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Coseismic deformation of the May 21st, 2003, $M_w = 6.8$ Boumerdes earthquake, Algeria, from GPS measurements

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[1] On May 21st, 2003, a $M_w = 6.8$ earthquake struck the central part of northern Algeria causing extensive damage in the Boumerdes area, 40 km east of Algiers. It is among the largest events to occur in the western Mediterranean over the past 25 years. We present GPS measurements of horizontal coseismic displacements that provide new constraints on the rupture geometry. Modeling the data with a uniform dislocation on a rectangular fault in an elastic half-space, we find that the rupture occurred on a reverse fault dipping 42°S , with its upper edge 6 km offshore and lower edge 4 km inland. The amplitude distribution of the coseismic displacements indicates that the rupture did not reach the surface, at least in its western part, and ended to the west around 3.4°E . Offshore faults like that of the Boumerdes earthquake could account for part of the Africa-Eurasia relative plate motion in the western Mediterranean and represent a significant seismic threat for Algeria. **INDEX TERMS:** 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 7215 Seismology: Earthquake parameters; 7230 Seismology: Seismicity and seismotectonics. **Citation:** Yelles, K., K. Lammali, A. Mahsas, E. Calais, and P. Briole (2004), Coseismic deformation of the May 21st, 2003, $M_w = 6.8$ Boumerdes earthquake, Algeria, from GPS measurements, *Geophys. Res. Lett.*, *31*, L13610, doi:10.1029/2004GL019884.

1. Introduction

[2] The trace of the Africa (Nubia)-Eurasia plate boundary in the western Mediterranean is well depicted by both historical and instrumental seismicity, in particular in Algeria (Figure 1). Recent GPS results show that both plates are currently converging obliquely ($\text{N}60^\circ\text{W}$ direction) at about 5 mm/yr at the longitude of Algiers [Nocquet and Calais, 2004]. They also show that most of the relative plate motion is accommodated in northern Africa, with no significant strain in Iberia, the Ligurian basin, and the Corsica-Sardinia block, that are rigidly attached to Eurasia (Figure 1).

[3] Well identified active faults in Algeria are also concentrated in a narrow coastal stripe in the northern part of the country. Active structures define a series of NE-SW trending folds and reverse faults affecting Neogene and

Quaternary basins, with a right-stepping en échelon pattern [Meghraoui *et al.*, 1986, 1996]. These reverse faults are connected by NW-SE to E-W trending strike-slip faults, some of them with a reverse component [Meghraoui, 1991]. This structural pattern is continuous with, and similar to, the one observed in the Moroccan Riff to the west [e.g., Calvert *et al.*, 1997].

[4] In addition to on-shore structures, a recent oceanographic survey of the central and western parts of the Algerian margin [Déverchère *et al.*, 2003] has shown that the margin and the proximal part of the deep basin east of Algiers are affected by a series of active north-verging reverse faults and folds, probably developing over south-dipping ramps. These observations indicate that part of the Africa-Eurasia plate convergence in Algeria may be accommodated offshore. Our analysis of the Boumerdes earthquake presented hereafter supports this idea.

2. The Boumerdes Earthquake

[5] On May 21st, 2003, a $M_w = 6.8$ (USGS Fast Moment Tensor Solution) earthquake struck northern Algeria, about 40 km east of Algiers, causing extensive damage (intensity X) in the Algiers-Dellys area [Ayadi *et al.*, 2003]. About 2,300 people were killed, 11,000 injured, and 200,000 homeless. It is among the largest well monitored earthquake in the western Mediterranean since the $M = 7.3$ October 10, 1980 El Asnam event, which occurred 200 km west of Algiers. The epicenter of the Boumerdes earthquake has been located by the Algerian Research Center for Astronomy and Geophysics (CRAAG) about 7 km north of the Zemmouri village (36.91°N , 3.56°E) (Figure 1) [Yelles-Chaouche *et al.*, 2003]. Its location corresponds to a previously undocumented fault. Other epicenter locations derived from permanent seismic stations around the Mediterranean, like that of the European-Mediterranean Seismological (EMSC) also indicate an off-shore epicenter, consistent with that of CRAAG within about 10 km.

[6] The various moment tensor solutions calculated so far using long-period data from world-wide broad-band seismic stations (e.g., USGS, ETH Zurich) show reverse motion on NE-SW trending faults, with a shallow centroid depth (less than 10 km) and a moment magnitude ranging from 6.8 to 7.0. The slip vector estimated from the seismological data exactly parallels the Africa-Eurasia relative motion. A body

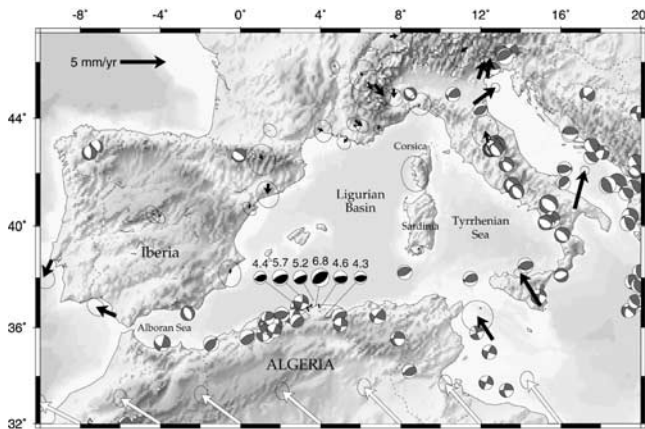


Figure 1. Active tectonic framework of the western Mediterranean basin. The May 21, 2003, Boumerdes earthquake is shown in red by its focal mechanism, with its major aftershocks (USGS database). Other focal mechanisms (dark grey) are from the Harvard CMT database. White arrows at the bottom of the figure show model velocities for the Nubia plate with respect to Eurasia [Calais *et al.*, 2003]. Black arrows show observed geodetic velocities with respect to Eurasia [Nocquet and Calais, 2004].

waveform model [Vallée *et al.*, 2003] shows a centroid at shallow depth (<10 km), an $M_w = 7.0$, and a 12 sec source duration with a directivity to the WSW, that may partly explain the significant damage observed in Algiers. According to earthquake parameter scaling laws [e.g., Wells and Coppersmith, 1994], the magnitude should correspond to a 25–30 km long rupture with 1–2 m of average coseismic slip. The size of this earthquake is comparable with that estimated for several earthquakes reported in northern Algeria in historical times [Aoudia *et al.*, 2000].

[7] The Boumerdes earthquake was followed by several large aftershocks (Figure 1), including $M_b = 5.1$, $M_b = 5.2$, and $M_w = 5.7$ events (EMSC). However, from the aftershock distribution or the geologic data alone it was not clear whether the causative rupture happened on a north-dipping blind fault or on a south-dipping fault outcropping offshore. The Boumerdes earthquake shares the characteristics of smaller events (magnitude 5 and greater) in the past 10 years, clustered in a narrow zone along the coast of Algeria, with focal mechanisms showing mostly reverse motion on NE-SW trending faults, in some cases combined with left-lateral strike-slip motion (Figure 1).

3. GPS Data and Processing

[8] Two months before the Boumerdes earthquake, in March 2003, a 10-site GPS network had been surveyed in the area of Thenia, about 20 km southwest of the epicenter. The network only covers the easternmost part of the area affected by coseismic deformation as it was originally intended to study the Thenia fault [Boudiaf, 1996], thought to be a potential seismic threat to the city of Algiers. Each site was observed during 3 to 4 24-hour sessions using dual-frequency Ashtech Z-12 and Z-Xtreme receivers with Geodetic III antennas. The network was resurveyed in June 2003, two weeks after the event, using dual-frequency Ashtech micro-Z receivers with Choke-ring antennas. Each

site was observed during four 24-hour sessions. Site THEN, located on a damaged building, was not resurveyed.

[9] We processed the GPS data using the GAMIT software (R. W. King and Y. Bock, unpublished manuscript, 2003), including 10 well-determined IGS sites to serve as ties with the ITRF-2000. We solved for station coordinates, satellite state vectors, one tropospheric delay every four hours at each site, and phase ambiguities using double-differenced GPS phase measurements, with IGS final orbits and IERS earth orientation parameters relaxed. We combined our regional daily solutions with global SINEX (Solution Independent Exchange format) files from the IGS daily processing routinely done at Scripps Institution of Oceanography and imposed the reference frame by minimizing the position deviations of IGS core stations with respect to the ITRF2000 while estimating an orientation, translation and scale transformation.

[10] We calculated the coseismic displacement at each site by subtracting the average position after the earthquake from the one before. Unfortunately, vertical displacements are not usable because of unreliable antenna heights measurements. We accounted for the motion of the African plate by subtracting the secular displacement at each site derived from the latest available Africa (Nubia)/ITRF angular velocity [Calais *et al.*, 2003]. We find coseismic displacements up to 25 cm, directed in a general westward direction, and decreasing in magnitude with the distance to the epicenter (Table 1). These displacements include the contribution from 2 weeks of postseismic deformation, which, by comparison with similar events elsewhere [e.g., Heflin *et al.*, 1998], should not exceed 1 cm. The north-directed coseismic displacement at station ZEMB, together with the uplift reported along the coast in that area are indicative of a south-dipping rupture.

4. Coseismic Models

[11] We model the earthquake as a dislocation on a rectangular rupture plane embedded in an elastic half-space. The width and length of the rupture plane are chosen (1) to be consistent with the rupture dimensions from preliminary source studies (see <http://iisee.kenken.go.jp/staff/yagi/eq/algeria20030521/algeria2003521.html> and http://www-geoazur.unice.fr/EQUIPES/DRO/seisme_algerie_25_05_03/index.html), and (2) to result in a seismic moment similar to the one inferred from seismological data (2.4×10^{19} N.m), given the coseismic slip estimated in the model. We use a rigidity modulus of 3×10^{10} N.m⁻² and take the strike, dip and rake from the Harvard focal

Table 1. Measured Coseismic Displacements: East-West (d_e) and North-South (d_n) Components, and Their Uncertainties (σ_{d_e} and σ_{d_n})^a

Lat.	Lon.	d_e	d_n	σ_{d_e}	σ_{d_n}	Site
3.56	36.80	24.0421	90.8682	3.5	3.1	ZEMB
3.46	36.75	-126.02	-88.2448	2.4	3.4	BOUM
3.40	36.77	-231.868	-72.608	3.2	1.9	BOUB
3.40	36.73	-171.779	-105.002	3.1	3.4	BOUD
3.34	36.74	-115.005	-51.5685	3.3	2.5	REGA
3.28	36.79	-25.0637	-18.1391	2.4	3.1	ATAY
3.28	36.73	-88.8259	-24.8107	3.5	2.3	ROBA
3.25	36.80	-2.84225	-6.04951	3.6	3.4	EMAR
3.20	36.71	-9.6852	-10.1981	2.8	2.6	DARB

^aUnits are millimeters.

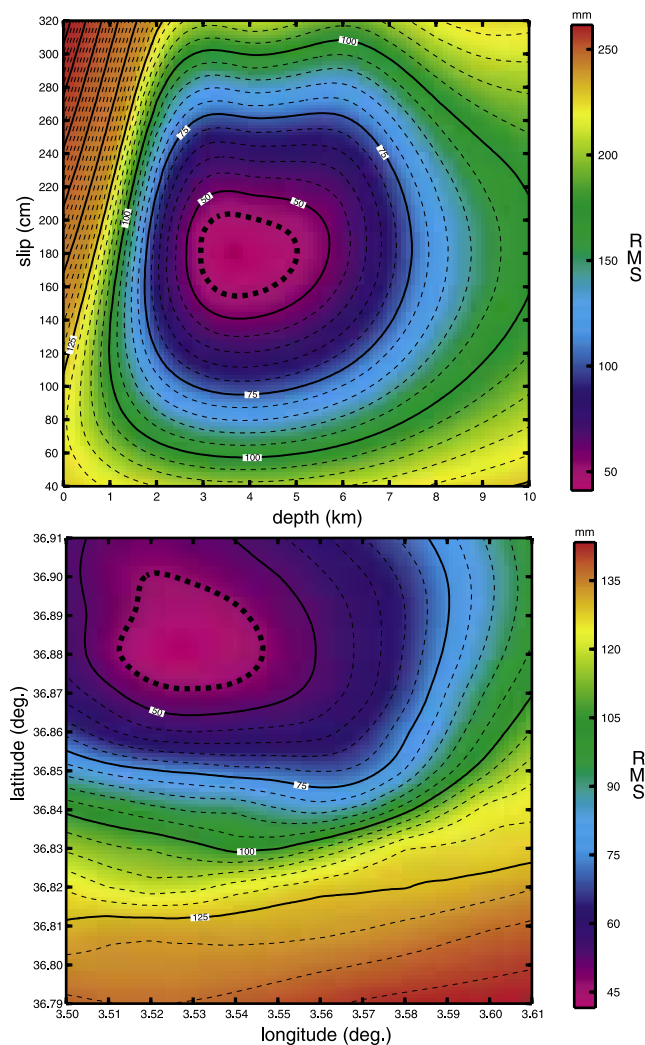


Figure 2. Root Mean Square (RMS) contour of the coseismic displacement residuals. Thick black dashed line show the 95% contour interval. Bottom: For a series of latitude-longitude of the center-point of the rupture. The best fit is obtained for a center-point located at 36.88°W/3.53°N (center point). Depth and slip were fixed to their best-fit values of 4 km and 180 cm, respectively. Top: For a series of depth-slip values. The best fit is obtained for a depth of 4 km and a slip of 180 cm. The latitudes and longitude of the center point of the rupture were fixed to their best-fit values of best-fit values of 3.53°N and 36.88°W respectively.

mechanism (55°, 43°, and 84°, respectively). This rupture azimuth is consistent with the azimuth of the active reverse faults mapped offshore.

[12] Although preliminary source studies have shown heterogeneous slip distribution, with two patches of higher slip (up to 2.3 m) around 3.6°E and 3.75°E (<http://iisee.kenken.go.jp/staff/yagi/eq/algeria20030521/algeria2003521.html>) [Vallée et al., 2003], we assume uniform slip in our model. This is because of the limited amount of available GPS data and spatial coverage restricted to the western end of the rupture, which does not provide sufficient spatial coverage and resolution to account for heterogeneous slip. We estimate the latitude/

Table 2. Source Parameters of the Best-Fit Model^a

Slip	Length	Depth	Width	Dip	Long.	Lat.	Azim.
180 cm	32 km	4 km	14 km	42°	3.53°	36.88°	205°

^aThe latitude, longitude, and depth are those of the middle point of the top of the rectangular fault.

longitude of the rupture, its depth, and the coseismic slip by minimizing the χ^2 using a grid search algorithm in a 4-parameter space.

[13] We run forward models for a series of latitude/longitude of the center point of the rupture. At each latitude/longitude node, we calculate the weighted root-mean square of the residual (observed-modeled) coseismic displacements for a series of rupture depth/coseismic slip values. The best-fit model gives a coseismic slip of 180 cm and a top edge of the rupture plane located at 36.88°N/3.53°E (center point) and 4 km depth (Figure 2, Table 2). We also formally inverted the observed coseismic displacements for uniform slip on the fault, imposing the best-fit fault location and depth found above. We obtain a coseismic slip of 178 ± 14 cm, consistent with the value found with the forward models.

5. Discussion

[14] Our best-fit model (Figure 3 and Table 2) predicts up to 70 cm of coseismic coastal uplift between Boumerdes

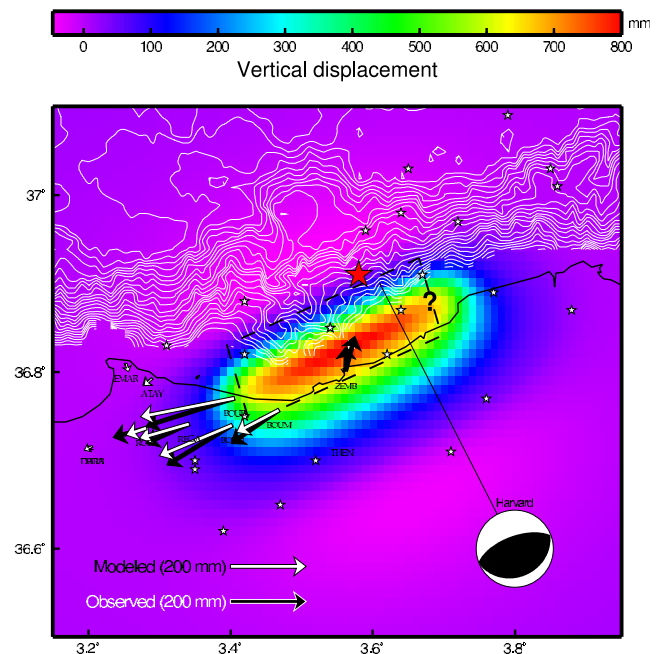


Figure 3. Observed (black arrows) and modeled (white arrows) horizontal coseismic displacements. Rupture parameters are given in Table 2. The surface projection of the modeled rupture is shown by the dashed black line. Background colors show modeled vertical coseismic displacements. Thick black line: coastline. Thin white contours: bathymetry. White stars: aftershock locations. Red star: main shock. Locations shown here are from the CRAAG. The Harvard focal mechanism and epicenter are also shown. Note that the eastern termination of the rupture is not constrained by our data and is therefore indicated by a question mark (explanations in text).

and Cap Djinet, consistent with field observations (S. Maouche, personal communication, 2003). Coastal uplifts up to 80 cm observed further east near Dellys (longitude 3.9°E) are not reproduced by our model due to the lack of GPS data at the eastern end of the fault.

[15] In order to further constrain the slip distribution with depth, we inverted the coseismic displacements for slip on three rectangular patches: (1) the one found above, (2) its upward prolongation to the surface, and (3) its downward prolongation to a 18 km depth. The inversion yields coseismic slips, respectively, of 178 ± 15 cm, 3 ± 19 cm, and 60 ± 447 cm, confirming that the rupture did not reach the surface. Similarly, the GPS data require that the rupture does not propagate west of $\sim 3.4^{\circ}\text{E}$, unless a significant strike-slip component is allowed, which is inconsistent with the seismological data.

[16] This absence of shallow slip was not possible to constrain from the seismic inversions alone (<http://iisee.kenken.go.jp/staff/yagi/eq/algeria20030521/algeria2003521.html>) [Vallée et al., 2003]. Also, the aftershock locations are still too coarse to precisely delineate the rupture plane. The GPS results shown here place useful constraint on the location of the western termination of the rupture and on its depth.

[17] One of the major issues after the May 21st, 2003, Boumerdes earthquake was to locate the fault responsible for this event. Marine investigations between longitudes 3.2°E and 3.4°E (Figure 3) undertaken 3 months after the earthquake showed a series of cumulative scarps at the bottom of the continental slope and at mid-slope, corresponding to reverse faults striking roughly parallel to the coast [Déverchère et al., 2003]. The preferred rupture plane found here using GPS data and coseismic models is consistent with this overall structural pattern. Its projection on the surface falls about 4 km south of the mid-slope reverse fault mapped offshore (Figure 4). This could mean that the rupture occurred on a yet unmapped fault or that the fault dip decreases towards the surface, connecting with either of the two mapped faults (dashed lines on Figure 4).

6. Conclusion

[18] Horizontal coseismic displacements derived from GPS data allow us to place new constraints on the rupture of the Boumerdes earthquake. The data are well fit by a uniform slip model on a plane dipping 42° to the south with a rupture that does not reach the surface, at least in its western part. The down-dip end of the preferred rupture plane reaches about 4 km inland, with predicted vertical coseismic displacements that match well the observed coastal uplift. The GPS data indicate a western end of the rupture around 3.4°E .

[19] These findings are consistent with the structural pattern observed offshore [Déverchère et al., 2003], that shows a series of south-dipping active reverse faults on the Algerian margin and at its toe. The Boumerdes earthquake is therefore a strong indication that offshore faults account for some of the Africa-Eurasia plate motion in the western Mediterranean and represent a significant seismic threat for Algeria. This study enhances previous results obtained in the El Asnam region [Lammali et al., 1997] demonstrating

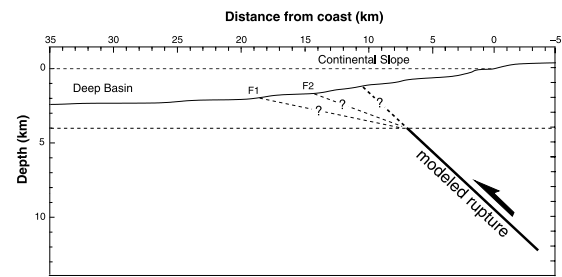


Figure 4. Cross section perpendicular to the Algerian margin at the longitude of Boumerdes. No vertical exaggeration. The thick red line shows the preferred rupture plane, from the GPS data. F1 and F2 are the surface trace of two active reverse faults mapped during the Maradja cruise [Déverchère et al., 2003].

the importance of the reverse faulting in the central part of northern Algeria.

[20] The GPS data alone is however not sufficient in quantity and spatial coverage to constrain the geometry of the eastern part of the rupture and to estimate the slip distribution on the fault plane. Further work incorporating teleseismic data and possibly interferometric synthetic aperture radar (InSAR) data in a joint inversion should bring additional constraints on the source mechanism of the Boumerdes earthquake.

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