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Coastal uplift and thrust faulting associated with the $M_w = 6.8$ Zemmouri (Algeria) earthquake of 21 May, 2003

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[1] A shoreline uplift marked by a continuous white band visible at rocky headlands occurred during the 21 May 2003 earthquake (Mw 6.8) in northern Algeria. We measured the amount of coastal uplift on a white band (emerged algae) and harbors quays between Boumerdes and Dellys. Most of measured points were collected using tape and differential GPS on rocky headlands with σ ± 0.15 m error bar (tidal prism). Leveling lines running parallel and orthogonal to the coast also provide the precise amount of uplift in the epicentral area. The uplift distribution shows an average 0.55 m along the shoreline with a maximum 0.75 m east of Boumerdes and a minimum close to 0 near Cap Djinet. The active deformation related to a thrust fault is modeled along the ∼55 km coastline. The dislocation model predicts surface slip on a N 54°E trending reverse fault, dipping 50° SE in agreement with CMT solution and coastal uplift. The faulting characteristics imply a fault geometry with possible sea bottom ruptures between 5 to 10 km offshore. *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 7230 Seismology: Seismicity and seismotectonics; 8107 Tectonophysics: Continental neotectonics; 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Meghraoui, M., S. Maouche, B. Chemaa, Z. Cakir, A. Aoudia, A. Harbi, P.-J. Alasset, A. Ayadi, Y. Bouhadad, and F. Benhamouda (2004), Coastal uplift and thrust faulting associated with the $M_w = 6.8$ Zemmouri (Algeria) earthquake of 21 May, 2003, *Geophys. Res. Lett.*, *31*, L19605, doi:10.1029/2004GL020466.

1. Introduction

[2] Coastal tectonics related to thrust faulting imply uplifted and tilted tectonic blocks visible on marine and alluvial terraces. The Zemmouri earthquake of 21 May 2003 (Mw 6.8) that occurred along the coast, east of the city of Algiers, is the largest felt since the 3 February 1716 (I = X [*Rothé*, 1950; *Ayadi et al.*, 2003]) (Figure 1). The seismicity in northern Algeria results from the ∼6 mm/yr. NNW-SSE trending plate convergence of Africa towards Eurasia [*DeMets et al.*, 1990]. The focal mechanisms (Harvard CMT) of recent earthquakes display consistent NE-SW trending thrust faulting across the Tell Atlas (Figure 1). The active deformation and related thrust faulting system along the plate boundary in North Africa are, however, poorly known.

[3] The Zemmouri mainshock has been relocated at 36.83N, 3.65E with 10 km hypocentral depth and the aftershock study indicates a ∼40°–50° south dipping fault plane [*Bounif et al.*, 2004] (Figure 1). From the analysis of teleseismic waveforms, the earthquake rupture lasted 17 sec. and shows a thrust faulting mechanism with a seismic moment of $2.86\ 10^{19}$ N-m [*Delouis et al.*, 2004]. The earthquake is hence related to a thrust rupture that likely corresponds inland to the southern limit of the Mitidja basin formed by the Blida thrust and fold system (Figure 1). The mainshock coastal location and earthquake characteristics imply a significant surface deformation that may constrain physical fault dimension and related location at sea bottom rupture.

[4] In this paper, the seismotectonic characteristics of the Zemmouri earthquake constrains the fault dimensions and infers a coseismic sea bottom rupture a few km offshore. The measured coseismic shoreline changes of emerged algae are combined with GPS and conventional leveling lines in the epicentral area (Figure 2). The surface deformation constrains the slip distribution and the inferred dislocation model and suggests two rupture patches along a planar reverse fault geometry. The geometric moment-magnitude, vertical slip distribution and local tectonic characteristics infer a fault tip with possible surface ruptures at a maximum of 10 km from the coast.

2. Seismotectonic Setting and Active Deformation

[5] The active deformation along the plate boundary in North Africa results from the transpression tectonics along the Atlas Mountains [*Morel and Meghraoui*, 1996]. The largest seismic event (10/10/1980; Ms 7.3) that was associated with the El Asnam fault-related folding exhibited a NE-SW trending 36-km-long surface rupture with a maximum 6 m of vertical deformation [*Ouyed et al.*, 1981; *King and Vita-Finzi*, 1981; *Ruegg et al.*, 1982]. More recently, the Tipasa earthquake of 29 October 1989, Mw 6.0, that occurred along the coast 70 km west of Algiers is also related to a thrust mechanism (Figure 1) [*Meghraoui*, 1991]. The NE-SW to east-west trending folds and associated active faults of the Tell Atlas, which are visible mainly in the intermontane and coastal Quaternary basins (Cheliff and Mitidja basins), result from north-south to NNW-SSE shortening movements (Figure 1) [*Meghraoui and Doumaz*, 1996]. The active deformation visible along the thrust and fold systems that form the Tell Atlas of northern Algeria may accommodate ∼1–2 mm/yr

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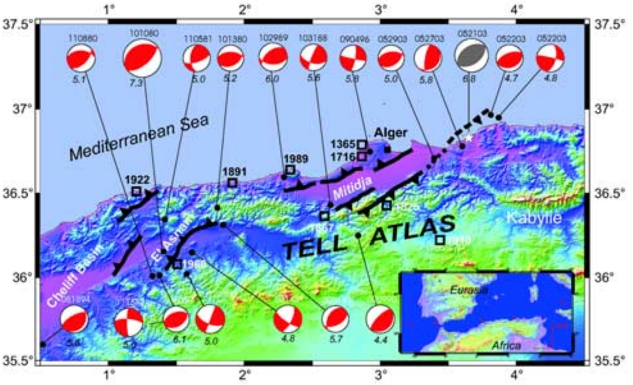

Figure 1. Seismotectonic framework of north-central Algeria [*Meghraoui*, 1988]. Focal mechanisms (Harvard CMT Zemmouri event in grey) with thrust faulting mechanism are in agreement with the Africa-Eurasia plate convergence (see inset). Historical earthquakes reflect the persistent active deformation along the Tell Atlas [*Rothé*, 1950; *Benouar*, 1994].

of shortening along the coastal mountains [*Meghraoui and Doumaz*, 1996]. Uplifted marine terraces on the Sahel anticline along the western coast of Algiers yield a minimum 0.2 mm/yr of uplift rate that can be converted into 0.4 mm/yr shortening rate across the coastal thrust-and-fold structure [*Meghraoui*, 1991]. The seismic moment tensor summation yields 1.5 mm/yr convergent movement obtained from the 20th century seismicity catalogue of Algeria [*Benouar*, 1994; *Pondrelli et al.*, 1995].

[6] The ENE-WSW trending Blida thrust-and-fold system limits the Mitidja basin to the south and delineates a sharp topographic offset (~1500 m) where Mesozoic and Cenozoic structures overthrust Neogene and Quaternary formations (Figure 1) [*Meghraoui*, 1988]. Here, folded and faulted Neogene and Quaternary units mark the NE-SW trending neotectonic structures. The earthquake fault is therefore oblique to the coastline but was poorly constrained near Boumerdes and the epicentral area. Near the coast and on the hangingwall block, folded Neogene units are overlain by flat lying and uplifted late Quaternary alluvial and marine terraces. The coastal neotectonics show a steplike morphology with up to 600-m-high flat surfaces overlying the bedrock.

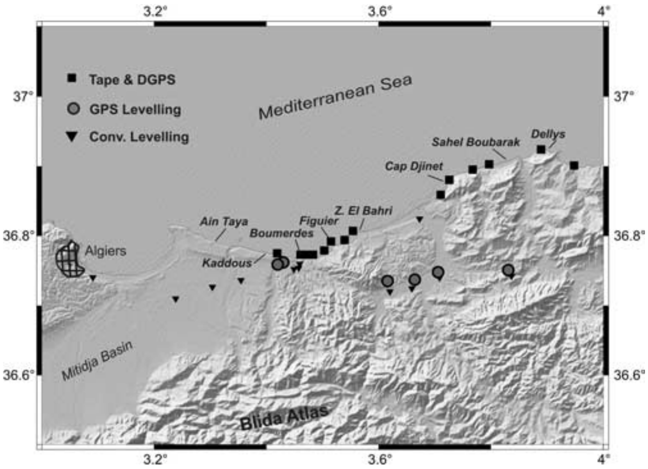

Figure 2. Coastal, leveling and GPS measurement stations distributed in the epicentral region of the 21 May 2003 Zemmouri earthquake.

3. Evidence of Coastal Uplift

[7] The shoreline emergence associated to the Zemmouri earthquake exhibited immediately after the mainshock an impressive white strip visible mainly on rocky headlands. Local fishermen and inhabitants corroborate the sudden phenomenon and the uplift of sea rocks, harbor quays and related marine organisms along the coastline between Boumerdes and Dellys. The white band correspond to Rhodophytes algae and more specifically to "Coralina Elongata", a common marine organism of coastal regions of the Mediterranean Sea. The algae has a reddish-brown color when immerged and alive in the intertidal zone. The algae pigmentation color turns white (death of algae) when permanently exposed to the atmosphere after the coastal uplift. The coseismic permanent deformation affected the algae that left the white band as a distinct trace of the preseismic sea level (Figure 3). No white band trace exists west of Boumerdes and local witnesses observe that sea rocks disappeared offshore the Ain Taya region. No uplift occurred at Kaddous beach, 1.5 km west of Boumerdes city, where Roman aqueduct walls also mark the sea level. Furthermore, older wave-cut notches and uplifted shoreline terrasses that can be observed at different sites along the coast testify for repeated coseismic movements in the past (Figure 3). Similar evidence of repeated coastal uplift were observed after the 1953 Cephalonia earthquake (Ms 7.2, western Greece) where the coseismic vertical deformation reached 0.7 m along the eastern coast of the island [*Stiros et al.*, 1994].

[8] We have measured the uplift at 56 different locations from the difference between the uppermost white band (algae level) trace and the present-day sea level along the coastline using tape and differential GPS equipment. Although the uplift did not show a significant difference at some locations, 5 to 10 measure were averaged for each measurement site. Most of measurements were collected

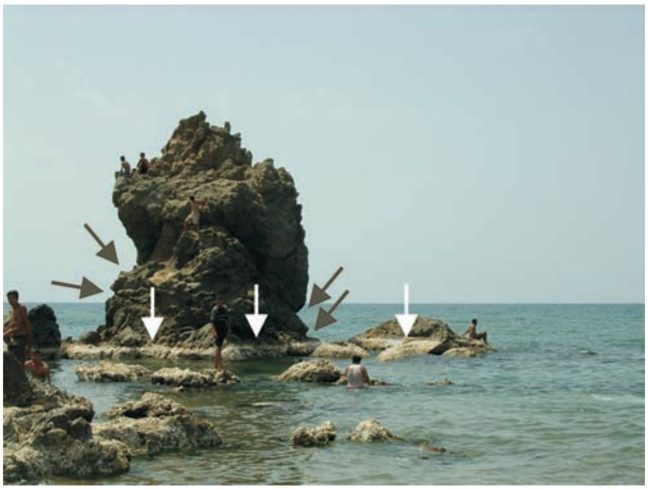

Figure 3. Coseismic coastal uplift at Le Figuier (0.55 m, white arrow) measured from the white band of emerged algae along the coastline (see also Figure 4). Black arrows indicate the possible markers of fossil sea-level and related paleoseismic uplift.

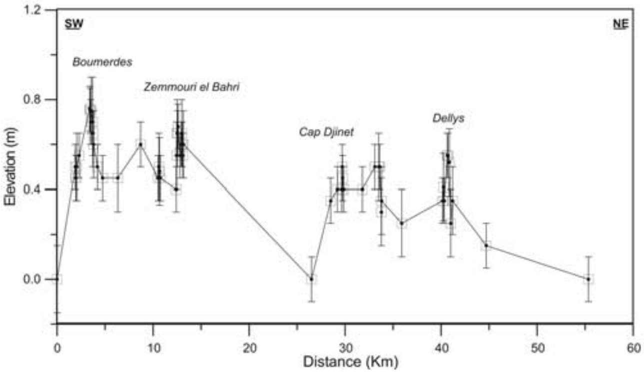

Figure 4. Coastal uplift distribution obtained from tape and differential GPS measurements of white band algae. Each measured point along the fault corresponds to the average of 5 to 10 measurements for each location. The maximum error bar σ = ±0.15 m includes the tidal daily fluctuations and error in measurements. The slip distribution shows two rupture patches and the uplift distribution suggests a coseismic fault scarp a few km offshore at the sea bottom.

during daytime from 10:00 to 16:00 and takes into account a maximum error range of σ = ±0.15 m that includes the daily tidal fluctuations and measurement error.

[9] Moving eastward along the coastline from Kaddous, the first amount of uplift (0.5 m) was measured at the Boumerdes beach on an isolated rock. An equivalent amount of uplift of 0.45 to 0.55 m was measured at the Boumerdes rocky headlands at about 1 km east of Kaddous. The maximum uplift of 0.75 m was reached at about 3.4 km east of Kaddous where rocky headlands show an impressive large white band and related emerged algae. The measured uplift fluctuates between 0.4 and 0.6 m between 4 and 12 km east of Kaddous. At Zemmouri el Bahri harbor, the quays presented continuous impressive marks of the previous sea level and recorded 0.55 to 0.65 m of uplift. Furthermore, we could not obtain precise uplift measurements along the long beach (∼10 km) east of Zemmouri el Bahri. Shoreline buildings at the electrical power plant and rocky headlands at Cap Djinet showed a negligible trace of uplift. Further east between Cap Djinet and Dellys harbor, the uplift fluctuates between 0.35 and 0.55 m except at Sahel Boubarak where a ∼5-km-long beach prevented precise measurements. The uplift became permanently negligible again along the coastline, east of Dellys and at about 55 km from Kaddous. The general uplift configuration indicates two ∼25-km-long segments with an asymmetrical shape of slip distribution (Figure 4). The maximum displacements are on the western segment close to the Boumerdes-Zemmouri el Bahri coastline.

4. Surface Deformation From Leveling Profiles

[10] The uplift observed along the coastline reflects a broad surface deformation that includes the epicentral area. Therefore, 14 geodetic benchmarks have been measured using GPS and total station equipments (Ashtek and Leica-Wild respectively). The benchmarks are mainly along the railway that connects Algiers to the Algerian eastern cities, and at bridges and along main roads. Preseismic geodetic leveling was performed by the INCT and dates from 1987. Geodetic campaigns of re-measured benchmarks were done immediately after the earthquake for GPS leveling measurements and from September 2003 to January 2004 for conventional leveling. The error bar of leveling lines is related to the GPS and theodolite measurement error range and is less than 1 cm. The uplift distribution along the railway shows a negligible displacement west of Boumerdes city in agreement with the negligible displacement observed at Kaddous (see Figures 2, 4, and 5). The displacement increases along the railway line to reach 0.42 ± 0.01 m immediately south of Boumerdes. Further east, the uplift ranges between 0.14 and 0.20 ± 0.01 m along the ∼20 km-long railway line. There is not many extant benchmarks along the coastal road, but the few measured points, mainly near Boumerdes, corroborate the uplift distribution obtained from the coastal white band algae (see previous section). In particular, measured uplift at Boumerdes show 0.45 to 0.55 ± 0.15 m from the algae and 0.42 ± 0.01 m from the leveled benchmarks. To the east at Zemmouri el Bahri harbor, we obtained 0.55 to 0.65 ± 0.15 m of uplift from the white strip algae and 0.45 ± 0.01 m from the coastal leveling line. Finally, the GPS and conventional leveling lines show consistent uplift values and complement the coastal uplift obtained from the white band algae measurements. The uplift values indicate a general coastal uplift and tilting towards the south and south-east of the continental region in accord with the thrust faulting mechanism.

5. Fault Parameters and Rupture Modeling

[11] The uplift measurements along the coastline and inland are used to constrain the fault rupture parameters. To model the observed measurements, we use dislocations on rectangular faults embedded in an elastic homogenous half space [*Okada*, 1985]. Using the surface deformation coupled with the coastal tectonics we constrain the model

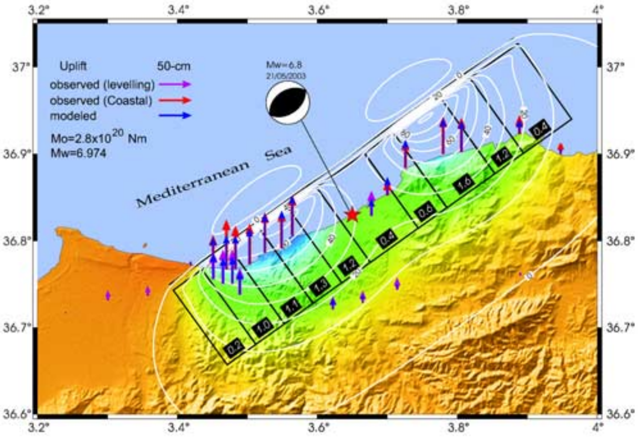

Figure 5. Model of vertical deformation with contours of 20 cm interval (topographic shade from SRTM data). Black rectangles are the model fault patches projected to the surface. The amount of reverse slip on each patch is also shown in black boxes. The model shows the best fit with the coastal deformation and infers a 50-km-long fault plane, striking N 54°E and dipping 50° SE. The red star corresponds to the relocated mainshock [*Bounif et al.*, 2004] and focal mechanism is from CMT Harvard.

fault to have a strike of N 54°E and a dip of 50° to the southeast (Figure 5). The model fault is consistent with the focal mechanism solutions and with the aftershocks distribution [*Bounif et al.*, 2004]. The fault is 54 km-long and extends from 1 km below surface to 15 km depth. To deduce the along-strike slip variation we discretize the fault rupture into 10 patches of 4.5 and 7.5 km wide. Because of the incomplete surface coverage of measured GPS and leveling points, further discretization along dip direction could not be performed to obtain a more realistic variability of dip slip distribution. However, the observed measurements are fit by trial and error using pure dip-slip dislocations in agreement with focal mechanism solutions. As shown in Figure 5, the best model predicts high slip concentrations at two locations along the fault near Boumerdes and Dellys, with minimum slip in between. The maximum slip at depth reaches 1.6 m east of Dellys and the geodetic moment calculated by the synthetic model is 2.75×10^{19} Nm (equivalent to Mw 6.9). Furthermore, the model appears to be comparable with that of *Delouis et al.* [2004] deduced from the waveform inversion.

6. Discussion and Conclusion

[12] The 21 May 2003 Zemmouri earthquake occurred along the coastline of Algeria and revealed an important continental deformation. The surface vertical displacements with a maximum 0.75 m of uplift along the coast and the model of 50-km-long planar rupture illustrate the fault parameters involved during the coseismic deformation. Moreover, the distribution of coastal uplift suggests two fault patches that image the coseismic rupture complexity at depth (Figure 5). The variation of uplifts during the 1953 Cephalonia earthquake also shows two main patches related to the offshore Poros Thrust (eastern coast of Cephalonia Island [*Stiros et al.*, 1994]). The aftershock distribution [*Bounif et al.*, 2004] shows two distinct clusters of seismic events that may be correlated with the coastal slip distribution of Figure 4. From the inversion of seismic waves, *Delouis et al.* [2004] obtain seismic source characteristics and rupture dynamics along a planar fault with two distinct areas of maximum slip consistent with our model. The surface deformation documents the extent of rupture propagation and termination and indicates the earthquake fault dimension. The consistency between different types of field data and modeling constrains the tectonic characteristics of an active zone along the Africa-Eurasia plate boundary.

[13] The Zemmouri earthquake rupture shows two slip patches according to the coastal uplift and modeling (Figure 5). The rupture characteristics of the Zemmouri earthquake appear to be well constrained by the vertical slip distribution (Figure 4), mainshock and aftershock locations [*Bounif et al.*, 2004] and seismic source parameters [*Delouis et al.*, 2004]. In particular, these seismic, geodetic and tectonic data provide a clear constraint on the southwest fault limit. On the other hand, the disappearance of sea rocks near Ain Taya to the north west confirms the footwall block movements. Similarly, the 1980 El Asnam earthquake rupture was related to a thrust faulting made up of distinct patches of slip [*King and Yielding*, 1984]. The evidence of repeated coseismic uplift clearly visible along the coast illustrates the long term seismic behavior of the fault and shows the potential for future paleoseismic studies. The Zemmouri fault is at the northeastern end of the Blida thrust fault segment that shows no significant seismic activity since the 1825 earthquake [*Rothé*, 1950]. Therefore, the southern Mitidja fault system has considerable seismic potential that should be considered in any scenario of earthquake mitigation in northern Algeria.

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