicted peak horizontal ground acceleration. The values 0.26 and 0.24 in Equations (1) and (2) are the respective standard deviation. The parameter P takes a value of zero for 50% probability that the predicted parameter a (ground acceleration) will exceed the real (observed) value and a value of 1 for 84% probability.

Recently, Laouami et al. (2006) published for northern Algeria a new attenuation law (Equation (3)) derived from the strong motion dataset of four moderate Algerian earthquakes (Constantine, 1985; Mont Chenoua, 1989; Mascara, 1994 and Ain Benian, 1996).

$$a(m/s^2) = 0.38778\exp(0.32927M_s)\left[D^{0.29202} + 1.557574\right]^{-1.537231-0.27024R} + 0.03 \tag{3}$$

Where $D = \sqrt{R^2 + d^2}$ is the hypocentral distance, the constants are obtained by fitting the experimental maximum acceleration of the three components at each distance the least square technique (Laouami et al. 2006).

The 2003 Zemmouri earthquake occurred in an area for which no other reliable and complete isoseismal maps exist for previous seismic events. It is important, therefore, to analyse the attenuation for this single event by taking into consideration the local lithological characteristics. Based on the analysis of the attenuation of intensities during an earthquake, the variation of the intensity is assumed to be primarily related to the surface wave propagation, which is controlled by the change of soil conditions. The Zemmouri earthquake represents a good example for assessing the intensity attenuation with distance in several ways. The approach we followed here consists in performing a regression analysis using an equation of the form:

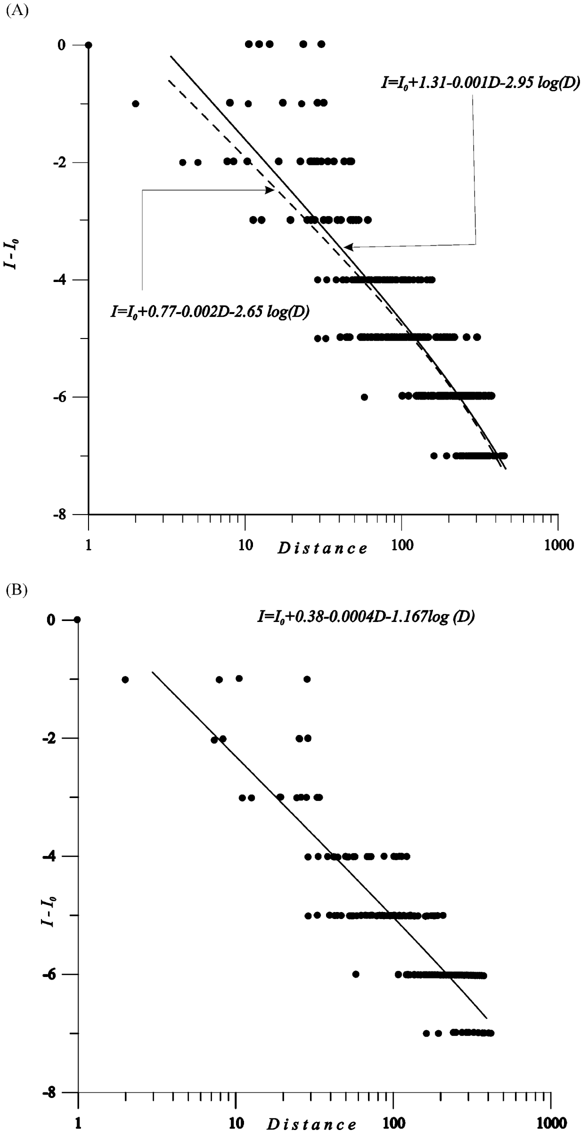
$$\mathrm{I} = \mathrm{I}_0 + \mathrm{a} + \mathrm{b}^*\mathrm{D} + \mathrm{c}^*\log(\mathrm{D}) \tag{4}$$

for all the data set (Douglas 2001). For all computations I_0 is 10, D is the macroseismic epicentral distance in km and the coefficients a, b and c are given in Table 2 for various cases. For practical reasons and since the instrumental epicentre is coastal and the activated fault emerged at about 8 km offshore, we used in our computations the macroseismic epicentre estimated at the city of Zemmouri. From the isoseismal map, the intensity decreases gradually until 3 within a radius of ~ 500 km to the SE as well as in the NE–SW direction parallel to the fault rupture strike. The intensity-distance relationship for all the combined data is shown on Fig. 4a. We calculate this attenuation using two directions: to the SE (perpendicularly to the fault azimuth) and to the SW (parallel to the fault azimuth) (Fig. 4b and 4c). The regression is performed using average values of D (from isoseismals) and also all data in the two directions with respect to the macroseismic epicentre (Fig. 4d). For soil classification, Fig. 4e shows that the intensity decreases clearly at the rock soil

Table 2 Regression coefficients for the used equation

Parameters	All data	Fault azimuth (FA)	FA+ 90°	Isoseismals	
				FA	FA+90°
A	1.31	0.137	0.38	1.22	0.159
B	−0.001	−0.0032	−0.0004	−0.01	−0.0004
C	−2.95	−1.193	−1.167	−1.820	−2.325

Fig. 4 Intensity attenuation curves. (**a**) all data, (**b**) perpendicular to the fault azimuth, (**c**) fault azimuth, (**d**) based on isoseismals, (**e**) combined with the geological cross-section, (**f**) PGA distance attenuation, (**g**) PGA-Intensity correlation



level. In this case we use subjectively four categories of site classification which are related to the lithofacies as shown in the used geological cross section. One may consider that attributing an amplification value to broad areas such as at the Blida Mountains is useless.

To determine the contribution of the source of the 2003 earthquake to the seismic hazard, it is essential to estimate how the seismic parameters such as the peak acceleration or EMS intensity decrease with distance. Our attempt is to use previous works on the elaboration of an empirical attenuation law for northern Algeria and

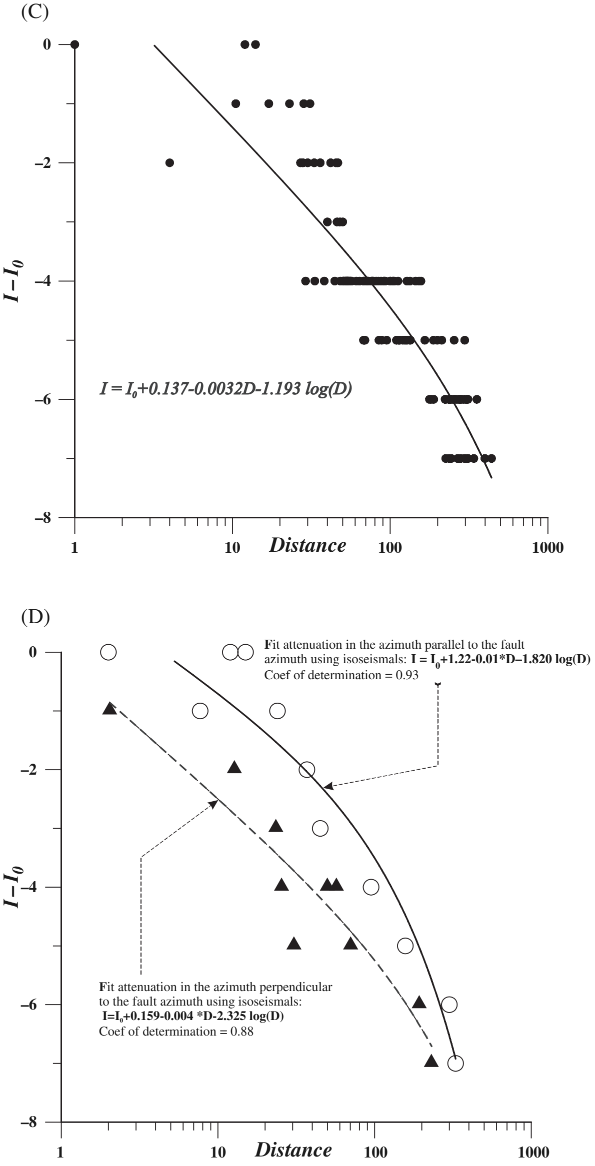


Fig. 4 (continued)

horizontal peak acceleration decays as a function of distance (Laouami et al. 2004) and provide a comparison with the attenuation of intensities for the Algiers region. Only the PGA values at sites for which the intensity is available are considered and we obtain a good correlation between the distance and PGA parameters (Fig. 4f). All observed PGA values show a better fit than the average values predicted by

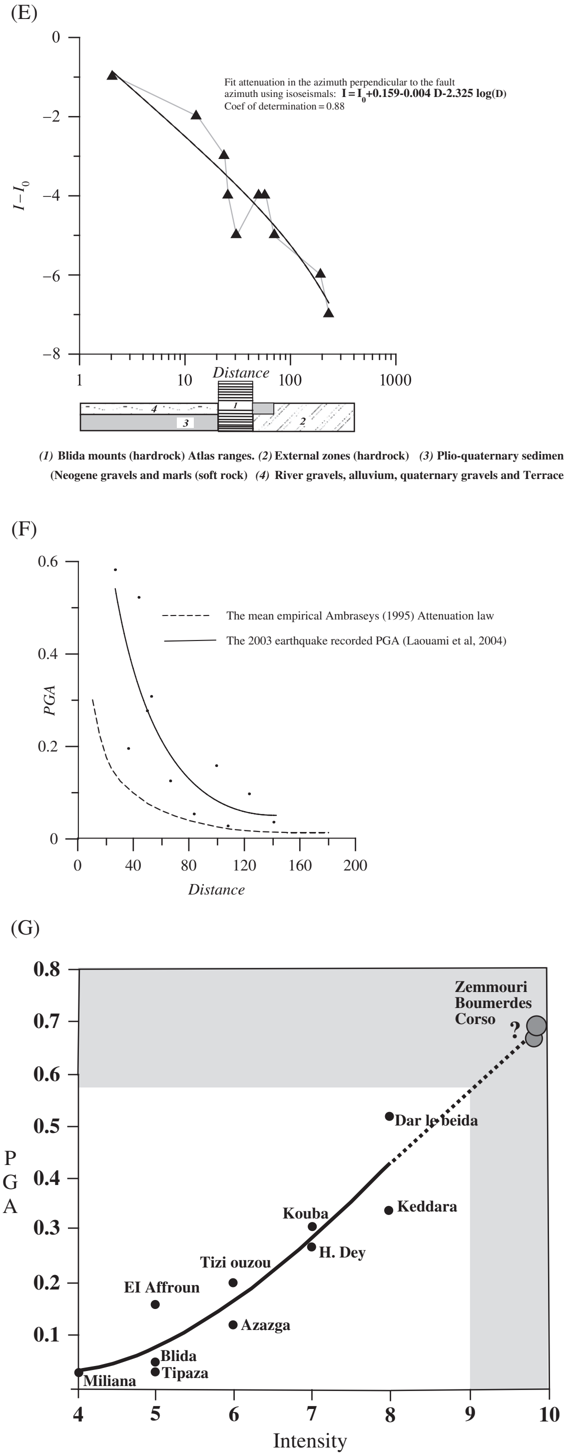


Fig. 4 (continued)

Ambraseys (1995) which clearly underestimates the recorded accelerations for all distances less than 50 km. This significant variation up to 50 km can be interpreted as due to the amplification effects but it requires further field investigations. The site amplification, however, is clearly highlighted by Laouami et al. (2004) at Kaddara site in which a significant PGA variation is observed between two stations of 150 m distance (0.34 g and 0.58 g) suggesting site effect phenomena. Unfortunately, there are no ground acceleration records in the epicentral zone of intensity IX and X in which the ground motion was certainly strong. The plot on Fig. 4f suggests that the peak ground horizontal acceleration at the macroseismic intensity IX and X locations is probably more than 0.70 g. On the basis of the strong-motion and intensity databases ($I \geq 4$) of the 2003 Zemmouri earthquake (Laouami et al. 2004, Harbi et al. 2007b, respectively), we investigated the correlation between the available strong ground-motion and earthquake damage through a regression analysis. The peak ground acceleration (PGA) well correlates with the earthquake damage. The empirical relationship between PGA and the intensity (I) is determined in this study as follow:

$$(\mathrm{PGA}) = 0.403 + 0.292(\mathrm{I}) - 2.554\ \mathrm{Log}(\mathrm{I}) \tag{5}$$

This PGA-intensity correlation is particularly useful in real-time applications for damage prediction and assessment. This empirical relationship shows (Fig. 4g) that the PGA value could be higher for $I > 8$ particularly in the zones (the grey area on Fig. 4g) close to the epicentre (Zemmouri ($I = 10$) and at Boumerdes ($I = 10$) for which PGA records are not available.

6 Comparison with Historical Damaging Events

The Djidjelli earthquake of 22 August 1856 and its foreshock and aftershocks as well as the Villebourg earthquake of 15 January 1891 and its following seismic sequence caused the largest catastrophes affecting respectively the eastern and the central Algeria coastal area before the 2003 Zemmouri earthquake. They are also considered as among the most well documented historical seismic events. The detailed re-appraisal of the damage and surface effects of these historical events allowed us to obtain a complete isoseismals map for each one of them. The comparison with the recent Zemmouri earthquake is thus pertinent since these earthquakes, being the largest that occurred along the coastal area, contributes considerably to the reduction of seismic risk in northern Algeria.

6.1 The Djidjelli Earthquake

The 1856 Djidjelli earthquake produced damage effects in a large area along the Algerian coast and was felt at several points of the northern Mediterranean coast

(Fig. 5a). A first study of the Djidjelli earthquake has been accomplished by Ambraseys (1982) who published the corresponding isoseismals map (VI^+ and VII^+) and assigned intensity VIII MSK to the city of Djidjelli (now Jijel). Recently, Harbi et al. (2003a) re-assessed the extent of the damage and the people reaction by making a comprehensive research using contemporary accounts relative to this event and confronting all the available reports, press accounts and published papers (Aucapitaine 1856, Gaultier de Claubry 1856, De Senarmont 1857, Rothé 1950, Ambraseys 1982; contemporary press: *Akhbar, Le Moniteur Algérien, L'illustration, La Seybousse, Le Courrier mercantile, La Gazette de Lyon, 1856*). The analysis shows macroseismic data with a relatively good description of the impact of the earthquake on humans, man-made buildings and ground movements. Although the maximum damage is reported in a rather small area (Fig. 5b), the mainshock caused the loss of at least five lives and triggered a sea wave of 2–3 m high that flooded the Djidjelli coast a number of times.

6.2 The Villebourg Earthquake

The earthquake of 15 January 1891 of Villebourg (now Larhat) is considered among the largest event after the 2003 Zemmouri earthquake that occurred in the coastal area of north-central Algeria. Due to the location of maximum damage, one may question the inland epicentre location as previously suggested by Rothé (1950) at 36.5°N, 1.80°E and Ambraseys and Vogt (1988) at 36.50°N, 1.90°E. Therefore, it became important to reassess the macroseismic data in light of the new information retrieved mainly from the local press reports. The most extensive accounts are given in "La Dépêche Algérienne" and the contemporary document of Pomel (1891). All the macroseismic information (Appendix 2) retrieved from the available sources at 20 sites, were carefully analysed and used in the reassessment of the ground shaking with reference to EMS intensity scale. As a result of the analysis of the reconstructed macroseismic field, an isoseismal map has been drawn (Fig. 6) and accordingly a macroseismic epicentre was located on the coast, between Villebourg (Larhat nowadays) and Gouraya, at 36°56N, 1°85E.

All sources describe surface effects such as rock falls and landslides triggered by the Villebourg earthquake. The retrospective study and related construction of the macroseismic field of this earthquake coupled with a morphological analysis has allowed a better understanding of the seismotectonic framework of the study area. We present an aerial photo which shows the landslide (Fig. 7) on which the city of Larhat (ex Villebourg) is constructed today. This landslide was certainly reactivated during the earthquake (see Appendix 2) and is characterized by the presence of marine terraces showing multiple scarps displaying gliding planes inclined northwards. The recent tectonics of the epicentral area is highlighted by a set of uplifted terraces incised by the Damous River running parallel to the NE-SW trending active geological structure.

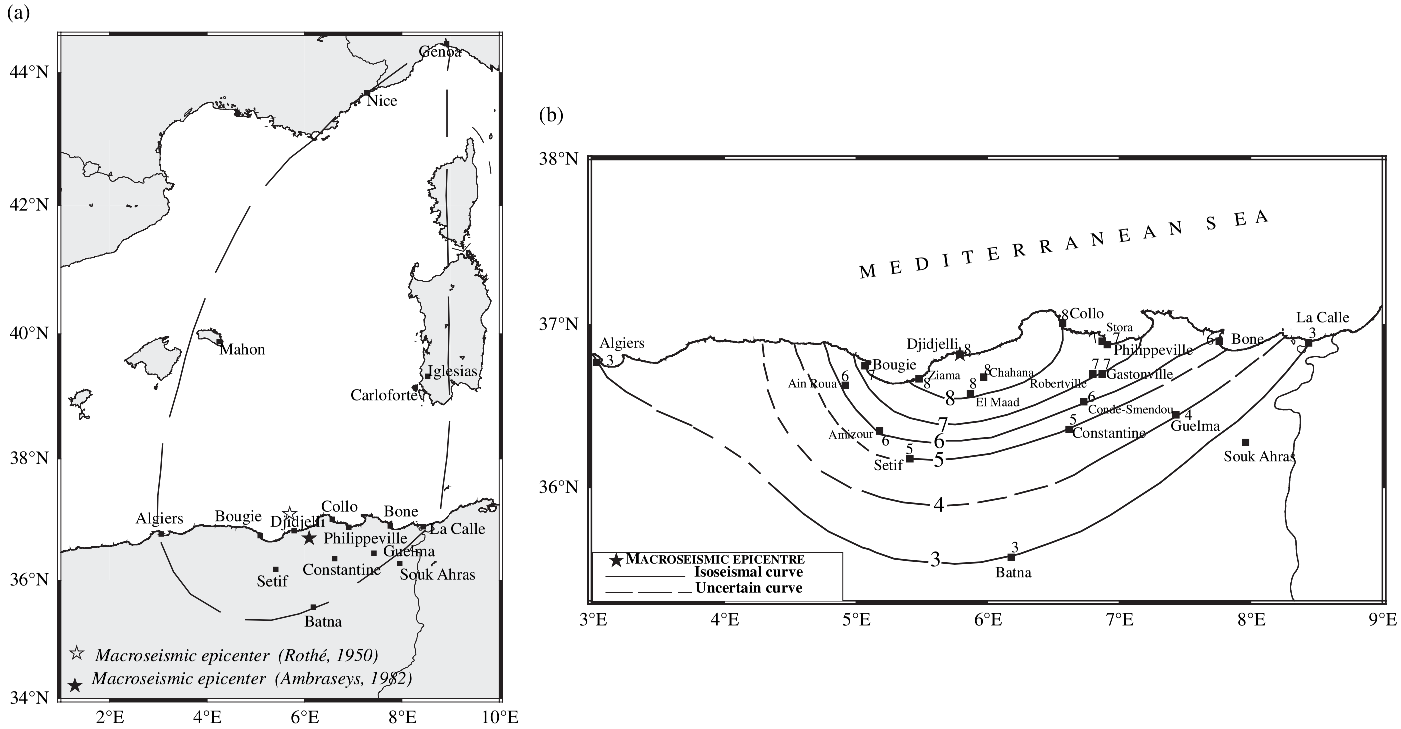


Fig. 5 (**a**) Area of perceptibility of the Djidjelli earthquake of 22 August 1856 (after Harbi et al. 2003a modified from Ambraseys, 1982). (**b**) Isoseismal map of the Djidjelli earthquake (Ms 6.0, I_0 VIII EMS), modified from Harbi et al. (2003a)

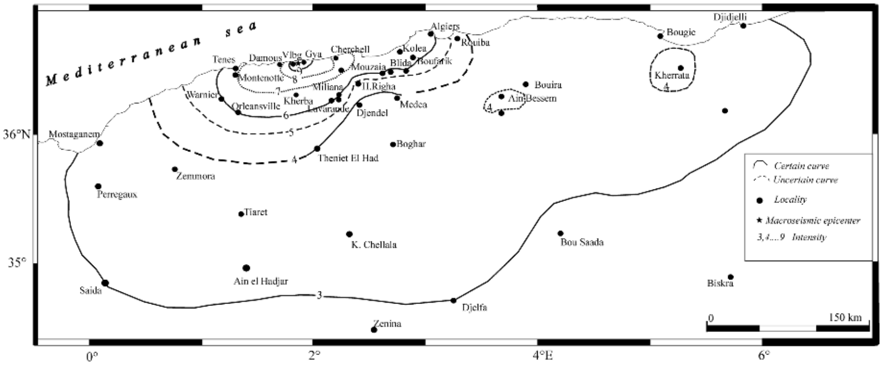


Fig. 6 Isoseismal map of the Villebourg earthquake of 15 January 1891 (Ms 6.0, I_0 IX EMS) (Vlb: Villebourg, Gya: Gouraya)

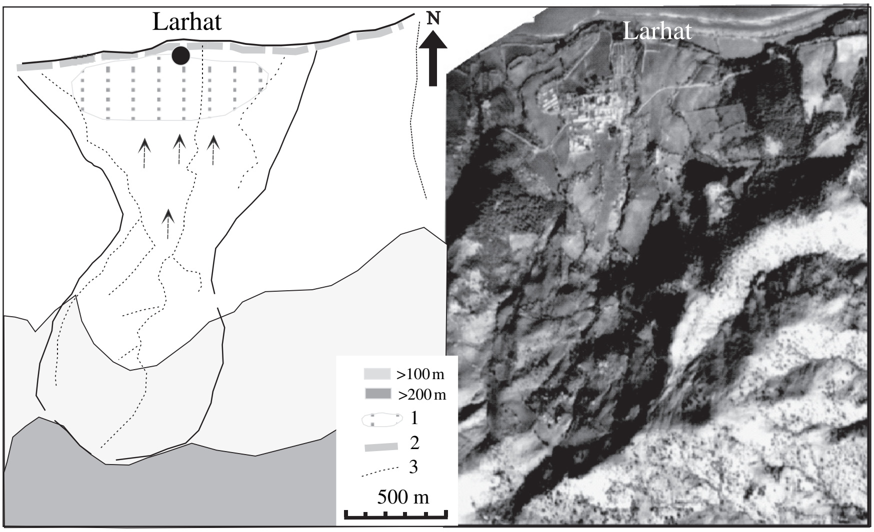


Fig. 7 The landslide reactivated by the Villebourg earthquake of 15 January 1891 (1: compressive pad, 2: zone uplifted during the earthquake, 3: hydrographic network)

7 Discussion and Conclusion

The 2003 Zemmouri earthquake induced a large number of fatalities and serious damage along the Algerian coast. The results of the detailed macroseismic survey indicate the spatial distribution of the related effects in terms of an isoseismals map and related intensity attenuation. A maximum intensity of X (EMS) has been assessed inside numerous isolated areas separated by others with a lower intensity

(VIII and IX). The decrease of intensity with the epicentral distance is not homogeneous and depends strongly on the azimuth at a regional scale. The area with intensity greater than or equal to VI is elongated in the NE-SW direction with a length of 160 km and a width of 50 km. A regression analysis performed in two different azimuths conduced to eliminate the effect of the fault itself and the low attenuation around the faulted area. The results obtained, using the average radii of isoseismals, show a clear difference between the fault azimuth and its perpendicular direction. This difference is related to the geological conditions which are marked by the thrust-and-fold Atlas belt and the Mitidja intermountain basins.

As shown in diverse attenuation curves related to the Zemmouri mainshock, this study suggest a low attenuation in the affected area. The intensity attenuation is clearly stronger along the NW-SE direction with an abrupt decrease to the South at the Blida Atlas Ranges. This highly fractured E-W zone could have played the role of a screen for the seismic waves propagating to the South. The occurrence of an earthquake with epicentre further to the west part along the tectonically active zone, at Blida for example, will have a strong impact on the Algiers capital city. The different attenuation relationships deduced for the Zemmouri earthquake can be inferred to calculate the probability of damage due to a future earthquake occurring in the same area including Algiers and its surroundings (Table 3).

The Djidjelli 1856 and Villebourg 1891 earthquakes are smaller than the Zemmouri event which produced significant surface effects and deformation. However, the three earthquakes are almost comparable in the extent of the affected area as well as in some of their characteristics (Table 4). As we know, the magnitude of historical events may be assessed roughly from the area of perceptibility. By using the relationships derived by Benouar (1994) for Algeria: $Ms = -0.04 + 2.56 \log(r_3)$ (where r_3 corresponds to the mean epicentral distance of an area within which the shaking was felt with intensity III (MSK or EMS)), we calculated the surface-wave magnitude of both historical events (Table 4). It is worthwhile noting that the Djidjelli and Villebourg earthquakes were also felt far from the shore by sailors of the *Aviso Tartare* located at 15 mi at North 7° of Djidjelli and the ship *Porro* located at 6 mi of Cherchell, respectively. The maximum intensities VIII+ and IX EMS have been estimated, respectively, for the 1856 and 1891 historical events. For both of them, the intensity could easily exceed these estimations in the case of an epicentre closer to the coast. In the same way, the respective surface-wave magnitude may differ from those calculated (Table 4). Regarding the Djidjelli earthquake if we consider an area of perceptibility including the localities of the north-Mediterranean coast

Table 3 The different attenuation relationships deduced for the Zemmouri earthquake

	Attenuation relationship
All data	$I = I_0 + 1.31 - 0.001D - 2.95 \log(D)$
Perpendicular to the fault azimuth	$I = I_0 + 0.38 - 0.0004D - 1.167 \log(D)$
Parallel to the fault azimuth	$I = I_0 + 0.137 - 0.0032D - 1.193 \log(D)$
Parallel to the fault azimuth using isoseismals	$I = I_0 + 1.22 - 0.01D - 1.820 \log(D)$
Perpendicular to the fault azimuth using isoseismals	$I = I_0 + 0.159 - 0.004D - 2.325 \log(D)$

Table 4 Similarities of the characteristics of three destructive coastal earthquakes

	Zemmouri 2003	Djidjelli 1856	Villebourg 1891
Type of location	Coastal	Offshore*	Coastal
Magnitude	Mw 6.8	$Ms \geq 6.0$	$Ms \geq 6.0$
Intensity I_0	X (EMS)	VIII$^+$ MSK	IX EMS
Source	Offshore	Offshore	Offshore
Mean radius of $I = VIII$	40 km	$\sim$ 40 km	15 km
Mean radius of $I = III$	$\sim$ 350 km	$\sim$ 230 km	$\sim$ 260 km
Direction of the isoseismals	NE-SW	NE–SW	NE–SW to E–W
Other parameters	– Faulted area: 50 km – Coastal uplift: 50 cm – The sea retreated and flooded the *Balearic* coasts – Tsunami	– The sea retreated by $\sim$ 35 m and a sea-wave of $\sim$ 3 m flooded the *Algerian* coast a number of times. – Tsunami – No evidence of coastal uplift	– Coastal uplift of 30 cm – The sea retreated by $\sim$ 30 m and flooded the *Algerian* coast. – No strong evidence of tsunami

* Even if the macroseismic epicenter is coastal, we think that the instrumental one could be offshore.

where the shock was felt (Fig. 5a), we obtain $Ms = 6.6$ when Ms is equal to 6.0 if only the Algerian part is taken into account (r_3 on Fig. 5b). On the other hand, the lack of intensity points offshore determines the shift of the epicentre onshore. We assume that the strongest earthquake, which hit Djidjelli in the past, may be due to an offshore causative fault (Harbi et al. 2003b). The comparison of the isoseismal maps of the three earthquakes presented in this work show quite similar attenuation laws with a slight shift for the 2003 Zemmouri event. This difference is due to the size of shock ($Mw = 6.8$, greater than the magnitude of the two others events). In order to develop a curve that predicts the intensity for the Algerian offshore events, we used the equation in the form of:

$$I = a + b^{*}D + c^{*} \log(D) \tag{6}$$

Where $D^2 = (r^2 + h^2)$, h is the focal depth (taken at an optimum value of $h = 8$ km), r is the epicentral distance in km. The results of the fitting are presented in Fig. 8 from which, we can see that the relation fit the used data with a certain degree of reliability and thus, they can be used in seismic hazard analysis for Algerian offshore events.

Destructive earthquakes occur very infrequently along the Algerian coastline but the Zemmouri 2003 event (Mw 6.8) warns us against possible strong events

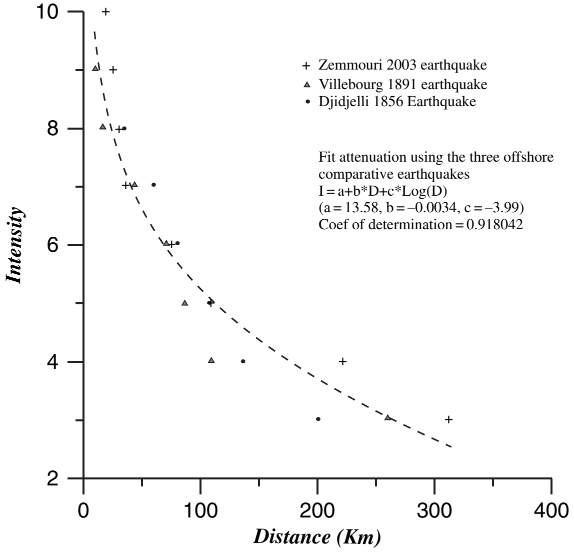


Fig. 8 Attenuation regression curve computed for the Djidjelli, Villebourg and Zemmouri earthquakes, using isoseismals

which should be expected in the future, accompanied by geodetic effects and tsunamis. The comparison between the three reviewed earthquakes shows the potential for destructive seismic events and the presence of seismogenic sources along the coastline.

Acknowledgments This article is dedicated to Jean Vogt who showed a constant interest in the historical seismicity of Algeria. Anonymous reviewers are gratefully acknowledged for critically reading the manuscript and helpful suggestions. This research is supported by CRAAG and benefited from the ICTP-OEA (Trieste) Programme in the framework of the North African Seismological Group (NASG). The field investigations were also supported by the INSU research project ACI Cat-Nat "Risque sismique de la région d'Alger".

Appendix 1

Table A.1 Rate of the population (*) living in the earthquake area and corresponding intensity

Wilaya (district)	Population	Number of persons living in the earthquake area	Number of victims	Intensity
Boumerdes	742,466	~ 4 millions	1,382	I = X, IX and VIII
Algiers	3,335,142		883	
Tizi ouzou	1,115,352	~ 4.5 millions	7	I = VII, VI and V
Tipaza	686,660		–	
Bouira	773,118		2	
Blida	1,116,292	~ 4 millions	2	I = V and IV
Médéa	860,592		–	
Béjaia	838,484		2	
Relizane	668,828		–	
Bordj Bou Arréridj	633,514		–	
Djelfa	750,126		–	
Mostaganem	752,380	~ 4 millions	–	I = III
M'sila	866,198		–	
Mascara	818,612		–	
Oran	1,666,218		–	
Constantine	1,036,518		–	
Tissemssilt	281,498		–	
Batna	1,034,422		–	
Skikda	956,994		–	
Guelma	590,746		–	
Total	*24,232,152*	*Downwards: 17%, 19%, 16%, 32%nd 16%*		

*From official reports.

Appendix 2

This appendix summarizes the macroseismic effects of the Villebourg-Gouraya earthquake as reported in the original and contemporaneous sources cited in the text.

On 15 January 1891, at 3 h 55 min, a destructive earthquake struck the locality of Gouraya and its surroundings villages. The epicentral area, which is centred between Gouraya and Villebourg (Larhat nowadays, a village of the Gouraya commune), is located at 110 km west of the capital Algiers. Two shocks were felt in the time span of 10 min and the earthquake was strong enough to awake people and caused great panic in the coastal zone of Tenes-Algiers. The whole population of Gouraya, was evacuated and camped in the streets. Many people of Algiers fled their homes and as reported 500 crowded to the Government square. Two Europeans and 37 native persons were killed, buried under the ruins of their traditional houses, in the commune of Gouraya and many people were injured. It is said that about hundred people were killed in farms near Gouraya due to bad local traditional housing units called "gourbis". The cost of damage was estimated, by the administration, at 47,000 French Francs. The earthquake was felt over an area of 300 km; in Djelfa, 240 km south of Gouraya, where the shock was noticed by very few persons.

The earthquake caused widespread damage in the epicentral area mainly associated with the high vulnerability of the traditional housing units. All the sources of information concentrate on the destruction and serious damage in the localities of Gouraya and Villebourg and their close farms. Gouraya was almost razed, 53 European houses collapsed as the country police barracks and the telegraph house were heavily damaged beyond repair. Several traditional houses and even concrete structures in villages crashed down. At Villebourg, 22 houses out of 24 were almost totally demolished; the remaining sections of walls are disconnected, the foundations unusable and the factory of Oued Mellah is described as an accumulation of ruins. The Bonefoy farm located between Gouraya and Villebourg was completely destroyed. Several houses were shattered at Marceau (Menaceur nowadays) and Blida but more precise details are lacking. At Montenotte (Oued Allalah near Tenes) some buildings sustained damage and several ceilings collapsed and at El Affroun several houses cracked. At Koléa, an individual house collapsed and the losses were severe. At Orléansville, a report mentions some cracks and damaged ceilings as well as broken glasses and many overturned objects. No serious damage nor casualty are reported at Tenes where only few houses cracked and the communications disrupted between Tenes, Cavaignac and the Trois Palmiers because of the breaking of the footbridge. In the capital Algiers, damage consisted of the partial collapse of a terrace of one house located at Bab El Oued; several houses cracked in this locality and furniture moved and dishes rolled on the ground; at Mustapha, the mayor evacuated the inhabitants of one building threatening collapse; at Mustapha Supérieur, one villa cracked and in the Casbah a section of a wall fell down and some houses cracked; in general broken glass and overturned furniture are reported in various places of the city.

It is reported in the press and contemporary accounts that in Kherba and Lavarande the water sources dried up. The direction of the shock was vertical. The earthquake was associated with long and deep cracks with one of 40 cm wide running through the village of Villebourg. It was reported that "... it is to be feared that the ground will come down in the sea". In fact, the mausoleum of Sidi Braham was projected into the sea. The inhabitants and local authorities wondered whether they could rebuild at the same place. We found no reports of sign of liquefaction but rockfalls and landslides, as a result of the shake, were considered as the most spectacular phenomena at that time. Rockfalls were observed at Beni Hendel and landslides cut the road Mouzaïa-Algiers. Moreover, the landslide on which the Village of Villebourg has been built, was re-activated by the earthquake. After the earthquake, a coastal uplift of 30 cm, attested by the uplift of algae levels of the coastline and the change of the depth of the sea level, was observed. It was also said that as a result of the shock the sea retreated 30 m from the shore and returned flooding the coast. A comparable phenomenon was observed during the 2003 Zemmouri earthquake.

The Gouraya earthquake occurred without any premonitory sign but was followed by a series of aftershocks with the two most important strong events (that occurred the same day) showed no further damage or casualties. According to Ambraseys and Vogt (1988), the aftershocks continued to the beginning of the following month. However, Hée (1950) reports some shocks which hit the Cherchell region on June, July and September 1891.

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