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EDICIONES COMPLUTENSE

The large Algerian earthquakes (267 A.D.-2017)

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Abstract. In northern Algeria, large earthquakes occurred in the past as the El Asnam earthquake of October 10th, 1980 (Ms:7.3), one of the strongest event ever recorded in the western Mediterranean region. There were located mostly in the Tellian Atlas, some of them off the coastline as the Algiers (1365), Oran (1790), Djidjelli (1856) earthquakes or the last Boumerdes earthquake (2003). On land, no strong earthquakes have been recorded in the High plateaus or along the Saharan Atlas.
From a synthesis of seismological or geodynamical studies carried out on the Algerian seismicity, we conclude that these main events along the African-Eurasiatic plate boundary are representative of the actual deformation pattern of the different geological domains of northern Algeria. They are generated mainly by reverse faults or strike slip faults in relation with the NW-SE to NNW-SSE stress regime (σ 1 striking N330°- N350°) inherited from the oblique convergence process between the two main plates in the western Mediterranean region. They are in general superficial located in the upper part of the crust (no more than 20 Km). Important earthquakes do not occur very often in Algeria in comparison with other seismic regions of the world. Their return period are estimated in some regions to be of many hundred of years.
Large earthquakes still cause important damage to cities and villages, sometimes with the loss of thousand of citizens.
Key words: Earthquakes; northern Algeria; reverse faults; source parameters; focal mechanisms, stress regime.

[es] Los grandes terremotos argelinos (267 a.C.-2017)

Resumen. En el norte de Argelia han ocurrido grandes terremotos, como el de El Asnam de 10 de Octubre de 1980 (Ms:7.3), uno de los mayores registrados en el Mediterráneo occidental. La mayoría de estos sismos se localizan en el Atlas Telliano, algunos de ellos cerca de la costa (Argel, 1356; Orán, 1790; Djidjelli, 1856) o el más reciente de Boumerdes (2003). Tierra adentro, en la zona de las Altas Mesetas o a lo largo del Atlas Sahariano no se han registrado grandes terremotos. A partir de estudios de sismicidad o geodinámica de Argelia, se puede concluir que los grandes terremotos localizados a lo largo del límite de placa Eurasia-Africa muestran la deformación actual en los diferentes dominios geológicos del norte de Argelia. Estos esfuerzos se deben principalmente a fallas inversas o de desgarre relacionadas con el régimen de esfuerzos NW-SE a NNW-SSE (σ 1 en dirección N330°- N350°) consecuencia del proceso de convergencia entre las placas de Africa y Eurasia. En general son superficiales, localizados en la corteza superior (a menos de 20 km). En comparación con otras zonas del mundo, los grandes terremotos no son muy frecuentes en Argelia, estimándose su periodo de retorno en cientos de años para alguna regiones. Estos grandes terremotos han causado daños importantes en ciudades y pueblos, con la pérdida de miles de vidas.
Palabras clave: Terremotos; norte de Argelia; fallas inversas; parámetros de la fuente; mecanismos focales; régimen de esfuerzos.

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1. Introduction

Due to its particular location, along the African-Eurasiatic plate boundary, northern Algeria is exposed to an important seismic activity. Daily, several minor shocks are recorded by the Algerian seismological network with an average of about a hundred of events per month. However, sometimes moderate to large seismic events could happen as demonstrated by the occurrence of the main El Asnam earthquake (200 Km west of Algiers) in October 1980 (Ms:7.3) (Ouyed et al., 1981) or the recent Boumerdes earthquake of May, 2003 (Mw: 6.8) (Yelles-Chaouche et al., 2003a).

By large earthquakes, we mean events which cause human losses and important damages on the cities. These are historical events with an Intensity of IX -X or instrumental earthquakes with a magnitude equal or greater than 6.0.

During history, many archives, reports, newspapers revealed destructive earthquakes near important cities (Rothe, 1950; Ambraseys, 1988). We know for example that Algiers, the capital of Algeria was repeatedly shake by important earthquakes (Harbi et al., 2007; Sebai et Bernard, 2008). For the more recent instrumental period, seismic catalogs report many damaged earthquakes (Mokrane et al., 1994, Benouar, 1994).

Nevertheless, if we compare seismicity of northern Algeria with other seismic regions over the world as the eastern Mediterranean or the Indian-Pacific regions, large earthquakes in Algeria are relatively infrequent. If we consider the last century (1900-2017), only six events overlay the magnitude 6. These are the Aumale event of June 24th, 1910, the two main events of Orleansville and Chleff (1954, 1980), the earthquake of Tipaza of September 1990 (Ms:6.0), the Constantine earthquake of October 1985 (M: 6.0), the earthquake of Boumerdes of May 2003 (Mw:6.8).

The main Algerian earthquakes are in general concentrated in the Tellian part of northern Algeria. Some of them located offshore generated small tsunamis as the Djidjelli earthquake of August 22nd, 1856 (Benhallou, 1985).

Although, the knowledge of the seismic activity in northern Algeria has improved consequently with the study of the large earthquakes, some important geophysical projects recently implemented led to know more about the Algerian seismicity. Indeed, such projects as the installation of the new digital seismic network (ADSN Network) in 1998 (Yelles-Chaouche et al., 2013), the Maradja project (Yelles-Chaouche et al., 2006a), the Spiral project (Yelles-Chaouche et al., 2010) or the REGAT Atlas GPS network project (Lammali et al., 2015) provide valuable results to understand mechanisms of the Algerian seismicity.

Study of large events in Algeria provide the opportunity to understand more about the seismogenic regions, to proceed reevaluation of the seismic hazard and to reinforce the seismic risk mitigation in our country.

2. Historical seismicity

To investigate main earthquakes in the past in Algeria deals with the several historical periods of Algeria. If the first historical studies were concentrated mainly in the

French period due to the abundance of the literature, the actual work is now more focused on the Turkish, Arab or Roman periods.

Interest of historical seismicity of Algeria started mainly in the 19th century. Many publications (Perrey, 1848; Chesneau, 1892; Hée, 1950) have reported the occurrence of many low to moderate events and some important events, covering the period before 1840, 1888 and 1900.

First macroseismic seismic catalogues for the 20 th century were produced by Hée, 1933; Grandjean, 1954; Roussel, 1973a. Based on these previous works, Rothé (1950), Roussel (1973b) published catalogues considered today as a reference.

In the eighties, publications of Benhallou (1985) and Ambraseys (1988) review the previous works and present the more complete listing of events. Their works were later updated by other new catalogs of Mokrane et al., (1994); Benouar (1994); Harbi et al., (2007); Yelles-Chaouche et al. (2002, 2007) and Hamdache et al. (2010).

In the present days, these catalogues are continuously updated by the historical works lead at CRAAG. Many earthquakes in the roman period were recently revealed through analysis of archives and archeological monuments (Ferdi and Harbi, 2014). J.P. Laporte et X. Dupuis (2009) discovered the first earthquake known in Algeria which happened in Negrine (eastern part of Algeria) at 267 (A.D.). The authors reported that under the consul Paternus Arcelisaus the city was damaged seriously. Another strong earthquake could have occurred in this period, the Sitifis earthquake in 419 as reported by Saint Augustine, an early Christian theologian of Hippone (now Annaba) (Yelles-Chaouche et al., 2009 a).

In this historical period, we can consider that for the Arab and Turkish periods, three major earthquakes have provoked such effects that they have impacted history of some Algerian cities (Rothe, 1950; Ambraseys, 1988). These three main events are:-the major earthquake of Algiers of 1716,-the second one is the Oran earthquake of 1790 (Figure 1 a) which push the Spanish to leave the city (Lopez-Marinas and Salord, 1990) and the last one is the Blida earthquake of 1825 which caused just before the French occupation the loss of 3000 citizens. For this period, poor of available archives, Sebai and Bernard (2008) make a first attempt to collect detailed information about the several seismic events. From their work, many new earthquakes were discovered and included in the Algerian seismic catalog.

For the French period, many large events are reported in the table 1 as the one of Djidjelli in August 1856, or the Gouraya earthquake of 1891 (Figure 1b).

Analysis of the main historical earthquakes permit a first seismic zoning where the Tell region is the more exposed to such events. From north to south, the seismic activity decreases with no seismic events south of the Atlasic flexure related to the Saharan Atlas. In this later area, a relative important event occurred in 1869 destroying the small Saharan city of Biskra (Roussel, 1973b, Harbi et al., 2010).

The MOI (Maximum Observed Intensity) map carried out from intensities estimation of several moderate to strong events (Mokrane et al., 1994) (Figure 2) shows that the Chleff region present the strongest Intensity value reached after the El Asnam event (Intensity X-XI), one of the strongest event in the western Mediterranean region.

The study of historical seismicity in Algeria gives an important outlook on some characteristics of the Algerian seismicity as location of important events, their recurrence and their effects. Important results have been also obtained recently in the seismic hazard evaluation (Hamdache, 1998; Aoudia et al., 2000). However, the completeness of the catalog still remains an urgent task to know more about the seismogenic zones.

Figure 1. Pictures of the historical earthquakes
a) Oran earthquake October 9th1790 (I:X) b) Gouraya earthquake of January, 15th,1891

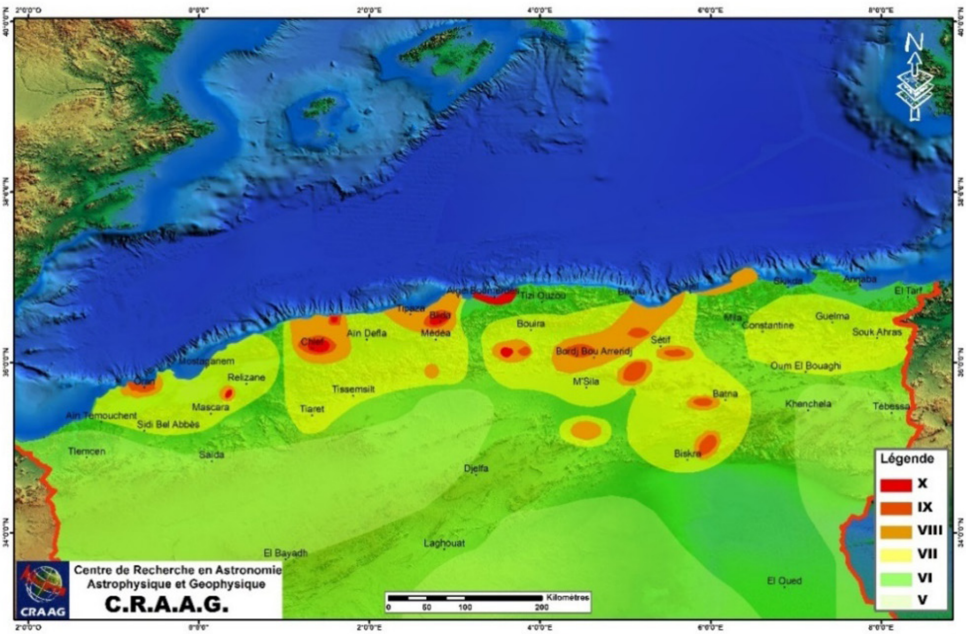


Figure 2. Maximum Observed Intensity Map of northern Algeria
(from Mokrane et al., 1994)

3. Seismotectonic context

Seismic activity in Algeria results from the oblique convergence of the two main African-Eurasiatic plates (Figure 3).This collision which started since the Cenozoic time has conducted to the creation of the Alpine belt in the north, the Atlas belt in the south and the reorganization of the Tethys ocean through several subduction zones and the splitting of the ALKAPECA block (Bouillin, 1986; Schettino et Turco, 2006).From the Pleistocene period, the northern limit of the Tell belt region experienced a tectonic inversion (Strzerzynski et al., 2009) represented by a compressional active tectonics attested by the present-day compressive stress field regime and the seismicity (Serpelloni et al., 2007). By now, the several plate kinematics studies demonstrate that the velocity rate of the collision in the western Mediterranean region is estimated to 0.5 cm/year in northern Algeria along the NNW-SSE direction (Stich et al., 2006; Nocquet et al., 2012).

The recent Maradja and Spiral projects (Yelles-Chaouche et al., 2010) analyzing the superficial and deep seismic structures of the Algerian margin demonstrate that the deflection of the oceanic lithosphere of the Algerian basin near the continental slope supposes the existence of an incipient subduction zone in the central segment of the margin (Hamai et al., 2015).

The active deformation mainly concentrated in northern Algeria expresses in the Atlasic belt through a network of active faults (Meghraoui, 1988). This network is representative from the transpressional convergence marked by rotating blocks (Meghraoui et al., 1996a). From west to east, active faults are visible as en echelon system represented by inverse faults or faults related to fold mainly oriented NNE-SSW or strike slip faults oriented NNW-SSE. In the eastern part, recent earthquakes on E-W active faults indicate a reorientation of the most compressive stress axis σ_1 in a NNW-SSE to N-S (Buforn et al., 1995; Ousadou et al, 2014; Abacha, 2015).

In the several Neogene basins of the Tell region, active faults are mainly concentrated along their borders as observed in the Chleff or the Mitidja basins.

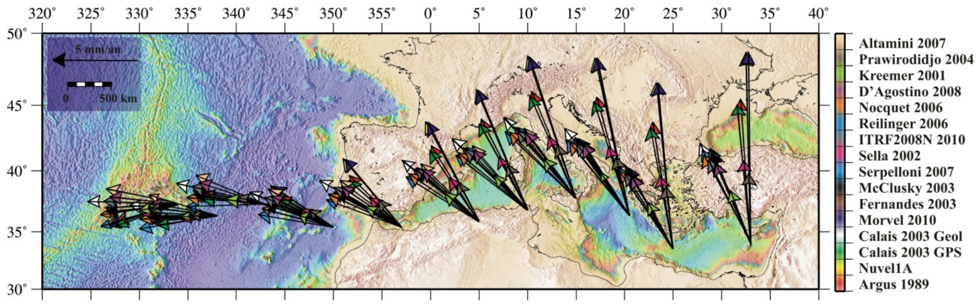


Figure 3. A synthesis of velocity vectors along the Nubia plate boundary (from Abacha, 2015)

4. Data and methodology

This synthesis carried out on the large earthquakes of Algeria is based first on main historical investigations and information collected from reports and archives. As already mentioned above, many studies have been carried out these last years especially for the French period (Harbi et al., 2010).

Second, this synthesis is issued from the several studies based on data collected by the Algerian seismic network (Beldjoudi, 2011, Kherroubi, 2011, Abacha, 2015). Indeed, since the installation of the Algerian network in 1990 (Bezzeghoud et al., 1994), and although some damage in the period (1991-1997), it was possible to record with accuracy the seismic activity of northern Algeria. This network was improved technically in 1998 by its transformation from the analog mode to the digital mode (Yelles-Chaouche et al., 2013). It permitted to face the moderate Ain Temouchent earthquake of December 22nd, 1999 (Mw: 5.7) (Yelles-Chaouche et al., 2003b), many several moderate event and the strong Boumerdes crisis of May 2003. The network was also renewed in 2007 by the integration of many Broad Band stations. Now the network is equipped with eighty stations (Figure 4) and is working as a rapid alert system.

To understand seismicity of northern Algeria, we also launched fifteen years ago two main projects: the Maradja project (2003-2009) for the study of the active tectonics of the Algerian margin and also the SPIRAL project (2009-2014) to understand the crustal structure along the transitional zone between the Ocean and Continent. Among the main results of these two projects, the identification of several active faults off the Algerian coastline (Figure 5) and delineation of the African-Eurasiatic plate boundary in northern Algeria (Domzig, 2006, Mauffret, 2007).

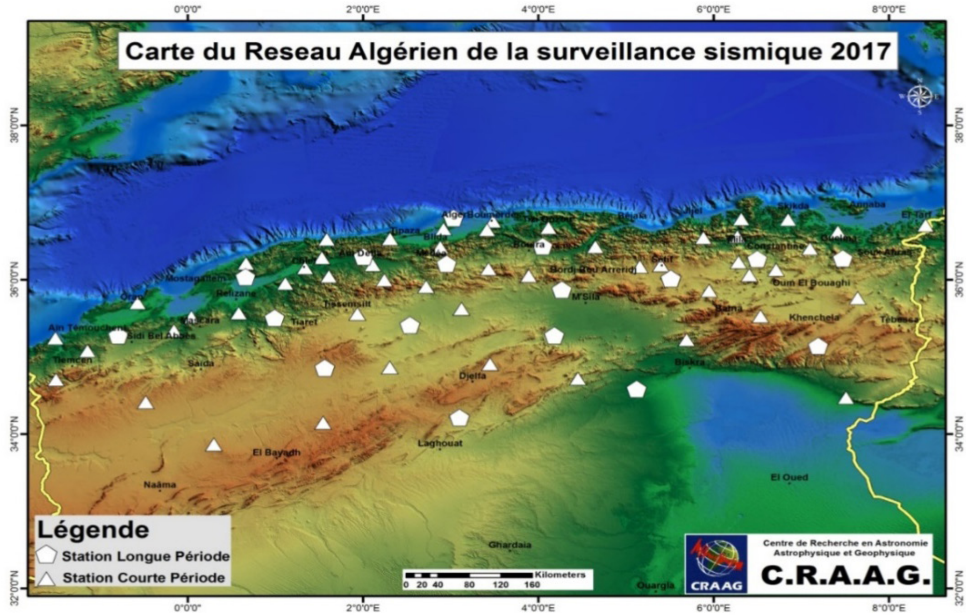


Figure 4. Algerian Digital seismic network (from Yelles-Chaouche et al., 2013)

5. The large Algerian earthquakes

Among the main historical earthquakes of northern Algeria (Table 1), we select the Algiers one of 1716, the one of Oran of 1789, the two Blida-Mouzaia earthquakes of 1825 and 1867 and the Djidjelli one of August 1856.

The Algiers earthquake of February 1716 (I:X)

It is one of the most important earthquake in northern Algeria and more particularly in the Algiers region (Rothe, 1950). It destroyed the Casbah city and caused the death of about 20 000 persons. Taking into account of all effects reported, it seems that the epicenter location is close of the Kolea village, situated about 20 km west of Algiers. This indicates that this shock could be have occurred on the Sahel reverse fault, one of the main active fault of the neogene Mitidja basin. (Figure 5).

The Oran earthquake of October 9 th1790 (I:X)

This is one of the major historical earthquake in northern Algeria. It is well documented by the Spanish reports as a lot of details were reported (Rothe, 1950). It caused the leaving of the Spanish authorities from Oran, ruined by this shock. Its magnitude could be estimated to M: 7.0 or more. It also provoked a small tsunami with affects the southern Spanish coast.

According to our knowledge of the active tectonic investigations made onland and offshore, this earthquake might be generated by the offshore extent of the main Murdjadjo reverse fault.

The Blida earthquake of March 2 nd 1825(I: X)

This earthquake destroyed the city of Blida where thousand of people died (around 7000) (Ambraseys, 1988). Effects of this terrible event was still observed when the French occupied Algiers and its suburbs in 1830.

According to what is known today about active tectonics in the Mitidja where the main faults are now identified (Yelles-Chaouche et al., 2006b; Guemache, 2010), this destructive earthquake (Figure 5) corresponds to the activation of one segment of the main Blidean Atlas active fault system located along the southern boundary of the Mitidja basin. (Boudiaf, 1996; Yelles-Chaouche et al., 2017)

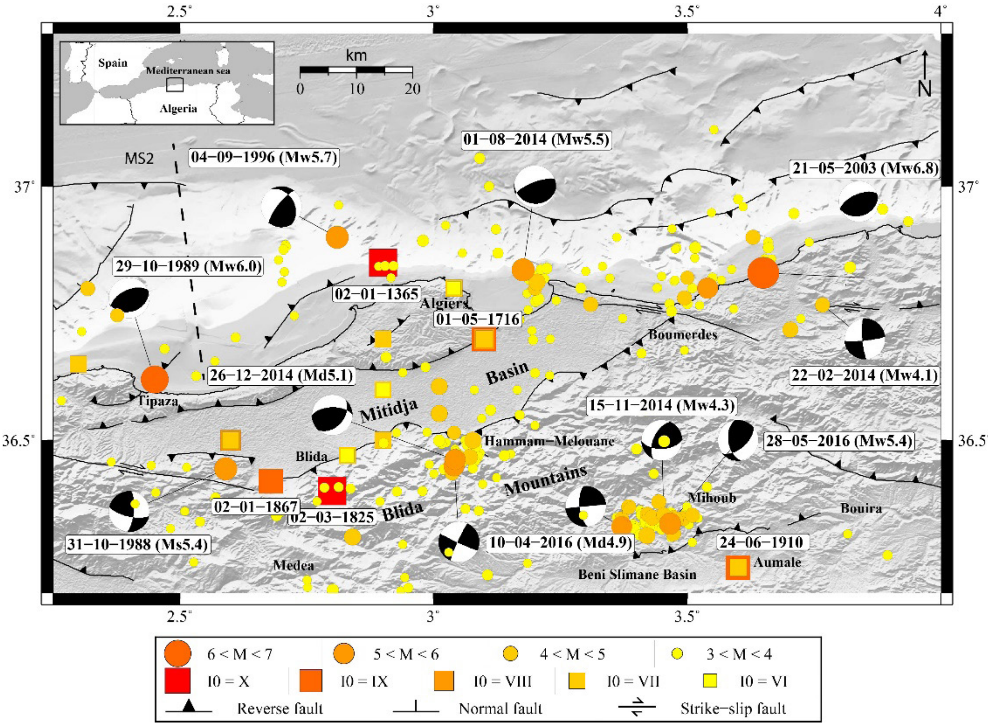


Figure 5. Seismotectonics of the Algiers region (North-Central Algeria) (from Yelles-Chaouche et al., 2009c, modified).Instrumental seismicity (2007-2016). Focal Mechanisms for moderate and strong events Squares: historical events. Black lines: Main actives faults. MS2 Dashed line: MARADJA Profile

The Mouzaia-El Affroun earthquake of January 2 nd 1867 (I:X)

This is another important earthquake which benefited of an extensive study published recently by Harbi et al. (2017). It caused extensive damage in the western part of Blida, in the area located 50 km south of Algiers (estimated intensity IX). This earthquake outlines active tectonics of the southern border of the Mitidja basin along the Blidean Atlas fault (Figure 5) where the last Hammam Melouane earthquakes of 2013-2014 happened (Yelles-Chaouche et al., 2017).

The Djidjelli earthquakes sequence of August 21 st-22 nd 1856 (I:X)

Many french reports and documents indicate in detail what's happened in August 21st, 22nd, 1856 (Harbi, 2011). The Djidjelli city suffered terribly from the two main shocks which occurred on the 21 st and the 22 nd (Rothe, 1950). In relation with this earthquake, a moderate tsunami with a sea wave of about 1m hit the western Mediterranean region. From all information reported, we proposed a tsunamigenic model of the main shock considering a set of three faults as the main seismogenic source of the earthquake (Yelles-Chaouche et al., 2009b).

In the instrumental period from 1900 to the actual period, the main earthquakes in Algeria (Table 1) are summarized by the following events.

The Aumale earthquake of June 24th, 1910 (Ms: 6.6).

It was one the strongest event recorded the instrumental period (Benouar,1994). It was located instrumentally at 36, 3°N and 3,7°E near the village of Aumale, 200 km south east of Algiers. Its magnitude was estimated to Ms: 6.6. It caused the loss of 81 persons. According to the several effects, an Intensity of IX was attributed. Recently, a moderate event happened in May, 2016 close to the Aumale epicenter, few kilometers north of the village of Mihoub (M:5.0). This later displays a reverse focal mechanism indicating the compressional stress regime in this region. These two important events are representative of the actual seismicity of the Tellian belt.

The Orleansville earthquake of Septembre 9th, 1954 (Ms:6.7) and the El Asnam earthquake of October 10 th, 1980 (Ms :7.3)

In twenty four years, the Ech Chellif region, two hundred km west of Algeria experienced two strong earthquakes. The first one of magnitude Ms:6.7 happened during the french occupation (1954). The epicenter was located near Beni Rached north east of Orleansville. Its focal mechanism calculated from P wave first motions outlined a northeast-striking, northwest dipping nodal plane on which reverse or oblique/reverse slip would occur (Dewey, 1990). These data suggests that this strong earthquake was triggered by an adjacent segment of the El Asnam fault (Bezzeghoud et al., 1995).

The second event, the El Asnam earthquake in 1980 is the largest earthquake to have occurred in northern Africa during the twentieth century (Benhallou,1985). This earthquake of magnitude Ms: 7.3 (Mw: 7.1) destroyed a great part of the city of El Asnam and also many villages around the city (Ouyed et al., 1981). In the epicentral area of intensity X, about three thousand people died and 50 000 persons were homeless. The main shock of depth 12 km was located at 36.18°N and 1.38°E near the Oued Fodda village. It displayed a reverse focal mechanism indicating the activation of a N45°reverse fault dipping 54° to the NW with a 83°rake angle. In fact, there are three segments of this fault still visible on the land surface (Figure 6) which ruptured on a about 40 Km displaying mainly a reverse focal mechanism (Ouyed et al., 1981) (Table 1). Many secondary effects as liquefaction, floods, rock falls were associated with this main event (Meghraoui, 1996).

This earthquake is still considered as a reference event in the west Mediterranean region because it demonstrated how the active deformation process resulting from the convergence of the Eurasiatic and Africa plates occurred in northern Algeria through active foldings.

Figure 6. The El Asnam fault scarp
(El Asnam earthquake of October 10th, 1980) still visible (Picture in 2013).

The Constantine earthquake of October 27 th, 1985 (Ms :6.0)

An earthquake of Magnitude Ms:6.0 occurred near the main city of Constantine (eastern Algeria) on October 27 th,1985 (Bounif et al.,1987). The main shock with a depth of 10 km, was located precisely at 36°42'N, 6°85 E north of the El Khroub village (Ousadou et al., 2013). In the epicentral area surface breaks were observed in three zones, affecting quaternary deposits. The focal mechanism using P and SH waveforms inversion shows a left lateral strike slip mechanism representative of the triggering of a left-lateral strike slip fault trending N 217°, dipping 84 with a rake of 19° (Table 1).

The Tipaza-Algiers earthquake of October 29 th, 1989 (Ms: 6.0)

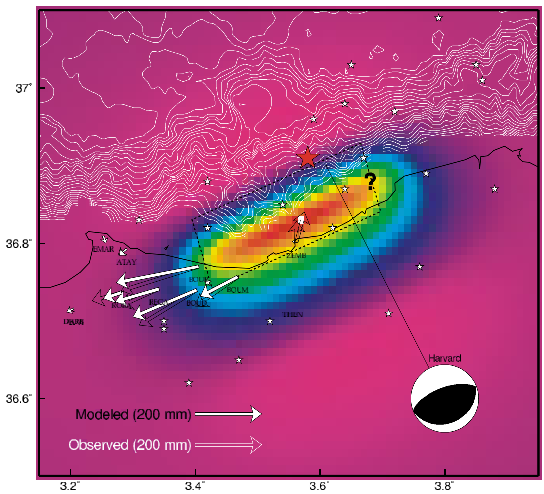
This earthquake of magnitude Ms: 6.0 was strongly felt in Algiers in its suburbs. Between Algiers and Tipaza many villages suffered as many public buildings and colonial farms were destroyed. In the epicentral area, the earthquake of Intensity VIII MSK (Meghraoui, 1991) caused 22 deaths and more than 300 injuries. The main shock epicenter with a depth of 10 km was located at 36,61° N and 2,42°E (Bounif et al., 2003). The focal mechanism determination by P and SH body-wave modelling gives an almost pure reverse faulting along a plane striking N246° dipping 56° with a rake of 86°(Table 1). From the seismological and geological investigations, it was pointed out that the earthquake was triggered by a blind reverse faulting extending from land to the offshore region.

The Boumerdes earthquake of May 21 st, 2003 (Mw :6.8)

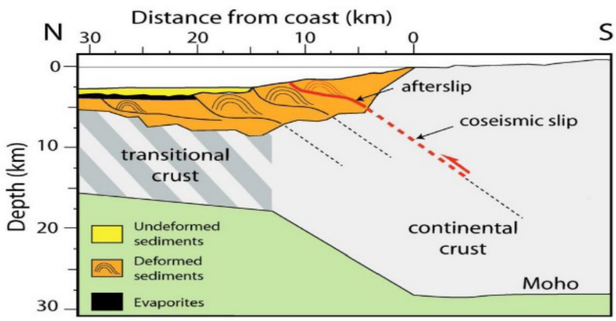
This earthquake is the most recent strong event in Algeria (Yelles-Chaouche et al., 2003a). It benefits from well instrumental coverage by seismological, geological, geodetic and marine methodologies. The epicenter of this earthquake of magnitude of Mw: 6.8

was located at 36,83°N, 3,65°E near the coastal village of Zemmouri (Bounif et al., 2004, Ayadi et al., 2008). It caused the death of 2360 persons and caused important damages.

From our seismological records through the algerian network, marine investigations through the Maradja project and geodetic measurements through the first GPS network installed in Algeria (Figure 7a), an identification of the marine active fault was possible (Deverchere et al., 2005) and a rupture model was proposed (Delouis et al., 2004, Yelles-Chaouche et al., 2004, Mahsas et al., 2008). This model was precised later by several authors (Semmane et al., 2005; Belabbes et al., 2009, Beldjoudi, 2017) to integrate all measurements carried out in this region. This earthquake displays the first south dipping active fault along the margin (figure. 7b). Indeed, the focal mechanism given by Harvard CMT displays a thrust mechanism with an azimuth of 57°, dip 44° and rake 71° (Table 1). This earthquake revealed the uplift of the coastline of about 0.5m (Meghraoui et al., 2004) and also the likely incipient subduction zone in the central part of the Algerian margin (Auzende, 1975, Yelles-Chaouche et al., 2009c, Hamai et al., 2015). From an analysis of the more complete aftershock's sequence of one year recording, Kherroubi et al., 2017, propose a more precise vision of this earthquake.



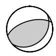
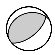
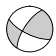
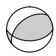
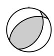
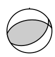
a)



b)

Figure 7. a) Co Seismic Model for the Boumerdes earthquake (from Yelles-Chaouche at al., 2004):
Arrows: velocity vectors, Red Star: Main shock
b) cross-section displaying the Boumerdes fault (from Deverchere et al., 2005)

Table 1. Main earthquakes of northern Algeria. FM parameters(Φ: Strike, δ: dip, λ: slip) Numbers indicated references **:** (1) Espinoza and Lopez-Arroyo, 1984; (2) Ouyed et al. 1981, (3) Deschamps et al., 1991, (4) Bounif et al., 2003, (5) Yelles-Chaouche et al. 2003b, (6) Bounif et al., 2004

Location	**Location**	**I**	**M/Mw**	**Depth (km)**	**Death toll**	**Focal Mechanisms (Φ, δ, λ)**
Negrine (Tebessa) 267						
Sitifis (Setif) 419						
Algiers 03.01.1365	36,70°N; 3,10°E	X			?	
Mitidja 03.02.1716	36,70°N; 3,10°E	X			20 000	
Oran 09.10.1790	35,70°N; 0,70°W	X	6.5-7.5		2 000	
Blida 02.03.1825	36,40°N; 2,80°E	X-XI	7.5		7 000	
Djidjelli 21-22.08.1856	36,70°N; 6,10°E	X	7.5		?	
Mouzaia-El Affroun 02.01.1867	36,42°N; 2,68°E	IX	7.0		100	
Biskra-Aures 16.11.1869	34,90°N; 5,90°E	IX	6.5		30	
Gouraya 15.01.1891	36,50°N; 1,80°E	X	7.5		38	
Aumale 24.06.1910	36,3°N; 3,7°E	X	6.4		81	
Orleansville 09.09.1954	36.29°N; 1.52°E	X	6.7	7	1 243	46 32 76 (1) 
El Asnam 10.10. 1980	36, 16°N; 1,41°E	X	7.3	5	2 633	225 54 83 (2) 
Constantine 27.10.1985	36, 34°N; 6,65°E	VIII	6.0	10	10	217 84 19(3) 
Tipaza 29.10.1989	36,61°N 2,33°E	VIII	6.0	10	22	246 56 86(4) 
Ain'Temouchent 22.12.1999	35.25°N 1.3°W	VII	5.8	4	25	29 45 67 (5) 
Boumerdes 21.05.2003	36.93°N 3.58°E	X	6.8	9	2360	57 44 71 (6) 

6. Characteristics of the main Algerian seismicity

From the several seismological studies on large seismic events of Algeria, one can depict major trend of the Algerian seismicity. A brief summary indicates that the main Algerian seismic events are concentrated mostly in the Tellian region and its related Neogene basins (Figure 8). Many of the epicenters occurred offshore indicating that active deformation in the Algerian margin is high (Figure 9,10) (Kherroubi, 2011). The High Plateaus of northern Algeria are marked by a lack of major seismic event where no significant seismic events have been reported (Figure 8). In the Saharan Atlas, the Biskra event of 16 November, 1869 (I: IX) is the most important earthquake (Table 1). It could be generated by an active fault of the South Atlasic flexure.

The Algerian earthquakes are superficial, no deeper than 20 kilometers. Hamai et al., 2015 demonstrate from geophysical profiles analysis during the Spiral project (Figure 11 a,b) that seismic events occurrence is linked with the existence of an incipient subduction zone along the slope of the Algerian margin.

Seismicity of northern Algeria reveals the compressional stress regime with a NNW-SSE direction of compression in the western and central regions as evidenced by the focal mechanisms of many events as the El Asnam, Mascara, Ain Temouchent, Tipaza and Boumerdes earthquakes (Figure 8) (Buforn et al., 2004). In the eastern part of Algeria, more strike slip focal mechanisms characterize seismic events. Large earthquakes are in general triggered by reverse or thrust faults related to folding, trending generally NE-SW (the El Asnam fault, the Tipaza fault, the Ain Temouchent fault). In the eastern part, earthquakes are mostly related to strike slip movements.

Anyway, for the first time in November 18 th, 2016, near Biskra (southeastern Algeria) an earthquake of Mw: 5.1 close of the South Atlasic flexure accident displays a normal faulting mechanism (Figure 8). The tectonic pattern of this region has still to be investigated.

The main earthquakes caused important damage and human losses to cities and village affected. Because of the vulnerability of the buildings, their intensity is estimated to VIII to X in the MSK scale.

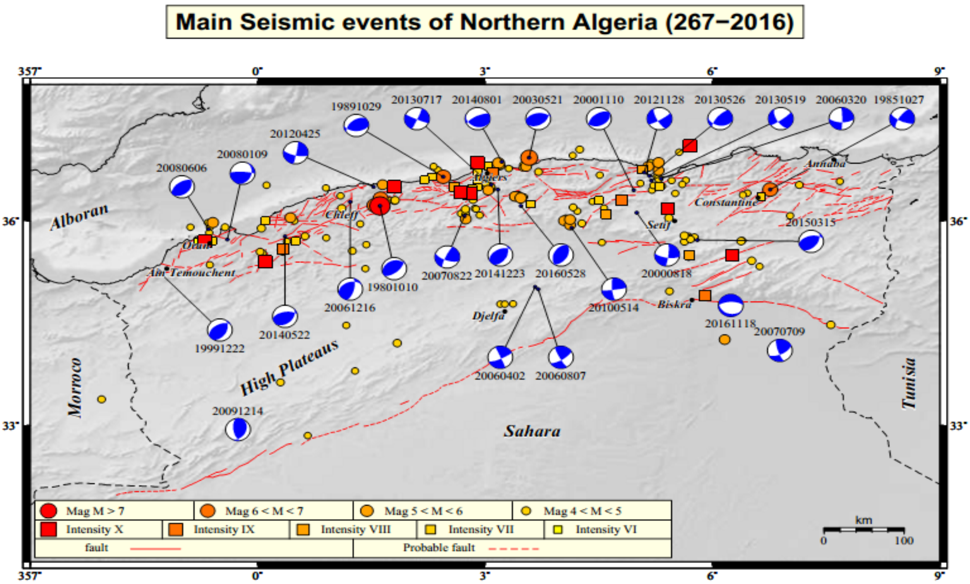


Figure 8. Focal mechanisms of the main seismic events of northern Algeria

7. Discussion

Many Algerian historical events have been described in the past as major events because of their important effects (Harbi, 2007, El Mrabet, 2005). However, the instrumental period demonstrates that moderate earthquakes with a magnitude no greater than 5.5 are also destructive because of the vulnerability of the buildings.

In other hand, analysis of the focal mechanisms indicates a reorientation of the stress regime between the western part and eastern part of Algeria from compressive to a strike slip movement, associated with a reorientation of the stress axes (Ousadou et al., 2014). The study of many recent moderate events in the eastern part of Algeria as the Bejaia event (2013-2014), (Abacha, 2015) or the Ain Azel-Merouana (Setif region) (2015) (Chami et al., 2015) or the last Biskra event will contribute more to see how the stress pattern evolves from west to east.

Regarding the deformation process some authors (Meghraoui et al., 1996) propose that in the Maghrebian region, NW-SE shortening between the two major plates led to the creation of tectonic blocks with a 50 Km length and 10 to 20 Km width. The presence of E-W dextral faults and sinistral inverse NE-SW faults defines dimensions of these tectonic blocks.

From seismological and seismotectonic studies on large events, many major fault system have been identified in northern Algeria as the Cheliff fault system (Meghraoui, 1988, Aoudia and Meghraoui, 1995, Beldjoudi, 2012), the Khayr Din bank fault (Yelles-Chaouche et al., 2009c), the offshore Annaba fault system (Kherroubi et al., 2009) (Figures 9, 10) or the major E-W north-Constantine fault (Abacha, 2015).

A careful analysis of their segmentation or stress transfer could indicate how the future rupture processes could occur.

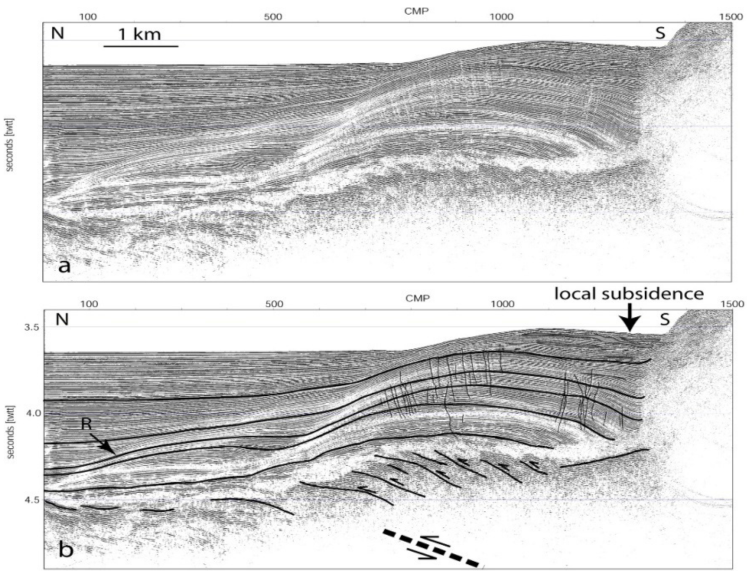


Figure 9. Folding of the Plioquaternary unit on the bottom slope of the Algiers margin Maradja Profile (MS2 Profile, figure 5) (from Yelles-Chaouche et al., 2009c).

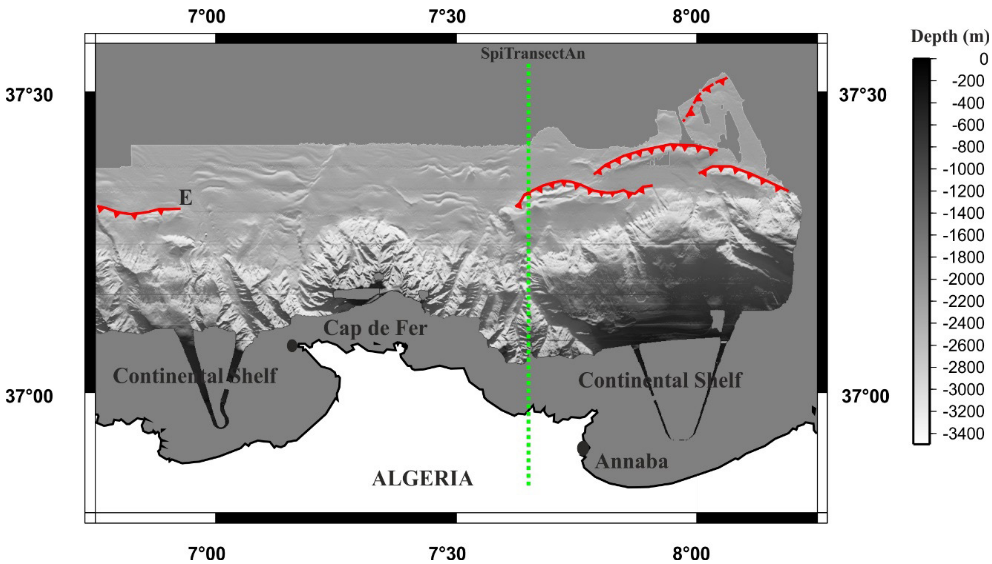
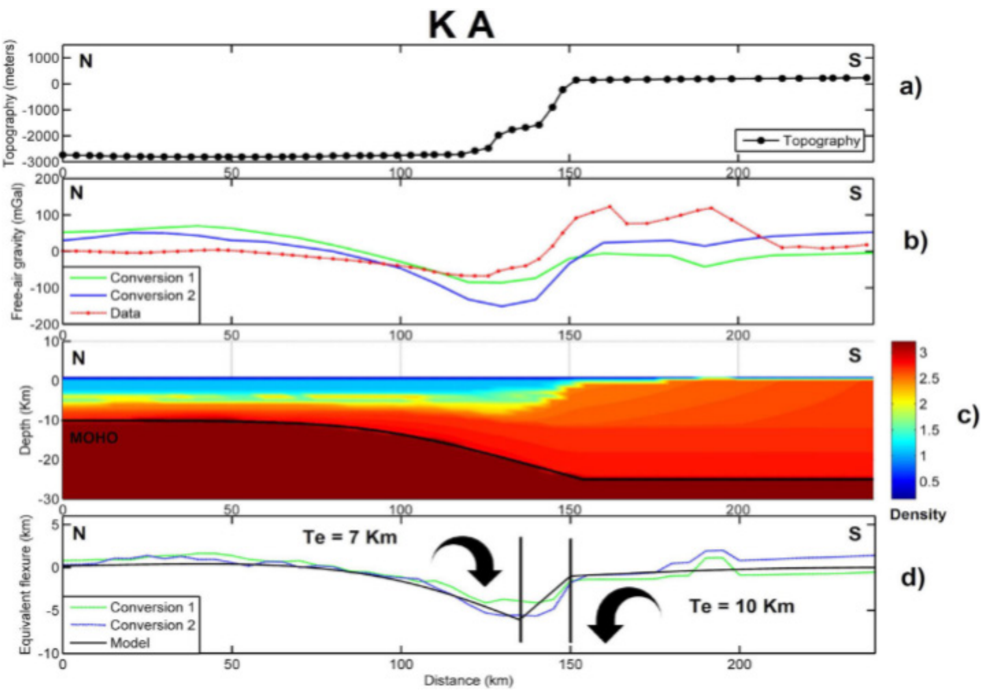


Figure 10. New active fault (red lines) system off Annaba (from Kherroubi et al., 2009) Green NS dotted line: The Spiral Transect Profile in the Annaba region

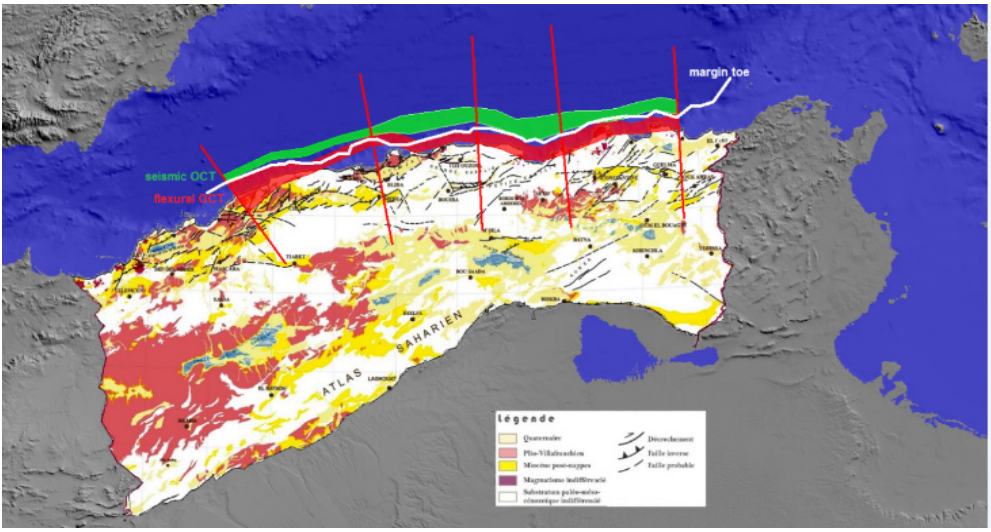
The recent seismic activity in the Algiers region let us also to suppose through the occurrence of the several earthquakes from 1365, 1765 to the present-day period a possible stress transfer between the several faults of the Mitidja basin. It was recently demonstrated by Lin et al. (2011) a transfer of the seismic activity between the Boumerdes fault and the two other western faults as the Thenia fault or the Blida fault system. This stress transfer has to be also confirmed between the Blida earthquake of 1825 and the more recent activity in the Hammam Melouane region (Yelles-Chaouche et al., 2017). A stress transfer could have also occurred between the earthquake of Tipaza in 1990, the Ain Benian event of 1996 and the more recent event of Algiers in 2014.

This stress transfer model could be completed by the recent paleoseismic investigations we have made in the region of Algiers (Babonneau et al., 2017) where we demonstrate that strong earthquakes have return period of more than centuries as in the case of the El Asnam region (Meghraoui, 1996).

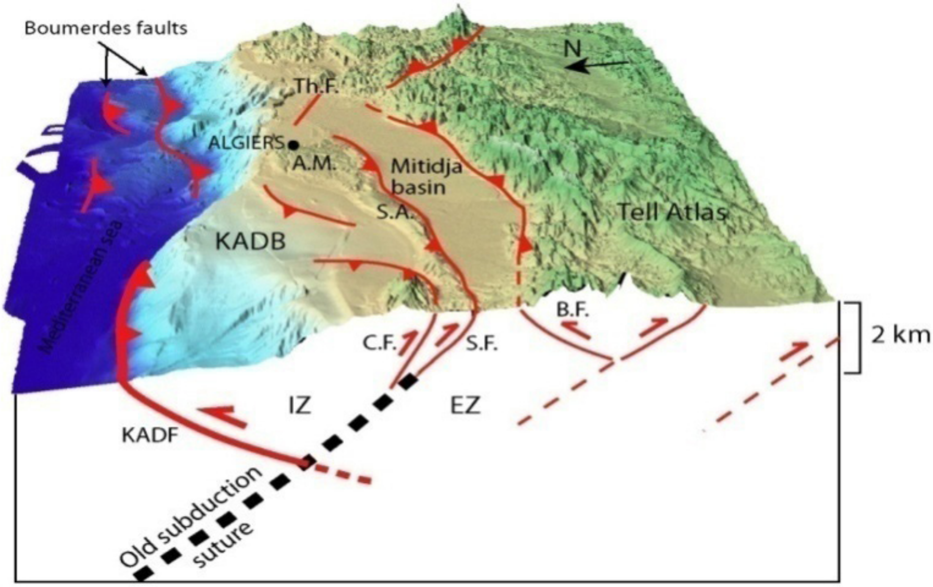
Major earthquakes could generate the uplift of the coastline as observed significantly during the Boumerdes earthquake with an average of 0.5 m. The gradual uplift has been also demonstrated in the marine terraces of the Sahel anticline in the region of Algiers (Maouche et al., 2011; Authemayou et al., 2016). The implementation of the Geodetic network of Algeria with presently 56 stations and very soon with more than hundreds of stations will allow to precise the convergence pattern proposed by Yelles-Chaouche et al.(2009c) in the Algiers region leading step by step to the closure of thee Neogene basins and the uplift of the Atlas mountains.



a)



b)



c)

Figure 11. a) Flexural model along the Greater Kabylia margin (Hamai et al., 2015). a) Topography and Bathymetry for the Great Kabylia Profile b)Free Air Anomaly c) Density model d) 2-D Flexural model.

b) TOC (Transition Oceanic Continent zone along the Algerian margin)(Hamai et al., 2015) in red and green color. Lines are the five N-S transect Spiral profiles.

c) Tectonic 3D model in the Algiers region (from A.K Yelles-Chaouche, 2009c) (KADB: Khayr Al Din Bank, KADF: Khayr Al Din Fault Th F: Thenia Fault, A.M.: Algiers Massif, S.A. Sahel Anticline, S.F.: Sahel Fault, C.M. Chenoua Mount, C.F. Chenoua Fault, B.F.: Blida fault, IZ: Internal Zones, EZ External Zones

8. Conclusions

From a synthesis of recent studies on the large earthquakes in northern Algeria, we can conclude that these events occurred generally in the Tell belt region (Buforn et al., 2014). Strong earthquakes with magnitude greater than 6.5 are rare. During the pre-instrumental period, the Oran earthquake of 1790 remains the only one which could have such magnitude.

Although some large faults were already identified, recent large earthquakes highlighted new active faults of primary importance (Yelles-Chaouche et al., 2006b). In the western and central part of northern Algeria, main faults are identified in the Cheliff or Mitidja basins. In the eastern part, recent studies revealed the major E-W North Constantine strike slip fault where a recent 4.7 event happened. Along the margin, the Maradja 1 and 2 surveys reveal several other important faults as the Khayr Din fault, the Djidjelli or Annaba faults.

Large earthquakes in northern Algeria could result from a stress transfer between fault segments. This could be the case in the Mitidja basin between the several earthquakes from 1365 to the present period involving the progressive rupture of the several fault segments of the main Sahel fault in the north and the main Blidean Atlas fault system in the south (Yelles-Chaouche et al., 2017).

From the large earthquakes focal mechanisms, it is evidenced that northern Algeria is under compression due to the convergence of the two main African and Eurasiatic plates as also suggested by the moment tensor solutions for small and moderate earthquakes (Stich et al., 2003). It is now understood that from west to east, the main compression axis reoriented from NW-SE to NNW-SSE in association with a change from reverse movement to strike slip movement as suggested by several authors (Buforn et al., 1995; Stich et al.,2006).

Finally, the large Algerian earthquakes still cause strong effects on the urban centers and the population. It is important to deploy all efforts to mitigate the seismic risk in the Algerian society.

9. Acknowledgments

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