The Algiers, Algeria Earthquake (M_W 6.8) of 21 May 2003: Preliminary Report

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INTRODUCTION

On 21 May 2003, at 18:44 UTC (19:44 local time), a strong shallow earthquake of magnitude M_W 6.8 (M_S 6.9) struck Algiers, the capital of Algeria, causing extensive damage in different *wilayas* (provinces) in the north-central part of Algeria. The epicenter was located offshore at 3.58°E, 36.91°N, 7 km to the north of Zemmouri in the province of Boumerdes, about 50 km northeast of Algiers (Yelles-Chauche *et al.*, 2003). This earthquake took place where we have no evidence of previous significant earthquakes, either instrumental or historical. It is the largest and the most destructive to occur in northern Algeria since the 1980 El Asnam (M_W 7.3) earthquake.

The original location, obtained by the Centre de Recherche en Astronomie, Astrophysique et Géophysique (CRAAG), shown in Figure 1, is slightly different from those given by the European-Mediterranean Seismological Centre (EMSC) (3.76°E, 37.02°N) and the U.S. Geological Survey (USGS) (3.78°E, 36.86°N). The focal mechanism computed by the International Seismological Centre (ISC) corresponds to a northeast-southwest thrust fault (strike 54°, dip 47°, rake 86°). According to Yagi (2003), the seismic moment was $2.4 \cdot 10^{19}$ Nm. The mainshock was followed by a small tsunami, which affected the Spanish coast. Specifically, along the coast of the Balearic Islands, a sea wave of about 1.5 m height sunk a hundred small boats docked in the ports. During the mainshock, a temporary withdrawal of the sea of about 100 m was observed.

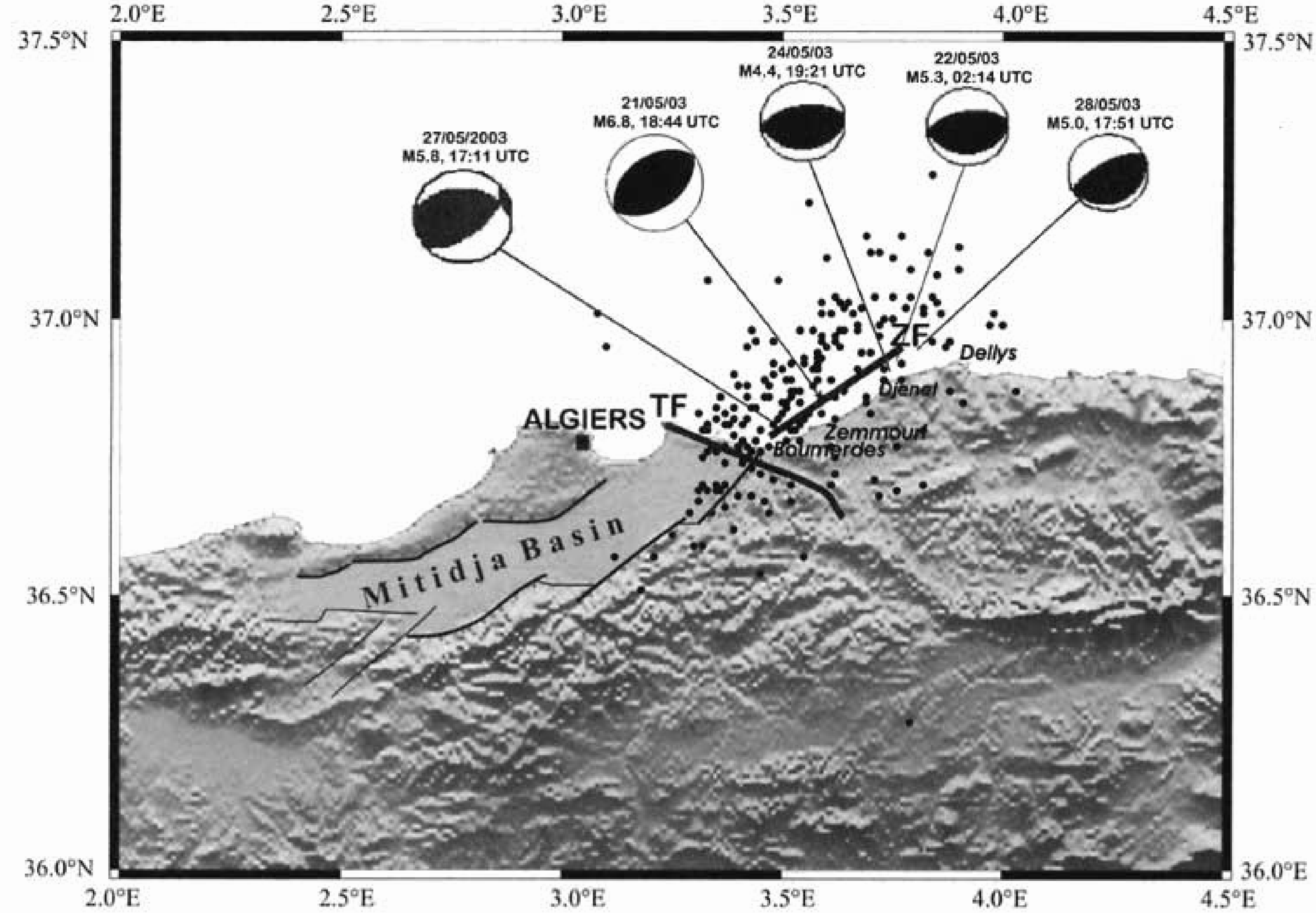
This earthquake, with a macroseismic maximum intensity of IX–X in two small cities near the epicenter, Zemmouri and Boumerdes, and an intensity of VII–VIII in several districts of Algiers, caused significant economic and social losses, especially in the city of Boumerdes and the main villages in the region, such as Zemmouri, Dellys, and Thenia. In these cities, many modern buildings collapsed and many others were seriously damaged. Available statistics reveal extensive damage, including more than 2,274 fatalities, more than 11,000 injuries, numerous missing people, 200,000 homeless, and more than 19,000 residential structures destroyed. The highest number of fatalities was registered in the province of Boumerdes, in which 60.5% of the deaths occurred, while 38.8% were in Algiers.

SEISMIC AND SEISMOTECTONIC FRAMEWORK

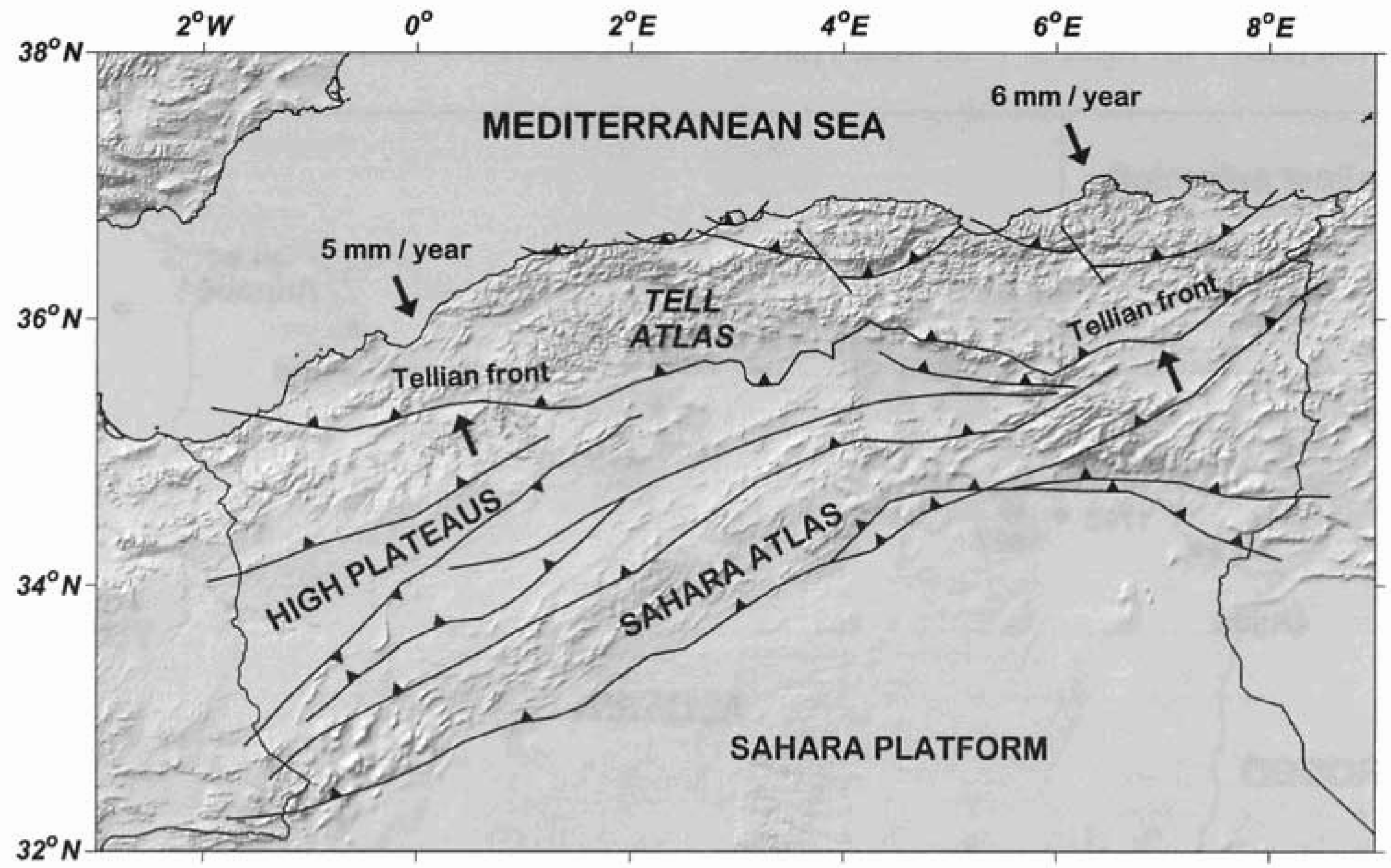
Northern Algeria is known as one of the most active and hazardous zones in the western Mediterranean basin. Seismic activity in this region is directly associated with the plate boundary between the Eurasian and African plates (Figure 2).

Located in the eastern part of the Ibero-Maghrebian region, northern Algeria comprises the following main structural domains, the formation of which is directly related to the different openings and closings of the Mediterranean Sea: the Tell Atlas or Tell-Rift system, the High Plateaus, the Sahara Atlas (Atlas mountains system), and the Sahara Platform (Figure 2).

The tectonics of this region have been the subject of several studies, including Meghraoui (1988), Yielding *et al.* (1989), Aoudia and Meghraoui (1995), Mickus and Jallouli (1999), Frizon de Lamotte *et al.* (2000), and Aoudia *et al.* (2000). The main structures are briefly and clearly summarized in Peláez *et al.* (2003). The Tell is part of an Alpine orogen that includes the Spanish Betic Mountains in the west and the Italian Apennines in the east. The Tell Mountains consist of a succession of valleys (alluvial basins) and ridges formed by thrusts and folds with east-west to northeast-southwest trending parallel to the coastline (Figure 2). The High Plateaus zone is situated between the Middle Atlas, the Tell, and the Sahara Atlas, in an elevated region with a relatively tabular topography characterized by a thin Meso-Cenozoic cover. The Sahara Atlas belongs to the Atlas Mountains



▲ **Figure 1.** Location of the mainshock computed by CRAAG. The map shows the spatial distribution of the aftershocks recorded by the permanent seismological network of CRAAG. The focal mechanisms are those computed by the Harvard CMT. TF: Thenia Fault; ZF: Zemmouri Fault.



▲ **Figure 2.** Regional tectonic framework (simplified from Bracene *et al.*, 2003).

system (Anti, High, and Middle Atlas in Morocco, Sahara Atlas in western Algeria, Aures in eastern Algeria, and Tunisian Atlas in Tunisia), a mountain range with a deformed faulted and folded Mesozoic-Cenozoic cover.

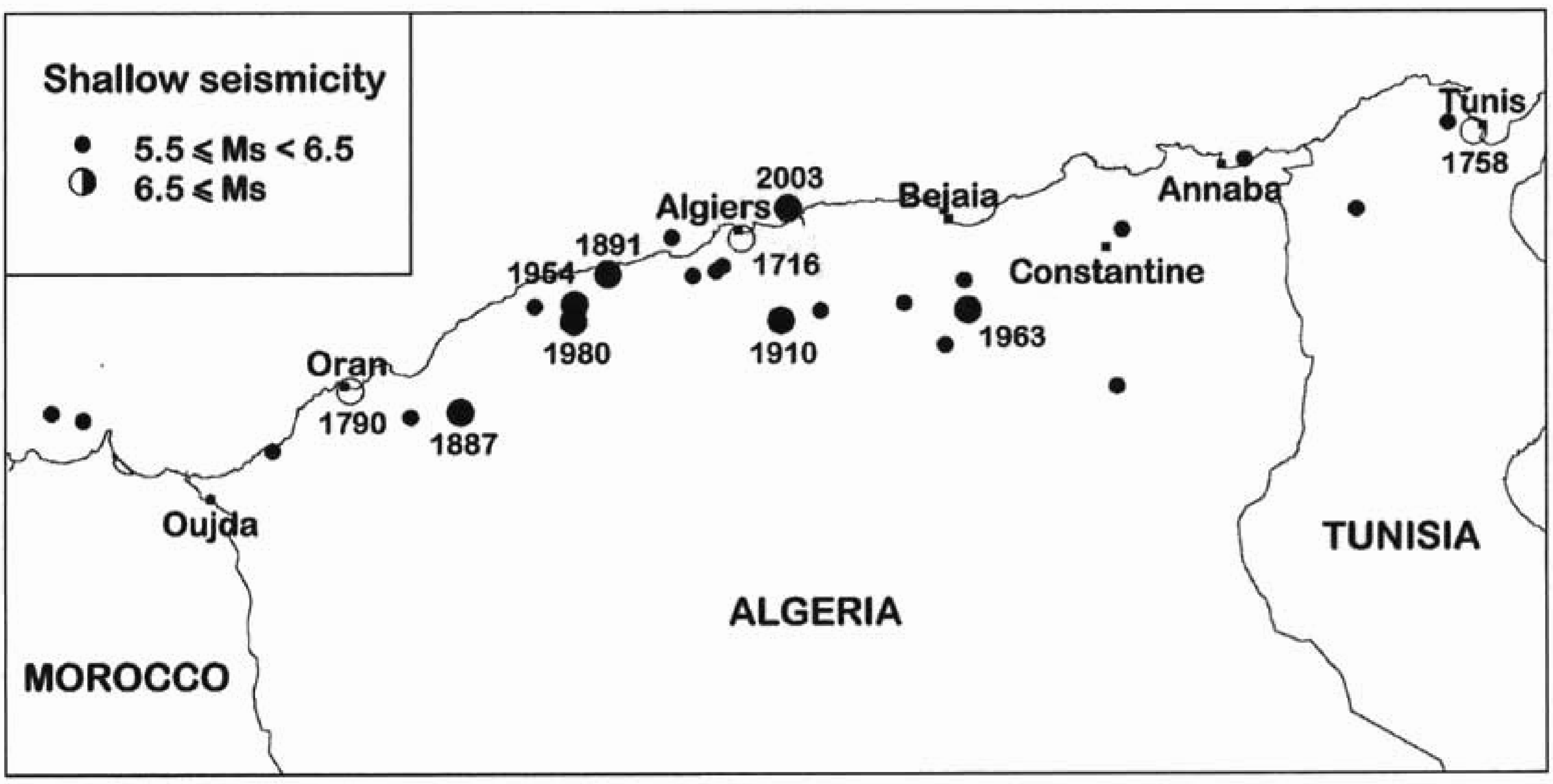
The region of Boumerdes is located along the coast, in the central part of Algeria. Much of the coastal area is characterized as broad alluvial plains punctuated by metamorphic rocks from the Atlas thrust belt to the south. The gently sloping alluvial plains have been uplifted by past earthquakes. The marine terraces along the coastline have been uplifted at an estimated rate of about 0.25 mm/yr (Wang *et al.*, 2004). This region is at the eastern tip of the Quaternary Mitidja basin (Figure 1), which has been formed during north-south Miocene extension (Philip, 1983). This extension has been followed by a north-south to north-northwest–south-southeast compression. The compressional movement continued during the Quaternary (Meghraoui, 1988; Boudiaf, 1996; Boudiaf *et al.*, 1998) and is still active, as shown by the recorded seismicity (CRAAG, 1994) and recent deformation. This deformation is represented by active folding oriented northeast-southwest, and by thrust and strike-slip faults trending northeast-southwest (Meghraoui, 1988). The east-west to ENE-WSW–trending Mitidja basin is bordered by the Mediterranean Sea and Blida Mountains to the north and south, respectively. The northeast margin of the Mitidja basin is bordered by the Thenia Fault, which trends northwest and extends offshore of Algiers (Boudiaf *et al.*, 1998).

Recorded regional seismicity reveals a high rate of low ($M_s \leq 5.0$) to moderate ($5.0 < M_s \leq 6.5$) earthquakes. The most important events that occurred during the last three centuries, including the destructive ones, have taken place in the Tell Atlas (Table 1 and Figure 3). In the western part of this region, the 1790 Oran earthquake and the 1887 El Bordj earthquake both generated a maximum intensity of IX–X. Notable earthquakes in the central area include the 1716 Algiers earthquake, the 1891 Dupleix earthquake, the 1910 Masqueray earthquake, the 1954 and 1980 El Asnam earthquakes, and the most recent, the 2003 Algiers earthquake (IX–X). Finally, in the eastern region, the 1963 Bir Hadada earthquake and the 1907, 1908, and 1985 Constantine earthquakes all generated a maximum intensity of VIII.

Long-term regional seismicity reveals several large earthquake in the Algiers region. These events include the 1365

TABLE 1
Most Important Events in the Tell Atlas Mentioned in the Text

Event	Max. Intensity	Magnitude
1716 Algiers	X	
1790 Oran	IX–X	
1887 El Bordj	VIII	
1891 Dupleix	X	
1907 Constantine	VIII	
1908 Constantine	VIII	
1910 Masqueray	X	m_b 6.4
1954 El Asnam	X–XI	m_b 6.7
1963 Bir Hadada		m_b 6.3
1980 El Asnam	IX	m_b 6.5, M_w 7.3
1985 Constantine	VIII	
2003 Algiers	IX–X	M_L 6.2, M_S 6.9, M_w 6.8



▲ **Figure 3.** Major events in northern Algeria from 1700–2003. Open circles: earthquakes from 1700–1850. Filled circles: earthquakes since 1850.

earthquake, just northwest of Algiers city, which had an epicentral intensity of IX and a damaging tsunami, and the 28 January 1716 event, which had an epicentral intensity of X, destroying Algiers and causing more than 20,000 deaths (CRAAG, 1994; Boudiaf *et al.*, 1998). The Boumerdes region has been affected by recent small earthquakes with magnitude up to 5.3. The most important seismic event near Algiers during the twentieth century was the 16 September 1987 earthquake (m_b 5.2). This earthquake did not cause significant damage. Other minor events occurred in the region of Boumerdes and Thenia, including some felt events.

The 21 May 2003 earthquake is characterized by offshore reverse faulting as a result of the compressive plate motion. Several earthquake solutions have been proposed, with magnitude estimates varying from 6.2 to 7.0. The U.S Geological Survey gives moment magnitude M_w 6.8. The National Earthquake Engineering Research Center (CGS), which operates the strong-motion network in Algeria, computed an epicentral location of (3°53′E, 36°81′N), magnitude M_w 7.0, and a strong-motion duration of about 10 s. The Algerian seismological network, operated by CRAAG, located the epicenter of the mainshock on the continental margin at 3°58′E, 36°91′N (Figure 1). Using the time duration of the seismic signals from the CRAAG stations, a magnitude of M_L 6.2 was calculated. A depth of 10 km was determined, which is typical of Algerian seismicity. The rupture pattern was bilateral but asymmetric, with 30 km propagation to the southwest and 20 km propagation to the northeast. In a recent study, Yagi (2003) inferred a rupture model with two asperities and the maximum dislocation 25 km southwest from the hypocenter. In this model, most of the rupture energy is directed toward the southwest. Directivity effects might thus have exacerbated the damage to the southwest, in the cities of Zemmouri, Boumerdes, and Algiers.

Preliminary geophysical and geological investigations (Yelles-Chauche *et al.*, 2003) suggest the earthquake occurred on an offshore fault oriented N45°, the Zemmouri Fault, which was previously unknown. In a comprehensive report, Wang *et al.* (2004) hypothesize that the Zemmouri Fault is the predominant reverse fault located in the basin to the immediate east of the Mitidja basin. This fault appears to be offset to the southeast by a cross-over fault structure, previously identified as the Thenia Fault. The Thenia Fault has been mapped as a right-lateral strike-slip fault in earlier studies (Boudiaf, 1996; Boudiaf *et al.*, 1998).

We suggest that the Zemmouri Fault reflects the regional compression in a similar manner as the Mitidja basin, but on the east side of the Thenia Fault. Furthermore, some historic seismicity recorded in the vicinity of the Thenia Fault, judging from preliminary investigations, could be associated with this newly discovered Zemmouri Fault. The Thenia Fault appears to be a cross-over fault between large reverse structures and may be too small to generate large earthquakes (Figure 1).

In contrast, the western part of Algiers has experienced three moderate earthquakes: the 31 October 1988 Oued Djer earthquake (m_b 5.0), the 27 October 1989 Tipaza (Mont Chenoua) earthquake (m_b 6.0), and the 4 September 1996 Ain Benian earthquake (m_b 5.7). The last two earthquakes displayed reverse mechanisms and were generated by ENE-WSW reverse faults. Although the historical seismicity in the region remains still poorly known, some evidence of active faulting has been pointed out by several studies (Meghraoui, 1988; Boudiaf, 1996; Boudiaf *et al.*, 1998).

TABLE 2
Major Aftershocks Recorded by the Permanent CRAAG Seismological Network

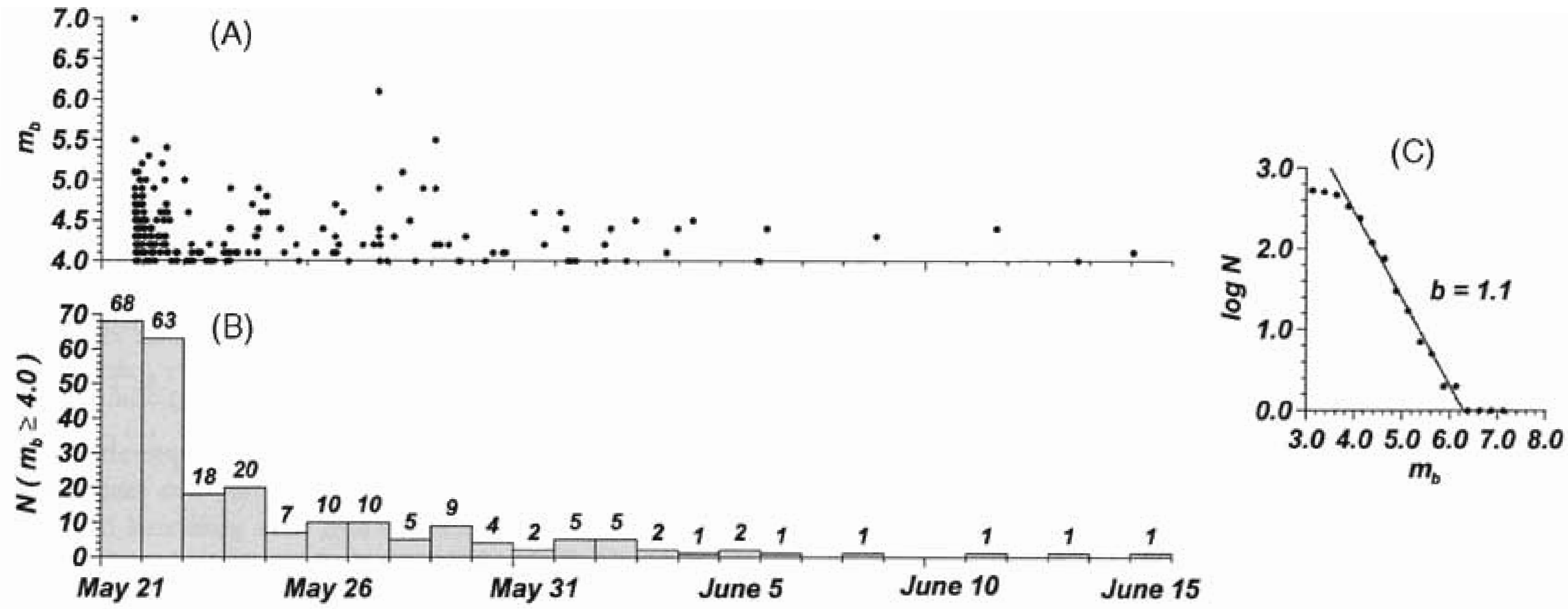
Date	Origin Time (UTC)	Location	M_L
21/05/2003	18:51	36.87°N, 3.64°E	5.0
22/05/2003	03:14	36.98°N, 3.64°E	5.3
27/05/2003	17:11	36.88°N, 3.55°E	5.8
28/05/2003	06:58	36.03°N, 3.32°E	5.2
29/05/2003	02:15	36.20°N, 3.42°E	5.8

AFTERSHOCK ACTIVITY

Following the occurrence of the mainshock, significant aftershock activity has been recorded. These aftershocks were recorded by a portable seismic network installed in the epicentral area. In Figure 1, we show the spatial distribution of the aftershocks recorded by the Algerian seismological network. Activity is mainly located offshore, along a northeast-southwest direction extending from Corso to Dellys. Aftershock activity is still being monitored and the processing of the records is still underway. The focal mechanisms (Harvard CMT solution) shown in Figure 1 are consistent with expectations for a compressional environment and the orientation of the regional stress field (Henares *et al.*, 2002). Three large aftershocks caused damage to previously affected structures, especially in Reghaia and Zemmouri: the 27 May event, at 17:11 UTC, with magnitude M_L 5.8; the 28 May event, at 06:58 UTC, with magnitude M_L 5.2; and the 29 May event, at 02:15 UTC, with magnitude M_L 5.8. In Table 2 we show the major aftershocks, including their locations and magnitudes. In the two months after the mainshock, about 260 aftershocks with magnitude greater than or equal to 4.0 have been recorded. Figure 4 shows the temporal distribution of the aftershocks located in the epicentral area as well as the number of aftershocks per day with magnitude greater than or equal to 4.0. Using the m_b magnitude, we have obtained a b value for the aftershock activity equal to 1.1 (Figure 4). This result is higher than the regional b value (*e.g.*, López Casado *et al.*, 1995; Hamdache, 1998; Hamdache *et al.*, 1998) obtained using the regional catalog of mainshocks.

SURFACE FRACTURES AND COASTAL DEFORMATION

The mainshock generated significant environmental disruption in a large zone surrounding the epicentral area. The



▲ **Figure 4.** Temporal distribution of the (A) aftershocks and (B) aftershock rate with magnitude greater than or equal to 4.0. (C) Plot of the recurrence relationship for the aftershock sequence.

regional road network has been affected by some fractures. Settlement and liquefaction phenomena have been also observed in many locations.

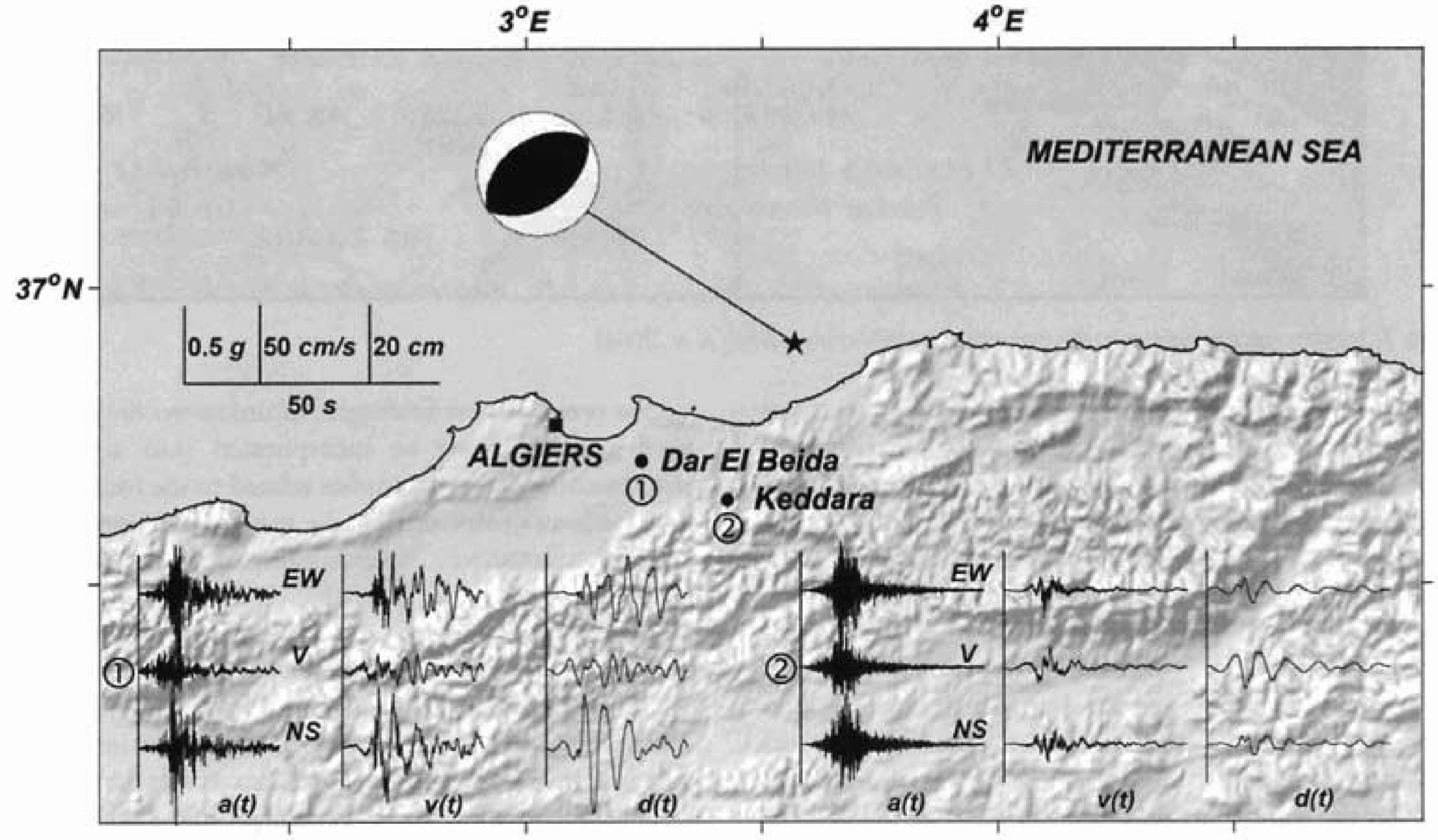
Fractures were observed onshore in the epicentral area, especially in the Corso area, in Zemmouri port, and in the Dellys region. The fractures were visible on the Thyrrhenian marine terraces of the eastern coast of Algiers. They generally have a N130° and N20° orientation, and were observed in the unconsolidated sediments discontinuously from Ain Taya to Zemmouri. These fractures are assumed to be a result of localized surface extension and not due to the fault rupture. The road network has been damaged and different breaks have been observed, especially in the Zemmouri and Dellys regions.

Geological research revealed liquefaction. Figure 5 shows, for example, liquefaction and lateral spreading of the Isser River banks, in the region of Boumerdes, and a liquefaction-induced cavity at the Algiers port, where liquefaction created a large cavity up to 2.5 m in depth. The earthquake also caused offshore effects, such as uplift of the seafloor of at least 50 cm, and minor landslides and liquefaction phenomena along the coastline.

▲ **Figure 5.** Liquefaction-induced cavity at the Algiers port; lateral spreading and sand fissures at the Isser River around Boumerdes city.

TABLE 3
Peak Ground Acceleration for the Mainshock and the 27 May (M_L 5.8) Aftershock

Event	Date	Magnitude	Station	Epi. Distance	Acc_{E-W}	Acc_{N-S}	Acc_V
Mainshock	21/05/03	M_W 6.8	Keddara 1	20 km	0.34 g	0.24 g	0.26 g
			Keddara 2	20 km	0.58 g	0.22 g	0.35 g
			Hussein Dey	36 km	0.27 g	0.23 g	0.09 g
			Dar El Beida	29 km	0.52 g	0.46 g	0.16 g
			Blida	72 km	0.05 g	0.04 g	0.03 g
			El Affroun	86 km	0.16 g	0.09 g	0.03 g
Aftershock	27/05/03	M_L 5.8	Boumerdes	78 km	0.29 g	0.13 g	0.40 g



▲ **Figure 6.** Processed acceleration records at the sites of Dar El Beida and Keddara. These are the two accelerograph stations, monitored by the CGS, nearest to the epicenter (Laouami *et al.*, 2003).

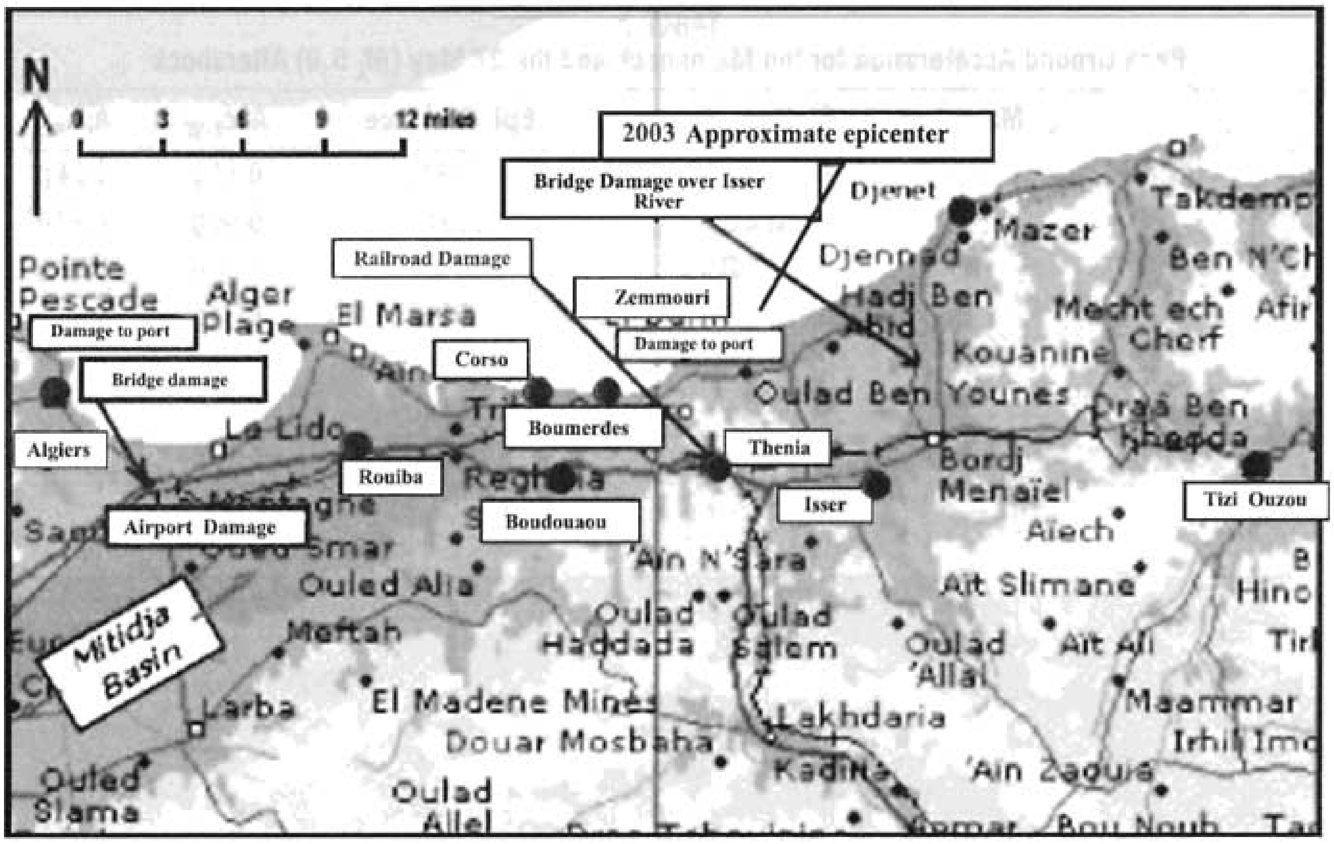
GROUND MOTION RECORDS AND DAMAGE

The National Earthquake Engineering Research Center (CGS) operates the Algerian strong-motion station network. Peak ground acceleration values are shown in Table 3 and waveforms from two stations are shown in Figure 6. The ground-motion data reveal the following. (1) The duration of ground motion shaking was about 10 s, with a predominant frequency of about 3 or 4 Hz (Laouami *et al.*, 2003). (2) Shaking was strongest in the east-west direction. (3) The strongest peak ground acceleration values, of the order of 0.58 g for the east-west component, were recorded at the Keddara soil site, about 20 km from the epicenter. The Keddara rock site, about 150 m from the previous location, recorded peak ground acceleration of about 0.34 g for the same component. (4) In general, recorded peak ground accelerations are higher than mean values expected using attenuation relationships for reverse faulting, as provided by Boore *et al.* (1997) and Abrahamson and Silva (2000). (5) A vertical peak ground acceleration of 0.40 g for the M_L 5.8 aftershock was recorded, indicating an unusually high vertical motion.

Computed and corrected velocities and displacements at Dar El Beida and Keddara sites are shown in Figure 6.

A recent update (Hamdache *et al.*, 2003; Peláez *et al.*, 2004), including the 2003 Algiers earthquake, of the previously published seismic hazard map (Peláez *et al.*, 2003) shows an increase of about 40% in PGA values for a return period of 475 years in the central part of the Tellian Atlas, specifically in the surrounding area of Algiers.

The 2003 earthquake caused damage in an area about 100 km long and 35 km wide, centered on the city of Boumerdes. The most damaged areas were in the coastal



▲ **Figure 7.** Notable damage caused by the mainshock (modified from Wang *et al.*, 2004).

province of Boumerdes (the province immediately to the east of Algiers); the cities of Boumerdes, Zemmouri, Thenia, and Reghaia; and the eastern zone of Algiers. In addition, several large buildings dating from the colonial era (early 20th century) were severely damaged in the districts of Belcourt, Bab-El-Oued, and El-Casbah in Algiers. According to the last official report, 7,400 buildings were destroyed and about 7,000 others were heavily damaged in the province of Boumerdes. In the province of Algiers, 8,500 apartments were lost and more than 20,000 others were heavily damaged. Three factors strongly contributed to the damage: the magnitude of the earthquake, the significant urbanization close to the epicentral area, and lacks in the design and construction of buildings (poor conceptual design, lack of structural design, and poor quality of structural materials). The earthquake damaged twelve hospitals and clinics, including extensive damage to the eight-story hospital in Thenia city. About 330 schools were damaged, including 90% damage to a large building in a major technical university in Algiers. The earthquake affected roads and highway bridges. Eighteen bridges were damaged between the cities of Algiers and Boumerdes (Figure 7). Most of the bridge damage was due to superstructures moving off their bearings onto bent caps. Most of the road damage was the result of settlement of embankments and bridge approaches (Edwards *et al.*, 2003).

CONCLUDING REMARKS

The 21 May 2003 Algiers earthquake was the most important and destructive earthquake in northern Algeria since the El Asnam earthquake of 1980. The occurrence of this earthquake revealed new findings: An unknown fault was discovered and can now be incorporated into seismic hazard assessment. Additional studies related to the focal mechanism and location of this earthquake may provide more conclusive data for an improved understanding of the regional seismicity and tectonics.

The severity of damage suggests that the provisions for ground-shaking levels in the building code are too low, and that soil amplification effects should be taken into account in the updated code. The peak ground acceleration attenuation relation model should include data from the 2003 event, which will increase the expected ground-shaking levels for reverse faults, especially on soils.

The destructive 2003 earthquake occurred in a location where we have no evidence of previous significant earthquakes, either instrumental or historical. Located offshore, this event gives a significant opportunity to develop several field missions to explore in depth the Algerian continental margin, to understand properly the fault that caused this event.

The spatial distribution of the aftershocks reveals a preliminary pattern corresponding to the northeast-southwest fault orientation. These preliminary results are in agreement with the regional stress field. More data on the depth of these events could give us information on the 3D spatial distribution of the aftershocks and provide a better representation of fault structure.

Some preliminary information on different topics related to this earthquake have been presented in this paper. It appears that the area to the southwest of the epicenter experienced the most damage, but some damage occurred in other regions as well. Several field missions have observed changes in the geographical distribution of damage that seem to indicate significant soil/site effects due to the earthquake. It will be interesting to explore in detail the causes of the different levels of damage and to relate the damage observed to the soil/site effects and/or to building quality.

The Algerian building code (RPA-99, 2000) has to be reexamined in light of the results of the different areas, especially in the epicentral area. The last earthquake must be included to improve a new probabilistic seismic hazard map which can then be used in a re-evaluation of the building code in northern Algeria. As pointed out previously, soil amplification effects should be taken into account. Preliminary results which include the 2003 earthquake show seismic hazard values in terms of mean PGA for a return period of 475 years, greater than the previous value of about 40% in the central part of the Tell Atlas.

ACKNOWLEDGMENTS

The authors wish to thank the very helpful review provided by Susan E. Hough. We also thank N. Laouami from CGS, and A. Talbi and F. Bellalem from CRAAG, for sharing unpublished data.

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