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Los mayores sismos en Argelia en la época moderna: las fallas de El Asnam y Zemmouri-Boumerdès

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Resumen. Argelia ha experimentado muchos terremotos destructivos en los últimos siglos (e.g., Ayadi and Bezzeghoud, 2015). La ciudad de El Asnam (antes Orléanville, hoy Chelef) sufrió graves daños en 1954 y 1980 por terremotos de magnitud 6,7 y 7,3, respectivamente. El 29 de octubre de 1989, un terremoto de magnitud 5,9 golpeó el Mont Chenoua-Tipasa, zona costera situada a unos 150 km al oeste de Zemmouri, donde ocurrió el terremoto del 21 de mayo de 2003 (M_w6.8). Muchos otros grandes terremotos históricos e instrumentales causaron graves daños a las ciudades costeras de Argelia durante los últimos siglos (alrededor de Argel, Orán, Mascara, Djidjelli, Constantina y Bejaia). Estos terremotos son pruebas evidentes de una deformación activa del margen, junto con la clara extensión de las fallas activas costeras. Según varios estudios, la principal estructura geológica activa en torno a El Asnam, Argel, Zemmouri y Boumerdes experimentó varios terremotos desastrosos. Muchos otros terremotos ocurrieron en y alrededor de las cuencas de Chelef y Mitidja subrayando la actividad de la zona. En este capítulo se destacarán las principales características de los dos mayores terremotos ocurridos en Argelia en la época moderna: los terremotos de El Asnam del 9 de septiembre de 1954 (M_w6.7) y del 10 de octubre de 1980 (M_w7.3), así como el terremoto de Zemmouri-Boumerdes del 21 de mayo de 2003 (M_w6.8).

Palabras clave: Fuente sísmica; Mecanismo focal; Deformación; terremotos de El Asnam y de Zemmouri-Boumerdes; Argelia.

[en] The largest earthquakes in Algeria in the modern period: the El Asnam and Zemmouri-Boumerdès faults

Abstract. Algeria has experienced many destructive earthquakes during the last few centuries (e.g., Ayadi and Bezzeghoud, 2015). The city of El Asnam (formerly Orléanville, today Chlef) was severely damaged in 1954 and 1980 by magnitude 6.7 and 7.3 earthquakes, respectively. On October 10, 1989, a magnitude 5.9 earthquake struck the Mont Chenoua-Tipasa coastal area approximately 150 km west of

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Zemmouri, which is where the May 21, 2003 earthquake occurred (M_w6.8). Many other large historical and instrumental earthquakes have severely damaged the coastal cities of Algeria over the last few centuries (i.e., around Algiers, Oran, Mascara, Djidjelli, Constantine and Bejaia). These earthquakes suggest active deformation of the margin in conjunction with the clear offshore extent of active coastal faults. According to several studies, the main active geological structures around El Asnam, Algiers, Zemmouri and Boumerdès have experienced several disastrous earthquakes. Many other earthquakes have occurred in and around the Chlef and Mitidja Basins, underlining the seismic activity in the area. In this chapter, we highlight the main characteristics of the two largest earthquakes that have occurred in Algeria in the modern period: the El Asnam earthquakes of September 9 (M_w6.7) and October 10 1980 (M_w7.3), and the Zemmouri-Boumerdès earthquake of May 21, 2003, (M_w6.8).
Key words: Seismic source; focal mechanism; deformation; El Asnam and Zemmouri-Boumerdès earthquakes; Algeria.

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1. Introduction

Since the beginning of the 21st century, changes in Algeria's seismicity have been monitored by a telemetered seismic network. In 1990, a set of 32 stations were installed along the Tellian Atlas region, which is the most active seismic zone in northern Algeria. Seismic phenomena are a recurring cause of damage and loss of life in Algeria, and we must keep in mind that nearly all of the earthquakes that have affected Algeria occurred in or around big cities. Because of the great population concentration in those areas, the danger of a great catastrophe is always present. Upon reading the Algerian earthquake catalogue and looking at a map of the maximum observed intensities, we can see that all of northern Algeria is characterized by zones of high seismic risk. Unfortunately, the seismic crises that have been experienced throughout Algeria have generated the injury and loss of thousands of lives. Some examples include the following earthquakes: Algiers (1716, Io=X, 20,000 deaths), Oran (1790; Io=X, more than 2000 deaths), Blida (1825, Io=X, 7000 deaths), El Asnam (now known as Chlef, 10/10/1980, Io=IX, M_w=7.3, 2633 deaths), Tipasa-Chenoua (29/10/1989, Io=VIII, M_w=6.0, 22 deaths), Constantine (27/10/1985, M_w=5.9, 10 deaths), Mascara (18/08/1994, Io=VIII, M_w=5.7, 171 deaths), Algiers (04/09/1996, M_w=5.5), and Zemmouri-Boumerdès (21/05/2003, M_w=6.8, 2278 deaths). This seismic activity is related to the collision between the African and Eurasian plates. The entire pattern of seismicity shows that there is a concentration of seismic activity along the northern Algeria border, especially in the zone near the coast, that is defined along the plate boundary zone between Africa and Eurasia and ranges from the Azores to the Aegean Sea. The epicentres are clearly located along the Tellian Atlas where numerous earthquakes have occurred over the last few decades, and the largest shocks include the following: El-Asnam (October 10, 1980; M_w=7.3), Constantine (October 27, 1985; M_w=5.9), Tipasa-Chenoua (October 29, 1998; M_w=6.0), Mascara (August 18, 1994; M_w=5.7) and Algiers (September 4, 1996; M_w=5.5).

These events were located within the seismogenic zones of the El Asnam, Tipasa and Algiers thrust faults and the Constantine and Mascara strike-slip faults.

A map of the maximum observed seismic intensities (see figure 7 of Ayadi and Bezzeghoud, 2015) of Algeria clearly shows that the seismogenic zones are concentrated along the Tellian Atlas of Algeria. These zones (i.e., Oran, Mascara, El Asnam, Tipasa-Blida, Jijel, and Constantine) are concentrated linearly from the west to the east and define a boundary between the African and Eurasian plates.

The purpose of this study is to review the 1954 and 1980 El Asnam and 2003 Zemmouri-Boumerdès earthquakes (Fig. 1). The seismic energy released by all of the earthquakes with M>5.5 that occurred in Algeria during the period between 1900 and 2015 shows that 81% of the total energy was derived from the El Asnam (October 10, 1980; M_w7.3) and Zemmouri—Boumerdès (May 21, 2003; M_w6.8) earthquakes. Accordingly, we can consider the El Asnam and Zemmouri-Boumerdès faults as the largest earthquake sources in Algeria in the modern period, and therefore, in this chapter, we have selected them to be analysed.

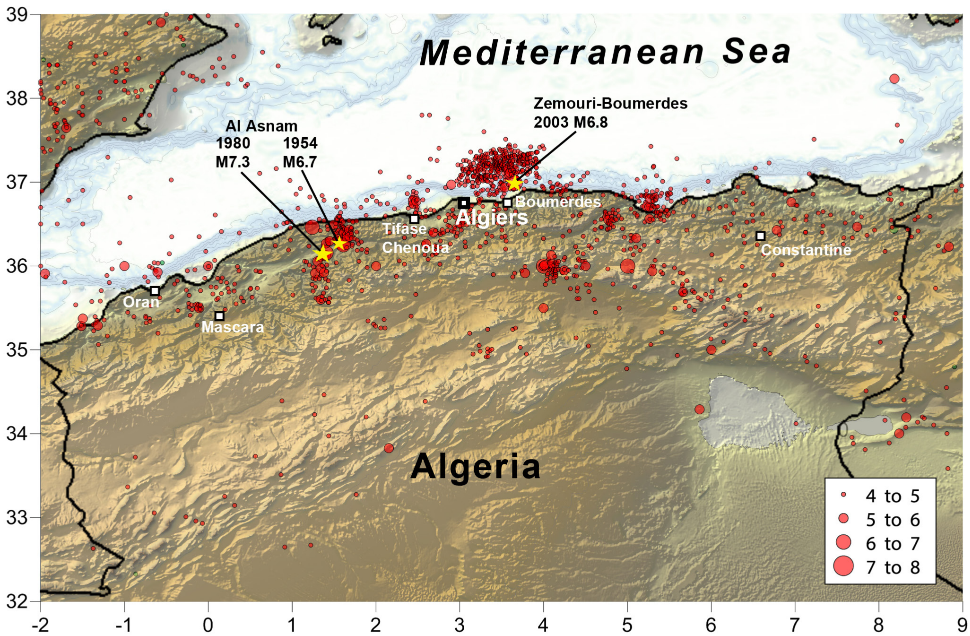


Figure 1: Seismicity (M≥4.0) of Algeria for 1910-2016. Seismic data were taken from the ISC database. The yellow stars represent the three major earthquakes discussed in this study. The topography and bathymetry data were extracted from the Shuttle Radar Topography Mission 1 Arc-Second Global (SRTM 1 Arc-Second Global) dataset.

2. Seismicity and tectonic setting

The seismicity of Algeria is located along the Nubia-Eurasia plate boundary starting from the Azores triple junction and stretching to Tunisia, thereby crossing the Strait of Gibraltar and the Ibero-Maghrebian region (i.e., Portugal, Spain, Morocco, Algeria and Tunisia). This seismicity is related to the dynamics of Quaternary basins under an oblique convergent NW-SE stress regime. The seismic activity, which is distributed over a wide zone, is characterized mainly by fault-related folds that strike NE-SW and are distributed along the major tectonic features (Fig. 1).

The Ibero-Maghrebian region is vulnerable due to the shallow character of its seismicity, which is located in the crust between depths of 5 and 20 km, except for beneath the Gibraltar Arc, the westernmost Alboran Sea, and the southern reaches of Spain where intermediate and deep earthquakes have been recorded. This seismicity is a subject of debate as to whether it should be attributed to active subduction beneath the Gibraltar Arc or to another origin (Gutscher et al., 2012). The distribution of seismicity in the Maghreb region gives a clear E-W trending shape to the activity along the Africa-Eurasia plate boundary. Morocco and Algeria appear as more active areas relative to Tunisia, which exhibits low seismicity levels. The seismicity is mainly concentrated in the Rif, High Atlas and Middle Atlas Mountains of Morocco, the Tell Atlas of Algeria and the Atlas of Tunisia and spreads across a band extending down to the Saharan Atlas. According to El Mrabet (2005) and El Alami et al. (2004), Morocco has experienced large seismic events principally in Al Hoceima (1848, Io IX; 1994, Ms 6.0; 2004, Ms 6.4) and Agadir (1731, Io IX; 1960, Mb 5.9).

In Algeria, seismicity is generally characterized by moderate- to low-sized magnitudes with strong events once every decade (Fig. 1). During the last 60 years, several strong events have been recorded that are associated with large and severe damage. Most of the events have been reported in the Tell Atlas of Algeria adjacent to Quaternary basins such as those of Chlef, Mitidja and Constantine. The easternmost Maghreb region in Tunisia has not experienced strong earthquakes because most of the seismicity is of relatively low magnitude (Bahrouni et al., 2013). Generally, most of the available focal solutions exhibit strike-slip faulting in northern Morocco, reverse faulting in Algeria and strike-slip faulting in eastern Algeria and Tunisia, especially in the Tunisian Sahel near the Gabès Gulf (Ayadi et al., 2002; Bahrouni et al., 2013; Bezzeghoud and Buforn, 1999; Buforn et al., 2004; Harbi et al., 1999).

The stress regime inferred from the focal mechanisms of shallow earthquakes is compatible with the horizontal N-S to NW-SE convergence between Eurasia and Nubia. However, in the Betics-Alboran area, there is also horizontal extension in an approximately E-W direction. The convergence rate, obtained from a seismic strain analysis, decreases from the Azores plateau to the Ibero-Maghrebian region (e.g., Bezzeghoud et al., 2014). According to the same authors, the corresponding values of the slip velocity range between 1.4 and 6.7 mm/yr except for within the Gloria fault zone, which displays a much higher value (18 mm/yr). For the northwestern part of Algeria and the Tell Mountains, the seismic velocity is 3.7 mm/yr. This seismic velocity assumes that the earthquake cycle is much shorter than the history of the available earthquakes, may be considered as instantaneous, and is independent from the derived geodetic data. In addition, these values may underestimate the geological deformation and may not include the energy released by aseismic processes (e.g., folding, thickening, plastic deformation, and slow aseismic slip).

3. The El Asnam earthquakes

The Chelif Basin is one of the most active seismogenic zones in the western Mediterranean area. This region has produced many seismic events in the past, including two of the most destructive earthquakes of the last century in the western Mediterranean region: September 9, 1954 (M_s=6.5, Karnik, 1969; M_w=6.9, Bezzeghoud et. al., 1995) and October 10, 1980, (M_s=7.3, USGS; M_w=7.1, Bezzeghoud et al., 1995) (Fig. 2). These main shocks have been studied by several authors.

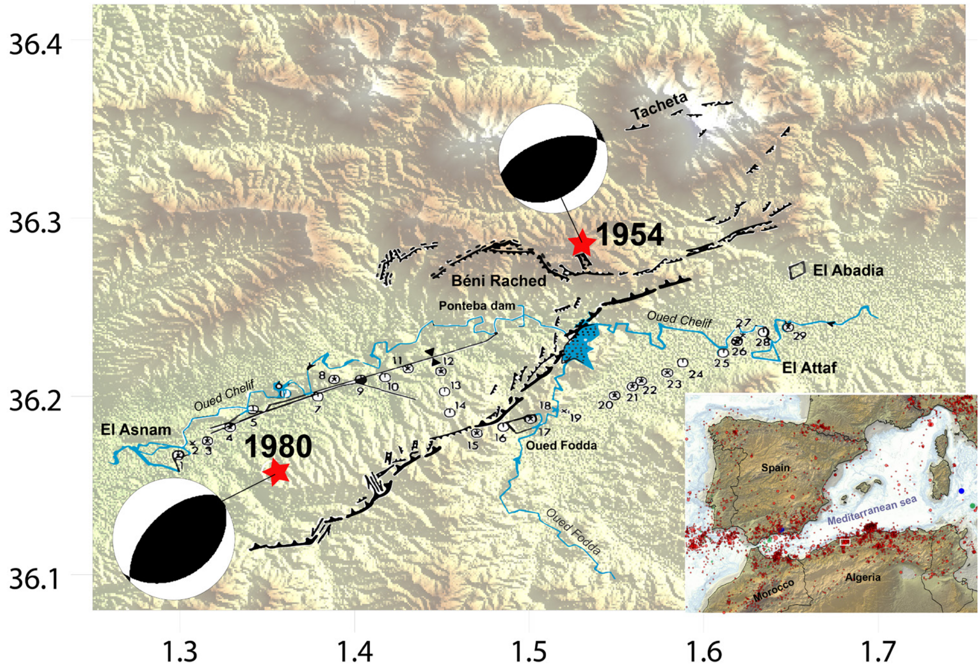
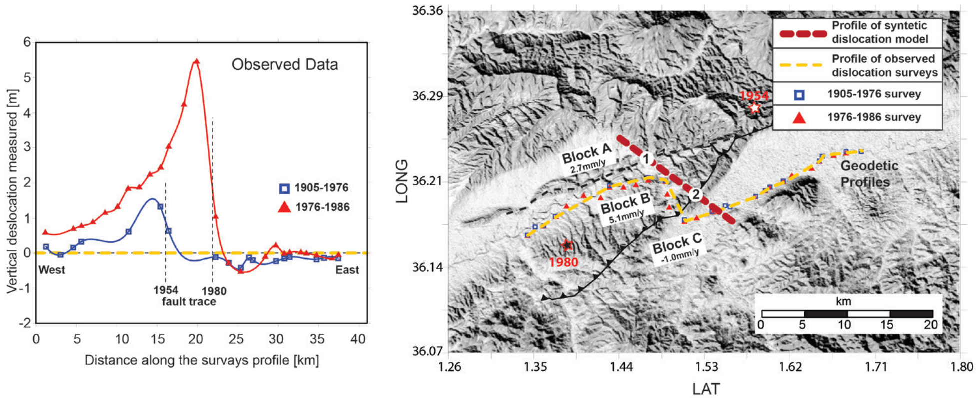


Figure 2. Map of the El Asnam thrust fault of 10 October 1980. 1954 surface breaks (dashed line) are from Rothé (1955). Epicentral locations (from Dewey, 1991) and focal mechanisms of 1954 (from Espinoza and Lopez-Arroyo, 1984) and 1980 (Deschamps et al., 1982) earthquakes. Levelling route (see text) following the Algiers-Oran railway, is indicated by circular symbols (from 1 to 29) crossing the surface breaks. Maximal deformations that occurred after the 1954 main shock (from Thevenin, 1955) are indicated by arrows on the water main and by (]) on the Ponteba dam. Map showing the location of the study area is presented in the right box. Modified from Bezzeghoud et al. (1995).

3.1. 1954 earthquake

Macroseismic and structural studies of the surface effects of the 1954 earthquake were conducted by Rothé (1955), Rothé et al. (1977) and Thévenin (1955). The focal thrust fault mechanism of the 1954 earthquake was determined and discussed by Shirokova (1967), McKenzie (1972) and Espinoza and Lopez-Arroyo (1984) (Fig. 2, Tab. 1). The 1954 earthquake produced substantial damage and rupturing in the El Asnam region. Rothé (1955) reported the generation of surface breaks around the Béni Rached zone, which is an important deformation (offset) along the 4.5-km segment of the Algiers-Oran railway, and published an isoseismal map with a recorded intensity of I_o=X in the El Asnam region. The maximal vertical displacement of 1.34 m that was observed by Bezzeghoud et al. (1995) from elevation changes between 1905 and 1976 is situated inside this deformed segment (Fig. 3, Tab. 1). Thévenin (1955) showed that the principal extent of damage and surface breaks were observed within a radius of 10 km and were centered on the village of Béni Rached, and mapped the perturbations of the hydrographic network associated with the topographic changes (Figs. 2, 3 and Tab. 1). Thévenin (1955) showed that the maximum deformation produced by the 1954 earthquake severely damaged the water main situated southwest of the Ponteba dam (Fig. 2). In some places, the circular cross-section of this canal was deformed into a NNW-SSE-oriented ellipse and underwent an elevation change of 1.5 m at a location 3-5 km west of the Ponteba dam, where the same order of magnitude of the maximum vertical displacement (1.34 m) was observed. At this site, the flow of the Oued Chelif was perturbed (Figs. 2, 3 and Tab. 1).



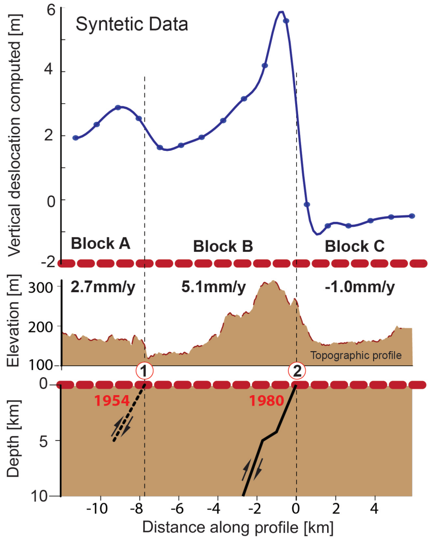


Figure 3. Top left: Levelling "1976-1905" (blue line) and "1986-1976" (red line) profiles showing observed co-seismic elevation changes along the profiles.
Top right: The levelling route that follows the Algiers-Oran railway, which is indicated with a yellow line crossing the surface breaks.
Bottom right: The top panel shows the vertical displacement induced from a global dislocation (1954 and 1980) model proposed by Bezzeghoud et al. (1995). The bottom panel shows the topographic level oriented N108E through the El Asnam fault trace. The dashed and full lines indicate, respectively, the 1954 buried and 1980 thrust faults. The three blocks (A, B and C), which are separated by the 1954 blind fault and the 1980 surface breaks, are discussed in the text. Modified from Bezzeghoud et al. (1995) and Lammali et al. (1997).

Table 1. Summary of source parameters of the E1 Asnam (1954 and 1980) and Zemmouri-Boumerdès (2003) earthquakes given by several authors.

EQ date	Lat. (º)	Lon. (º)	Seg.	φ (º)	δ (º)	λ (º)	ho (km)	Max. Slip (m)	Mo (Nm) x 10^{19}	M_w	Ref.
09/09/1954	36.28	1.57	—	217	67.5	104	1	3	0.98	6.7	EL84,B95, L97
10/10/1980	36.16	1.39	DS[a]	217	67.5	83	5^b	8	2.85	7.1	B95, L97
			S1, S2	217	67.5		3.7, 0^b	4, 1.5	0.093		
			S3, S4	217	60		3.5, 0^b	4, 1.0	0.227		
			S5	217	53.5		0^b	8	0.442		
			S6	217	30		3.3^b	8	0.887		
			S7, S8, S9	217	60		2.2, 1.1, 0^b	5, 3, 2	0.387		
21/05/2003	36.846	3.660	—	64	50	97	8	3.8	1.40	6.7	S14

EQ date: earthquake date; Lat., Lon.: location of the epicentre; Seg.: segment of the fault; the strike (φ), dip (δ), and rake (λ) are the geometric parameters; $h_{0:}$ hypocentre depth; Max. slip: maximum slip that occurred; M_o: seismic moment; M_w moment magnitude; EL84: Espinoza and Lopez-Arroyo (1984); L95: Bezzeghoud et al., 1995; B97: Lammali et al., 1997; S14: Santos et al., 2015; (a) deep segment; (b) depth of the upper edge of the fault.

3.2. 1980 earthquake

The 1980 earthquake was mainly characterized by its widespread 40-km-long observed surface faulting that was mapped by geologists immediately following the main shock (Figs. 2, Tab. 1). It is one of the most studied large events in the Mediterranean. Field studies (i.e., geological, seismotectonic, aftershock and geodetic studies) have been performed by Ambraseys (1981), King and Vita-Finzi (1981), Philip and Meghraoui (1983), King and Yielding (1984), Ouyed (1981), Ouyed et al. (1983), Yielding et al. (1981, 1989) and Ruegg et al. (1982). The focal mechanism and seismic source were modelled by Yielding et al. (1981), Deschamps et al. (1982), Kanamori and Given (1982) and Romanowicz and Guillemeant (1984). Cisternas et al. (1982) and Yielding (1985) relocated the 1980 main event and several of the largest 1980 aftershocks. The aftershock zone extended over a length of approximately 40 km in the NE-SW direction (Ouyed et al., 1981) and ranged between depths of 5 and 14 km following the relocation procedure using HypoDD performed by Ousadou et al. (2014). Three segments were identified on the rupture zone as shown by the aftershock distribution and surface fault traces (Ouyed et al., 1981). The NE edge leads along an approximately N-S direction. However, the source mechanisms determined by Deschamps et al., (1982) and Nabelek (1985) are consistent with the geodetic determinations obtained from the vertical and horizontal movement models reported by Ruegg et al. (1982) and Bezzeghoud et al. (1995) and with the complex fault segmentation along the El Asnam area as evidenced by surface rupture and aftershock studies (Ouyed et al., 1981; Philip and Meghraoui, 1983) (Figs. 2, Tab. 1).

3.3. Modelling and dislocation models for the 1954 and 1980 earthquakes

Using the Joint Epicenter Determination method, Dewey (1991) recalculated the epicenters of 72 earthquakes that occurred from 1954 to 1987 in the Chelif Basin and proposed a specific model of the 1954 fault, which was associated with the 1980 thrust fault. Avouac et al. (1992) combined topographically detailed measurements with seismic and geological data to analyse the El Asnam fault and proposed a displacement model for both earthquakes. Afterward, Bezzeghoud et al. (1995) reexamined the mechanisms of the 1954 and 1980 events by modelling the associated vertical movements and compared them with those of the models from Dewey (1991) and Avouac et al. (1992) (Fig. 3). Bezzeghoud et al. (1995) used all of the available data, particularly those of the levelling profile along the Algiers-Oran railway, which was remeasured after each event. A comparison between the 1905 and 1976 levelling data shows observed vertical displacements that could be related to the 1954 earthquake (Fig. 3, Tab. 1). On the basis of the 1954 and 1980 levelling data, Bezzeghoud et al. (1995) proposed a global model for the 1954 and 1980 fault systems (Fig. 3).

Finally, Lammali et al. (1997) presented an overview of the seismicity and seismotectonics of the El Asnam region based on the geological features, earthquake distribution, focal mechanisms and coseismic movements associated with the 1980 El Asnam earthquake and the postseismic movements along the entire El Asnam fault zone obtained from periodical surveys from 1986 to 1991 using a precise levelling method (Fig. 3 and Tab. 1). Since 1986, the ‘Centre de Recherche en Astronomie, Astrophysique et Geophysique’ (CRAAG, Algiers) has organized a systematic survey of the horizontal deformation around the El Asnam thrust fault with a horizontal geodetic network tied to the National Triangulation Network. The first results were published by Dimitrov et al. (1991). Lammali et al. (1997) showed that the relative horizontal deformation was oriented perpendicularly to the fault with a NNW-SSE shortening orientation. This compression of the two blocks correlates rather well with the uplift of the northwestern zone that was evaluated from observed vertical movements. Moderate elevation changes of the benchmarks were observed, where the elevation changes were more intense in the NW block of the fault (5.1 mm/yr) than in the SE block (Fig. 3, Tab. 1). The Sar El Maarouf anticline appears to grow with a local velocity of approximately 10 mm/yr, which is in agreement with geological and seismological data (Fig. 3, Tab. 1). The 1954 blind thrust fault is likely situated at the boundary of these two blocks, which are labelled A and B. Elevation changes are more intense in block B (5.1 mm/yr) than in block A (2.7 mm/yr). The 1980 thrust fault is situated along the boundary of blocks B and C (-1.0 mm/yr). These ascending and descending movements are probably associated respectively with the seismic and/or aseismic activity of the thrust faults responsible for the 1954 and 1980 earthquakes (Fig. 3, Tab. 1).

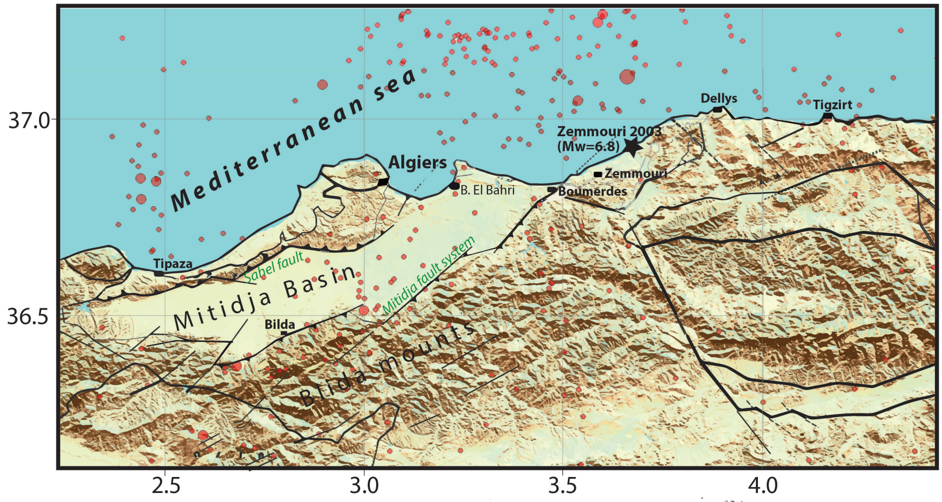


Figure 4. Tectonic and seismicity (M≥4.0, 1910-2016) map of the Mitidja basin (central Algeria). The tectonic framework is adapted from Ayadi et al. (2003) and the seismic data were taken from the ISC database.

4. 2003 Zemmouri-Boumerdès earthquake

The Mitidja Basin, which is located in the central Tell Atlas, is one of the most active structures in the region similar to the Chelif Basin (Fig. 4). This basin has experienced many seismic events since the first reported earthquakes of 1365 and 1716 that struck Algiers. Many other events have occurred around the basin along its edges, such as the 1858 earthquake of Blida and the 1989 earthquake of Tipasa Mont Chénoua. The seismicity of the Mitidja basin is characterized by moderate earthquakes with episodic strong events (Ayadi and Bezzeghoud, 2015). Tectonic studies of the Mitidja Basin showed that it is filled with more than 3000 m of Quaternary sediments and is bounded by two systems of faults (Fig. 4): the Sahel fold-related fault on its northern edge and the southern Mitidja fault system that separates the basin from the Blida mountains, which demonstrate an elevation reaching more than 1000 m above sea level. The seismic activity is mainly associated with these two systems of faults (Fig. 4), particularly the southern Mitidja fault system, which was most active during the period of 2000-2017.

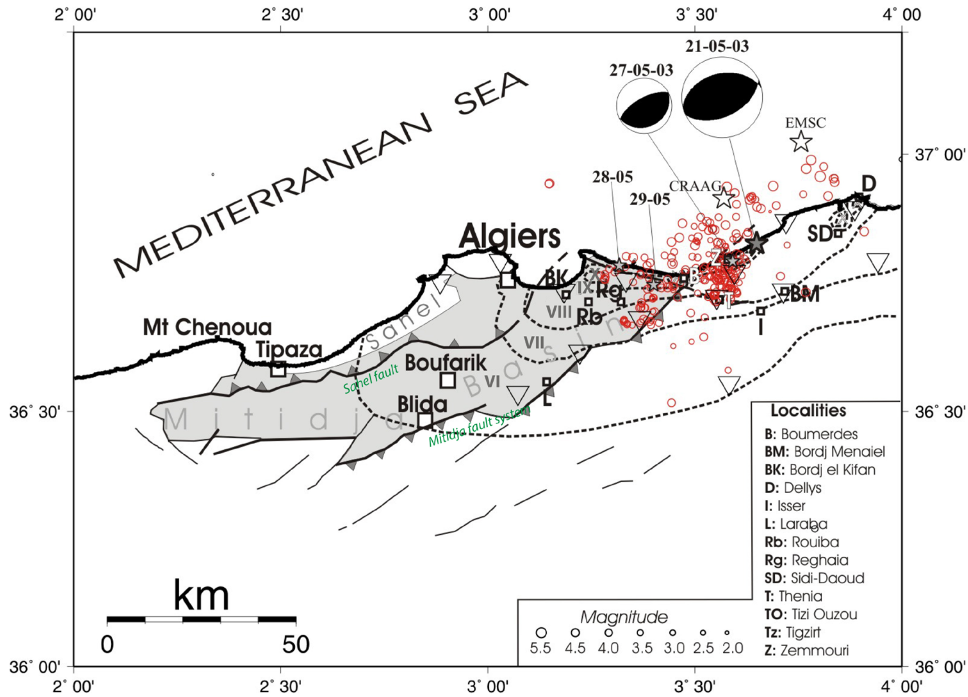


Figure 5. Isoseismal map and tectonic background of the epicentral area (adapted from Ayadi et al., 2003) are plotted with the aftershocks distribution map of the earthquake of May 21, 2003. Aftershocks magnitude is ranging between 2.0 and 5.8 within the period May 21 to June 10, 2003. The relocation of the epicenters of the main shock and of the 3 large aftershocks are represented by grey start. Large open stars show the epicenters of the M_w6.8, May 21, 2003 Zemmouri-Boumerdes earthquake given by two different institutions: Centre de Recherche en Astronomie, Astrophysique et Géophysique (CRAAG, Algiers) and European Mediterranean Seismological Center (EMSC). The large grey star represents the relocation of the main shock obtained by Ayadi et al. (2004). The focal mechanisms of the main shock and the M_w5.8 aftershock of May 27 are determined by Santos et al. (2015). Open squares: cities; open triangles: seismological stations.

4.1. Damage and casualties

The most important and strongest event that occurred in the Tell Atlas (Algeria) after that of El Asnam (1980) was that of Zemmouri (M_w6.8), which struck the eastern part of the capital city of Algiers on May 21, 2003, at 18:44 UTC in an area where none of the catalogues have reported the occurrence of a strong event during the past (Figs 1 and 4). This earthquake generated immense damage and caused 2,278 fatalities, and left an additional 11,450 injured and 250,000 homeless. The buildings in the area were seriously affected; 6,000 buildings were destroyed and 20,800 housing units were severely damaged. This earthquake was the most disastrous event since the El Asnam earthquake, which also occurred near Algiers, the capital city. A macroseismic study (Harbi et al., 2007) reported that the Zemmouri-Boumerdès earthquake affected a large area with a radius of approximately 150 km around the epicentral locality. The maximum intensity observed during the main shock was X (according to the European Macroseismic Scale, EMS98), which was observed for Bordj Menail, Zemmouri, and Corso in the Boumerdès Province. The zone that demonstrated an intensity degree of X was concentrated along the coast between El Marsa and Dellys and was mostly related to site effects and poorly engineered buildings (Fig. 5).

The Zemmouri-Boumerdès earthquake also generated a spectacular coastal uplift along the shoreline from Algiers to Dellys, for which a mean uplift of approximately 0.75 m was observed (Meghraoui et al., 2004). Liquefaction, including the extrusion of sand and sliding of river banks, was also observed between Algiers and Dellys. Rock falls and landslides were also reported between Corso and Dellys. The main shock also triggered a tsunami with waves up to 1 to 3 m that caused damage on the Balearic Islands, while in the epicentral area the sea retreated approximately 200 m away from the coast (Alasset et al., 2006).

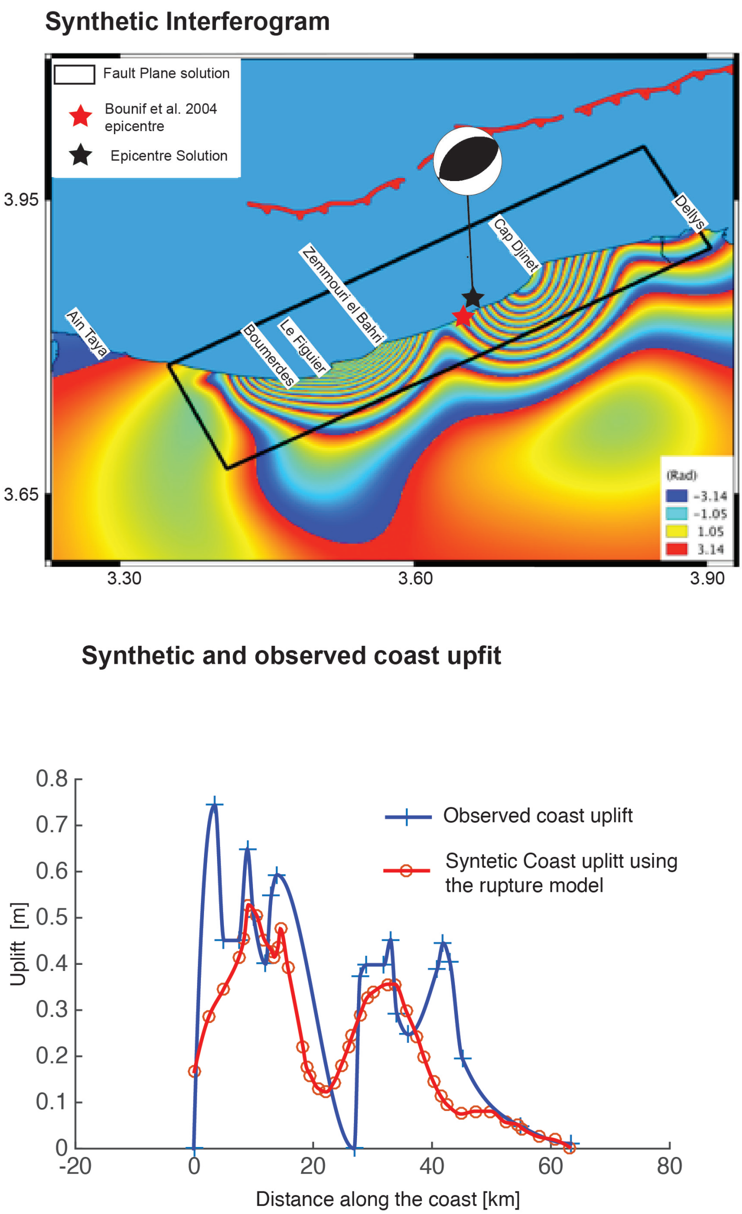


Figure 6. Top: Vertical displacement model and synthetic interferogram for the focal solution given by Santos et al. (2015) (see Tab. 1). The red star is the epicentre relocation proposed by Bounif et al. (2004), and the green star is the location of the solution given by Santos et al. (2015). The black polygons are the projections of the fault plane on the Earth's surface, and the red line is the fault location proposed by Déverchère et al. (2005). Bottom: graphs of the vertical profiles and uplift measurements (Meghraoui et al., 2004) of the Algerian coast (blue line); the red line identifies the best fit of the vertical profile to the uplift measurement (Santos et al., 2015).

4.2. Source location and parameters

The source parameters of the main shock and related principal aftershocks were modeled by Bezzeghoud et al., (2004), Braunmiller and Bernardi (2004), Delouis et al., (2004) and Santos et al. (2014). The focal solutions calculated by these authors and by different seismological agencies give a thrust mechanism with a NE-SW direction (Fig. 5). The location of the earthquake was estimated to be approximately 20 km offshore by the CRAAG, EMSC and NEIC, and all of these locations are in conflict with observed coastal uplift, source modelling and aftershock locations (Ayadi et al., 2008; Bezzeghoud et al., 2004; Bounif et al., 2004; Meghraoui et al., 2004; Delouis et al., 2004; Santos et al., 2014). The relocation of the mainshock by Bounif et al., (2004) shifted the location to the coastline at a depth between 8-10 km (Figs. 6, 7). These observations lead us to suggest that the main shock was associated with a fault that is a continuation of the southern Mitidja fault system. The distribution of the aftershocks of the 929 well-located events (Fig. 5) was used by Ayadi et al. (2008). The aftershock distribution and cross sections reveal a fault plane striking NE-SW and dipping toward the SE. The seismic crisis was characterized by a main shock that occurred on May 21st and by three main aftershocks that occurred on May 27th, 28th and May 29th with respective magnitudes of 5.8, 5.0 and 5.8. All of these large aftershocks occurred on the western side of the Zemmouri-Boumerdès affected area, suggesting the migration of the activity towards the west as proposed by Santos et al., (2014), who proposed a fault scheme of several segments involved in the seismic crisis (Fig. 7).

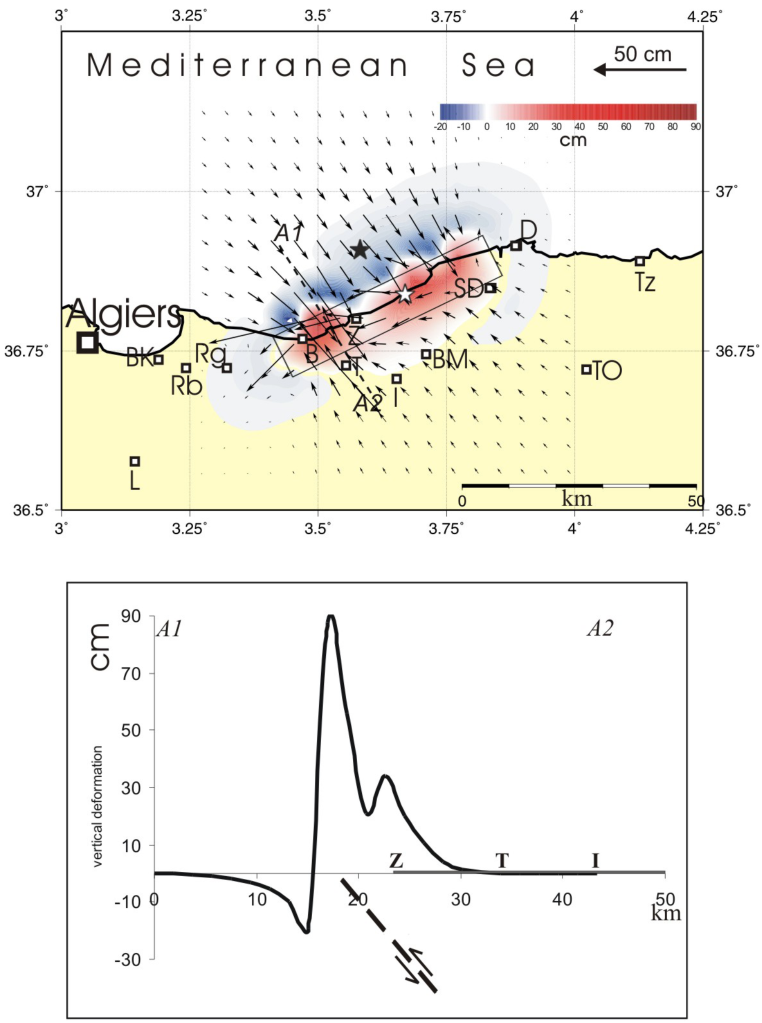


Figure 7. Predicted co-seismic displacement field model. Top: Vertical and horizontal co-seismic distribution map. Blue and red colors indicate, respectively, subsidence and uplift. Bottom: profile along A1-A2 from top of figure.

The Zemmouri-Boumerdès earthquake provided good indications about the activity along the eastern edge of the Mitidja Basin. The analysis of the crisis related to this event attests the interaction of the segments involved during the May 21st earthquake with a migration of the seismicity towards the west along different individual fault segments. A Coulomb stress transfer analysis (Lin et al., 2011) demonstrated that part of the energy is currently transferred along both the Sahel fold-related fault and along an eastern segment of the southern Mitidja fault system. This is confirmed by the latest seismic event that struck the south Mitidja Basin in July 2013 (M5.1).

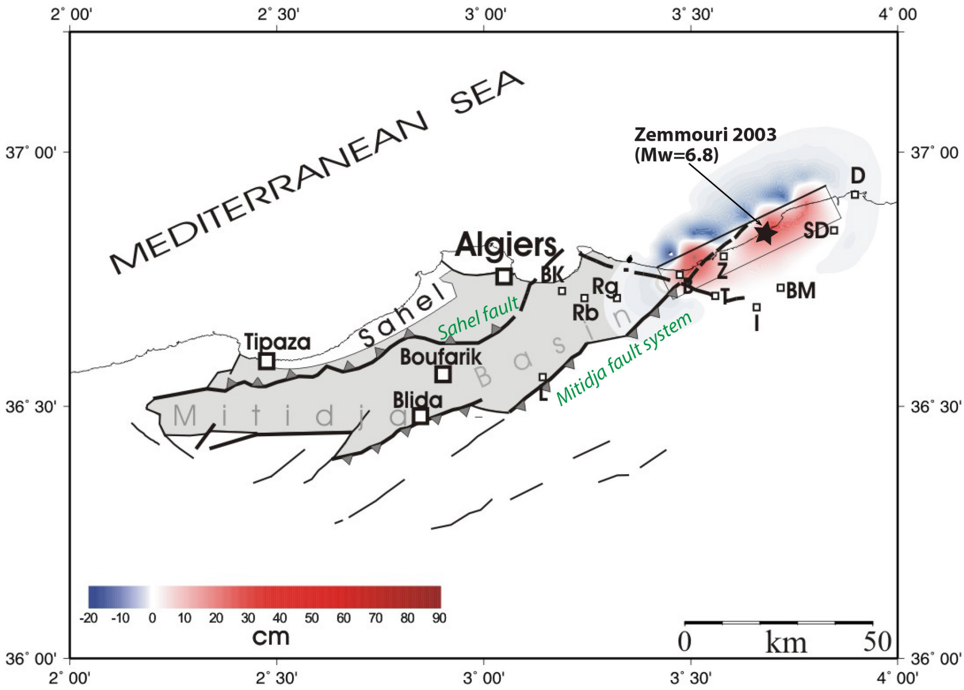


Figure 8. Predicted co-seismic vertical displacement map plotted together with the tectonic background of the epicentral area and the main shock epicenter represented by the open star.

The model presented by Santos et al. (2014) is similar to several models published by other authors (Delouis et al., 2004; Meghraoui et al., 2004; Belabbés et al., 2009) with respect to two well-defined asperities in the rupture (Tab. 1). The obtained models of the slip distribution are compatible with the geodetic and seismic results. The seismic magnitude (6.7) is compatible with the estimation presented by the scientific community (between 6.7 and 6.9: Yagi, 2003; Delouis et al., 2004; Meghraoui et al., 2004; Belabbés et al., 2009). With respect to the duration of the rupture, the model obtained by Santos et al. (2014) gives a duration of approximately of 15 s, although 85% of the seismic moment was released within the first 12 s. The maximum slip (3.8 m) determined is similar to those obtained by Semmane et al. (2005), Delouis et al. (2004) and Belabbés et al. (2009) and reveals a similar mechanism with a strong reverse component and a small strike-slip component (Tab. 1). The result induced from fault slip distribution model, dipping to the SSE, gives a field displacement model shown on figure 6 with vertical and horizontal maximum displacement values, respectively, of about 90 cm and 68 cm (Figs. 6, 7). If we consider that the measured uplift of the continent between Algiers and Dellys, the vertical displacement value of displacement explains 90% of the minimum (100 cm) and 60% of the maximum (150 cm) of these observations. This vertical value is comparable to the maximum co-seismic slip observed (132 cm) after the El Asnam (Mw=6.7) earthquake of 9 September 1954 (Bezzeghoud et al., 1995, Lammali et al., 1997).

The synthetic interferograms demonstrate that the model determined by Santos et al. (2014) is well adjusted (Fig. 6). The projection of the fault trace on the surface of the solution given by Caldeira (2005) shows that this part of the fault is located in the sea (9 km from the coastline) and does not reach the seabed (Figs. 7, 8). These results are in agreement with those given by several authors (Belabbés et al., 2009; Ayadi et al., 2008, 2010) and are also in agreement with the aftershock relocation proposed by Ayadi et al. (2008), wherein one aftershock cloud corresponded to a fault that dipped toward the SE. However, the fault advocated by Déverchère et al. (2005, 2010) is far from the coastline (Fig. 8), and the co-seismic displacements observed along the coast could not be modelled for this distance (in agreement with Ayadi et al. 2010).

We remark that the vertical displacement values estimated from the fault slip distribution model infer location of the causative fault of the Zemmouri-Boumerdes earthquake close to the coastline as shown by the position of the vertical and horizontal displacement model on the figure 8. The rupture propagated upwards, with most of the slip occurring near the surface. The total area of displacement is estimated to be about 500 km^2 (Fig. 8). The vertical displacements estimated from the fault slip distribution model, the main shock relocation and the aftershock distribution suggest a fault close to the coastline as origin of the Zemmouri-Boumerdes earthquake. This location supported by the observed values of costal uplift is compatible with the offshore continuation of the south Mitidja basin faults system.

5. Final remarks

The Tell Atlas of Algeria, one of the most active areas in the western Mediterranean Basin, experienced three strong seismic events over the last three decades that occurred on the two most active structures in the Chelif and Mitidja Basins. Based on the catalogue of Ayadi and Bezzeghoud (2015), the seismic energy released by all of the earthquakes with M>5.5 that occurred in Algeria during the period between 1900 and 2015 indicates that 69% of the total energy originated from the El Asnam earthquake of October 10, 1980. The 1980 El Asnam earthquake is the seismic event that dominates all of the seismicity in the region for this period (1900-2015). The earthquake (M_w6.8) that occurred in the Zemmouri—Boumerdès region on May 21, 2003, represents only 12% of the total energy released by the earthquakes occurring within the same period (1900-2015). In addition, other recent earthquakes have released very low amounts of energy (1%) when compared with the total seismic energy released by the El Asnam earthquake of October 10, 1980.

For the total period ranging from 1365 to 2015 listed in the catalogue of Ayadi and Bezzeghoud (2015), the seismic energies released by the El Asnam earthquake of October 10, 1980, and the Zemmouri—Boumerdès earthquake of May 21, 2003, of 8% and 1%, respectively, are much less significant when compared to that released (88%) by the 6 largest major historical earthquakes (January 2, 1365, October 9, 1790, March 1819, March 2, 1825, January 2, 1867 and January 1, 1891). All of the other recent earthquakes have released an insignificant amount of energy (<1%) when compared with the total seismic energy released by all of the seismic events recorded during the period of 1365-2015.

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