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Active thrust faulting offshore Boumerdes, Algeria, and its relations to the 2003 Mw 6.9 earthquake

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[1] We investigate the active seismogenic fault system in the area of the 2003 Mw 6.9 Boumerdes earthquake, Algeria, from a high-resolution swath bathymetry and seismic survey. A series of 5 main fault-propagation folds ~ 20 – 35 km long leave prominent cumulative escarpments on the steep slope and in the deep basin. Fault activity creates Plio-Quaternary growth strata within uplifted areas such as a rollover basin on the slope and piggyback basins in the deep ocean. Most thrusts turn to fault-propagation folds at the sub-surface and depict ramp-flat trajectories. We find that the two main slip patches of the 2003 Mw 6.9 Boumerdes earthquake are spatially correlated to two segmented cumulative scarps recognized on the slope and at the foot of the margin. The overall geometry indicates the predominance of back thrusts implying underthrusting of the Neogene oceanic crust. **Citation:** Déverchère, J., et al. (2005), Active thrust faulting offshore Boumerdes, Algeria, and its relations to the 2003 Mw 6.9 earthquake, *Geophys. Res. Lett.*, 32, L04311, doi:10.1029/2004GL021646.

1. Introduction

[2] Seismic activity in the Western Mediterranean is concentrated in northern Africa, where GPS measurements suggest that most of the ~ 5 mm/yr oblique convergence ($\sim 50^\circ$) between the African and European plates is accommodated [Calais et al., 2003; Nocquet and Calais, 2004]. The October 1980, Ms 7.3 El Asnam and May 21, 2003, Mw 6.9 Boumerdes events are two well-documented examples of destructive earthquakes that struck northern Africa. Regional seismicity shows that strain is distributed over a broad area, from the Atlas front to the offshore margin

[Bufo et al., 1995]. This renders the identification of seismogenic faults a difficult, although essential, task for earthquake hazard assessment.

[3] Although historical and instrumental seismicity indicates significant activity offshore [e.g., Roussel, 1973; Ambraseys and Vogt, 1988; Yelles et al., 1999], little attention has yet been paid to potentially seismogenic structures along the Algerian margin until the 2003 Boumerdes earthquake [Yelles et al., 2003]. However, 2–3 mm/yr of shortening may occur offshore, since the Tell-Atlas systems should accommodate only about 50% of the total convergence between the African and Eurasian plates [Meghraoui and Doumaz, 1996]. We provide here the first detailed tectonic frame of the area offshore Boumerdes (Figure 1) deduced from high-resolution swath bathymetry and seismic reflection profiling acquired during the *Maradja* cruise, scheduled just prior to the May 2003 Boumerdes earthquake. We compare the offshore active structures with source studies of the Boumerdes earthquake, propose a possible location for the rupture area, and interpret the geomorphic structures considering the recent geodynamic evolution of the Algerian margin.

2. Geological and Tectonic Framework

[4] Tectonic studies in the Tell-Rif and Atlas domains show predominantly NE-SW trending folds and reverse faults defining a right-stepping pattern [e.g., Meghraoui et al., 1986; Morel and Meghraoui, 1996; Boudiaf et al., 1998]. This deformation system is a ~ 200 km wide Alpine-type orogen (Maghrebides) resulting from the opening and subduction of a Tethyan ocean [Auzende et al., 1973]. The region offshore Boumerdes, located offshore the internal zone of Great Kabylie, shows the transition from the continental crust of the Maghrebides hinterland to a newly formed oceanic domain, namely the Algerian basin, interpreted as an Oligocene back-arc basin born behind the Tethyan subduction [Frizon de Lamotte et al., 2000; Jolivet and Faccenna, 2000].

[5] Available focal mechanisms of earthquakes in the Tell domain depict mostly pure reverse faulting along NE-SW-trending planes, arguing for a \sim SE-NW-directed compression [Bufo et al., 1995; Stich et al., 2003]. Both the 1980 El Asnam and 2003 Boumerdes events follow this pattern, but unlike the El Asnam event, the Boumerdes earthquake occurred on a south-dipping fault plane [Yelles et al., 2004, Figure 1]. According to Delouis et al. [2004], the 2003 rupture strikes 70° E and extends for ~ 55 km, with two main slip patches at depths ranging from 0 to 11 km. The

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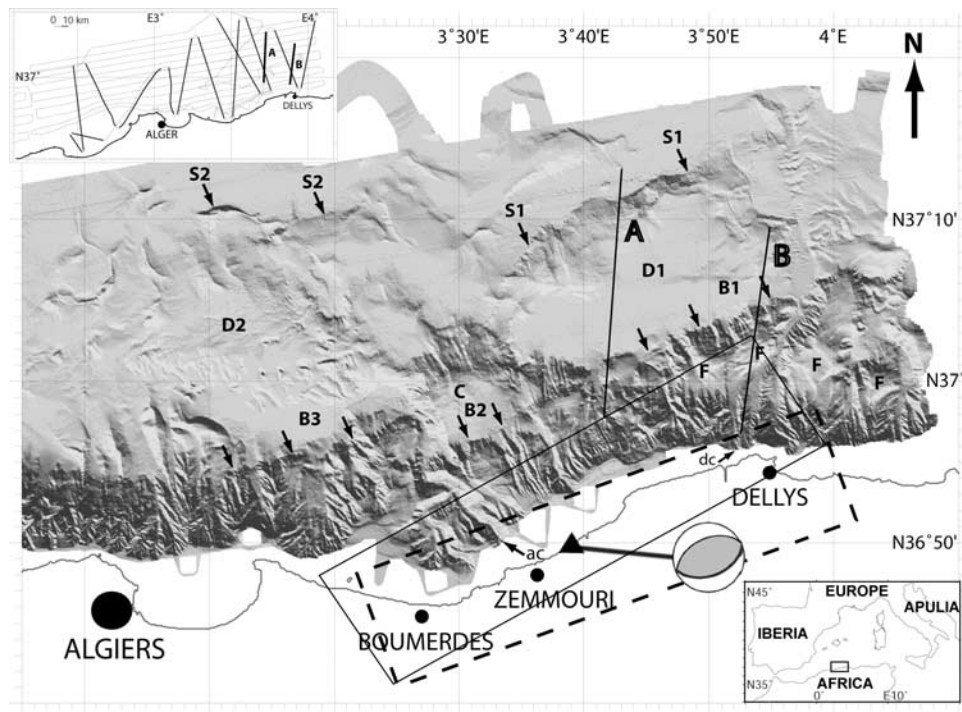


Figure 1. Shaded relief bathymetry from the *Maradja* cruise in Boumerdes region. Deep basin is at -2700 m depth. Epicentre (triangle), slip zone (dashed rectangle) and fault plane solution [bold] of the 2003 Boumerdes mainshock from *Delouis et al.* [2004], and rupture area [continuous parallelogram] from *Semmane et al.* [2005] are shown. Lower inset shows location of the study area. Upper inset shows seismic tracks acquired during the cruise. F: flat surface at mid-slope; C: circular surface in the lower slope; B: slope breaks 1, 2, 3 near the foot of the margin; S: curved scarps 1, 2 within the deep basin; D: uplifted domains 1, 2 in the deep basin. B1 and B2 are ~ 35 and ~ 20 km long, respectively. Note that Scarp B2 looks smoother than B1. Algiers (ac) and Dellys (dc) heads of canyons are shown by arrows. Lines A and B are positions of sections A and B (Figures 2 and 3).

most recent relocation of the events places the epicenter near the coastline (Figure 1).

3. Submarine Geomorphology Offshore the Boumerdes Area

[6] During the *Maradja* cruise (August–September 2003, R/V *Le Suroît*), a full coverage of the slope and basin off the Algiers region was obtained from continuous seafloor imagery (Kongsberg Simrad EM-300 echosounder), high-resolution seismic profiling (Chirp sonar, 6- and 24-multi-channel seismics) and corings. The EM-300 vertical accuracy ranges laterally from 2 m to 10 m. The 50 m digital elevation model (DEM) constructed (Figure 1) highlights the steep margin slope and basin escarpments offshore Boumerdes-Dellys. The most striking features of the submarine landscape are: (1) a mid-slope break with a flat surface F getting narrower from $4^{\circ}05'E$ to $3^{\circ}40'E$, followed westward (to $3^{\circ}20'E$) by a more gentle upper slope, and downslope by a circular surface C near $3^{\circ}30'E$; (2) three prominent slope breaks B striking $\sim 70^{\circ}E$ near the foot of the margin, averaging 25 km long each, and two main curved scarps S striking ~ 60 – $70^{\circ}E$ within the basin; (3) deeply incised, relatively straight canyons, with numerous tributaries upslope, turning to deflected drainages away from two main uplifted domains D in the deep basin; and (4) ridges and depressions often depicting en échelon

systems besides large depressions in the deep basin, together with isolated, arcuate ridges. This pattern highlights the importance of modern turbidite transport in the area, as demonstrated by the numerous deep-sea telecommunication

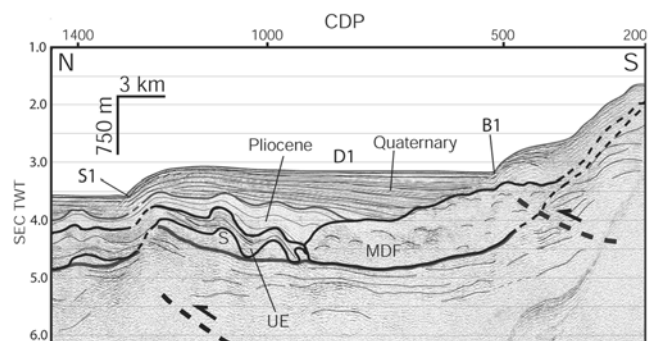


Figure 2. Time-migrated, stacked 6-channel seismic line A and its interpretative cross section showing cumulative wedge and progressive unconformity in the deep basin (see Figure 1 for location). S: salt; MDF: Messinian detritic fan; UE: Upper Evaporites (roof at ~ 5.3 Ma). S1 and B1 are scarps (Figure 1). Heavy dashed lines are thrust ramps inferred. Note that the UE layer has a roughly constant thickness, indicating that it predates tectonic activity.

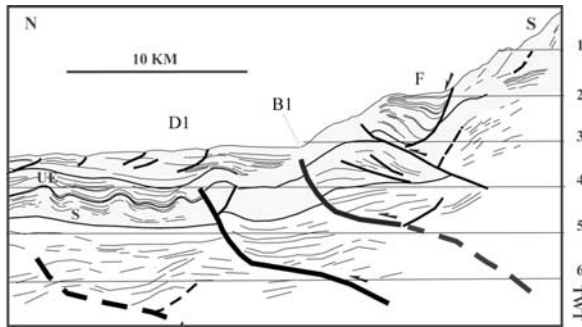


Figure 3. Line drawing based on multichannel seismic reflection line B (location on Figure 1), from a 2D 480-channel survey [Cope, 2003]. S: Messinian salt layer; UE: Upper Evaporite Layer.

cable failures following the 2003 earthquake [Ayadi *et al.*, 2003].

4. Structural and Stratigraphic Framework Offshore

[7] Seismic sources used together with the 6- and 24-channel streamers are a combination of 2 and 6 double-chamber gas-injection air-guns. As shown by a representative seismic section across the lower slope and deep basin (Figure 2), we find that the eastern uplifted domain (D1, Figure 1) is a wedged, piggyback basin where active growth strata develop above a thrust ramp rooted below the Messinian salt layer. This structure resembles a fault-propagation fold model, although the exact geometry is difficult to assess

because of limited penetration and salt diapirism. Curved scarp S1 (Figure 1) shows that aggradation is slower than the uplift rate of the fault-propagation fold. From the thickening of strata (Figure 2), we observe that tilting of Basin D1 begun within the Pliocene, increased during the Quaternary, and is still active. The height of the S1 scarp is ~ 400 m, indicating an uplift rate of at least ~ 0.2 mm/yr if we refer to the shift of the base of the salt layer. Data from a 2D multichannel seismic survey [Cope, 2003] further demonstrate the control exerted by two active ramps on the development of the flat surface F and the associated rollover basin (Figure 3). A buried anticline also appears to develop within the piggyback basin as a fault-propagation fold affecting the pre-salt Miocene deposits. Using all seismic lines (Figure 1), we map the lateral extent of the structures described above and construct an onshore/offshore tectonic sketch (Figure 4). We identify a rollover basin on the slope off Dellys-Boumerdes, and several piggyback basins controlled by ramps in the deep basin. Thrust fronts are generally blind and display widely overlapping curved segments. Salt diapirs and walls (Figure 4) and lateral levees of Dellys and Algiers canyons (Figure 1) are also evidenced. Large-scale folds recognized at various distances from the blind thrusts clearly influence the distribution of eroding turbidity channels (Figure 4).

5. Discussion and Conclusion

[8] Data collected during the *Maradja* cruise allow us to document rapidly filling basins that have recorded recent tectonic activity as evidenced by the deposition of growth strata in a narrow rollover on the slope and in wide piggyback basins within the deeper domain (Figure 4). Five

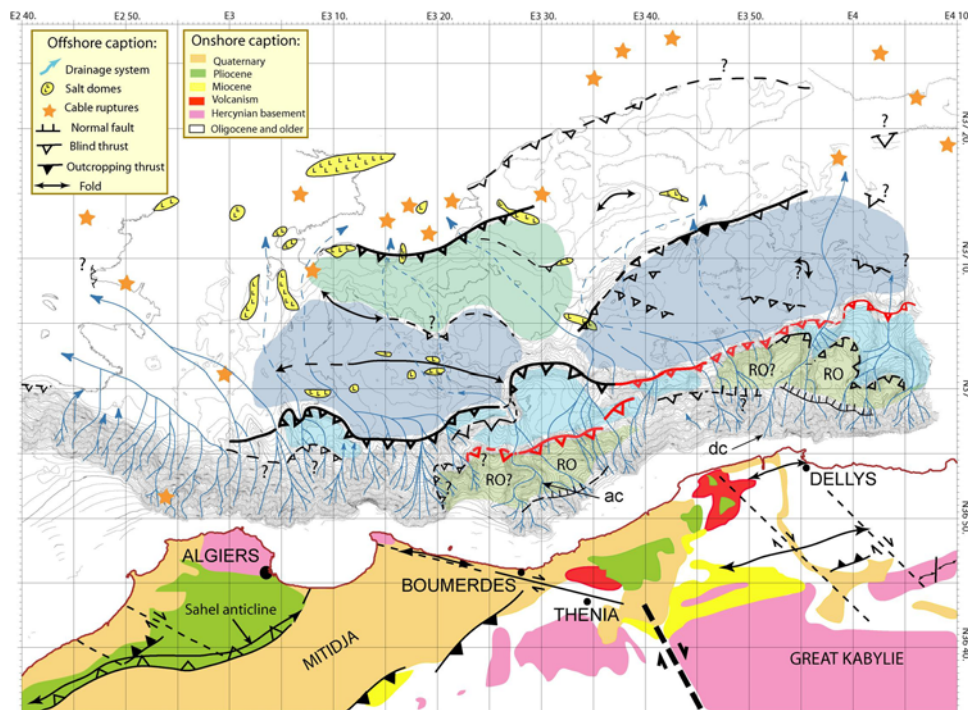


Figure 4. Morphotectonic map from data analysed in this study and onland geology [Boudiaf *et al.*, 1998; Ayadi *et al.*, 2003]. Red line is the proposed prolongation of the 2003 rupture determined by Delouis *et al.* [2004] to the seafloor, depicting two main segments [B1 and B2, Figure 1]. RO: Rollover basin. Coloured areas off RO are piggyback basins.

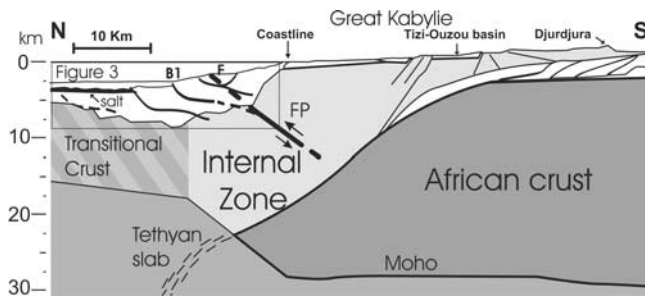


Figure 5. North-South tectonic cross section near 3°50'E illustrating the spatial relationships between the 2003 fault rupture position (FP, bold line) inferred by *Delouis et al.* [2004] and the main faults identified on seismic line B (frame, see Figure 3). No vertical exaggeration. Depth conversion of the seismic line is made using velocities of 1.5 and 3 km/s for the sea floor and faults, respectively. Apparent dip of FP is taken as 38°. Background geological structure is inspired from *Roca et al.* [2004]. FP is drawn continuously in the depth range where aftershocks are clustered [*Bounif et al.*, 2004].

main south-dipping ramps (B1-2-3, S1-2, Figure 1) exert a strong control on the seafloor morphology and depositional patterns. Cumulative displacement on the ramps fades laterally, suggesting lateral propagation of blind thrusts and surface folds. From the limited vertical accuracy of our data, whether the Boumerdes earthquake rupture reached the seafloor is unclear. However, the two thrusts B1 and B2 documented here (Figure 1) match in along-strike position, length and direction the seismic rupture proposed by *Delouis et al.* [2004]: their shallower NE slip patch coincide with the ~35 km long fresher scarp B1 observed, which may indicate locally destabilised sediments triggered by the rupture, whereas their deeper slip patch matches the smoother ~20 km long B2 segment. The upward prolongations of the rupture planes as derived from land data [*Yelles et al.*, 2004; *Delouis et al.*, 2004; *Semmane et al.*, 2005] are located 5–15 km north of the shoreline (Figures 1 and 5), i.e., 1–10 km south of our mapped active segments. This apparent discrepancy between the modelled rupture plane upward prolongations and the outcropping scarps may arise from changes in the fault dip with depth, consistent with the flat-ramp pattern observed on seismic lines (Figures 2 and 3) and with the aftershock distribution [*Ayadi et al.*, 2003]. Figure 5 shows that the rupture plane as deduced by *Delouis et al.* [2004] connects nicely upwards (at ~7 km depth) to the active flat-ramp faults outcropping near the foot of the margin (Figure 3). Further detailed surveys near the presumably destabilized zones are needed to strengthen this hypothesis.

[9] The main development of growth strata (post-Pliocene) coincides with the last (Pleistocene) uplift of the Atlas system, which could sign a strong coupling between European and African plates related to the end of the Tethys subduction [*Frizon de Lamotte et al.*, 2000]. The active faults evidence the ongoing underthrusting of the Neogene oceanic domain below the Algerian margin, which might represent an incipient stage of subduction [*Auzende et al.*, 1975]. Beyond the tectonic implications, the recognition of active compressional deformation offshore Algeria has important implications on seismic hazard in Algiers region

[*Harbi et al.*, 2004] and requires more detailed offshore investigations.

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