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Active coastal thrusting and folding, and uplift rate of the Sahel Anticline and Zemmouri earthquake area (Tell Atlas, Algeria)

Said Maouche [a,e], Mustapha Meghraoui [b,*], Christophe Morhange [c], Samir Belabbes [b,1], Youcef Bouhadad [d], Hamid Haddoum [e]

[a] CRAAG, Bouzareah-Alger, Algeria
[b] Institut de Physique du Globe, UMR 7516, Strasbourg, France
[c] CEREGE, Marseille, France
[d] CGS, Hussein-Dey, Alger, Algeria
[e] Faculté des Sciences de la Terre, USTHB, Alger, Algeria

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ABSTRACT

Major uplifts of late Quaternary marine terraces are visible along the coastline of the Tell Atlas of Algeria located along the Africa–Eurasia convergent plate boundary. The active tectonics of this region is associated with large shallow earthquakes ($M \geq 6.5$), numerous thrust mechanisms and surface fault-related fold. We conducted a detailed levelling survey of late Pleistocene and Holocene marine notches in the Algiers region that experienced 0.50 m coastal uplift during the 2003 Zemmouri earthquake (Mw 6.8). East of Algiers, Holocene marine indicators show three pre-2003 main notch levels formed in the last 21.9 ka. West of Algiers on the Sahel anticline, the levelling of uplifted marine terraces shows a distinct staircase morphology with successive notches that document the incremental folding uplift during the late Pleistocene and Holocene. The timing of successive uplifts related to past coseismic movements along this coastal region indicates episodic activity during the late Holocene. Modelling of surface deformation in the Zemmouri earthquake area implies a 50-km-long, 20-km-wide, NE–SW trending, SE dipping fault rupture and an average 1.3 m coseismic slip at depth. Further west, the 70-km-long Sahel fold is subdivided in 3 sub-segments and shows ~0.84–1.2 mm/yr uplift rate in the last 120–140 ka. The homogeneous Holocene uplift of marine terraces and the anticline dimensions imply the possible occurrence of large earthquakes with $Mw \geq 7$ in the past. The surface deformation and related successive uplifts are modelled to infer the size and characteristics of probable future earthquakes and their seismic hazard implications for the Algiers region.

1. Introduction

Well exposed Quaternary marine terraces along the Tell Atlas of Algeria favour coastal tectonic investigations. These morphological features provide a reference and chronological data for past sea-levels and constitute a datable record for the coastal uplift. The study of Quaternary marine terraces and surface deformation is among the important tools to estimate the uplift rates of coastal tectonic structures and the characterisation of thrust or reverse fault activity (Burbank and Anderson, 2001; Lettis et al., 1997). Located in the western Mediterranean area and along the Africa–Eurasia convergent plate boundary, the Algerian coast displays evidence of active thrust tectonics and coastal uplift associated to large earthquakes. The coastal area east of Algiers was significantly uplifted by an average 0.5 m during the 21 May 2003 Zemmouri earthquake (Mw 6.8) due to a major offshore NE–SW trending and south dipping reverse fault (Ayadi et al., 2008; Belabbes et al., 2009; Meghraoui et al., 2004). Although marine terraces, abrasion platforms and raised notches were described at various sites of the Algerian coastline (Betrouni, 1983; De Lamothe, 1911; Glangeaud, 1932; Gourinard, 1958; Stearns and Thurber, 1965), the issue of Pleistocene and Holocene tectonic characteristics and long term uplift rate was not addressed in previous works.

Relevant studies using the technique of measuring relative sea level fluctuations compared to the vertical tectonic uplift have been carried out in the eastern Mediterranean regions (Armijo et al., 1996; Laborel and Laborel-Deguen, 1994; Morhange et al., 2006; Pirazzoli et al., 1982, 1989, 1996; Stiros and Pirazzoli, 2008; Stiros et al., 1994). The seismic potential of active folding and thrusting in various tectonic domains (e.g., convergent or transcurrent plate movement) has been long identified and associated to buried, hidden or surface faulting (Stein and King, 1984). The Tell Atlas experienced in the last decades several earthquakes with $Mw > 5.5$ and reverse or thrust faulting mechanism. In the Tell Atlas of Algeria, the surface faulting of the large (Mw 7.3) 10/10/1980 El Asnam earthquake revealed reverse fault geometry (60°

* Corresponding author.
E-mail address: m.meghraoui@unistra.fr (M. Meghraoui).
[1] Now at SERTIT, Strasbourg, France.

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SE dipping fault plane) associated with flexural-slip folding (Philip and Meghraoui, 1983). The paleoseismic investigations across surface ruptures indicate that contemporaneous faulting and growth of folding were repeated in the past 6 ka with ~1000 years average recurrence interval of large earthquakes (Mw>7) (Meghraoui and Doumaz, 1996). When taking place along the sea shore, coastal folding and faulting may involve remarkable uplift movement of marine terraces and contribute to a better constraint of the past earthquake activity. Previous uplift indicated by successive notches and raised shorelines terraces has been clearly indentified after the Noto Hanto thrust earthquake in the western coast of Japan (25/03/2007, Mw 6.7; Shishikura et al., 2009). Uplifted river terraces and shoreline across the Transverse Ranges of California yielded the chronology and rate of faulting of San Andreas restraining bend (Rockwell et al., 1984). The study of coastal reverse or thrust faulting and related folding of the Tell Atlas provides a direct access to the incremental coseismic uplift and long term behaviour of the seismogenic structures near Algiers.

In this paper we study the coastal uplift east and west of Algiers using the geomorphic markers (raised marine terraces and notches) and related prominent Quaternary Sahel fold. The identification, mapping and dating of successive marine terraces and paleo-shoreline were conducted to constrain the successive tectonic uplift. The age constraint of marine terraces using isotopic dating (C^{14} and U–Th) and the eustatic sea level change allow an accurate estimate of the uplift rate. The elastic modelling of fault-related folding using coastal uplift and surface deformation illustrates the fault geometry at depth and provides with five possible scenarios for moderate to large earthquake fault rupture along the Sahel fold. Finally, we discuss the uncertainties of uplift amounts, the geomorphology of the Sahel fold and the implications for the seismic hazard assessment of the Algiers region.

2. Seismotectonic and folding structures

The Tell Atlas thrust belt of northern Algeria results from the 4 to 6 mm/yr convergence rate of Africa towards Europe (Nocquet and Calais, 2004; Serpelloni et al., 2007). As attested by the tectonic framework and focal mechanisms of earthquakes with Mw≥6 which struck the Algerian coastline, Quaternary folding structures with thrust and reverse faults mark the coastal zone (Fig. 1; Aoudia and Meghraoui, 1995; Maouche et al., 2008; Meghraoui, 1988). The active deformation characterised by E–W to NE–SW trending fold structures and related reverse and thrust faults, accommodates 2 to 3 mm/yr shortening across the Tell Atlas (Meghraoui and Doumaz, 1996).

Two NE–SW to E–W trending active structures of the Algiers region, namely the Blida thrust and fold system and the Sahel anticline, form the southern and northern edges of the Mitidja Quaternary Basin, respectively (Fig. 2; Glangeaud, 1932; Glangeaud et al., 1952; Meghraoui, 1991). The present-day prominent morphology of the Blida rocky mountains with an altitude larger than 1500 m above sea level (asl) and the Quaternary Sahel anticline (reaching 350 m asl) contrasts with the 20 to 60-m-high flat Quaternary sedimentary basin in the middle (Figs. 2 and 3). The major part of the ENE–WSW trending Mitidja basin is located onshore with the exception of its eastern limit that may extend into the Mediterranean Sea. To the south, the Blida Mountains show granitic and micaschists Paleozoic basement rocks visible mainly in fold hinges overlain by strongly folded and overthrust structures of Mesozoic and Cenozoic limestones made of mainly flyschs formations (Durand Delga, 1969). Active faults of the Blida Mountains consist on ENE–WSW trending and right-stepping "en echelon" reverse faults that overthrust the Quaternary units of the Mitidja Basin (Meghraoui, 1988). This system extends to the ENE to reach the coastline and the offshore fault continuation of this structure was reactivated during the 2003 Zemmouri earthquake (Mw 6.8; Ayadi et al., 2008; Belabbes et al., 2009; Bounif et al., 2004; Meghraoui et al., 2004). To the north of the basin, the nearly ENE–WSW trending and ~70-km-long Sahel asymmetrical anticline made of Neogene calcarenitic structure show thrust and flexural faulting affecting the vertical bedding of Quaternary units on the southern flank (Fig. 4a). The gently dipping northern flank of the anticline exhibits a sequence of late-Pleistocene and Holocene marine terraces lying with unconformity on the Miocene and Pliocene folded units (Meghraoui, 1991; Fig. 4b). The Quaternary deformation of this zone is attested by the uplift and tilt of marine Pleistocene and Holocene terraces along the coastal side.

The seismicity catalogue indicates the existence of destructive earthquakes along both the southern and northern edges of the Mitidja basin (Figs. 1 and 2, and Table 1; Benouar, 1994; Harbi et al., 2007; Mokrane et al., 1994). The historical large earthquakes of 1365,

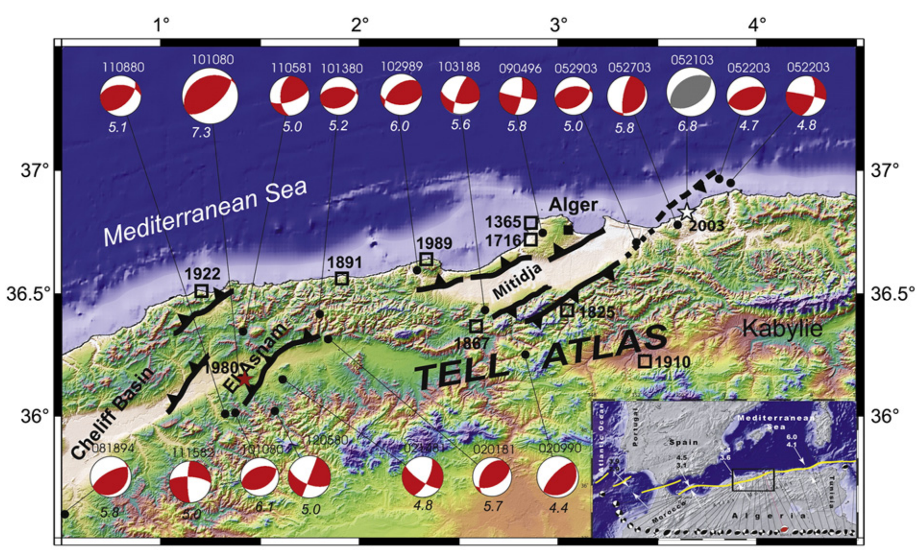

Fig. 1. Seismotectonics of north-central Algeria. Focal mechanisms (Harvard CMT solutions) are predominantly thrust faulting illustrated by the largest El Asnam Mw = 7.3 earthquake (red star) and Zemmouri Mw = 6.8 earthquake (grey mechanism and white star); open squares correspond to the significant historical earthquakes (Benouar, 1994; Harbi et al., 2007); shaded relief is SRTM 3-arc-second (~90 m) posting digital elevation model (Farr and Kobrick, 2000); bathymetry is from global data of GEBCO_08 grid. Thrust and reverse faulting that affect the Cheliff and Mitidja Quaternary basins (Meghraoui, 1988) result from the oblique plate convergence (see inset, yellow line is plate boundary and box is for north-central Algeria; minimum and maximum convergence rates in mm/yr from Nocquet and Calais, 2004).