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ORIGINAL PAPER

The active faults of the Mitidja basin (North Central Algeria): what does the seismic history of the region tell us? A review

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Abstract

The Africa–Eurasia plate boundary runs along Northern Algeria, which is thus an active seismic zone. However, surface ruptures from large earthquakes are rarely observed, which makes it difficult to define the characteristic parameters of any active fault. In this paper, we combine the results obtained in recent investigations of historical and instrumental seismicity with field observations and available geological maps and measurements of neotectonic ruptures to help comprehend the complexity of the active deformation of the Mitidja basin (MB). Our analyses reveal the tectonic characteristics of the Mitidja basin and indicate that the seismic activity is essentially concentrated along the system of the boundary faults. The general structural shape of the seismogenic Mitidja basin suggests that the southern fault system (Blida faults) would mimic the northern fault system (Sahel fault), and we observe a highest seismicity rate at the junction point of the NW–SE fault and the south thrust fault system.

Keywords Algeria · Mitidja basin · Earthquakes · Active tectonics

Introduction

The Mitidja basin (MB, North central Algeria) is increasingly the focus of interest of the scientists working on seismic hazards and risk. The reason for this is twofold: (1) the Mitidja basin is an earthquake prone area, which experienced several strong to destructive earthquakes along its seismic history (Table 1, Harbi et al. 2017); (2) the Mitidja basin includes Algiers, the capital city of Algeria, which is undergoing rapid urbanization through a massive high-density project planned during 2015–2030 that likely exacerbated its seismic vulnerability (Chemrouk and Chabbi 2016).

Several seismological and seismotectonic studies (see "Historical background" section) were carried out to better understand the tectonic activity of the Mitidja basin and for assessing its seismogenic potential. The elusive character of the active faults in this region still makes the active deformation pattern of the Mitidja basin a subject of debate. Even if these faults are known from neotectonic point of view, their level of activity and the type of deformation remain to be constrained to better understand the global deformation scheme. However, recent reappraisal of the historical seismicity of the southern edge of the Mitidja basin and seismological analyses of recent earthquakes have allowed us to get a better glimpse of the characteristics of its active tectonics and to answer some outstanding questions.

In this paper we:

1. Present a summary of the seismicity studies using a chronological approach that starts with the earliest studies of historical earthquakes of MB and related tectonics and continuing to the present day. This will allow us to provide an overview of important earthquakes that occurred in the MB along its seismic history.
2. Briefly present the Mitidja basin active structures.
3. Combine our own field observations with available geological maps, neotectonic ruptures, and earthquake distribution from recent investigations to discuss the current seismotectonic understanding of the MB.

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Table 1 The strong to destructive earthquakes of the Mitidja basin studied by previous authors

The earthquake	I_0^a	M	References
03/01/1365, Algiers	X EMS	–	Ambraseys and Vogt (1988), Mokrane et al. (1994), Harbi et al. (2007)
03/02/1716, Algiers	IX EMS	–	Ambraseys and Vogt (1988), Harbi et al. (2007), Sebaï and Bernard (2008)
29/11/1722, Algiers	–	–	Ambraseys and Vogt (1988), Sebaï and Bernard (2008)
17/03/1756, Algiers	–	–	Ambraseys and Vogt (1988), Harbi et al. (2007)
17/05/1760, Blida	Strong	–	Ambraseys and Vogt (1988)
09/06/1760, Blida	Destructive	–	Harbi et al. (2017)
08/11/1802, Koléa	–	–	Ambraseys and Vogt (1988), Harbi et al. (2017)
13/11/1807, Algiers	–	–	Ambraseys and Vogt (1988), Sebaï and Bernard (2008), Harbi et al. (2015)
02/03/1825, Blida	X EMS	–	Ambraseys and Vogt (1988), Harbi et al. (2017)
14/04/1839, Algiers	VII EMS	–	Harbi et al. (2007)
18/06/1847, Douéra	VI EMS	–	Ambraseys and Vogt (1988), Harbi et al. (2007)
30/08/1850, Algiers	IV–V EMS	–	Harbi et al. (2007)
16/01/1865, Arba	IV–V EMS	–	Harbi et al. (2007)
02/01/1867, Mouzaia–El Affroun	IX EMS	–	Ambraseys and Vogt (1988), Harbi et al. (2017)
23/03/1876, Mouzaïa–El Affroun	V EMS	–	Harbi et al. (2017)
04/02/1881, Boufarik	V EMS	–	Harbi et al. (2015)
1882/10/22, Marengo (Hadjout)	V EMS	–	Harbi et al. (2015)
06/01/1888, El Affroun	VII EMS	–	Harbi et al. (2017)
22/09/1895, Castiglione	V EMS	–	Harbi et al. (2015)
10/10/1901, Rovigo	V EMS	–	Harbi et al. (2017)
11/03/1908, Blida	VI EMS		Harbi et al. (2017)
26/01/1910, El Affroun	V–VI EMS	–	Harbi et al. (2017)
28/03/1910, Blida	V EMS	–	Harbi et al. (2017)
11/07/1911, El Affroun	V EMS	–	Harbi et al. (2017)
18/10/1916, Algiers	V EMS	–	Harbi et al. (2007)
14/04/1920, El Affroun	V–VI EMS	–	Harbi et al. (2017)
05/11/1924, Douéra	VIII MSK	5.0	Hée (1925), Benouar (1994), Mokrane et al. (1994)
02/06/1928, Staouéli	V EMS	–	Harbi et al. (2015)
25/11/1928, Castiglione	V EMS	–	Harbi et al. (2007)
20/01/1927, Blida	VI–VII EMS	–	Harbi et al. (2017)
04/03/1931, Camp des Chênes	VI–VII EMS	–	Harbi et al. (2017)
08/02/1937, Hammam Melouane	V EMS	–	Harbi et al. (2017)
03/10/1937, Boumedfaa	V EMS	–	Harbi et al. (2017)
02/03/1942, Haouch Meurdja	VI EMS	–	Harbi et al. (2017)
30/06/1942, Kouba	V M	–	Grandjean (1954), Mokrane et al. (1994)
25/10/1949, Ain Taya	V EMS	–	Harbi et al. (2007)
24/11/1949, Douéra	V EMS	–	Harbi et al. (2007)
07/11/1959 Boumedfaa	VIII	5.1	Benhallou (1985), Benouar (1994), Mokrane et al. (1994)
20/02/1960, Oued Djer	VI–VII M	3.3	Benhallou (1985), Mokrane et al. (1994)
13/03/1960, Cap Matifou	V EMS	4.4	Harbi et al. (2007)
14/08/1960, Boufarik	VI EMS	–	Mokrane et al. (1994), Harbi et al. (2007)
28/01/1961, Maison Carrée	IV EMS	–	Benhallou (1985), Mokrane et al. (1994), Harbi et al. (2007)
23/11/1961, Blida	IV–V EMS	–	Harbi et al. (2017)
25/10/1965, La Chiffa	V EMS	–	Benhallou (1985), Mokrane et al. (1994), Harbi et al. (2017)
03/04/1966, Blida region	VII M	4.2	Benhallou (1985), Mokrane et al. (1994)
11/11/1966, Champlain	V EMS	–	Mokrane et al. (1994), Harbi et al. (2015)
11/09/1967, Blida	VI EMS	4.6	Benhallou (1985), Mokrane et al. (1994), Harbi et al. (2017)
25/04/1972, Ain Taya	IV EMS	–	Mokrane et al. (1994), Harbi et al. (2015)
20/07/1975, Hammam Melouane	V–VI EMS	4.9	Mokrane et al. (1994), Harbi et al. (2017)
07/01/1978, Douéra	IV–V EMS	–	Mokrane et al. (1994), Harbi et al. (2015)

Table 1 (continued)

The earthquake	I_0^a	*M*	References
04/09/1978, Boufarik	IV–V EMS	4.2	Mokrane et al. (1994), Harbi et al. (2015)
06/06/1981, Sidi Fredj	IV–V EMS	–	Mokrane et al. (1994), Harbi et al. (2015)
30/06/1981, Staoueli	V EMS	4.2	Mokrane et al. (1994), Harbi et al. (2015)
29/09/1981, Hammam Melouane	V EMS	–	Mokrane et al. (1994), Harbi et al. (2017)
29/12/1981, Blida	V EMS	–	Mokrane et al. (1994), Harbi et al. (2017)
01/12/1982, Douéra	V EMS	4.3	Mokrane et al. (1994), Harbi et al. (2015)
07/12/1983, Mahelma	IV–V EMS	3.8	Mokrane et al. (1994), Harbi et al. (2007)
10/01/1986, Oued El Alleug	IV EMS	–	Mokrane et al. (1994), Harbi et al. (2015)
19/01/1986, Blida	V EMS	4.0	Mokrane et al. (1994), Harbi et al. (2017)
11/02/1986, Blida	V EMS	4.1	Mokrane et al. (1994), Harbi et al. (2017)
11/03/1986, Cheraga	IV–V EMS	–	Mokrane et al. (1994), Harbi et al. (2007)
19/03/1986, Ain Benian	IV–V EMS	–	Harbi et al. (2007)
17/12/1986, Hammam Melouane	IV–V EMS	–	Harbi et al. (2017)
19/12/1986, Bougara	V EMS	4.0	Mokrane et al. (1994), Harbi et al. (2017)
31/10/1988, El Affroun	VII EMS	5.8	Mokrane et al. (1994), Harbi et al. (2017)
12/02/1989, El Affroun	V–VI EMS	5.0	Mokrane et al. (1994), Harbi et al. (2017)
28/08/1989, Bourkika	V–VI EMS	–	Mokrane et al. (1994), Harbi et al. (2017)
29/10/1989, Chenoua-Tipasa	VIII MSK	6.0	Benouar (1994), Meghraoui (1991), Mokrane et al. (1994)
09/10/1990, Tipasa	IV–V M	4.7	Sebaï (1997)
04/09/1996, Ain Benian	VII MSK	5.7	Sebaï (1997), Maouche et al. (1998)
17/07/2013, Hammam Melouane	VI EMS	5.0	Yelles-Chaouche et al. (2017)
01/08/2014, Algiers bay	VII EMS	5.6	Benfedda et al. (2017)

[a] The intensity reported here corresponds to the last estimate determined by the most recent author

Historical background

The year 1980 was a pivotal period for the renewal and redefinition of the earthquake science in Algeria (Harbi et al. 2018). 1980 is the year when the largest earthquake that Algeria has ever known occurred, the El Asnam earthquake (*M* 7.3, I_0 X) (Ouyed et al. 1981). This earthquake produced widespread surface faulting (Philip and Meghraoui 1983) and provided a wealth of geological and seismological data. This is an ideal event for comparing geologically and seismologically derived models, particularly in reverse faulting area (Nabelek 1985). We will see hereafter what was done so far in terms of earthquakes and active tectonic studies of the MB before and after 1980.

The pre 1980 studies: first attempts

De Ballore (1906) drew the first seismicity map of North Africa, which shows that the seismicity is particularly concentrated in Algeria, and described the seismic geographical and geological provinces, including the Mitidja basin, according to the state of scientific knowledge of those days. The first study focusing on the MB was performed by Hée (1925) after the 5 November 1924 Douéra earthquake (*M* 5.0, I_0 VIII). The author presented a comprehensive macroseismic study that resulted in the first isoseismal map drawn for an Algerian earthquake and a list of the aftershocks, which struck the epicentral area. The 1924 Douéra earthquake was well recorded at Bouzaréah (Algiers) and the Spanish observatories as well as at Strasbourg, Paris, and De Bilt. Twenty years later, Rothé (1950) calculated an instrumental magnitude 4.9 for this event.

It was only in 1950 when the study of the geological structure responsible of an earthquake in Algeria with an attempt of identifying the active fault was performed. This study concerned the 17 February 1949 Kherrata earthquake (*M* 4.9, I_0 VII), about 200 km east of MB, for which an attempt was made to identify the causative fault (Rothé 1950). After the 9 September 1954 Orléansville (El Asnam from 1962 to 1980, Chlef now) earthquake (*M* 6.7, I_0 X), Glangeaud and Rothé (1954) observed that the seismicity of Algeria is located in the Tell Atlas and the Sahara Atlas, and is related to the Plio-Quaternary deformations. The first work, which considers the MB as a structure of recent tectonics, was that of Dubourdieu (1964). Based on Glangeaud et al. (1952 and references therein) and the intensity of the Algerian damaging and destructive earthquakes, Dubourdieu (1964) tried to identify what he called "Algerian corridors of earthquake safety" (couloirs algériens de sécurité antisismique, in French) and which correspond to zones where no fault and fold were observed, and in which intensity VIII was never reached. The first focal mechanisms of Algerian earthquakes were calculated by Girardin et al. (1977) for the period 1959–1970 during which the MB experienced few earthquakes of magnitude smaller than 4.5 (Harbi et al. 2015, 2017). We conclude that no study on seismotectonics or on neotectonics and associate seismicity of the Mitidja basin was performed before 1980.

The post 1980 period: first investigations

The interest in seismicity studies in Algeria increased after the 10 October 1980 El Asnam earthquake. This seismic event located 200 km southwest of the capital Algiers is the largest in Algeria during the instrumental era and is known to have produced surface faulting on a thrust fault 30–40 km long, with an average displacement of about 3 m (Philip and Meghraoui 1983). After this event, scientists focused on the study of the seismicity and tectonics of the El Asnam region (Cheliff basin) and of the whole Algeria (see Harbi et al. 2018 and references therein), including the Mitidja basin. Studies of local earthquakes of the MB were first mainly based on intensity. Benhallou (1985) presented six macroseismic maps in terms of Mercalli intensity scale for the earthquakes that occurred in the MB from 1960 to 1967 (Table 1). Mokrane et al. (1994) studied 32 additional earthquakes of the MB from macroseismological point of view (Table 1). By referring to historical archives, Ambraseys and Vogt (1988) discovered the first earthquake that struck the Mitidja basin and had destructive effects in the capital Algiers. It was the 3 January 1365 Algiers earthquake, which triggered a tsunami that flooded the lower part of the city. Based on original sources in most cases, Ambraseys and Vogt (1988) described the macroseismic effects of ten events of the MB (Table 1). Their work was continued by Benouar (1994) who determined or revised the macroseismic and instrumental epicenter, magnitude, and intensity (MSK) of two earthquakes of the MB (Table 1). The first work that deals with the geology of the Algerian seismic zones is that of Meghraoui (1988). For the first time in Algeria, Meghraoui (1988) addressed four issues of earthquake geology: paleoseismology, geomorphology, active tectonics, and seismotectonics. Based on the El Asnam case study and proceeding by analogy to the Sara El Maarouf (El Asnam region) fault-related folding, field observations led Meghraoui (1988) to consider the Algiers Sahel, which is the northern border of the MB, as an active compressive tectonic structure. He suggested the presence, on the south limb of the Sahel, of a blind fault evidenced by morphological indications as deformed terraces and density of drainage pattern. On 29 October 1989, the coastal area of the MB experienced at Mont Chenoua-Tipasa the largest felt and recorded seismic event (M 6.0, I_0 VIII), and provided Meghraoui (1991) with the opportunity to confirm his previous observations since this earthquake revealed the existence of a buried reverse fault system, beneath flexured neogene deposits and a Quaternary asymmetric anticline. Meghraoui (1991) carried out the first seismotectonic study of an MB earthquake. He observed on the southern side of Mont Chenoua a coseismic flexural slip faulting marked by 4.0 km of discontinuous surface ruptures associated with an active fold 5 km further to the south. The focal mechanism solution of the 1989 mainshock yielded an ENE–WSW reverse fault dipping to the NNW, which is in good agreement with the aftershocks that were distributed in an ENE–WSW to NE–SW zone extending offshore (Meghraoui 1991). Before the 1989 event, an earthquake struck the southern part of the Mitidja basin in El Affroun region on 31 October 1988 (M 5.8, VII). This earthquake was the first of the MB for which one has a focal mechanism and unfortunately, except a macroseismic study (Mokrane et al. 1994), no microseismic analysis was devoted to this event. In the beginning of the nineties, Boudiaf (1996) carried out a seismotectonic study, which focused on Algiers region that belongs to the MB and was particularly based on the analysis of seismicity, morphotectonic maps, and digital elevation model (DEM) from aerial photos and satellite images. Although the seismotectonic study by Boudiaf (1996) was not supported by field observations, it provided us with interesting geomorphologic details regarding the active deformation in the following zones: (1) in the southern border of the MB: Menaceur, Hadjout, Oued Djer–El Affroun, and Blida Soumaa; (2) in the northern edge of the MB, the Algiers Sahel: Mahelma, Ain Tagouraït–Attatba, and Tipasa–Nador. In the nineties, two seismic sequences that occurred in the Algiers Sahel in February 1990 and September 1996 were studied by Sebaï (1997), who carried out seismological analyses including aftershock distribution analysis and calculation of focal mechanisms for both sequences. The analysis of the 1990 Tipasa sequence evidenced three NE–SW active fault segments, over a width of 15 km near Ain Tagouraït, Tipasa, and Hadjout, respectively, and which were not visible at the surface. The 30 focal solutions calculated for the 1990 aftershocks indicated reverse and normal faults. The analysis of the Ain Benian 1996 seismic sequence highlighted a NNW–SSE active fault (not visible at the surface Maouche et al. 1998). The composite focal solutions calculated, using local network, for the 1996 seismic sequence showed reverse faulting (Sebaï 1997).

The twenty-first century investigations

At the beginning of the twenty-first century, there was no significant earthquake that occurred in the Mitidja basin. However, some authors reviewed the historical and/or recent seismicity of the Algiers Sahel, the northern edge of the MB, and interpreted this seismicity using the state-of-the-art in terms of seismological and tectonic analysis (Harbi et al. 2004, 2007; Sebaï and Bernard 2008). On 21 May 2003, the second most destructive earthquake (*M* 6.8, I_0 X), ever known in Algeria during the instrumental era, occurred on the eastern continuation of the southern edge of the MB, at Zemmouri in Boumerdes region, and resulted in a wealth of scientific articles (see Maouche et al. 2008 and references therein). This prompted the need for a better understanding of the seismogenic sources in the MB. Geological, seismotectonic, and paleoseismological field investigations were performed (Maouche et al. 2009, 2011; Guemache 2010; Heddar et al. 2013; Authemayou et al. 2016). Recently, two moderate seismic events struck the Mitidja basin: (1) the 17 July 2013 Hammam Melouane earthquake (*M* 5.0, VI) which occurred on the southern border of the MB (Yelles-Chaouche et al. 2017); (2) the 1 August 2014 earthquake (*M* 5.3, Benfedda et al. 2017), which occurred on the northern border of the MB. The seismological analysis of the Hammam Melouane earthquake (Yelles-Chaouche et al. 2017) revealed that the event occurred on a 5-km-long dextral strike-slip fault-oriented N114°E near Bouinan. In this case, as used for most of moderate earthquakes that the Northern Algeria experienced, the rupture did not reach the surface. The focal mechanism of the Hammam Melouane mainshock shows a strike-slip movement, whereas the largest aftershocks show a reverse faulting (Harbi et al. 2017). The epicenter of the 2014 Algiers earthquake was located offshore, and the aftershock sequence showed an ENE–WSW swarm of about 5 km length and 3 km wide. The focal solutions of the Algiers 2014 mainshock and its largest aftershocks indicate a reverse fault (Benfedda et al. 2017). After the occurrence of the 2013 Hammam Melouane earthquake, which was followed by a long seismic sequence over 3 years, with additional moderate earthquakes (Yelles-Chaouche et al. 2017, CRAAG datafile), we decided to revisit the historical seismicity of the southern edge[1] of the Mitidja basin through a large macroseismic survey (Harbi et al. 2017). The results that we obtained have shown that the investigated area has already experienced destructive to damaging earthquakes (VI $\le I_0 \le$ X) at Blida, Koléa, Haouch Meurdja, Bourkika, La Chiffa, Mouzaïa, etc. (Table 1) with the most damaging events at Mouzaia and El Affroun on 2 January 1867 (I_0 IX) and on 31 October 1988 (I_0 VII). The analysis of the seismic history of the MB led us to conclude that the southern edge has been more seismically active than the northern edge.

The Mitidja basin: an active structure

From the above, it becomes obvious that the Mitidja basin is an active structure. In Northern Algeria, the active tectonics characterized by E–W to NE–SW trending fold structures and related reverse and thrust faults accommodates 2–3 mm/year shortening across the Tell Atlas (Meghraoui and Doumaz 1996; Maouche et al. 2011). Morphotectonic and geological analysis allowed highlighting the main structural trends in the MB, in particular those of Blida Tell mountain ridges (average N075°E) and the neotectonic lineaments (E–W, NE–SW, and NW–SE, Fig. 1). Several studies recognized the NW–SE Miocene distension, with subhorizontal extensive tectonics which is marked by synsedimentary normal faults (Bonneton 1977). From late Burdigalian to lower Tortonian, the Mitidja basin collapsed and typical plate boundary calk-alkaline magmatism was installed (Ait-Hamou 1987; Belanteur 2001). Between lower Pliocene and Quaternary, NW–SE to NNW–SSE compressions shaped the actual frame of the Mitidja region (Maouche et al. 2011).

The Mitidja Quaternary basin is characterized by two major active structures that trend NE–SW to E–W: the Sahel anticline of the Algiers region and the Blida thrust and fold system (Fig. 1). The prominent present-day morphology of the Blida Mountains with an altitude greater than 1500 m above sea level (asl) and the Quaternary Sahel anticline (reaching 260 m asl) contrasts with the 20- to 60-m-high flat Quaternary sedimentary basin in the middle (Fig. 1). Active faults of the Blida Mountains consist of an ENE–WSW trending and right-stepping “en echelon” reverse faults that overthrust the Quaternary units of the MB (Meghraoui 1988; Guemache 2010; Maouche et al. 2011). This fault system extends to the ENE to reach the coastline, and the offshore fault continuation of this structure was reactivated during the 2003 Zemmouri earthquake (Mw 6.8; Meghraoui et al. 2004; Ayadi et al. 2008; Belabbès et al. 2009). The earthquake catalog indicates the occurrence of destructive earthquakes along both the southern and northern edges of the MB (Figs. 2, 3, Harbi et al. 2007, 2015, 2017). This attests to the activity of the Mitidja basin and reflects the present-day compressional tectonic regime.

Complexity of the active fault system in the Mitidja basin

The geological structures in the southern border of the MB are of high complexity. The NE–SW trending complex network of faults is subdivided into several segments (Fig. 1). The segmentation is marked by a typical left-lateral movement on the NNE–SSW faults (Figs. 2, 3). Furthermore, the morphological contrasts on the Digital Elevation Models

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[1] The historical seismicity of the northern edge was already investigated in Harbi et al. (2007) and Harbi et al. (2015).

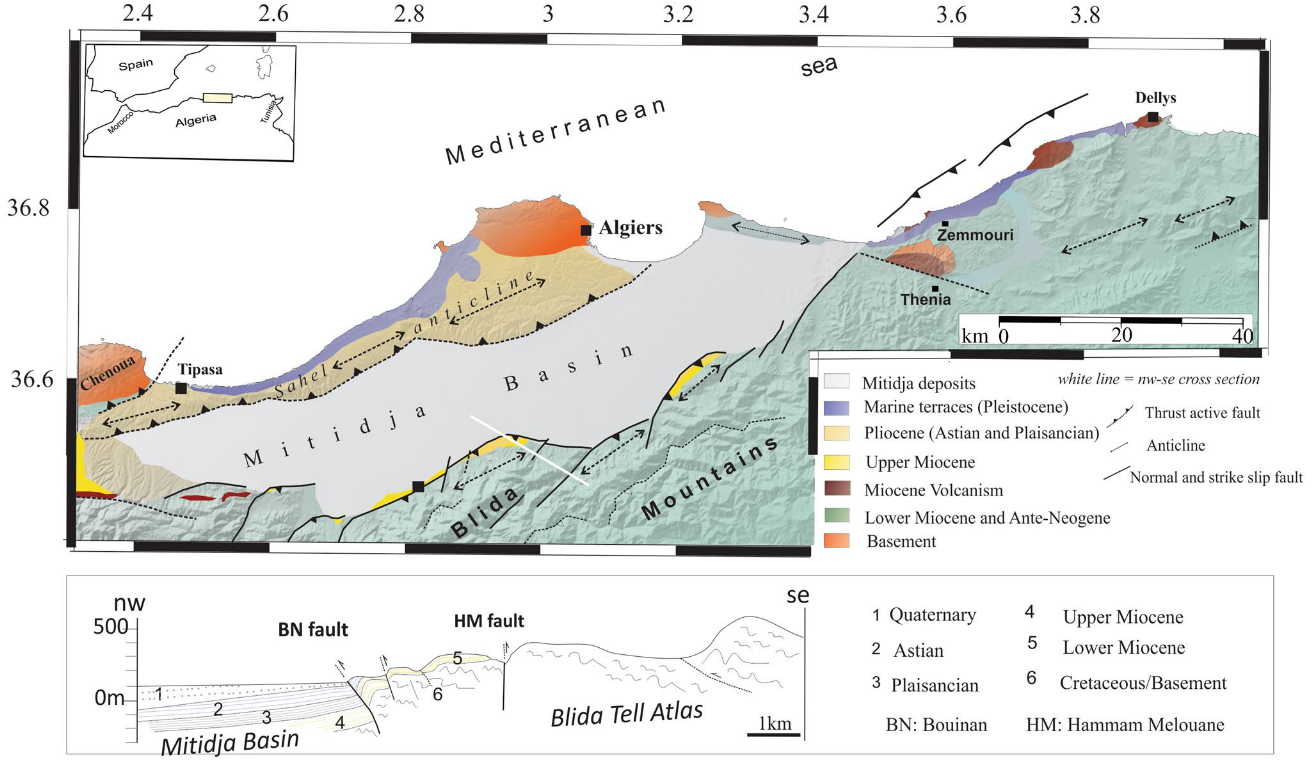

Fig. 1 Neotectonic map of the Mitidja basin tectonic framework from Meghraoui (1988, 1991), Guemache 2010, and Maouche et al. (2011); the geological cross section is based on field observations

(Boudiaf 1996) of each set of lineaments differ significantly. The ~ N60°E–N80°E lineaments, clearly expressed in the topography, are truncated by most likely recent perpendicular lineaments (i.e., Mazafran fault). These faults mark the contact between the Miocene (Tortonian) and Pliocene rocks (limestone, marl, and calcareous), slope deposits and the Quaternary subhorizontal fan gravel and river deposits of the MB. The cross section (Fig. 1) shows the Pliocene deposits overlapping the subhorizontal deposits in the vicinity of HM and Bouinan. The Astian sandstones are strongly deformed indicating post-Astian tectonics. This fault has NE–SW orientation and deeping towards the SE with an angle of 50°–60°. Considering their geometric parameters (high angle deeping) and nature (reverse fault), the Blida faults, which exhibit around 60° south dip, were probably reactivated during the Plio–Quaternary from normal to reverse movements indicating the beginning of the Quaternary transpressive tectonic regime period. It is clear that the defined active faults are not newly formed. Along the Oued Djer valley, uplifted and tilted alluvial terraces attest to the important Quaternary tectonics (Fig. 4). NE–SW segmented fault system, visible on the MB southern border, seems to separate tectonic blocks indicating a basin likely linked to transpressive tectonics. This configuration is in favor of the transpression model involving clockwise block rotation proposed by Meghraoui and Pondrelli (2012 and references therein) on the basis of tectonic data and by Derder et al. (2009 and references therein) using paleomagnetic data. This model was also evidenced in the Cheliff basin particularly in the northern part zones with strong clockwise rotation of smaller blocks (Derder et al. 2013).

Discussion and conclusion

The potential active faults and the largest earthquakes of the Mitidja basin

The more recent earthquakes of Zemmouri (2003), Hammam Melouane (2013, 2014), and Oued Djer (2018) located on the southern border of the MB exhibited shallow focal depths and reverse-thrust mechanisms (Fig. 2, Table 2). The Zemmouri earthquake occurred in the NE continuation of the Blida reverse system fault and is linked to a 50 km NE–SW reverse fault that produced 0.7 cm of coastal uplift (Meghraoui et al. 2004). The focal mechanisms calculated for the Hammam Melouane 2014 earthquake and major aftershocks indicate that this event was reverse faulting with a small left-lateral strike-slip component (Harbi et al. 2017), (Fig. 2, Table 2). This is the first time when such

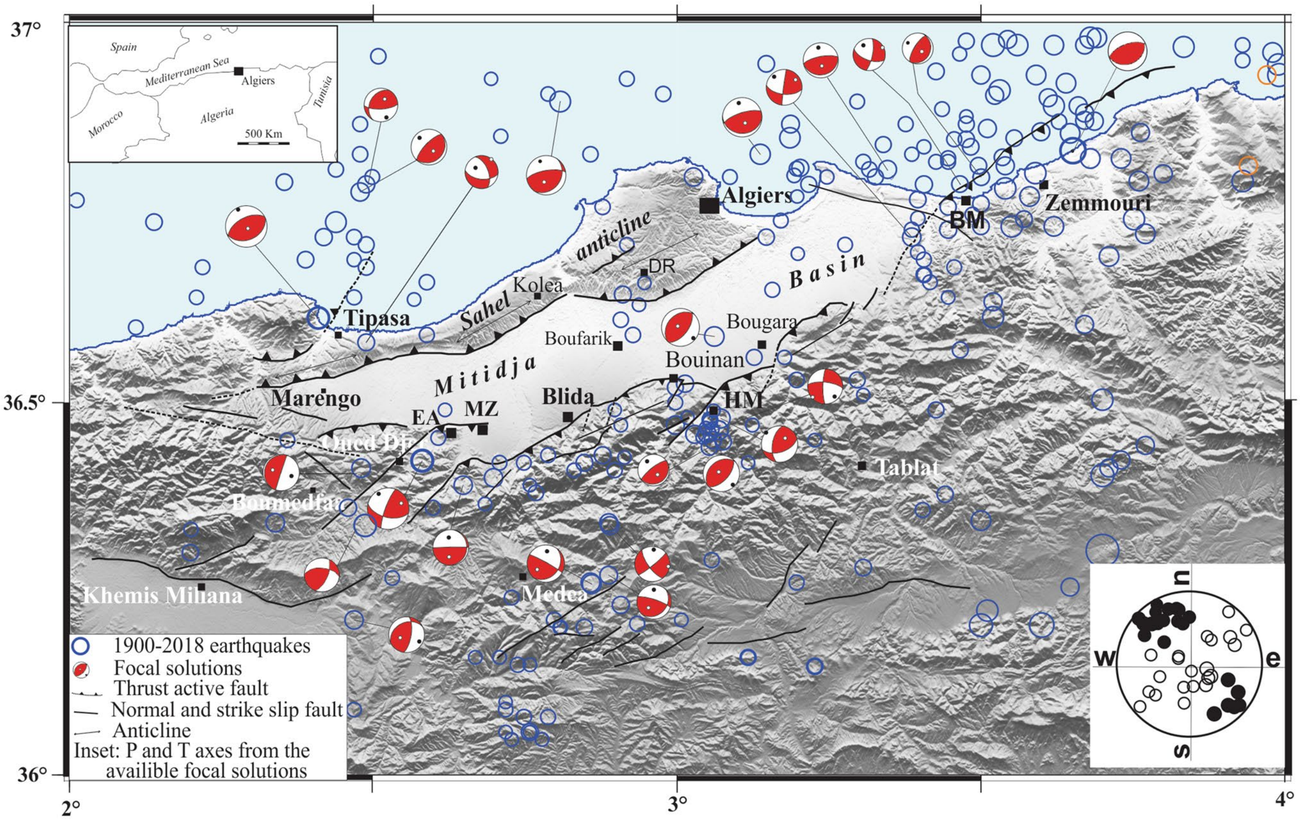

Fig. 2 The spatial distribution of earthquakes in the Mitidja basin from 1900 to 2018 ($M \geq 4$, modified from Harbi et al. 2017). Focal mechanism solutions are in Table 2. The abbreviations EA, MZ, HM, and BM correspond to El Affroun, Mouzaia, Hammam Melouane, and Boumerdes, respectively (modified from Harbi et al. 2017). The stereo-plot inset indicates the P-axes (black circles) and T-axes (open circles) derived from earthquake fault plane solutions showing a NNW–SSE stress

geometry is revealed by an earthquake focal mechanism in the southern border of the Mitidja basin. This focal mechanism fits well with the local tectonic setting (Bougara–HM fault segment, Figs. 1, 2). In Fig. 1, we show a geological cross section indicating the geometry of the Hammam Melouane fault that was most likely responsible of the different seismic sequences, which occurred in this zone. The SW continuation of the Bougara–HM segment superimposed the El Harrach river valley (Fig. 3). At this junction, there is a tectonic lineament crossing the Blida fault (Bouinan fault segment) in a tear fault configuration accommodating the segmentation.

The recent tectonic movement is reflected by tilted and folded Pliocene and ancient Quaternary levels (Fig. 1) along the southern border of the MB. This impressive tectonic scarp, approximately 100 km long and showing a topographic offset exceeding sometimes 1000 m, trends north-easterly along the northern base of the Blida Tell Atlas (Maouche et al. 2011).

Given the tectonic context described here and the recent macroseismic analysis of the 1867 and 1988 damaging earthquakes (Harbi et al. 2017), we think that both events took place on one of the segments of the Blida fault thrust. The Mouzaïa–El Affroun (MEA) fault (Fig. 3), which is reverse in its EW part and exhibits left-lateral strike-slip movement on its SW ending, could be the causative fault. The 1988 earthquake (*M* 5.4) occurred ~ 6 km south Mouzaia in the Oued Djer valley and was followed by several aftershocks. It exhibits a left-lateral strike-slip focal mechanism imaging the SW continuation of the MEA fault. This is similar to the Bougara–HM segment where reverse faulting ends in strike slip (Figs. 1, 2, 3). This configuration was also observed during the 2016 Mihoub earthquake sequence in which the causative fault seems to be strike slip with pure reverse nature on its north-eastern continuation (Khelif et al. 2018).

We combined macroseismic analyses with focal mechanisms of the recent seismicity and the geologic interpretation of the southern border of the MB to show that the fault of the 1867 and 1988 earthquakes occurred likely by slip on the steeply south dipping, the Mouzaia–El Affroun–Oued Djer fault (Fig. 3). The 1867 event would have been generated by the MEA fault, whereas the 1988 event occurred on the SW ending of the MEA–Oued Djer fault. The last Oued

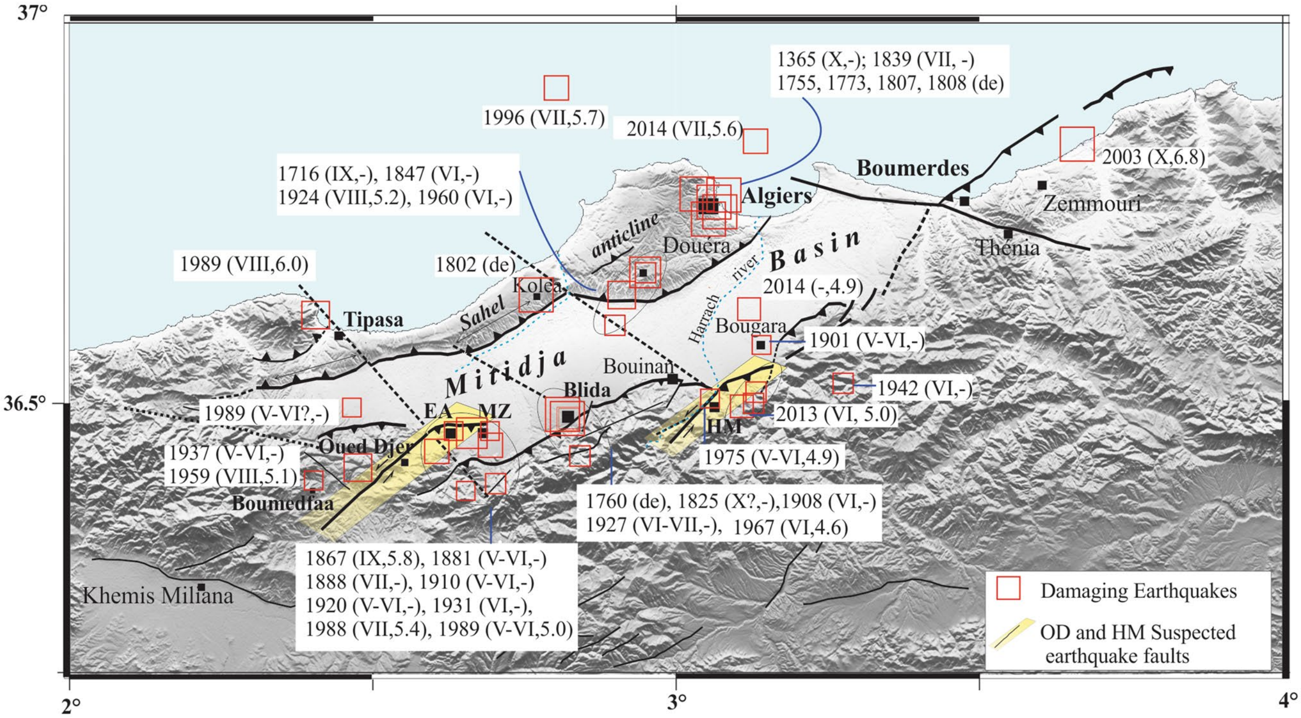

Fig. 3 The damaging earthquakes that occurred in the Mitidja basin from 1365; each event in the different transparent boxes is referred to by the year of its occurrence, the epicentral intensity I_0, and its magnitude when available [year (I_0, M)]; (de): destructive event. The MEA and Bougara–HM faults are highlighted in transparent boxes (modified from Harbi et al. 2017)

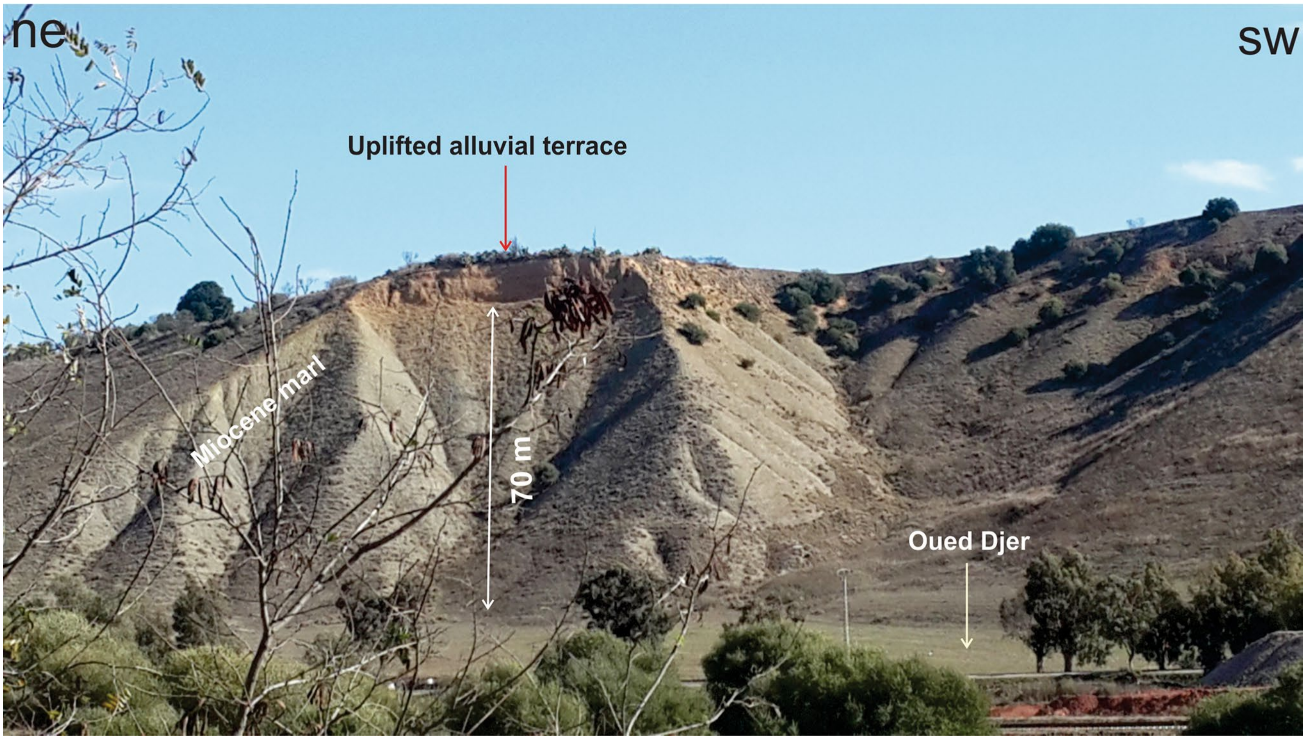

Fig. 4 Quaternary alluvial terrace along Oued Djer indicating important uplift along the OD fault related to active tectonics in this area

Table 2 Focal solutions of the significant earthquakes occurred in the Mitidja basin (ISC online focal solutions catalog)

Date	Time	LAT	LON	Depth	Strike (1)	DIP (1)	RAKE (1)	Strike (2)	DIP (2)	Rake (2)	Mw	Authors
07/11/1959	02:32:00	36.38	2.55	7	203	10	− 5	198	89	− 100	5.1	Henares et al. (2003)
23/04/1967	09:30:00	36.21	2.47	4	9	69	64.4	243	32.6	139	5	Hatzfeld (1978)
13/10/1980	06:37:00	36.31	1.59	5	63	42	69	270.3	51.3	107.9	5.2	HRVD CMT
31/10/1988	10:13:00	36.4	2.68	13	103	55	167	200.5	79.4	35.7	5.8	HRVD CMT
12/02/1989	12:02:00	36.39	2.65	7	10	11	10.6	269	88	100.8	5.0	NEIC
29/10/1989	19:09:00	36.61	2.42	13	242	55	87	67.2	35.1	94.3	5.8	Bounif et al. (2003)
09/02/1990	09:31:00	36.78	2.48	18	49	18	95	223.7	72.1	88.4	5.0	HRVD CMT
11/03/1990	08:30:00	36.58	2.49	8.28	338	57	− 44.5	96	54	− 137.7	4.6	Sebai 1997
12/04/1990	22:47:00	36.79	2.49	13.5	210	34	38	87.1	69.9	118	4.7	Thio et al. (1999)
04/09/1996	04:14:03	36.9	2.81	14	260	70	108	36	26	49	5.7	Stich et al. (2003)
01/01/2003	00:55:55	36.27	2.89	10	43	26	28	288	78	114	4.8	ZUR_RMT
21/05/2003	18:44:00	36.85	3.65	10	237	43	92	54	47	88	6.8	NEIC
28/05/2003	06:58:37	36.80	3.35	15	79	18	90	259	72	90	4.9	Braunmiller and Bernardi (2005)
29/05/2003	02:14:59	36.72	3.39	12	96	58	177	187	87	32	5	ZUR_RMT
10/01/2004	18:38:14	36.82	3.54	9	17	63	− 26	119	67	− 151	4.7	ZUR_RMT
01/12/2004	17:42:24	36.80	3.49	6	22	18	81	212	72	93	4.4	ZUR_RMT
05/12/2004	08:30:59	36.79	3.47	12	11	73	− 30	110	61	− 161	4.5	ZUR_RMT
08/05/2007	06:56:35	36.33	2.89	12	51	83	− 19	144	71	− 173	4.9	MED_RCMT
22/08/2007	18:08:35	36.25	2.86	10	299	85	118	38	28	11	5.2	MedNet
01/02/2008	07:33:40	36.84	3.49	12.5	10	83	− 7	101	83	− 173	4.4	MED_RCMT
04/01/2010	19:38:00	36.94	3.43	6	119	86	− 111	19	21	− 10	4.5	HRVD CMT
16/05/2010	06:52:00	35.98	4.00	12	245	50	128	14	53	53	5	HRVD CMT
17/07/2013	03:01:00	36.45	3.05	8.8	275.7	70	− 168	181	79	− 20	4.9	Harbi et al. (2017)
01/08/2014	04:11:17	36.83	3.14	13.2	90	19	107	252	71	84	5.5	MED_RCMT
19/12/2014	11:06:05	36.44	3.05	10	61	14	99	232	76	88	4.4	Harbi et al. (2017)
23/12/2014	08:00:21	36.58	3.06	25	37.1	57.8	85.9	224.7	32.4	96.4	5.3	Harbi et al. (2017)
23/12/2014	08:59:04	36.46	3.07	13.57	42	58	85.9	229.5	32.2	96.5	5.1	Harbi et al. (2017)
26/12/2014	17:55:00	36.47	3.07	12	190	58	45	72.1	53.2	138.5	5.1	Harbi et al. (2017)
02/01/2018	21:59:38	36.31	2.59	12	72	41	105	233	51	77	4.7	Harbi et al. (2017)

Djer event of 2 January 2018 (*M* 5) showing strike-slip focal mechanism seems to have occurred on this segment.

Figure 2 (see also Table 2) illustrates the most significant earthquakes that occurred in the Mitidja basin during its history and shows that there has been much historic seismicity in the vicinity of the southern edge of the basin than in that of the northern edge. Within the Mitidja basin, NW–SE faults (i.e., Tipasa–El Affroun, Mazafran–Hammam Melouane, and Thenia lineaments, Figs. 1, 2, 3) developed with somewhat regular spacing compartmentalize the basin into three zones. This segmentation is equally reflected on the south thrust fault system and on the Sahel anticline to the North. The results reveal the tectonic characteristics of the active tectonic basin and indicate that the seismic activity is mainly concentrated along the system of the boundary faults. However, the highest seismicity rate is observed at the junction point of the NW–SE faults, which segments the Mitidja basin, and the south thrust fault system. The general structural shape of the seismogenic Mitidja basin suggests that the southern fault system would mimic the northern fault system (Fig. 1). The earthquake distribution maps (Figs. 2, 3) show a strongest seismicity rate of significant earthquakes along the southern edge of the Mitidja basin (Blida faults). Taking into account this deficit, we may expect more earthquakes in the vicinity of the northern edge of the Mitidja basin. This fault interaction is also indicated by the cumulative changes in coulomb failure stress calculated by Kariche et al. (2017) from ruptures of large earthquakes that occurred in this region.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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