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The 21 May 2003 Zemmouri (Algeria) earthquake Mw 6.8: Relocation and aftershock sequence analysis

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[1] A strong earthquake (Mw 6.8) struck the coastal region east of Algiers and the Tell Atlas of Algeria on 21 May, 2003 and was responsible of severe damage and about 2400 casualties. The coastal mainshock was followed by a large number of aftershocks, the largest reaching Mw 5.8 on 27 May 2003. We study the mainshock, first major aftershocks and about 900 events recorded by temporary seismic stations using master-event approach and double-difference (DD) methods. Although the seismic station array has a large gap coverage, the DD algorithm provides with an accurate aftershocks location. The mainshock hypocenter relocation is determined using three major aftershocks ($5.0 \leq$ Mw ≤ 5.8) chosen as master events. The new mainshock location shifted on the coastline (36.83N, 3.65E) at 8–10 km depth. Seismic events extend to about 16-km-depth and form a N 55°–60°E trending and 45°–55°SE dipping fault geometry. Up to now, it is the unique among the recently studied seismic events of the Tell Atlas of Algeria. Mainshock and aftershocks relocation, the thrust focal mechanism (Harvard CMT: N 57°, 44°SE dip, 71 rake) and the seismic moment 2.86 10^{19} Nm, infer a 50-km-long fault rupture that may appear at the sea bottom at 6 to 12 km offshore north of the coastline. The Zemmouri earthquake occurred along the complex thrust-and-fold system of the Tell Atlas and provides with new constraints on the earthquake hazard evaluation in northern Algeria. *INDEX TERMS:* 7215 Seismology: Earthquake parameters; 7230 Seismology: Seismicity and seismotectonics; 8102 Tectonophysics: Continental contractional orogenic belts; 8123 Tectonophysics: Dynamics, seismotectonics; 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Bounif, A., et al. (2004), The 21 May 2003 Zemmouri (Algeria) earthquake Mw 6.8: Relocation and aftershock sequence analysis, *Geophys. Res. Lett.*, *31*, L19606, doi:10.1029/2004GL020586.

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1. Introduction

[2] The Zemmouri damaging earthquake of 21 May, 2003 (Mw 6.8, Figure 1) occurred north of the Tell Atlas of Algeria, in the northeastern continuation of the Blida Mountains front and related Mitidja Quaternary Basin (Figure 1). An intensity X (European Macroseismic Scale 98) was reached for the area immediately east of the capital Algiers and an important aftershock activity followed the mainshock [*Ayadi et al.*, 2003]. This active region of the Africa-Eurasia plate boundary was the site of several destructive earthquakes (Mw > 5.5) in the past and the largest are (Figure 1): Algiers on 02/01/1365 and 03/02/1716 with I_0 = X, Blida on 02/03/1825 I_0 = X, Mouzaia on 02/01/1867 I_0 = IX, El Asnam on 10/10/1980 Ms 7.3, Mont Chenoua on 29/10/1989 M_S 6.0 [*Rothé*, 1950; *Meghraoui*, 1991; *Benouar*, 1994; *Bounif et al.*, 2003; *Harbi et al.*, 2004]. Earthquake sources of the Tell Atlas are, therefore, in major part located along the thrust-and-fold system and related intermountain basins. Seismogenic faults of the Tell Atlas and related earthquake distribution are, however, not very well known and some earthquake-prone regions of northern Algeria remain unexplored.

[3] Global models of plate tectonics in the western Mediterranean predict an average 6 mm/yr convergence of Africa towards Eurasia which is the likely driving mechanism at the origin of the seismic activity [*DeMets et al.*, 1990]. The NE-SW thrust-and-fold structures of the Tell Atlas align along an E-W deformation strip parallel to the plate boundary [*Morel and Meghraoui*, 1996]. Recent large earthquakes show that seismogenic faults of the Tell Atlas of Algeria have a predominant thrust mechanism consistent with the NE-SW trending thrust and fold tectonic structures [*Meghraoui*, 1991; *Harbi et al.*, 2004; *Ayadi et al.*, 2003; *Bounif et al.*, 2003]. The El Asnam earthquake which is the largest recorded earthquake in the western Mediterranean area, was associated with a thrust mechanism and NE-SW trending surface faulting [*Ouyed et al.*, 1981]. The El Asnam earthquake revealed that the seismogenic fault can be intimately associated with active folding [*King and Vita-Finzi*, 1981], and that the average NNW-SSE shortening rate across the fault during the late Holocene may reach ~1 mm/yr, [*Meghraoui and Doumaz*, 1996]. The Zemmouri earthquake was at 8–10 km depth, with a seismic moment of 2.89 10^{19} Nm and shows a thrust focal mechanism solution [*Delouis et al.*, 2004]. However, its coastal location accompanied by the uplifted shoreline and south dipping fault geometry imply a possible offshore location of surface faulting [*Meghraoui et al.*, 2004]. The faulting characteristics and geometry are, therefore, difficult to constrain

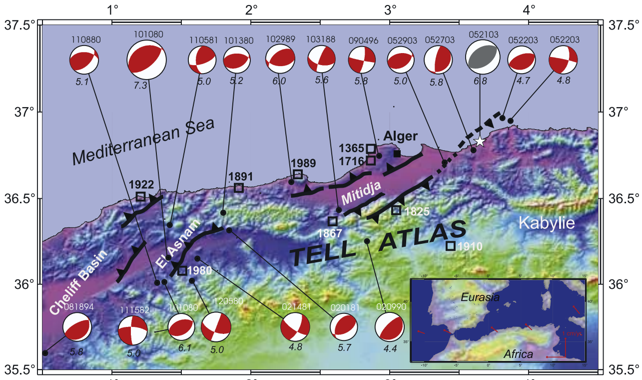

Figure 1. Seismotectonic map of the Tell Atlas of north-central Algeria [*Meghraoui*, 1988]. Historical seismic events indicated in squares are from *Rothé* [1950]. The Zemmouri earthquake focal mechanism is in grey.

without a detailed study with precise location of the earthquake sequence immediately after the mainshock.

[4] In this paper, we first introduce the seismotectonic setting and the active characteristics of the north-central Tell Atlas of Algeria. Second, we relocate the mainshock by a master events technique and the first major aftershocks by double-difference method, using local and regional data from Algeria, Spain, France and Italy. The relocation of 557 selected aftershocks collected during the period from May 25 to May 30 is also undertaken using the double-difference algorithm of HypoDD applied to the P and S wave differential travel times [*Waldhauser and Ellsworth*, 2000]. Finally, we discuss the fault plane 3D geometry and characteristics and its possible appearance at the sea bottom from mainshock and aftershocks distribution.

2. Mainshock and Major Aftershocks Relocation

[5] The mainshock locations obtained by the local and international seismological centers are 36.91°N, 3.58°E for CRAAG, 36.89°N, 3.78°E for NEIC and 37.02°N, 3.76°E for EMSC. All these locations are in conflict with the measurements of the coastal uplift (Meghraoui et al., submitted manuscript, 2004). We attempted to relocate the main shock by using local and regional data.

[6] Three large aftershocks occurred on may 27 (ML (CRAAG) 5.8), may 28 (ML 5.0) and may 29 (ML 5.8) during the first week of complete deployment of the temporary network. They were recorded by the local networks and regional seismic stations in Spain, France and Italy. We precisely located these three events using all Algerian permanent and temporary stations and used them subsequently as master events.

Table 1. Velocity Model

Thickness, km	Velocity, km/s
3	4.5
9	5
8	5.5
10	7
Half space	8

[7] We first relocated the mainshock using a simple double difference method [*Bounif et al.*, 2003]: we compared the mean of the differences of the arrival times between a master event and the main shock at two sets of distant stations where Pn is the first arrival. The first set consists of Italian stations for which the azimuth to the event is about the same as the N50° trending fault plane. The second set of Spanish stations is in a nearly orthogonal direction to the fault strike. The epicentral distances being large compared with the extension of the aftershocks zone, the differences of the arrival times to the Spanish stations are nearly equal to the difference of the origin times. If we subtract this value from the corresponding one calculated with the Italian stations, it remains only the mean difference of travel times to the Italian stations. Following this simple procedure, we finally located the main shock at 36.83°N, 3.65°E.

[8] In a second step, we relocated the mainshock and major aftershocks that occurred before the setting of the temporary networks (Figure 2). We selected events recorded by the same Algerian, Spanish, French and Italian permanent stations as the master events (Figure 2, inset), computed travel-times for P and S waves using CRAAG hypocentral determinations, and relocated them together with the master events using HypoDD program [*Waldhauser and Ellsworth*, 2000]. We can control the validity of this relocation with the master events: the maximum difference between the location calculated using all Algerian permanent and temporary stations and the hypoDD relocation is 0.02° in latitude and longitude. More over, the errors on the relocations have been calculated using Singular Value Decomposition method and are drawn on Figure 2. They are obviously larger for smaller magnitude events and vary

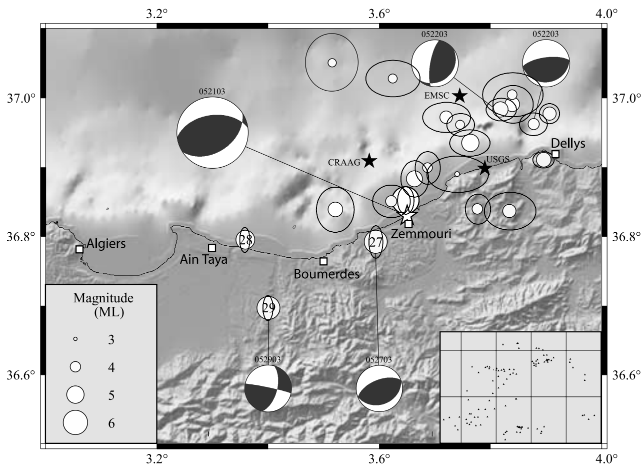

Figure 2. Relocation of the main shock (white star: master events technique, large circle: hypoDD code) and of major aftershocks (Ml > 3) from 21 to 30 May, 2003. Inset (lower right corner) shows the western Mediterranean seismic stations used for the relocation. Black stars are mainshock epicenter location from international and local seismological centers. The three master events are labeled by their date-number (i.e., 27, 28 and 29 May 2004). Focal mechanism solutions are Harvard-CMT.

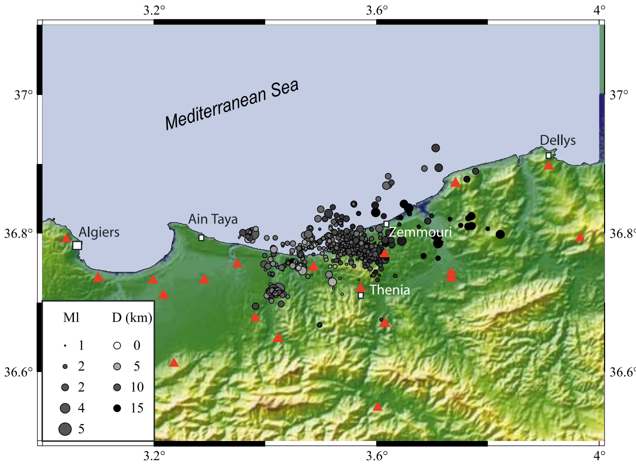

Figure 3. Map view 557 aftershocks located from 25 to 30 May, 2003. The red triangles are seismic stations.

from about less than 1 km (master events and main shock) to more than 3 km for the smallest (ML < 4.0) events. Using the hypoDD method, we relocated the mainshock epicenter at 36.85°N, 3.65°E which is quite close to the 36.83°N and 3.65°E obtained from the simple double difference method exposed in the previous paragraph.

3. Aftershocks Study

[9] A network of 21 three component short period digital seismic stations was installed by CRAAG and CGS in the epicentral area beginning from 22 May 2003 in addition to 4 permanent seismic stations of the Algerian Seismic Network. During the first week, about 1000 seismic events with magnitude Md $\geq$ 1 were recorded, including five large aftershocks with ML > 5. We present in this paper the analysis of the seismicity from 25 to 30 May, 2003.

[10] During the six days, nearly 900 events were localised using careful readings from the temporary network with hypoinverse program [*Klein*, 1978]. The velocity model was deduced from previous aftershocks studies in northern Algeria [*Bounif et al.*, 2003]. The magnitudes were deduced from coda length using the same coefficients as *Ouyed* [1981]. The aperture of the seismic array is far from ideal due to the offshore location of many hypocenters. Therefore, we considered very carefully the results and kept only high quality locations to obtain a set of 557 events that fulfill the following criteria: more than 9 P wave and 2 S wave readings, rms < 0.2, and conditioning factor <100. For these events, we obtain mean values of 0.09 s for rms, 1.32 km for horizontal error (Erh) and 1.91 km for the vertical error (Erz).

[11] Furthermore, the travel-times of selected aftershocks were used in order to provide with a more precise location with hypoDD program, using conjugate gradient method for least squares solution [*Waldhauser and Ellsworth*, 2000]. We tested the robustness of solutions (as indicated by the authors' code), by using singular value decomposition for subsets of events, changing station distribution, initial locations, data weighting, etc. Initial locations are taken from the catalog at reported locations, and not at a common location at the centroid of the clusters. The final locations are presented on map view (Figure 3) and on two cross sections (Figure 4).

4. Aftershocks Sequence and Faulting Geometry

[12] The study of the seismic sequence of the first ten days following the Zemmouri mainshock provides a first precise picture of the active zone. The aftershocks sequence depicts a SW-NE trending area, about 50 km long and 15 km wide (Figures 2 and 3). This general trend is in good agreement with the fault plane strike of the CMT focal mainshock solution (N 57°). The relocated mainshock epicentre is on the coast, about the middle of the aftershocks cloud. All major aftershocks (ML > 4) are located in the NE area of the mainshock epicentre within the three first days. Later on, we observe a migration of the seismicity with aftershocks mainly concentrated SW of the mainshock, including the three major events of May 27, 28 and 29. Looking more into detail, we observe a very dense seismic cloud between 3.5 and 3.6°E. The major events of May 28 and 29 and their respective aftershocks define the south-western limit of the seismicity.

[13] At depth, the seismicity is mainly concentrated between 5 and 13 km (Figure 4). A global cross-section orthogonal to the fault trend displays a southeast dipping fault geometry, consistent with the dip of the mainshock focal mechanism (44°SE). The extension towards the surface of the fault plane infers that, if the fault reaches the sea bottom, it may appear at 6 to 12 km distance from the coast. The cross section of Figure 4b, parallel to the fault trend, displays two clusters of aftershocks, the first at the

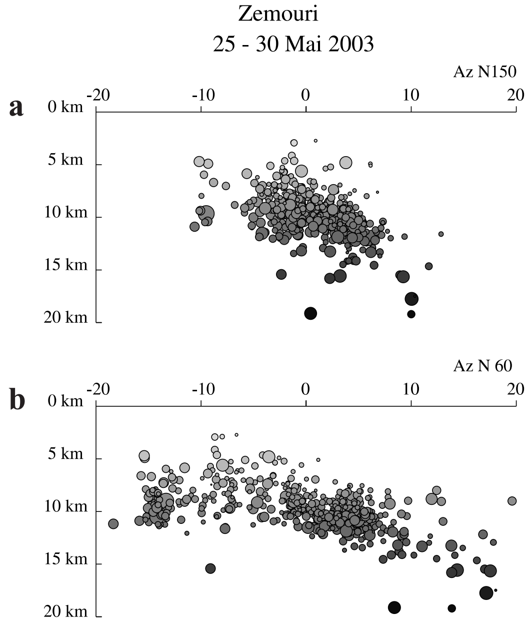

Figure 4. Cross sections through the aftershocks: a) Orthogonal to the fault strike (N150°E) and showing the south dipping elongation of the seismic cloud consistent with the focal mechanism of Figure 2. b) Along the fault strike (N60°E) with superficial concentration of seismic events to the SW and deeper events to the NE.

south-western end of the active zone and the second in the middle (3.5–3.6°E). The latter main cluster seems to slightly dip toward the NE.

5. Discussion and Conclusion

[14] The general pattern of aftershocks distribution is consistent with the seismic moment of 2.86 10^{19} Nm given by *Delouis et al.* [2004]. Taking a 50 km rupture length, as the length of the aftershocks sequence, we obtain a 1 m coseismic slip [*Wells and Coppersmith*, 1994]. Taking as fault width the 18-km-depth along dip of the aftershock cloud, we obtain a rupture surface of about 900 km^2, comparable to 860 km^2 deduced from the seismic moment.

[15] An average uplift of 0.55 m affected the coastal epicentral area and document the surface deformation associated with the coseismic thrust rupture. The earthquake fault dimensions and geometry correlated with the surface deformation determined from GPS and conventional geodesy measurements [*Meghraoui et al.*, 2004] imply a sea bottom surface faulting. One may also notice that the southwest end of rupture that corresponds with the minimum uplift coincide with the sharp end of aftershock cloud. This is the first example in the Tell Atlas (Algeria) which exhibits a SE dipping active fault, comparing to previous seismic events such as those of El Asnam (1980), Tipasa-Chenoua (1989), Mascara (1994), and many other seismic sources.

[16] The limits and asperities of the earthquake fault plane can be related with the control of preexisting geological structures on the rupture propagation. The strike-slip mechanism of the 29 May earthquake reflects the possible interaction of transfer fault with the rupture zone. Similarly, the clustering of the aftershocks with ~NW-SE trending observed between 3.5 and 3.6°E suggests the presence of a step-over or tear fault zone between two branches of the main fault. The Zemmouri aftershocks sequence extends inland and offshore and its obliquity to the coastline also reflects the offshore extension of the continental Blida thrust fault system. The Zemmouri earthquake rupture is a segment of the Blida fault system which consists of several seismogenic fault branches that did not rupture since the 1825 earthquake [*Rothé*, 1950]. This southern Mitidja fault zone has a potential for producing a large earthquake and constitutes a serious seismic hazard for Algiers region [*Aoudia et al.*, 2000]

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