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HISTORICAL SEISMOLOGIST

Seismicity of Algeria from 1365 to 2013: Maximum Observed Intensity Map (MOI_{2014})

by A. Ayadi and M. Bezzeghoud

Online Material: Earthquake database.

INTRODUCTION

Algeria is one of the most seismically active areas in the Mediterranean basin. The available catalogs reported numerous destructive earthquakes striking different regions, such as Algiers (1365, maximum observed intensity $I_o = X$; 1716, $I_o = X$; Ambraseys and Vogt, 1988), Oran (1790, $I_o = X$; Lopez Marinas and Salord, 1990), Djidjelli (1856, $I_o = IX$; Ambraseys, 1982), Orléansville (1854, M_s 6.7; Rothé, 1950), El Asnam (1980, M_s 7.3; Yielding *et al.*, 1989), Constantine (1985, M_s 5.9; Ousadou *et al.*, 2013), Tipasa-Chenoua (1989, M_s 6.0; Bounif *et al.*, 2003), Mascara (1994, M_s 6.0; Ayadi *et al.*, 2002), and Zemmouri (2003, M_w 6.8; Harbi, Maouche, Ousadou, *et al.*, 2007; Ayadi *et al.*, 2008). This seismicity is related to the collision between the African and Eurasian plates and is located within the Tell Atlas of Algeria along the plate boundary zone. Two periods that are related to the installation of the Algerian seismic network are identified from the seismic catalog of Algeria: the pre-1910 and post-1910 periods.

Before 1900, numerous authors conducted seismic studies following the macroseismic approach, such as Perrey (1847), Chesneau (1892), and Montessus de Ballore (1892). All of these studies were based on human perception of shaking along with interpretations of intensity and descriptions of each earthquake's effects and damage. Isoseismal curves were drawn for each earthquake showing the extent of damage near the epicenter and the attenuation of the macroseismic intensity. The absence of instruments in Algeria before 1900 confined the seismological studies to their macroseismic aspect until 1910, which coincides with the implementation of the first seismological station in Algiers and began the instrumental era of seismological surveys in Algeria. Before 1910, all of the seismic events were studied by evaluating the intensity in relation to the damage produced and the effects generated by the event (Fig. 1).

This study considered only the maximum observed intensity (MOI) for each earthquake, which enabled us to draw a map of seismic zonation that highlights the regions of high, medium, and low levels of seismic shaking. Our map of MOI_{2014} represents a fundamental document for land use, especially for countries with available databases limited primarily to macroseismic intensity. This map is an updated version of the latest one from Bezzeghoud *et al.* (1996) and incorporates all the data available between 1365 and 2013, including the strong events of the last two decades, such as Mascara (1994), Ain Temouchent (1999), Zemmouri (2003), Laalam (2001), and Beni Ilmane (2010). More than a thousand intensity data points were used in this study; a portion of the data, available in the Algerian catalog, was historical, but most was recorded instrumentally. We have also reviewed all of the MOI maps that have been drawn, including those by an anonymous author (1925), Bezzeghoud *et al.* (1996), Bockel (unpublished document, 1970), Roussel (1973a,b).

SEISMICITY

The seismicity of Algeria (Fig. 2) is concentrated in the northern part of the country along the Tell Atlas (32° N–38° N, 2° W–9.5° E), which occupies the southern side of the Mediterranean basin and has been structured into folds and thrusts since the early Cenozoic by compression oriented in a north-northwest–south-southeast direction, with a shortening between the African and Eurasian plates of ~4 mm/yr (Bezzeghoud *et al.*, 2014). Over the last three decades, the region has experienced numerous destructive events that were linked to specific seismogenic zones such as the El Asnam, Mont Chenoua-Tipasa, and Zemmouri thrust faults and the Constantine strike-slip fault. Most of the seismic data are presented as intensities for the period of interest between 1365 and 2013. During this period, we considered events with maximum intensities greater than or equal to VI (Table 1) according to the database published by the Center for Research in Astronomy, Astrophysics and Geophysics (CRAAG, Algiers, Algeria) (Mokrane *et al.*, 1994), with the largest earthquakes occurring in Algiers (1365 and 1716, $I_o = X$) and Oran (1790, $I_o = X$).

The historical record of seismicity in Algeria is incomplete and is characterized by discontinuous coverage, especially for small- or moderate-sized earthquakes (Fig. 2). Thus, we have reported only well-documented events that have been revised by different sources (Rothé, 1950; Harbi, Benouar, and Benhallou, 2003; Harbi, Maouche, and Benhallou, 2003). Numerous small seismic events are obviously missing from the database for many reasons. However, we are confident that all of the major or damaging earthquakes within or near large urban areas have been mentioned in the catalogs used for this study. The seismicity map shows a sparse distribution that must

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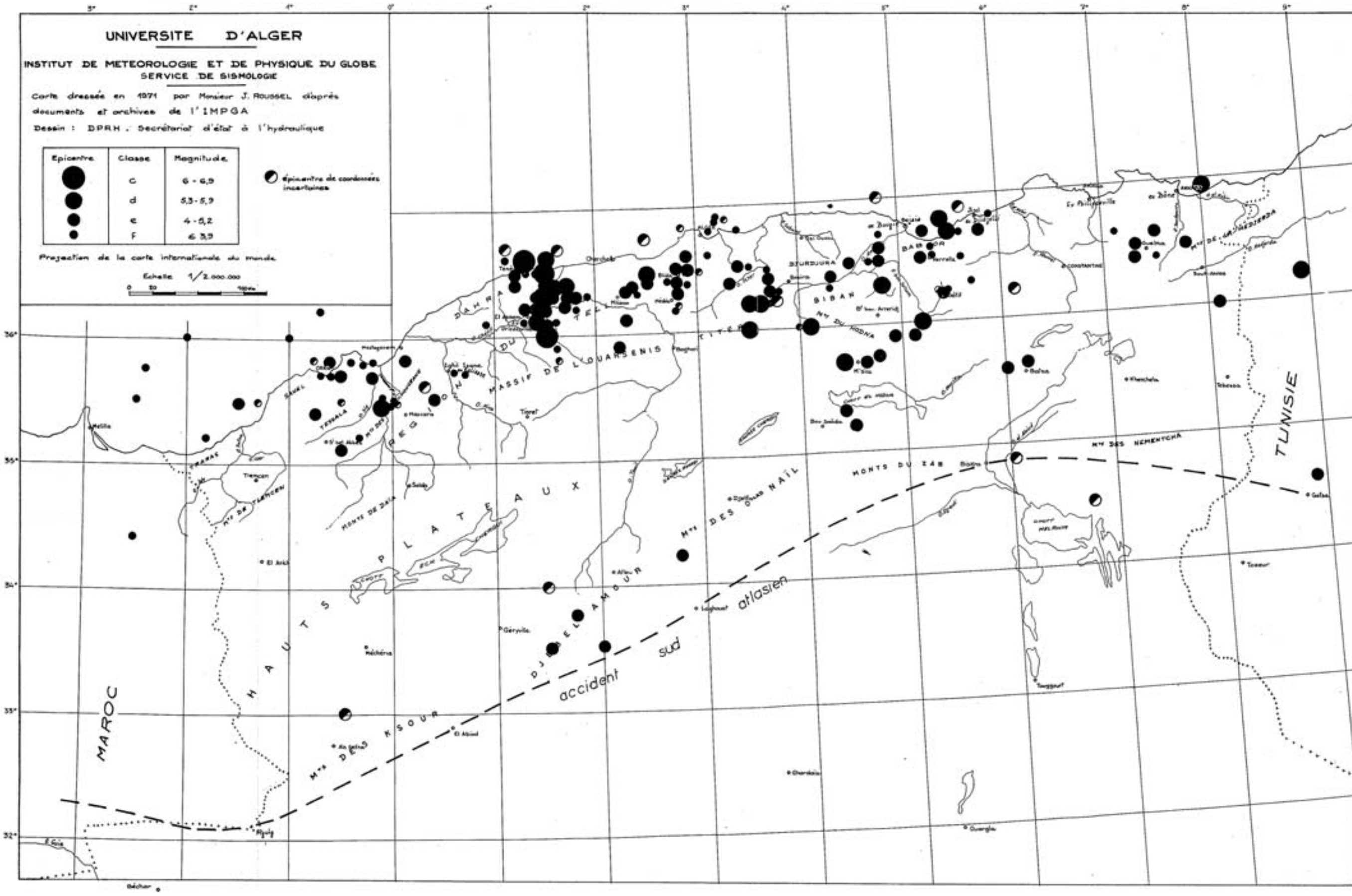


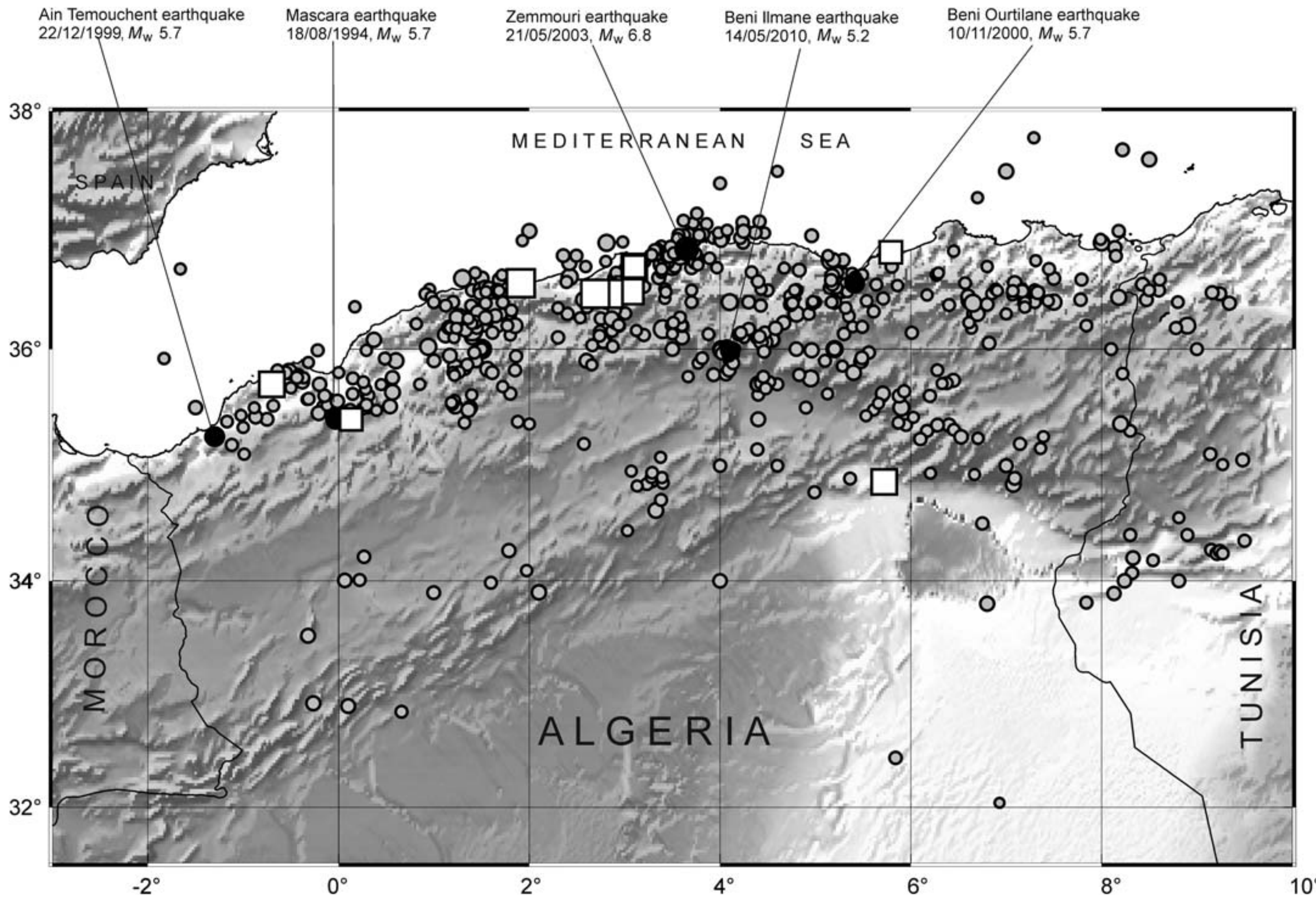
▲ **Figure 1.** Seismicity of Algeria from Roussel (1973b).

be attributed to the inferior reporting of events in sources that lacked material of local origin rather than to a lack of seismic activity. Figure 2 shows the distribution reported in the CRAAG catalog for seismic events with magnitudes greater than 4.0 that occurred during and after 1910, and most of the epicenters are concentrated around specific seismogenic areas such as the El Asnam, Mitidja, and Constantine basins.

To mitigate the incompleteness of the catalog, considerable effort was expended to retrieve as many events as possible for inclusion with the original historical documentary sources and to proceed with the investigation and analysis of these events by considering their geographical, cultural, and historical context. Many events might be discovered and added to the seismic database, which has been clearly demonstrated by Harbi, Benouar, and Benhallou (2003) and Harbi, Maouche, and Benhallou (2003). It is well known that the instrumental record of seismic events is incomplete because of inadequate instrumentation and the poor coverage of seismogenic areas from 1900 until the installation of the first Algerian Telemetered Seismological Network (Bezzeghoud *et al.*, 1994). The seismic events along the Tell Atlas of Algeria are of moderate magnitude, with strong events once or twice a decade. Special attention should be paid to offshore and coastal seismicity causing strong and destructive events, such as Djidjelli (1856; Harbi *et al.*, 2011) and Zemmouri (2003; Harbi, Maouche, Ousadou, *et al.*, 2007; Ayadi *et al.*, 2008), which were responsible for significant damage. The seismicity of the northern region of Algeria is dominated by thrust focal mechanisms to the west and centrally and by strike-slip faults to the east (e.g., Bezzeghoud *et al.*, 2014; Ousadou *et al.*, 2014).

MACROSEISMIC DATASET

The Algerian earthquake catalog is primarily based on historical data that were accumulated using a macroseismic approach, in which observed intensity values were assigned for each event. In this study, we used intensity data extracted from over ∼600 years (1365–2013) to produce a map of MOIs. We compiled the available macroseismic studies by extracting only the maximum intensity value for each event and used data regarding 421 earthquakes (see Ⓔ Table S1, available in the electronic supplement to this article) that occurred within the 600-year period and that were attributable to numerous authors: Perrey (1847), Chesneau (1892), Montessus de Ballore (1892, 1906), Hée (1925, 1933, 1950, 1953), Rothé (1950), Grandjean (1954), Benhallou *et al.* (1971), Roussel (1973a,b), Benhallou (1985), Benouar (1994), Mokrane *et al.* (1994), Bezzeghoud *et al.* (1996), Harbi, Benouar, and Benhallou (2003), and Harbi, Maouche, and Benhallou (2003). In addition, particular attention was devoted to earthquakes occurring in the vicinity of large



▲ **Figure 2.** Seismicity of Algeria considering events with a magnitude **M** ≥4.0. Black and grey circles designate events from 1900–2013. White squares designate events from 1365 to 1900.

cities, the countryside, and remote villages. The intensities were assigned according to the Mercalli scale, except for certain events that occurred before 1950, and were investigated using the Rossi–Forel scale. We considered all of the events that were studied up to 1978 using the Mercalli questionnaires to be accurately estimated. The data (I_o) for the 1980s were underestimated because of changes to the definition of urban coverage involving the type and method of construction; however, the questionnaires used for the inquiries remained the same as for earlier times. Although the intensities might have been over- or underestimated, the uncertainties remained in the confidence interval. In the previous version of the MOI map (Bezzeghoud *et al.*, 1996; referred to here as MOI_{1996}), many earthquakes were missing; a recent examination of archives and documentary sources in Algeria and France has led to the retrieval of data for various previously omitted events to enrich the existing macroseismic database (Harbi, Benouar, and Benhallou, 2003; Harbi, Maouche, and Benhallou, 2003).

HISTORY OF THE MOI STUDIES IN ALGERIA

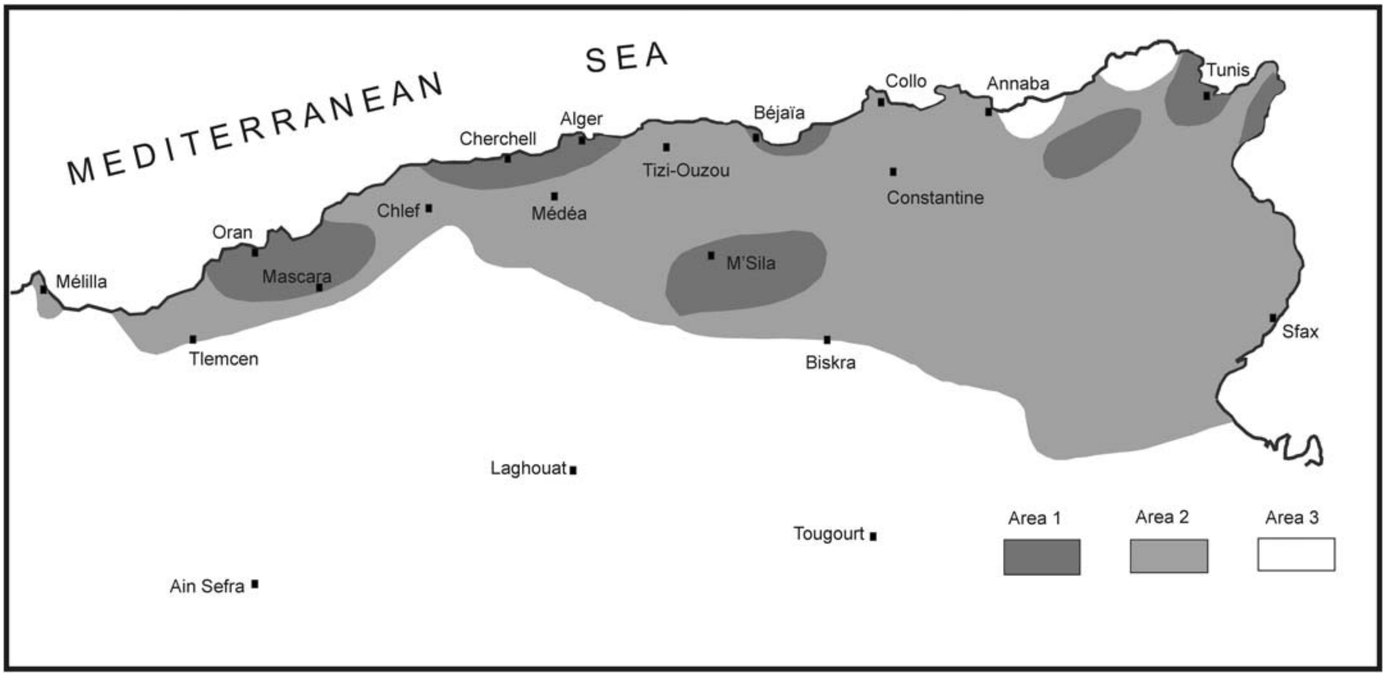
An earthquake-hazard assessment is usually conducted using peak ground accelerations. However, for regions in which most of the databases include macroseismic data, the seismic hazard is assessed using earthquake intensities. In Algeria, numerous maps have been produced to show the distribution of MOIs and the spatial distribution of the seismic hazard throughout northern Algeria. The first map (reproduced in Fig. 3 and in Bezzeghoud *et al.*, 1996) was created by anonymous authors (1925) based on an evaluation of the frequency of earthquakes. This map shows the distribution in Algeria and Tunisia of areas with high, medium, and low earthquake frequencies but no MOI values. Three frequency areas, designated 1, 2, and 3, were drawn on the map, with seven noncontiguous zones comprising area 1 and characterized by a high frequency of earthquakes, in which four zones in Algeria and three in Tunisia. In Algeria, parts of the Oranie region, including from west to east Oran, Mostaganem, Mascara, M'Sila, and the Algiers-Cherchell-Ténés, and Béjaïa-Djidjelli sectors, appear to be located in area 1. In Tunisia, three zones with a high frequency of earthquakes are identified: surrounding Tunis, surrounding Bizerte, and near the border between Tunisia and Algeria. Area 2, with a medium frequency, appears to include most of the Tell Atlas of Algeria and Tunisia, and a low frequency of earthquakes occurs in the rest of the territory. Chlef, Constantine, and Al Hoceima appear to be within the area characterized by a medium earthquake frequency, which contrasts with the seismic catalogs of the Ibero-Maghrebian region

Table 1
Historical and Recent Earthquakes in Northern Algeria (I_o > VI) from the Algerian Earthquake Catalog

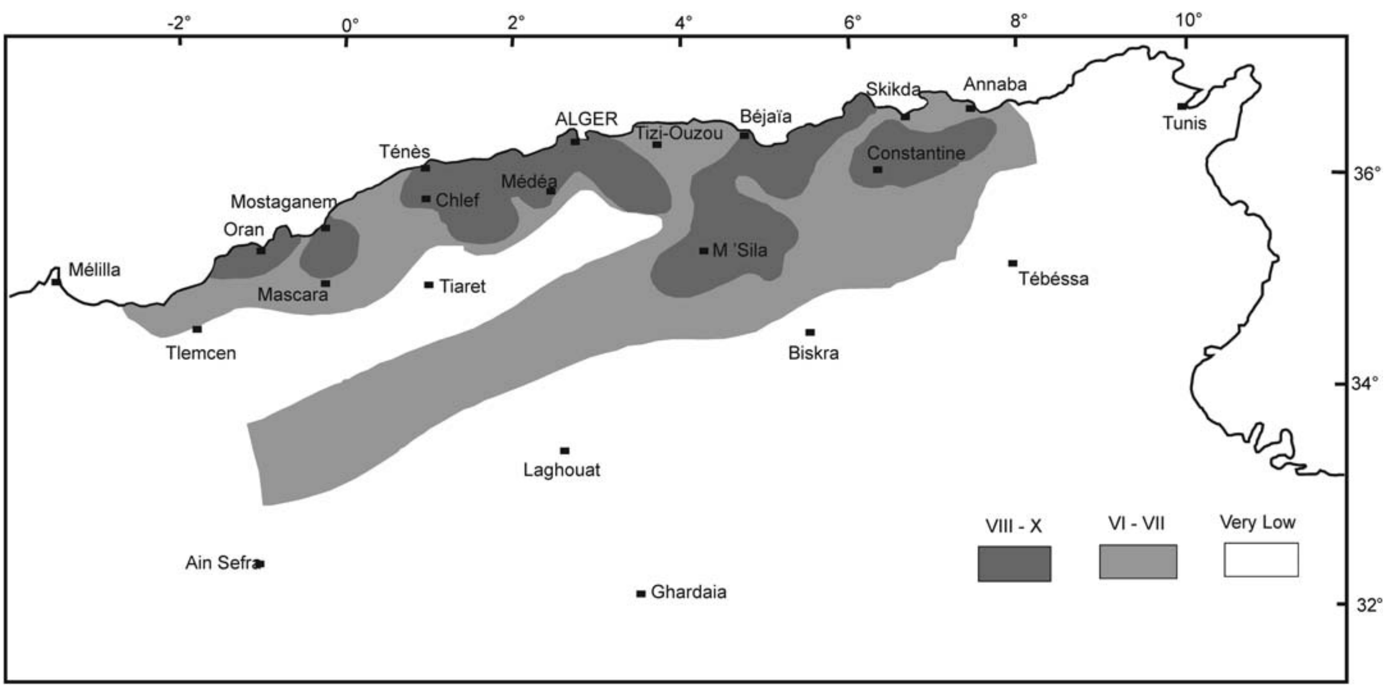
Date (yyyy/mm/dd)	Location	Intensity (*I*)	M	Observations
1365/01/03	Algiers	X		Algiers was completely destroyed. More than 100 aftershocks were reported. Part of the city was flooded. Many victims were reported.
1716/02/03	Algiers	IX		Reports of 20,000 victims. Heavy damage around Algiers. Aftershocks were felt until June 1716.
1790/10/09	Oran	IX–X		Event felt as far away as Malta; 2000 people were killed. Heavy damage in the city of Oran and its vicinity.
1825/03/02	Blida	X–XI		Blida was completely destroyed, and 7000 people were killed.
1856/08/22	Djidjelli	X		A tsunami was reported along the coast from La Calle to Mahon, and a large area was flooded. Djidjelli was heavily affected.
1867/01/02	Mouzaïa	X–XI		Reports of 100 people killed and 160 injured in Mouzaïa. The town was completely destroyed. Surface breaks were reported. Felt over a large area, including Algiers and Tipasa to Médéa.
1869/11/16	Biskra	IX		Heavy damage over a large area with 30 people killed.
1887/11/29	Mascara	IX–X		Destructive earthquake with 80 houses destroyed and 20 people killed.
1891/01/15	Gouraya	X		Heavy damage, with 53 buildings destroyed and 38 people killed. Felt for 200 km around Gouraya.
1910/06/24	Sour el-Ghozlane	X		Many villages were destroyed, and 81 people were killed. Aftershocks were felt until January 1911, with an **M** 5.5 aftershock on 11 January 1911.
1946/02/12	Béjaïa	IX		Heavy damage with 1000 houses destroyed, 264 people killed, and 112 injured.
1954/09/09	Orléansville	X	6.7	Destructive earthquake, with 1243 people killed and 20,000 houses destroyed. An uplift of 1.33 m was observed in the epicenter.
1980/10/10	El Asnam	IX	7.3	Destructive earthquake with 2633 people killed, 8369 injured, 348 wounded, and 1000s left homeless.
1985/10/27	Constantine	VIII	5.9	Limited damage, with 10 people killed and 300 injured.
1989/10/29	Tipasa-Chenoua	VIII	5.9	Limited damage, with 22 people killed. Strongly felt in Algiers. Numerous aftershocks recorded after six months.
1994/08/18	Mascara	VII	5.7	Reports of 171 people killed, 289 wounded, 1328 homeless, and 10,000 dwellings partially or completely destroyed.
1999/12/22	Ain Temouchent	VII	5.7	Heavy damage, with 26 people killed and 25,000 left homeless.
2000/11/10	Beni Ourtilane	VII	5.7	Reports of 2 people killed, 50 injured, and 3000 houses damaged.
2003/05/21	Zemmouri	X	6.8	Strong earthquake with 2278 people killed, 11,450 injured, 45 reported missing, and 44,000 houses damaged.
2006/03/20	Laalam	VII	5.2	Moderate damage with 4 people dead, 68 injured, 40 housing units destroyed, and dozens of people left homeless.
2010/05/14	Beni Ilmane	VII	5.2	Moderate damage with 4 people killed and 170 injured.

(Benouar, 1994; Mokrane *et al.*, 1994; Harbi, Maouche, Ousadou, *et al.*, 2007; Harbi, Maouche, Vaccari, *et al.*, 2007) in which significant earthquakes have occurred over the last 50 years, such as El Asnam (1954, **M** 6.5; 1980, **M** 7.3), Constantine (1985, **M** 6.0), and Al Hoceima (1994, **M** 5.8; 2004, **M** 6.0) (e.g., Bezzeghoud *et al.*, 1995; Bezzeghoud and Buforn, 1999; Bounif *et al.*, 2003, 2004; Cakir *et al.*, 2006, Ousadou *et al.*, 2014). However, there is no record of the intensities for the events used to draw the map in Figure 3.

In 1970, Bockel drew the first map based on observed intensities by considering only events that occurred between 1956 and 1970 (Fig. 4). This map remained unpublished until its inclusion in Bezzeghoud *et al.* (1996). Bockel's map indicated three main zones with the following intensities: quite low at less than VI, between VI and VII, and between VIII and X. Most of the map covered the northern part of the Tell Atlas of Algeria. The main seismogenic zones considered for this map were those in which strong earthquakes occurred and caused heavy damage, such as in Chlef, Algiers, Blida, Oran, M'Sila, Constantine, and Béjaïa. The area between Algiers and Tizi-Ouzou appeared as an extremely low-intensity zone. Unlike the anonymously drawn map (1925), Bockel's map only considers Algerian territory. Roussel (1973b) published an MOI map using all of the macroseismic data available for the 1716–1970



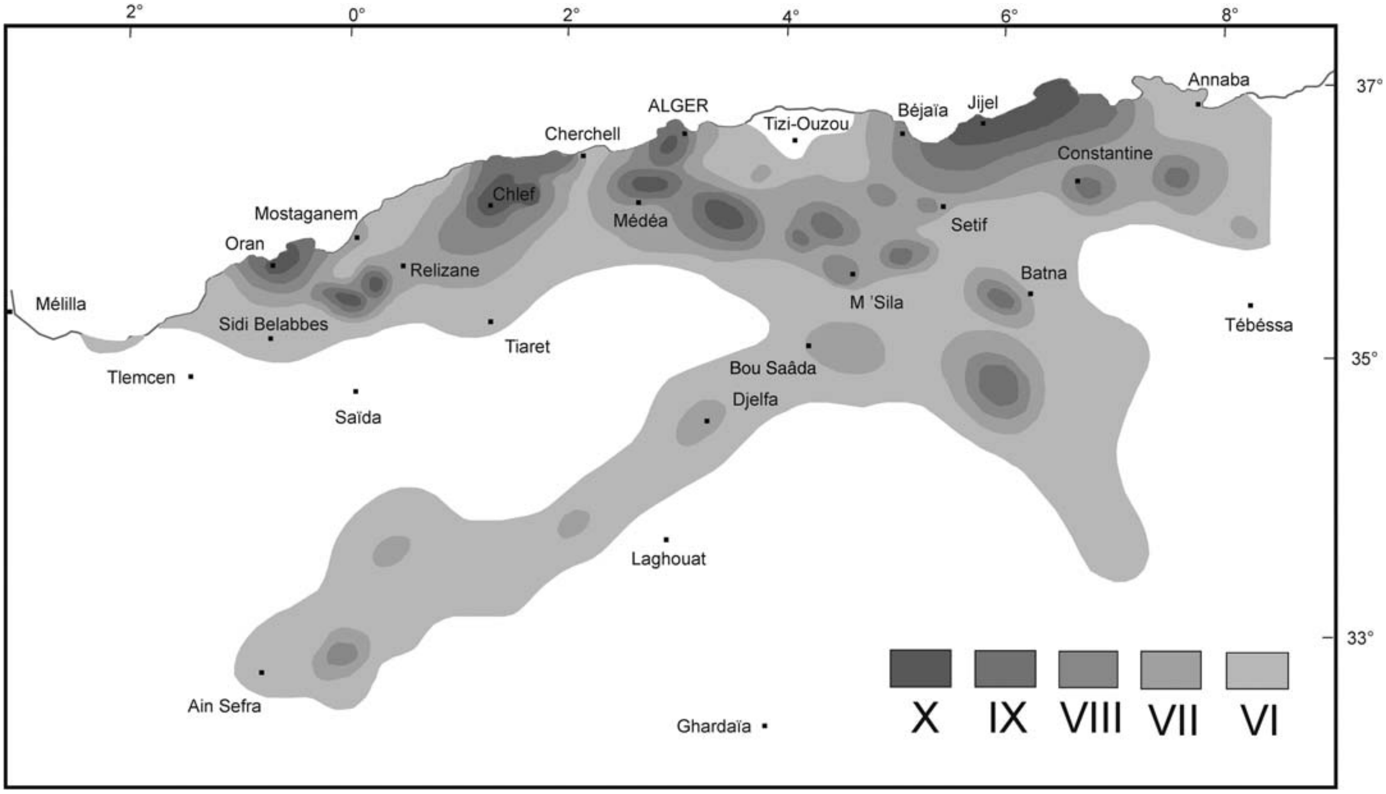
▲ **Figure 3.** First Algeria–Tunisia frequency map made by an anonymous author (1925) and taken from the Atlas d'Algerie et de Tunisie (1925); areas 1, 2, and 3 show high, medium, and low seismicity, respectively.



▲ **Figure 4.** Maximum observed intensity (MOI) map from Bockel (unpublished document, 1970).

interval (Fig. 5). Compared with Bockel's map (Fig. 4), Roussel's map contains greater detail, and the isoseismal contours are drawn degree by degree, which is important for the precise assessment of the spatial distribution of damage. Roussel drew his map using earthquakes with felt intensities greater than V, and his map exhibits damage zones from Biskra in the southeast to Ain Sefra in the southwest of Algeria. In this map (Fig. 5), three main zones were identified.

- A northern zone along the Tell Atlas of Algeria was identified as the most active zone, with a maximum observed degree of intensity of XI–X. Because of the multitude of events that occurred during the considered period, such as



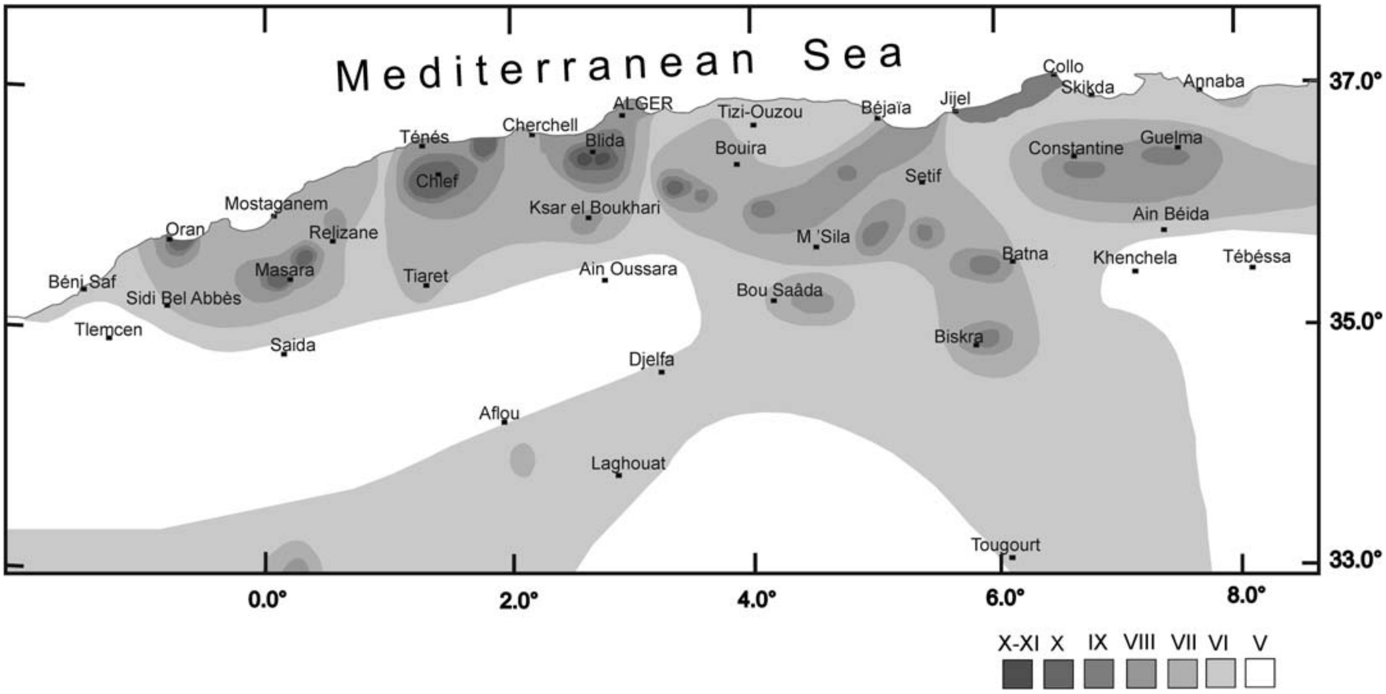
▲ **Figure 5.** MOI map from Roussel (1973a).

in Algiers in 1716, Oran in 1790, Jijel in 1856, Blida in 1825, Biskra in 1867, and El Asnam in 1954, numerous spots appear on the map, which is consistent with the tectonic activity of the different seismogenic zones present in the area, such as that of Oran, Chlef, and Jijel. These areas have experienced disastrous events that caused heavy damage.

- A meridional zone in the northern region of the south Atlasic flexure had a moderate seismicity, except for the Biskra and Batna regions, in which events with an intensity of IX were recorded.
- A Hauts Plateaux zone was considered an area of low activity, with an observed intensity less than VI. This zone was quasibounded by the VI isoseismal, which occurred in towns such as Saida, El Aricha, and Tlemcen. In addition to the Hauts Plateaux region, we also identified the Sahara, which was considered an aseismic zone in the seismic catalogs. The seismic-hazard assessment evolved by mapping the frequency or the observed intensity of the different seismic events that occurred in northern Algeria over the last six centuries. Once the seismic catalog is complete, the production of a more reliable map becomes paramount.

THE MAXIMUM OBSERVED INTENSITY MAP (MOI_{2014})

Considering the seismic events that occurred during the 1970s and 1980s, particularly the strong events, such as El Asnam (1980), Constantine (1985), and Tipasa-Chénoua (1989), Bezzeghoud *et al.* (1996) updated Roussel's MOI map and produced significant changes. Overall, Figure 6 (based on MOI_{1996}, Bezzeghoud *et al.*, 1996) exhibits four zones from east to west, and the first encompasses the region of Constantine, Guelma, and Ain Beida. This zone experienced a strong event on 27 October 1985 (M_s 5.9). According to the seismic catalogs (Benouar, 1994; Mokrane *et al.*, 1994), this area was affected several times by disastrous events that caused significant damage and casualties. The second zone included the Babors, Djurdjura, Aures, and Biban mountains. The Biskra region and Hodna basin were also included in this zone. The third zone included the regions of Algiers, Cherchell, and El Asnam, along with a southern extension to the Ouarsenis massif. This area experienced significant events similar to those of Algiers (1365, $I_o = \text{X}$ and 1716, $I_o = \text{X}$; Mokrane *et al.*, 1994; Harbi, Maouche, Ousadou, *et al.*, 2007) and El Asnam (1954 M_s 6.7 and 1980 M_s 7.3; Ouyed, 1981; Meghraoui *et al.*, 1986; Bezzeghoud *et al.*, 1995). The last zone consisted of the Oranie region, which included Oran, Relizane, Mascara, and Sidi-Bel-Abbes. Except Oran, which experienced a large event in 1790 at $I_o = \text{X}$, the other localities were struck episodically by moderate or weak events. Local patches with earthquake intensities of VII–VIII were observed near Bou Saâda, south Aflou, and southwest Al Bayadh; these patches represented rare events that occurred in recent decades. The remainder of the Tell Atlas was characterized by a zone of low intensity ($I_o = \text{VI}$). The



▲ **Figure 6.** MOI_{1996} map from Bezzeghoud *et al.* (1996).

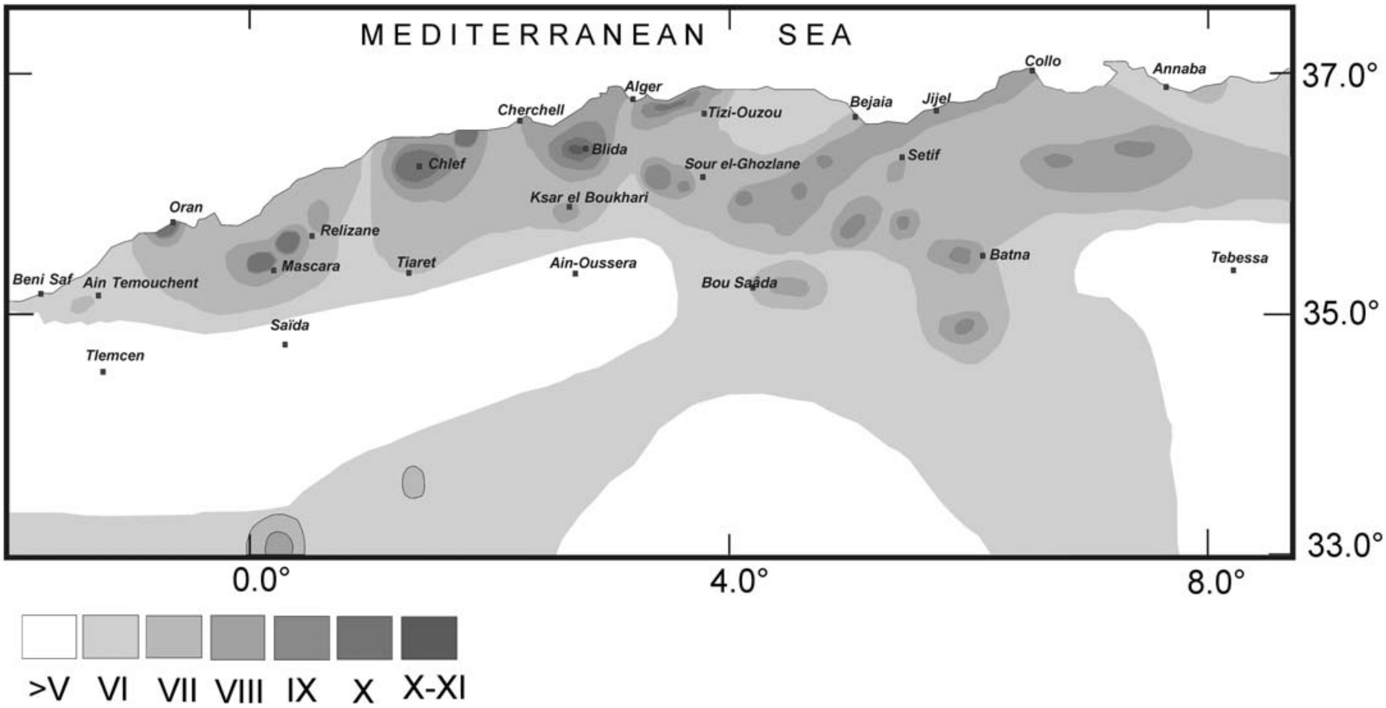
Hauts Plateaux was considered to be of very low activity because the few reported events did not exceed intensity V.

The notable changes between the two maps (Figs. 5 and 6, Roussel and MOI_{1996} maps, respectively) were induced by recent moderate events that have occurred in different parts of northern Algeria between 1970 and 1996. Boughacha *et al.* (2004) used an empirical attenuation law to draw a map of the maximum calculated intensities, which showed the same general trends compared with the MOIs of Bezzeghoud *et al.* (1996).

Regarding the recent seismic activity (1996–2013), the general aspects of the MOI_{1996} map remain the same, but there are three significant changes. The first occurred in the western part of Algeria near the Ain Temouchent region, which had an M_w 5.7 event on 22 December 1999, with an intensity of VII near the epicenter. This event caused severe damage in the city of Ain Temouchent and its surroundings; 25 people died and 25,000 were left homeless according to the official reports. The second main change corresponded to the area affected by the large, strong earthquake of 21 May 2003, that struck the Zemmouri region with a magnitude of M_w 6.8 (Ayadi *et al.*, 2008) and a macroseismic intensity of X (Harbi, Maouche, Vaccari, *et al.*, 2007). The map of the MOI_{2014} presented in this study (Fig. 7) shows a significant modification compared with the previously published map by Bezzeghoud *et al.* (1996, referred as MOI_{1996}), especially in the region east of the capital city of Algiers. Curves delineating intensities of VII–X are shown in the map, which highlights the importance of the event and its impact on the Zemmouri surroundings. Finally, a third significant change was also shown in the update of the MOI_{1996} because of the reappraisal of a past Djidjelli earthquake (1856) by Harbi *et al.* (2011), who provided valuable information on the intensity generated by the event in Djidjelli and its surroundings based on original archives and historical documents. This work highlights the importance of reprocessing historical information. For the remainder of the map, the earthquakes that occurred along the Tell Atlas of Algeria did not alter the general aspect of the map. However, the seismicity over the last two decades (1994–2013) induces some changes on the MOI_{1996} map.

CONCLUSIONS

This study provides an update of the MOI map for Algeria based on seismic activity that occurred during the last two decades within the region of the Tell Atlas of Algeria. These events caused significant changes, mainly in western Algeria (Mascara and Ain Temouchent), central Algeria close to the capital city following the strong earthquake that struck the Zemmouri region in 2003, and in eastern Algeria. Relative to earlier maps, the MOI_{2014} was greatly modified by the Zemmouri earthquake but less so by the Ain Temouchent event. The map clearly shows the Tellian domain is more active than the southern region, despite the two small events of magnitude 4.5 recorded southeast of Tamanrasset (~2000 km south of Algiers). The reappraisal of events that occurred in eastern Algeria by Harbi *et al.* (2011) has enabled us to better define the isoseismal near Djidjelli following the large historical earthquake of August 1856 with an intensity of IX in an area close to Djidjelli harbor. Macroseismic data are still important in seismological studies and earthquake engineering. Indeed, macroseismic data are abundant in seismological catalogs for many earthquake-prone countries. The maps of MOIs are useful documents for end users in charge of land use and urbanization. Ground shaking



▲ **Figure 7.** MOI_{2014} map from this study.

is directly related to the observed damage following an earthquake and obviously related to macroseismic intensity. Therefore, such documents are important and can improve seismic-hazard assessments, particularly in countries for which seismic networks are unavailable or have sparse coverage.

ACKNOWLEDGMENTS

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A. Ayadi
Centre de Recherche en Astronomie Astrophysique et Géophysique
Seismological Studies Division
Route de l'Observatoire
BP 63 Bouzaréah
16340 Algiers, Algeria
abdelhakim.ayadi@gmail.com

M. Bezzeghoud
Centro de Geofísica de Évora
Departamento de Fisica
Escola de Ciências e Tecnologia (ECT)
University of Évora
Colégio Luis Antonio Verney
Rua Romão Ramalho, 59
7002-554 Évora, Portugal
mourad@uevora.pt

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