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Strong Algerian Earthquake Strikes Near Capital City

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On 21 May 2003, a damaging earthquake of M_w 6.8 struck the region of Boumerdes 40 km east of Algiers in northern Algeria (Figure 1). The main shock, which lasted ~36–40 s, had devastating effects and claimed about 2300 victims, caused more than 11,450 injuries, and left about 200,000 people homeless. It destroyed and seriously damaged around 180,000 housing units and 6000 public buildings with losses estimated at $5 billion. The main shock was widely felt within a radius of ~ 400 km in Algeria. To the north, the earthquake was felt in southeastern Spain, including the Balearic Islands, and also in Sardinia and in southern France.

The main shock location, which was calculated at 36.91°N, 3.58°E (15 km offshore of Zemmouri; Figure 1), and the local magnitude (M_d 6.4) are from seismic records of local stations. International seismological centers obtained M_w 6.8 (NEIC) with a thrust focal mechanism solution and 1.83 x 10^{26} dyne.cm for the seismic moment. A sequence of aftershocks affected the epicentral area with two strong shocks reaching M_w 5.8 on 27 and 29 May 2003. Field investigations allowed us to assign a maximum intensity X (European Macroseismic Scale 98) and to report rockfalls, minor surface cracks, and liquefaction phenomena. The main shock was not associated with inland surface faulting, but one of the most striking coseismic effects is the coastal uplift and the backwash along the littoral of the Mitidja basin.

The Zemmouri earthquake is among the largest recorded events in North Africa. The heavy damage and death toll can be explained by the large magnitude, the poor quality of the constructions, and site amplification effects.

Seismicity and Neotectonic Setting

Northern Algeria experienced several disastrous earthquakes in the past: in Algiers on 2 January 1365 and 3 February 1716, with peak Modified Mercalli Intensity I_0=X; in Oran on 9 October 1790 I_0=X; in Blida on 2 March 1825 I_0=X; in Mouzaia on 2 January 1867 I_0=IX; in El Asnam on 10 October 1980 M_s 7.3; in Oued Djer on 31 October 1988 M_d 5.6; in Mont Chenoua on 29 October 1989 M_s 6.0; and in Ain Benian on 4 September 1996 M_d 5.3 [*Rothé*, 1950; *Ambraseys and Vogt*, 1988; *Meghraoui*, 1991; *Benouar*, 1994; *Mokrane et al.*, 1994; *Maouche et al.*, 1998; and *Harbi et al.*, 2003]. The active faulting and occurrence of past earthquakes indicate that the Algiers region is an active zone with significant seismic potential (Figure 1).

The Mitidja basin is part of the Tell Atlas, an east-northeast-trending, fold-and-thrust belt along the plate boundary in North Africa. The Quaternary tectonics, reverse faulting, and related north-northwest-south-southeast compression movements are consistent with thrust focal mechanisms of recent earthquakes that result from the 5–6 mm/yr of convergence of Africa toward Eurasia [*Argus et al.*, 1989]. The Tell Atlas may accommodate 2–3 mm/yr of shortening along the main thrust system of the plate boundary zone [*Meghraoui and Doumaz*, 1996]. The Mitidja basin is bounded to the south by the Blida fold-and-thrust system, which corresponds to imbricated southeast-dipping thrust sheets. The northern side of the flat basin is limited by the Sahel active fold parallel to the coast. The fold scarp is probably related to a hidden reverse fault where the westernmost section produced the Mont Chenoua earthquake in 1989 [*Meghraoui*, 1991] (Figure 1).

Surface and Macroseismic Effects

Ground deformations with rock falls, landslides, and liquefaction were observed between Bordj El Bahri and Dellys and mapped soon after the mainshock, the zone of maximum damage. Minor cracks, fissures, and small landslides are distributed parallel to the coastal cliff along a 10 km distance. Various geological and hydrological effects were also observed: altered flow of springs, modified water level in wells, liquefaction, and extrusion of sand and sliding of river banks between Algiers and Dellys (see Figure 2). The uplift of individual rocks in the sea and emergence of algae level measured in different places along the coast, with a maximum of 0.80 m between Boumerdes and Zemmouri El Bahri, suggest a vertical deformation with possible fault emergence a few kilometers offshore.

Macroseismic effects: The earthquake of 21 May generated severe damage in areas and cities and villages located along the coast between Algiers and Tigzirt, and further south to Bordj Menaiel (Figure 1). Many modern structures suffered "pancake" collapse in which hundreds of people perished. The Zemmouri village was almost completely razed, while other, nearby localities were severely damaged. We attributed an intensity X (European Macroseismic Scale 98) to the area between Dellys and Bordj El Bahri. Isoseismals of intensity X are localized (see Figure 1) and can be interpreted as probably due to the nature of the seismic source, wave path, and shallow depth, and the characteristics of the subsoil—which is generally clay and alluvial deposits—and to the poorly engineered recent building stock.

The main shock of 21 May triggered a tsunami with damaging waves of 1–3 m amplitude along the southern coasts of the Balearic Islands. (Press reports described several hundred damaged vessels in harbors.) In the epicentral area, several witnesses observed that, "the sea retired along the coast for about 200 m during

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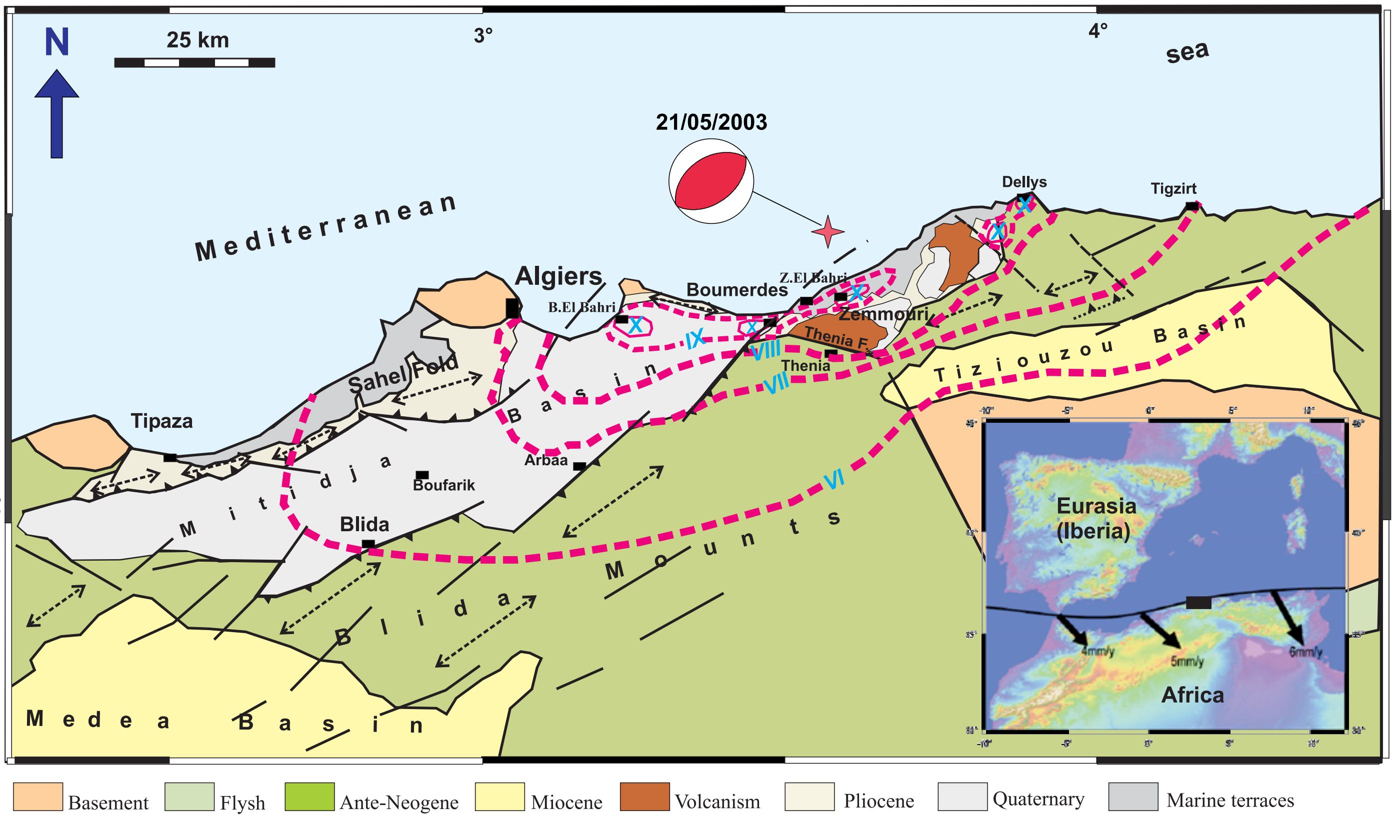

Fig. 1. Isoseismals of the Zemmouri earthquake (I_o=X, red dashed lines) and the geological and tectonic background of the epicentral area [Meghraoui, *1991]. The Mitidja basin is bounded by thrust fault systems consistent with the focal mechanism solution of the mainshock (ETH Zürich).*

the main shock," a phenomenon probably related to the vertical uplift observed along the coastline. On the other hand, undersea telephone cables were cut at ~45 km offshore from the epicentral area and disturbed the telecommunications link between Europe and several other countries in Asia and the Middle East. This suggests the occurrence of major undersea landslides and turbidite deposits.

Seismological and Geodetic Surveys

A temporary network of 18 three-component, short-period seismic stations and 13 accelerometers was installed soon after the main shock in the epicentral area. In addition, four ocean bottom seismometer stations were installed offshore, and two of them are still in operation. Four stations from the permanent Algerian Telemetred Seismological Network (ATSN) were also used to monitor aftershocks (Figure 3). The aftershock distribution from 21 May to 10 June 2003 is oblique to the coast and shows a northeast-southwest-elongated swarm about 100 km long and 40 km wide. The events were located using an average model with a two-layer crust over a Moho at 30 km depth (V_p = 5.5 km/s to 12 km depth, 6.5 km/s at greater depth, and 8 km/s for the lower layer). Errors range between 0.09 and 0.5 s for rms and as low as 5.5 km in vertical location. Most of the aftershocks are located offshore, but the southwestern part of the rupture zone overlaps the continent by 10–20 km (Figure 3). The aftershock elongation and northeast-southwest-striking reverse faulting mechanisms of the main events (Figures 1 and 3) suggest that the earthquake ruptured the offshore continuation of the Blida thrust and fold system.

A Global Positioning System (GPS) network was deployed three days after the main shock to measure co-seismic and post-seismic deformation. The first survey consists of six dual-frequency GPS receivers with antennas installed on tripods. Network densification is planned with an extension to the east and to the south of the epicentral area. The second network, located southwest of the faulted area, consists of seven dual-frequency GPS receivers that had been previously measured in July 2002 and February 2003 to monitor the presumably active Thenia fault. Furthermore, a campaign of precise leveling is in progress across the epicentral area and will be compared to the 1984 campaign.

Seismotectonics and Seismic Hazard Implications

The earthquake that struck the Zemmouri-Boumerdes region is among the largest seismic events recorded in northern Algeria. The seismic parameters and inferred surface rupture can be compared with the El Asnam earthquake [*King and Vita-Finzi*, 1981; *Ouyed et al.*, 1981]; they suggest a thrust fault that is probably located a few kilometers offshore. Several important observations were made. Except for ground features such as hydrological effects, liquefaction phenomena, landslides, and rock falls, no significant surface ruptures were observed inland. Aftershocks are elongated in a northeast-southwest direction oblique to the coastline, and a coastal uplift was observed with an average 0.5 m of vertical movement between Boumerdes and Zemmouri El Bahri. The offshore continuation of the Blida reverse fault system may likely be at the origin of the 21 May earthquake.

The Zemmouri earthquake generated 0.58 g and 0.34 g of maximum acceleration recorded at ~20 and 60 km from the epicenter, respectively. The observed maximum acceleration was fairly well predicted by the seismic hazard evaluation in the Algiers region by *Aoudia et al.* [2000]. For structures with a 0.25 s (4 Hz) period of vibration in the epicentral area, constructions should have been designed for an acceleration of 0.6 g [*Naili and Benouar*, 2000]. Unfortunately, the Zemmouri earthquake had an average frequency of 4 Hz and caused the phenomena of resonance for all of the structures in the range of 2–4 stories.

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Fig. 2. Surface effects and damage in the epicentral area are shown. No surface faulting was visible inland. Photos: Upper left, coastal uplift (average 0.5 m) marked by the intertidal zone (white band); upper right, liquefaction features (sand blows); lower left, "pancake" building collapse; lower right, secondary surface cracks.

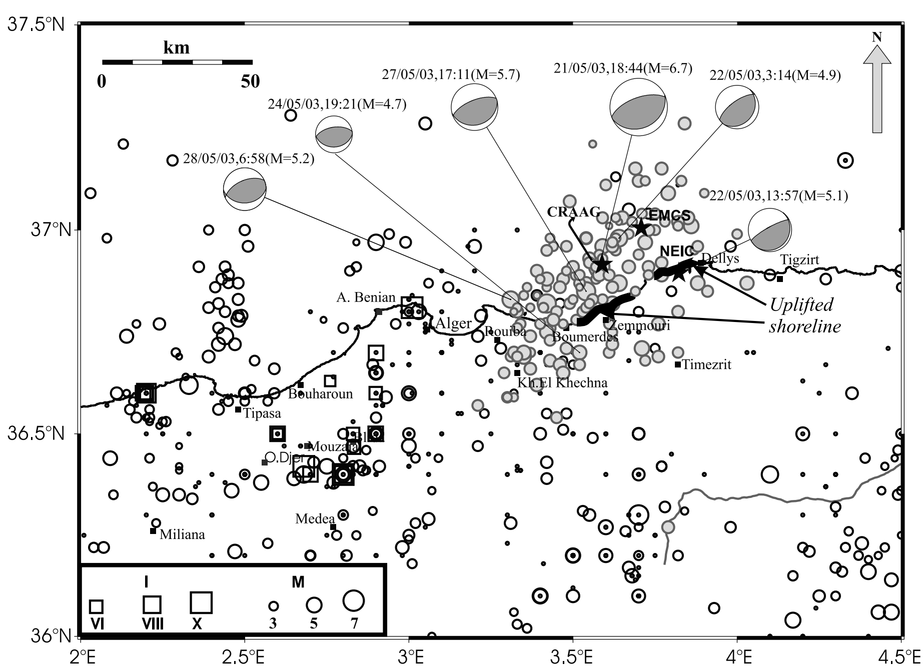

Fig. 3. Aftershock distribution (gray circles, M>2) from 21 May to 10 June 2003. Open squares show historical seismicity since 1365; open circles show instrumental seismicity since 1900. Stars are mainshock locations of the 21 May 2003 seismic event (M_w 6.8) based on information from seismological centers. Focal mechanism solutions are CMT (Harvard) showing thrust faulting consistent with field observations and uplifted coastline.

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