



Plio-Quaternary reactivation of the Neogene margin off NW Algiers, Algeria: The Khayr al Din bank

Abdelkarim Yelles^a, Anne Domzig^{b,c,1}, Jacques Déverchère^{b,c,*}, Rabah Bracène^d, Bernard Mercier de Lépinay^e, Pierre Strzeczynski^{b,c}, Guillaume Bertrand^f, Azzedine Boudiaf^a, Thierry Winter^f, Abdelaziz Kherroubi^a, Pascal Le Roy^{b,c}, Hamou Djellit^a

^a Centre de Recherche en Astronomie, Astrophysique et Géophysique (C.R.A.A.G.), BP 63, Bouzareah, Algiers, Algeria

^b Université Européenne de Bretagne, France

^c Université de Brest; CNRS, UMR 6538 Domaines Océaniques; Institut Universitaire Européen de la Mer, Place Copernic, 29280 Plouzané, France

^d Sonatrach Exploration, avenue du 1er Novembre, Boumerdès, Algeria

^e Géosciences Azur, CNRS-UMR 6526, 250 rue Albert Einstein, bât. 4, 06560 Valbonne, France

^f BRGM, 3 avenue Claude Guillemin, BP 36009, 45060 Orléans Cedex 2, France

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ABSTRACT

The Algiers region, northern Algeria, is known to be seismically active, with recurrent large ($M > 6$) earthquakes. Because of the lack of high-resolution bathymetry, the offshore structures remained for a long time poorly known. Thanks to a new marine data base (MARADJA 2003 cruise), the offshore part of the margin is accurately mapped, and new active and recent structures are described. West of the bay of Algiers, the margin enlarges, forming the Khayr al Din bank, interpreted as a tilted block of the passive margin born during the opening of the Algero-Provençal basin. At the slope break, a 80 km-long fault-tip Quaternary fold, namely the Khayr al Din fault, extends at the foot of the margin off NW Algiers and represents the largest active structure of the coastal area, together with the Sahel anticline. We also map for the first time a set of overlapping, en echelon active folds in the upper part of the Khayr al Din bank, located off previously known active structures on land. Most of these faults represent actually a threat for the Algiers region in terms of seismic hazard but also geological hazards, such as tsunamis, as most of them depicts significant dimensions and slip rates. The highest long-term horizontal shortening rate is found on the Khayr al Din fault and is estimated at 0.5 ± 0.1 mm/yr, with a maximal magnitude of 7.3, which provides one of the highest seismogenic potential in the region.

A new tectonic framework for the Algiers region is proposed, in which the main south-dipping offshore structure, of opposite vergence relative to most thrusts on land, appears to be nowadays the main driving fault system, as also found further east in the Boumerdès (M 6.8) 2003 rupture zone. The overall apparent pop-up structure of the recent and active faults may result from a progressive migration of the plate limit from the Late Miocene, north-dipping suture zone on land, to the Quaternary, south-dipping main Khayr al Din fault at sea, suggesting a process of subduction inception.

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1. Introduction

The Algiers region (Fig. 1) is located at the boundary between the African continent to the south and the Algero-Provençal basin to the north. This basin is thought to have been formed as a back-arc basin behind the subduction of the Tethyan ocean below the African plate

during the Miocene (Auzende et al., 1973; Réhault et al., 1985; Roca et al., 2004, and references therein). The Internal Zones of the belt drifted southward to finally collide the African plate ~18–15 Mys ago (e.g. Alvarez et al., 1974; Cohen, 1980; Réhault et al., 1984 and references therein; Vergés and Sàbat, 1999; Frizon de Lamotte et al., 2000; Roca et al., 2004). Since that time, the margin and the whole Alpine belt of Algeria have recorded several stages of shortening, forming the Tell and Atlas folds and thrusts (e.g. Benaouali-Mebarek et al., 2006). Nowadays, recent seismicity and neotectonics show that the plate boundary involves most of the Tell–Atlas domain over a broad zone of deformation ~150 km wide (Meghraoui, 1988; Buform et al., 2004; Stich et al., 2003), which includes the deep margin and the Alpine belt. The convergence rate between the Eurasian and African continents is presently relatively

* Corresponding author. Université de Brest; CNRS, UMR 6538 Domaines Océaniques; Institut Universitaire Européen de la Mer, Place Copernic, 29280 Plouzané, France.

E-mail address: jacdev@univ-brest.fr (J. Déverchère).

¹ Now at: Midland Valley Exploration Ltd, 144 West George Street, Glasgow G2 2HG, United Kingdom.

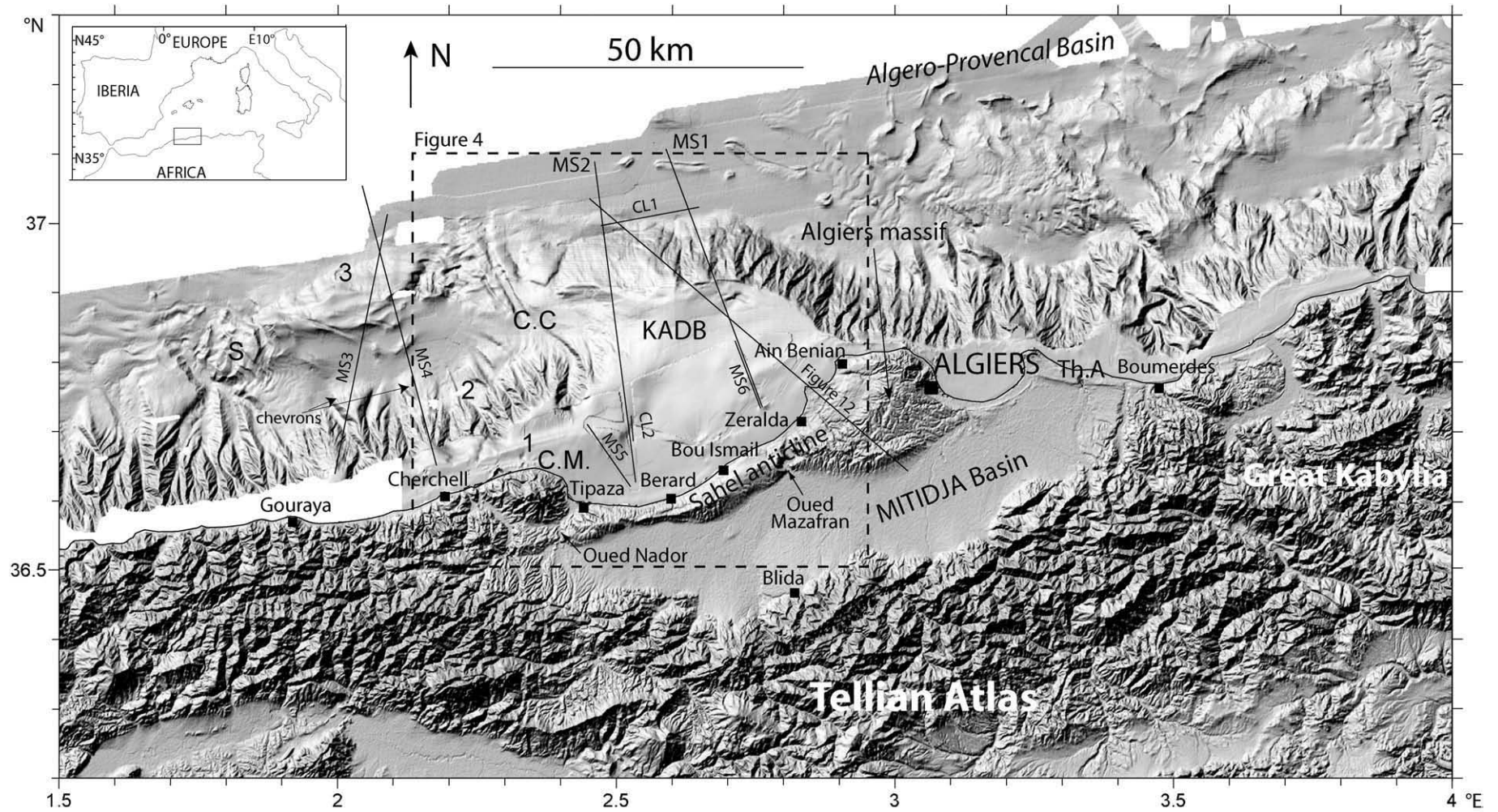


Fig. 1. Digital Elevation Model (100 m resolution) of the Algiers region including both offshore (MARADJA data) and onshore (SRTM data) domains. Coastal bathymetry, when available, is extracted from [Leclaire, 1970](#). A.M: Algiers massif, C.C: Chenoua canyon, C.M.: Chenoua massif, KADB: Khayr al Din bank, Th. A: Thenia anticline, S: slides; 1, 2 and 3: slope breaks (see text for details). The positions of the Chirp lines (CL) and multichannel seismic lines (MS) from [Figs. 5a \(CL1\), 5b \(CL2\), 6 \(MS1\), 7 \(MS2\), 8 \(MS3\), 9 \(MS4\) and 10 \(MS5 and MS6\)](#) are indicated. Frame is the position of [Fig. 4](#).

low, i.e. about 5 mm/yr at the longitude of Algiers, and is oriented roughly NW–SE (e.g., Nocquet and Calais, 2004). This strain pattern is characterized by low to moderate seismicity in the Tell-Atlas and occasionally by large events, as for instance the El Asnam 1980 Mw 7.3 (towards SW, besides our study zone) or Boumerdes 2003 Mw 6.8 events (Fig. 2).

Until recently, most attention concerning earthquake hazard has focused onland, in the Tell-Atlas belt, especially after the occurrence of the 1980 El Asnam earthquake (Philip and Meghraoui, 1983; Meghraoui, 1988; Aoudia and Meghraoui, 1995; Boudiaf, 1996; Morel and Meghraoui, 1996; Bezzeghoud and Buform, 1999). Highly populated regions as the Algiers area have been better studied, because of high exposure and hazard linked to several potentially critical seismogenic fault zones identified to the West (Chenoua, Sahel, e.g. Meghraoui, 1991), South (Blida thrust system, Ambraseys and Vogt, 1988; Meghraoui, 1988) and East (Thenia and southern Great Kabylia thrust systems, Boudiaf et al., 1998, 1999). However, several important past events, in particular the large historical earthquakes of January 2, 1365 (I=X), February 3, 1716 (I=X), and January 15, 1891 (I=XI), probably had offshore epicentres owing to the important water movements triggered and the known distribution of destruction reported (Rothé, 1950) or to the shore uplifts observed (Maouche, 2002). Recently, the May 21st, 2003, Mw 6.8, Boumerdes earthquake (Fig. 2) evidenced the presence of a large active fault offshore eastern Algiers (Ayadi et al., 2003; Yelles et al., 2003; Déverchère et al., 2005), which was previously unknown. Only indirect and inaccurate indications of faulting activity were available offshore (El Robrini, 1986; Yelles et al., 1999) until August 2003, when the MARADJA (MARge Active de l'Al DJazair) survey was carried out along the central and western margin of Algeria.

A previous paper by Domzig et al. (2006) provided the overall structure of the margin from Oran to Algiers, describing only roughly the main features identified offshore. Considering the importance of the seismic hazard assessment of the region of the capital of Algeria and our knowledge of the recent deformation pattern of the region (Fig. 2), we aim in this paper at focusing precisely on the seismogenic structures offshore NW and N Algiers from swath bathymetry and seismic imaging and at integrating these new results within the tectonic framework of the Algiers region. Indeed, faults suspected in this area are among the largest mapped in length (Domzig et al., 2006). A major challenge is to provide an interpretation of the offshore and on land seismo-tectonic system, provided that seismic activity concern obviously both domains (Fig. 2). Especially, we seek at better assessing the finite deformation, the style and geometry of the faults and folds observed, the timing and chronology of the recent strain pattern, and the link with reported large historical events or the microseismic activity of the region. Finally, the relative importance and possible connections of these recent faults need to be discussed, as well as their implications for seismic hazard in Algeria.

2. Geological framework

The Algiers region lies at the limit between the External Zones, which are units of the Alpine belt belonging to the African plate, and the Internal Zones, which are part of the AlKaPeCa block (Bouillin, 1986), a domain formerly located in the forearc of the European plate (Early Eocene, see e.g. Mauffret et al., 2004, and references therein). The Kabylies are forming two important blocks from this domain. A major south-verging thrust marks the limit between the Internal and External zones. All data available indicate that this geological contact may be deeply rooted (as shown in Roca et al., 2004) and is probably still active (Boudiaf et al., 1999). Near this limit, two prominent massifs belonging to the Kabylia Internal Zones dominate the topography between Algiers and Tipaza (Fig. 1) the Algiers massif (AM) and the Chenoua massif (CM). The Algiers massif, made of metamorphic rocks series (mainly, schists and gneiss), depicts several old thrust units but does not evidence any neotectonic activity. Conversely, the Chenoua Mount made

of Palaeozoic and Mesozoic series displays thrust sheets covered unconformably to the south by Neogene sediments, and is limited to the south by an active north-dipping thrust fault (Fig. 2) that was activated during the 1989 Tipaza earthquake (Meghraoui, 1991). At the coast, the Sahel anticline located between the two massifs constitutes one of the major active tectonic structures onland, extending over ~70 km (Boudiaf, 1996; Meghraoui, 1988). This asymmetric, south-vergent anticline is supposed to grow on a blind reverse fault on its steep southern flank (Fig. 2). The large Neogene Mitidja basin of about 80 km length lies between the Kabylies and the Chenoua massif (Fig. 1). This basin was created during the Miocene, after the setting of the Tell north-dipping nappes, and is filled with Neogene sediments (Glangeaud et al., 1952). During the N–S distensive period which created this basin, some calc-alkaline volcanism also appeared around the Mitidja region (Fig. 2). The normal faults limiting the Mitidja basin are apparently inverted through a N–S compression acting since the late Miocene. Indeed, the active faults identified depict opposite dips and thrust faulting close to the surface (Boudiaf, 1996).

Along the southern border of the Mitidja basin, several north-verging active faults mark the transition between the basin and the Tellian Atlas (Boudiaf, 1996). Further south, the Blidean Atlas is composed by folds and thrusts related to the setting of the Tellian nappes, during the collision between the AlKaPeCa block and the African plate. It depicts a systematic southern vergence of the structures and a general thin-skinned tectonics (Glangeaud, 1932; Wildi, 1983; Frizon de Lamotte et al., 2000; Benaouali-Mebarek et al., 2006). Finally, west of the Mitidja basin, several folds, also related to the Tellian nappes, constitute the highs facing the coast, west of Cherchell.

Offshore, Déverchère et al. (2005) and Domzig et al. (2006) have described the active structures east of the Bay of Algiers, in the Boumerdes area (the adjacent area to our study zone). They mainly find series of south-dipping blind thrusts (Fig. 2) oriented ENE–WSW. One of these thrust is associated to the Boumerdes earthquake (21/5/2003, M: 6.8). These active tectonic structures induce a very particular shape of the margin: domes and perched basins are found on the slope or in the deep basin, but the tectonic activity also influences the canyon paths, like the Algiers canyon (Babonneau et al., 2007). The frequent seismicity is at the origin of many mass-wasting deposits at the foot of slopes (Dan et al., in press, Domzig et al., 2009).

3. Seismotectonic framework

Several moderate to strong earthquakes occurred in the last decade in the Algiers region (among them, Oued Djer event, October 31st, 1988, M 5.4; Tipaza event, October 29th, 1989, M 6.0; Ain Benian September 4th, 1996, M 5.7; Boumerdes event, May 21st, 2003, M 6.8). They indicate through their focal mechanisms (Fig. 2) that the region is under compression with a NNW–SSE directed stress field (Groupe de Recherche Néotectonique de l'Arc de Gibraltar, 1977; Stich et al., 2003; Buform et al., 2004). Other local (e.g., Meghraoui, 1991; Aïte, 1995) or regional studies (Fernandes et al., 2003; McClusky et al., 2003; Nocquet and Calais, 2004; Serpelloni et al., 2007) by GPS geodesy confirm this regionally consistent trend.

One of the strongest event felt in the region, the M 6.0 Tipaza earthquake of October 29, 1989, occurred near CM, close to the coastline. It was followed by many aftershocks, including a magnitude 4.7 event on February 9, 1990. The main shock (Meghraoui, 1991) and the distribution of the aftershocks (Bounif et al., 2003; Harbi et al., 2004) shows that the earthquake sequence extended offshore towards the NE with a plane dipping to the NW, and underlines two distinct NE–SW seismogenic faults 8 km apart (Sebaï, 1997; Harbi et al., 2004). Harbi et al. (2004) propose that this behaviour can be explained by a single fault with a variable dip, both clusters corresponding to 60°–NW-dipping ramps separated by a flat. Onland, E–W to NE–SW striking soil ruptures were observed after the main shock west of Tipaza (Meghraoui, 1991). They were supposed to be associated with extrados fissures related to a

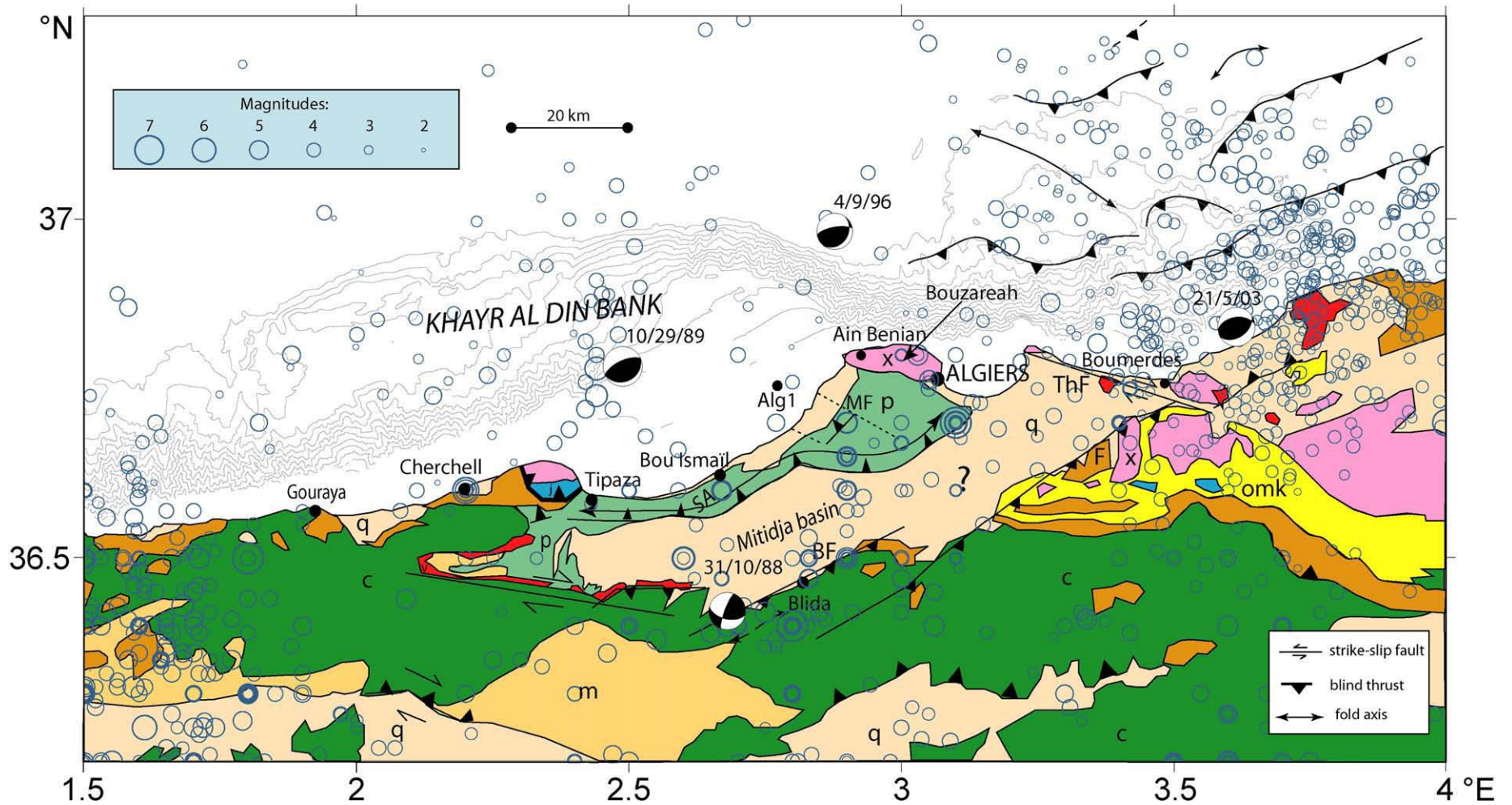


Fig. 2. Tectonic framework of the Algiers region (offshore east of Algiers: Déverchère et al., 2005), and instrumental seismicity (in moment magnitude) (sources: CRAAG catalogue from year 419 to September 2008, Stich et al., 2003, and Harvard CMT catalogue). BF: Blida fault, ThF: Thenia fault, MF: Mahelma fault, SA : Sahel anticline, X: Kabylian Internal metamorphic rocks, F: Flyschs, omk: Kabylian Oligo-Miocene, c: Cretaceous, m: Miocene, q: Quaternary, p: Pliocene, v: volcanism. The cluster of events located near the shoreline east of ThF corresponds to the westernmost part of aftershocks triggered by the 2003 Mw 6.8 Boumerdes earthquake. Focal mechanisms: 31/10/88: from Harvard-CMT; 10/29/89: from USGS; 4/9/96: from IAG; 21/5/03: from Harvard-CMT, relocated by Bounif et al. (2004).

superficial active anticline oriented NE-SW and related to a blind fold (Boudiaf, 1996).

The Sahel blind fault is assumed to be responsible for several past low to moderate-size ($M < 6$) earthquakes (e.g. the 1924 May 10 and November 5 events, H  e, 1924, 1925; Roth  , 1950). On its northern flank, several well-developed abrasion marine terraces found between Tipaza and Ain Benian depict recent tectonic movements (Fig. 1) and form stairs-like topography (Meghraoui et al., 1996). According to Glangeaud (1932), compression in the Sahel occurred during the Plio-Quaternary. However, according to marine terraces datings, the onset of uplift may have taken place only during the Pleistocene (Meghraoui, 1991). Meghraoui et al. (1996) calculated, for the Tyrrhenian terrace (5e highstand), uplift rates of 0.13 and 0.11 mm/yr in the Algiers and Tipaza areas respectively. According to Saoudi (1989), uplift rates from the same terrace range from 0.19 mm/yr near Ain Benian to approximately zero near Bou-Isma  l and Berard (-0.04 and -0.03 mm/yr respectively, considering a +6 m 5e sea level, as did Meghraoui et al., 1996). These values suggest that uplift is rather moderate close to the Sahel anticline but tends to increase northward. A recent study carried out in the area (Etude de la vuln  rabilit   de la Wilaya d'Alger aux catastrophes, 2006) implemented a measurement of the deformation of the ground by satellite interferometry Radar InSAR (technique of Permanent Scatters). It shows that during one decade (1992–2002) the Sahel was uplifted of 0.09 mm/yr to 1.2 mm/yr. Despite the uncertainty of these values, this additional result shows that the Sahel anticline is tectonically active. Terraces have been uplifted, depending on their precise location, by vertical displacements on this anticline and/or by other active structures offshore.

In the eastern part of the Bou Isma  l bay, off the city of Ain Benian, a magnitude 5.7 earthquake occurred on September 4th, 1996 (Fig. 2). Seismological studies (Yelles et al., 1997) have assumed that the seismic event was triggered by a NE-SW active structure close to the shoreline. Offshore studies by Glangeaud et al. (1967) identified the presence of a Plio-Quaternary anticline. The ALG1 drilling (Fig. 2), located on this anticline, shows a very thin Pliocene cover (~65 m) and ~1050 m of Miocene sediments, to finally reach pre-Langhian volcanic tuffs (Burollet et al., 1978). It shows that the Quaternary sediments are absent on the

shelf and that Pliocene layers are continuous. This observation strongly supports a recent tectonic uplift of this part of the shelf.

Along the southern boundary of the Mitidja basin, one segment of the south-dipping Blida fault system (e.g., Meghraoui, 1988) is assumed to have generated the major Blida 1825 earthquake, killing almost 20,000 citizens (Ambraseys and Vogt, 1988).

Finally, note that since the re-installation of the Algerian seismological network in 1998, many minor seismic events between Gouraya and Algiers were recorded offshore (Fig. 2). Off Cherchell for instance, several seismic events were recorded these last ten years. Most events located are shallow (less than 20 km), showing that brittle deformation occur within the upper crust.

4. Morphology of the coastal area and the margin

The MARADJA cruise (August 21 to September 18 2003) took place on board of the French (Ifremer) R/V Le Suro  t and aimed firstly at obtaining a precise bathymetric map of the structures between Algiers and Oran (western Algeria). For this purpose, Kongsberg EM300 (for the slope and deep basin) and EM1000 (for the continental shelf) Simrad multibeam echosounders were used. The bathymetric data have been processed with the Caribes   software (Ifremer). We produced a digital elevation model for the seafloor topography, with the resolution of 25–35 m (depending on depth) for the Algiers zone. Beside the Maradja cruise data, we have also gathered coastal bathymetric data, which were digitalized from Leclaire (1970)'s bathymetric maps.

Off Algiers bay, the Algerian margin depicts various morphologies with different directions. From East near Tamentefoust to West near Ain Benian, the margin depicts first a roughly 60  E and E-W direction. The continental shelf is relatively wide (up to 11 km) and the slope is crosscut by several N-S narrow gullies. Few kilometres to the west, in front of the Algiers massif (AM), the shelf disappears and the margin strike changes abruptly from E-W to NW-SE. Off Bou Isma  l (30 km west from Algiers, Fig. 1), the continental shelf widens, forming the large Khayr al Din bank (KADB, Fig. 1), which gently deepens westwards and reaches the basin with a global ~2   declivity. Off the Chenoua massif (CM), the shelf is

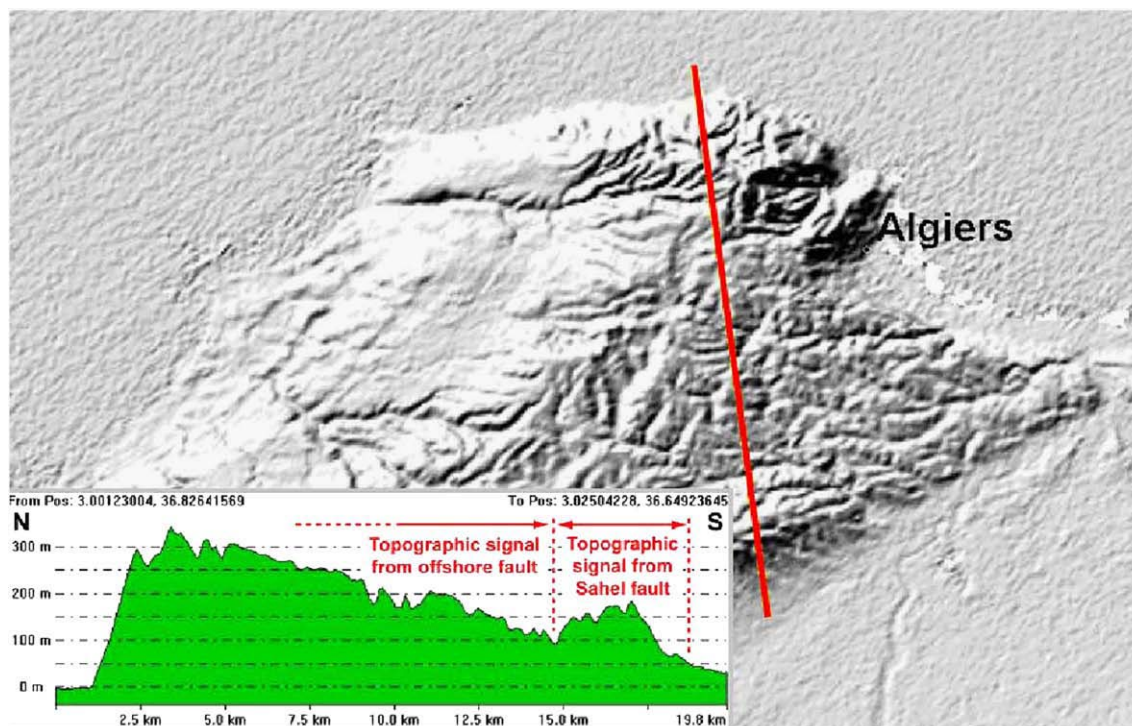


Fig. 3. Topographic profile across the Algiers massif and Sahel anticline, showing two topographic signals of distinct wavelength. The short wavelength topography to the south is the Sahel anticline uplifted by the associated Sahel fault; the long wavelength topography to the north is the Algiers massif which appears to be tilted continentward.

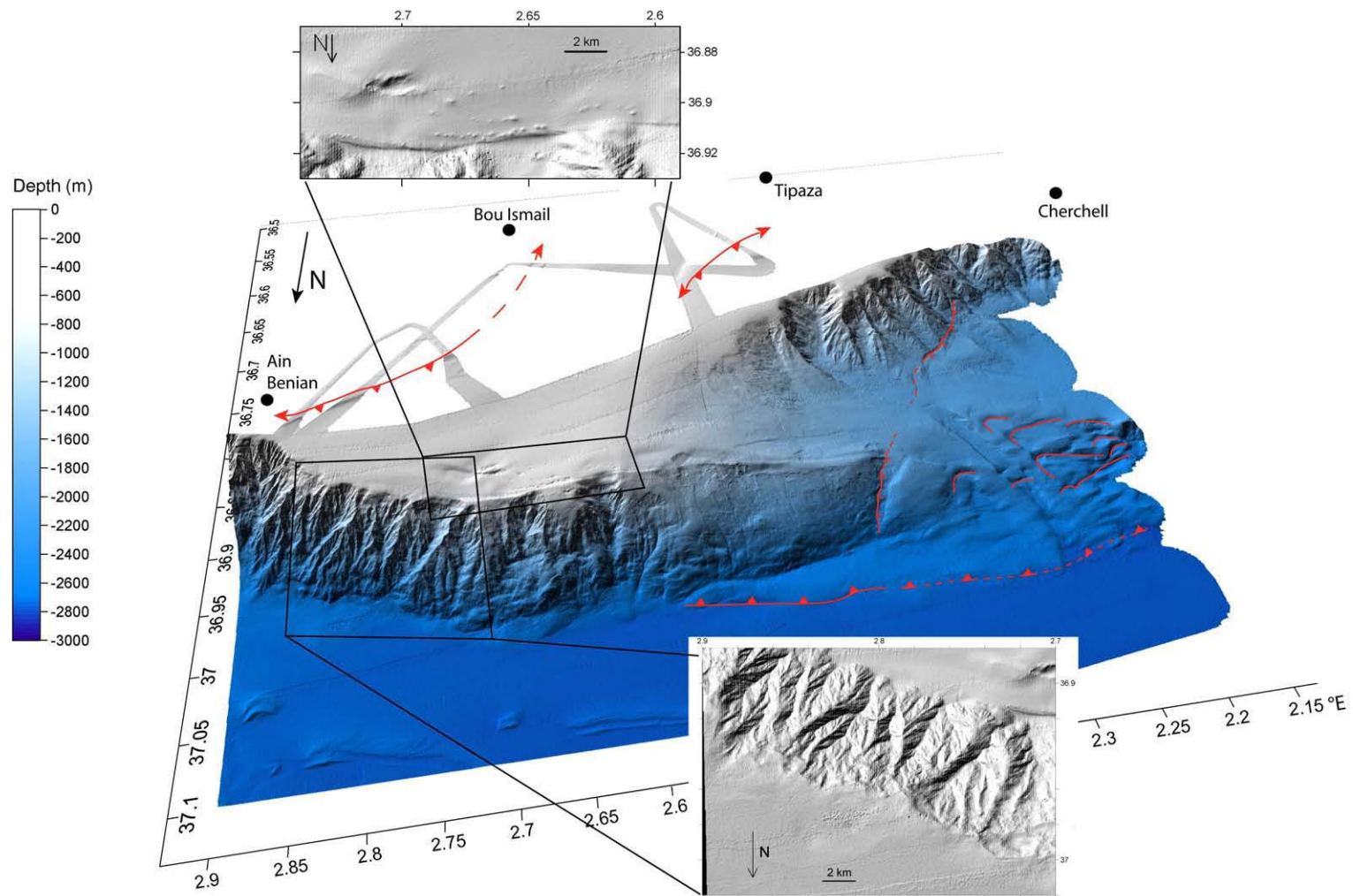


Fig. 4. 3D shaded bathymetric map (25 m resolution DEM) of the Khayr al Din bank showing a zoom in the pockmarks field (top inset) and on the lineaments along the NW-SE slope. In red, the general tectonic structures as well as the lineaments and slides observed on the bank. See location of the block on Fig. 1.

again very narrow, and the transition to the basin is marked by three topographic breaks striking ~E-W to ENE-WSW (Fig. 1): a small one just a few kilometers from CM (1, Fig. 1); a second, steeper one (slopes $> 10^\circ$), limiting the KADB to the south (2, Fig. 1); and a last one (slopes $> 10^\circ$), which marks the transition of the KADB to the deep basin (3, Fig. 1). Several important morphological features can be distinguished, which are analysed below into more details.

On land, the topography is dominated by the large Mitidja basin (Fig. 1), striking NE-SW as other Neogene basins of northern Algeria, and by the two internal massifs of Algiers (AM) and Chenoua (CM) which have a maximum elevation of approx. 350 m and 850 m respectively. The Sahel anticline, the major morphotectonic feature of the area extends along the coast between AM and CM (Fig. 1) and culminates at an altitude of 250 m. It is crosscut by several transverse structures such as the Mahelma fault (MF, Fig. 2) (Boudiaf, 1996). Near the AM, the direction of the Sahel anticline changes from NE-SW to E-W. A N-S topographic profile across the Bouzareah massif and Sahel anticline (Fig. 3) evidences two topographic signals of distinct wavelengths: the short wavelength southern topography is the Sahel anticline that grew in response to slip along the associated Sahel fault; the long wavelength northern topography is the Bouzareah massif, which uplift maybe reflects slip on a major fault located offshore Algiers, either during the rifting and opening of the Algerian basin or during the later tectonic evolution.

4.1. The Khayr al Din bank (KADB)

The KADB is a large prominent topographic high, 45 km wide from Bou Ismail to the deep basin, overhanging the deep basin of about 1900 m at

20 nautical miles from the shoreline (Fig. 1). It is about 80 km long in a W-E direction, from the front of the Algiers massif to the north west of Cherchell (west of the Chenoua massif). This bank was firstly and briefly described by El Robrini (1986) as a recent tilted block of the margin. It depicts an overall E-W direction with a major change in a NW-SE direction in its eastern tip off Ain Benian (Fig. 1). From East to West, the bank changes its morphology - its slope is remarkably smooth, rejuvenated (Fig. 1) -, and gradually deepens from a few hundred meters to 2500 m depth. Around 2.3°E , it is cut by a large canyon, the Chenoua canyon (c.c., Fig. 1), which extends in the deep basin through a deep-sea fan. This canyon, striking NW-SE, is probably fed by sediments coming from the Mazafran river that cuts the Sahel anticline near Zeralda, and from the Nador river, which reaches the sea near Tipaza city (Fig. 1). In the far western end of the KADB, off Gouraya, at 1.9°E (Fig. 1), the bank shows a chaotic topography with NW-SE trending fractures ("S", Fig. 1) interpreted by Domzig et al. (2009) as slides or slumps. West of this area, there are E-W sediment waves that are possibly related to contourites or turbidity currents (Domzig et al., in press). In its lower part, the KADB is bordered to the south-west by a steep slope with triangular chevron-shaped flat surfaces in the bathymetry (Fig. 1) between canyons, suggesting an apparent normal-fault planes (Domzig et al., 2006). Further west (at $\sim 1.8^\circ\text{E}$, Fig. 1), several canyons converge at the foot of the slope, at the place where the Khayr al Din bank disappears into the deep basin.

4.2. North of the bank and deep basin

This northern slope is steep ($\sim 15^\circ$) and cut by many gullies (Fig. 4). The slope gradient is particularly high compared to other margins not

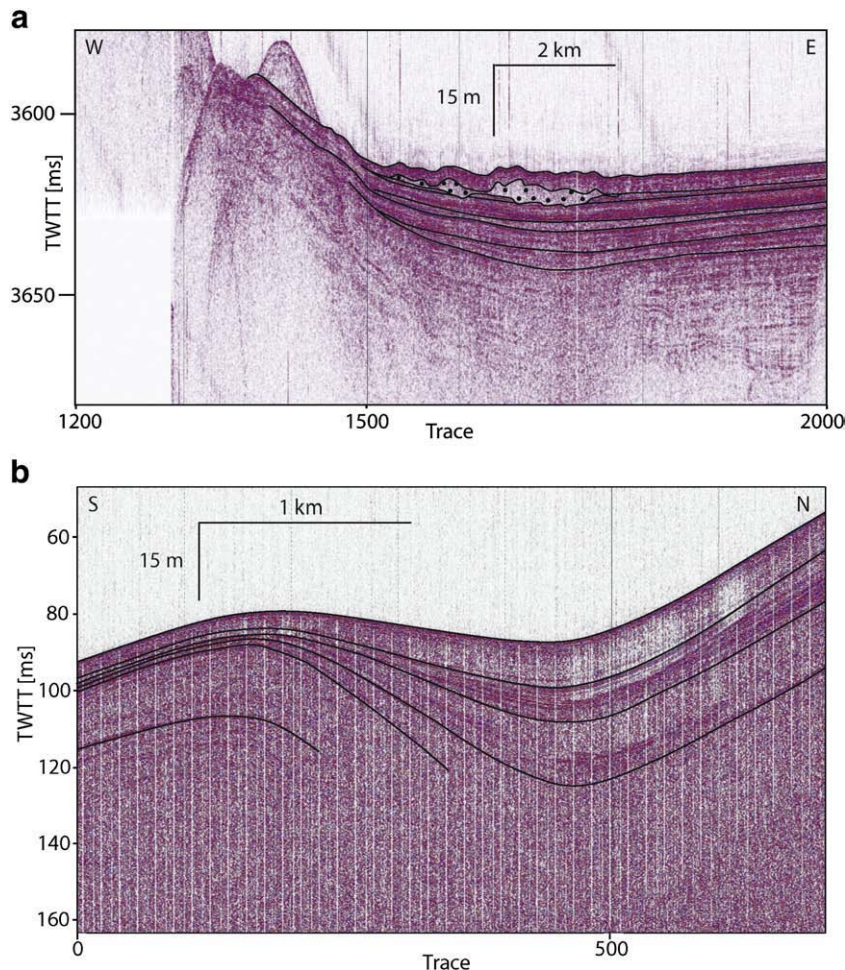


Fig. 5. Chirp (high-resolution) seismic lines showing detailed recent sedimentary architecture. (a) Line CL1 in the deep basin, on the eastern flank of the compressional ridge; (b) Line CL2 on the shelf (see location on Fig. 1).

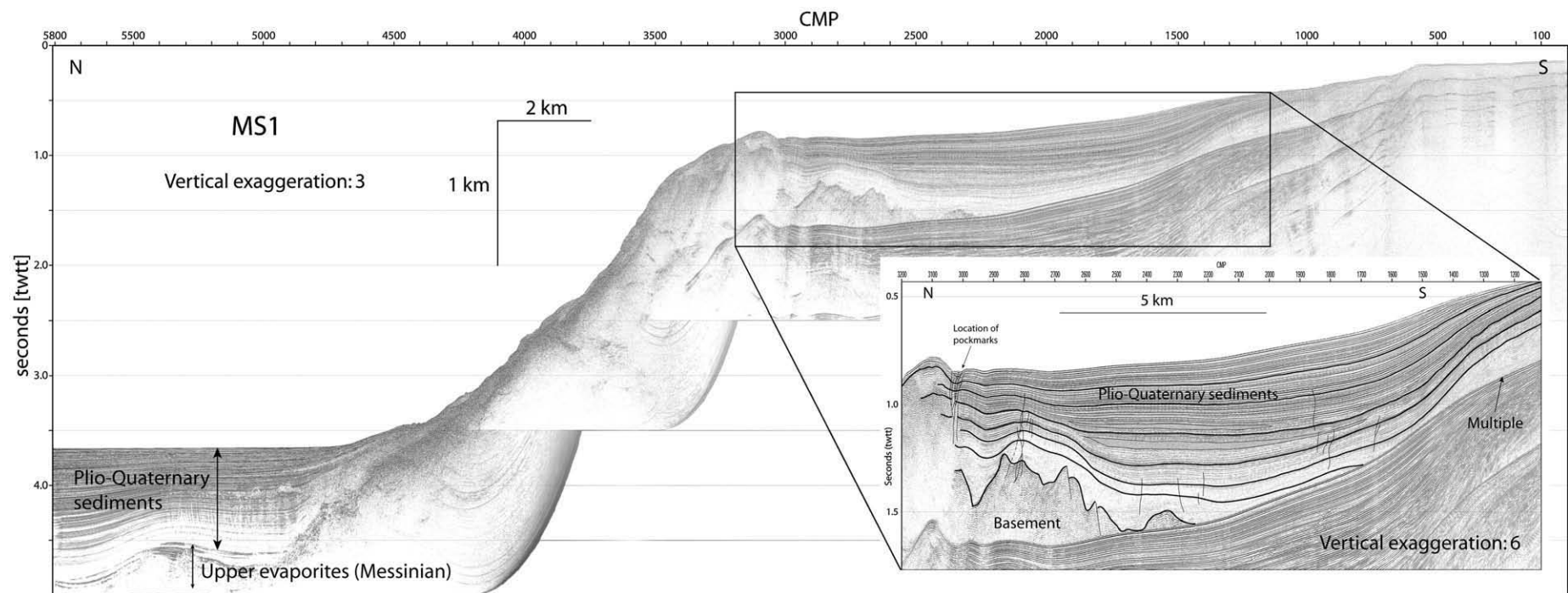


Fig. 6. Seismic cross-section (24-channel) MS1 across the Khayr al Din bank (see location on Fig. 1) from MARADJA'2003 cruise, including an enlargement (MS1A) on the shelf. Note the presence of a buried fold at the northern end of the line within the Plio-Quaternary layers. Vertical exaggeration: 3. **Inset :** Enlargement with a vertical exaggeration of 6 showing the internal structure of the Khayr al Din bank (KADB).

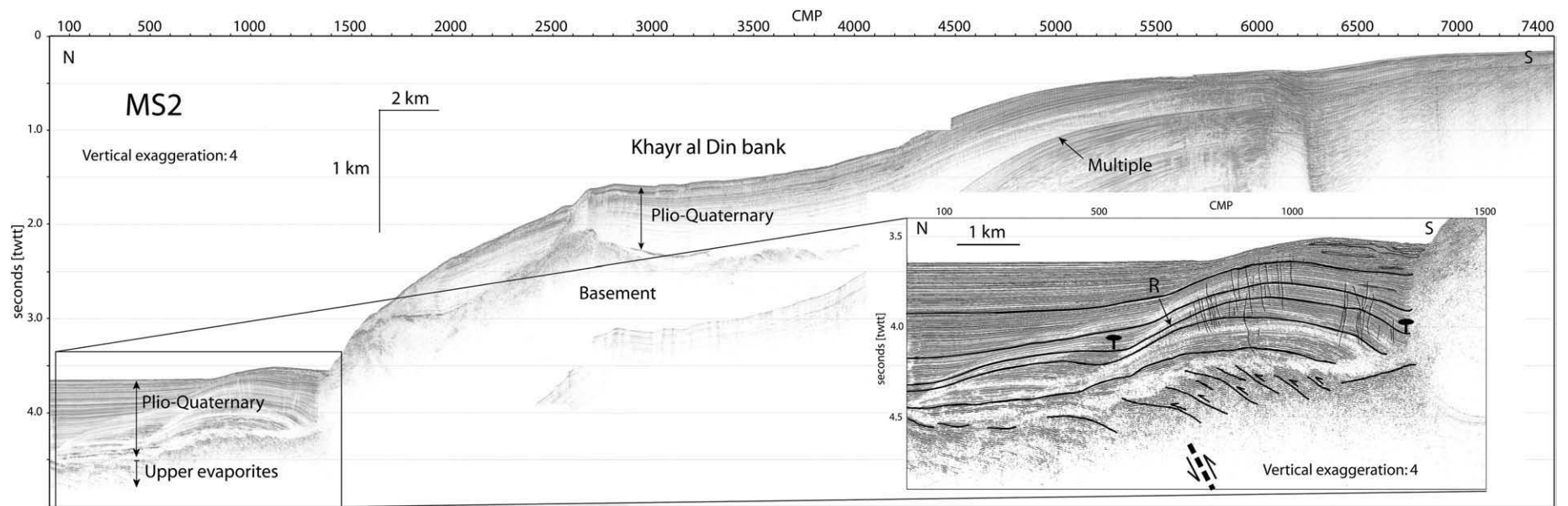


Fig. 7. Seismic cross-section (24-channel) MS2 across the Khayr al Din bank (see location on Fig. 1) from MARADJA'2003 cruise, including an enlargement (MS2A) at the foot of the margin. Vertical exaggeration: 4. **Inset** (modified from Domzig et al., 2006) : Compressive bulge at the foot of the margin which shows vertical proto-faults in its middle (thin black lines) and slicing of the lower layer. In grey: supposed ancient mass-waste deposits at the foot of the slope, R: reflector used for the shortening rate calculation (between the two pins), referred in text.

affected by tectonics (Gulf of Lions or Balearic islands, for instance), which display slopes of 4–5° or less. This difference could be attributed to a continuous Neogene uplift of the bank maintaining the high gradients of the slope. Analysis of the shape of the eastern part of the slope reveals that it is strongly affected by mass-wasting processes (Dan et al., in press).

The foot of the bank depicts a large, asymmetric bulge (Figs. 1 and 4). It is about 5 km wide, 100 m high at the longitude of Tipaza, and is clearly identified on the bathymetric map from the longitude of the Chenoua massif up to 2°E at least, forming a slightly arcuate feature at the foot of the bank (Figs. 1 and 4).

Along the northern border of the KADB, one can remark the presence of an E-W alignment of pockmarks (upper inset in Fig. 4). Pockmarks are generally the surface expression of fluid circulation, possibly associated with faults (Hovland and Judd, 1988). Further basinward, the sea floor appears very flat at 2700 m depth, except in specific areas where elongated ridges with a central depression along-strike reveal typical Messinian salt-wall structures (e.g. Domzig et al., 2009, and references therein).

4.3. The eastern flank of the bank

This area outlines a major change in the margin direction, from E-W to NW-SE. This part of the slope appears to follow roughly the same trend as the onland Thenia fault (Boudiaf, 1996) and is marked by several small linear, closely spaced canyons (Figs. 1 and 4). On the bathymetric maps (Figs. 1 and 4), we do not evidence a clear, fresh scarp along the foot of the margin there, but instead short NW-SE and WNW-ESE lineaments up to ~100–150 m high and steps spread on the slope (Fig. 4, lower inset). Most of them are oblique to the slope but some of them follow the trend of the shelf or the slope break. These lineaments could correspond either to lithological contrasts or to structural (inherited or active) features. Whatever their origin, the displacements that we may infer from them are quite weak. Further East (Fig. 1), in the deep basin, series of ridges and mini-basins in the surroundings of the Algiers deep-sea fan show a complex interaction of sedimentation inputs, salt tectonics, tectonics s.s. (folds) and bottom currents (Dan et al., in press; Domzig et al., 2006).

5. Structures from seismic sections

An other type of data acquired during the MARADJA cruise was seismic reflection. Two types of seismic reflection data were obtained, i.e. 6- (Fig. 8: MS3) or 24-channel (Fig. 6: MS1, Fig. 7: MS2, Fig. 10: MS5 and MS6) seismics. The SU (Seismic Unix) CWP/SU software (Center of Wave Phenomena, Colorado School of Mines) was used for the stack and migration of the seismic data. The bathymetric and seismic data were used for the study of morphology and the structure of the seafloor (Déverchère et al., 2005; Domzig et al., 2006). In addition, get 2–5.2 kHz CHIRP sonar data (CL1 and CL2, Fig. 5) to characterise the shallow subsurface sediments. For the purpose of this study, we also use some seismic lines of the Algerian Oil Company.

Several seismic lines were shot on the KADB and across the main topographic features described above, allowing to identify the internal structures of the bank and its limits. Here, we have selected two high-resolution Chirp seismic sections (CL1 and CL2, Fig. 5) and 6 multi-channel lines (MS1, MS2, MS3, MS4, MS5–6, Figs. 6–10, respectively) of different penetration in order to illustrate the organization of the most shallow deposition, then the older strata, and finally the basement of the margin.

5.1. The Khayr al Din bank: overall pattern, tilting

Since the Chirp profiles have no accuracy on steep slopes, we have extracted a seismic section sub-parallel to the bank in the deep domain (Fig. 5a) in order to estimate the relationship between tectonics and

recent sedimentation. It appears that recent strata are progressively overlapping the KADB from East to West, forming successive onlaps particularly tilted towards the basin, whereas a large, chaotic body is interbedded in the deeper part. Similar features have been described there by Dan et al. (in press), suggesting a progressive relative uplift of the KADB and the triggering of mass-wasting deposits.

At the scale of the margin along N-S sections (MS1 to MS4, Figs. 6–9), it clearly appears that the irregular basement of the KADB progressively sinks from the eastern part of the KADB (Figs. 6 and 7, depth of ~1.5 and ~2.3 s twtt respectively) to its western part (Figs. 8 and 9, depth of ~4 s twtt), in a way similar to the topography. Sediments are trapped on the bank, as the basement forms a depression. They appear slightly faulted close to the northern limit (Fig. 6, inset), with pockmarks visible in the bathymetry (Fig. 4). Furthermore, the pattern of strata changes from East to West: on Sections MS1 (Fig. 6) and MS2 (Fig. 7), the upper part of the sedimentary sequence depicts a progressive, fan-shape thinning towards the south; conversely, on Sections MS3 (Fig. 8) and MS4 (Fig. 9), the recent sedimentary strata (mostly Plio-Quaternary) deposited on the basement depicts a clear tilting and thickening towards the south. This pattern indicates a important infill of a previous large, irregular depression in the upper, eastern part of the block (MS1 and MS2), whereas the lower part (MS3 and MS4) is initially deeper and mostly records the recent (Plio-Quaternary) tilting of the basement toward the south. From the interpretation of the deeper penetration line MS4 (Fig. 9), the Plio-Quaternary deposition is controlled by a south-dipping ramp-and-flat fault system at depth which uplifts the basement. The faults are blind, that is why they do not offset Plio-Quaternary sediments at the seafloor. Considering the probable ages of the seismic sequences (Burolet et al., 1978), i.e. Plio-Quaternary and Messinian (Fig. 8), the onset of recent tilting of the deep Western Khayr al Din block is approximately dated at the transition from Upper Miocene to Pliocene (about 5.3 Ma).

5.2. The Khayr al Din bank: folding on the Chenoua and Ain Benian fault systems and faulting above the basement high

Analyses of the seismic lines CL2, MS2 (south, near CMP 6000), and MS5–6 (Figs. 5b, 7 and 10a–b, respectively) on the top of the KADB show that the Quaternary series display asymmetric folding. On the bathymetry map (Fig. 1) and a high-resolution seismic section (CL2, Fig. 5b), near the top of the Khayr al Din bank, an active fold that corresponds to the northern prolongation of the Chenoua fold is clearly identified. The asymmetry of the fold suggests the presence of an underlying NW-dipping fault, as also evidenced by aftershocks (Fig. 10; Bounif et al., 2003; Harbi et al., 2004). This NE-SW trending fold is found to have a lateral extension of about 30 km (Fig. 10). North of CM, a slight slope break is identified on coastal bathymetric data (which are of poor resolution and must be considered cautiously). It may not correspond to the expression of tectonic activity but rather to some sedimentary processes linked to a continental shelf edge prism forming a tangential clinoform (Fig. 10a), north of CMP 1500.

According to the bathymetry, another fold, namely the Ain Benian fold (MS6, Fig. 10b), would have a length of 25 km in the bay of Bou Ismail, where only several minor to moderate (e.g. September 4, 1996, M 5.7) earthquakes were recorded in the instrumental period. Considering the distribution of the aftershocks of the 1990 Tipaza earthquake (Harbi et al., 2004), the eastern swarm of aftershocks could correspond to the western segment of the Ain Benian fold-fault. Actually, the direction and dip of the aftershock cluster proposed by Sebäi (1997) and Maouche (2002) correspond nicely to the ones identified in our study for the Ain Benian fold.

The pockmarks identified on the northern limit of the KADB, some of them several hundreds of meters wide, are clearly associated with small faults just south of the major slope break, as shown on a seismic cross-section (Fig. 6), forming a slight topographic low. These minor faults are possibly associated to fractures within the bank, or simply

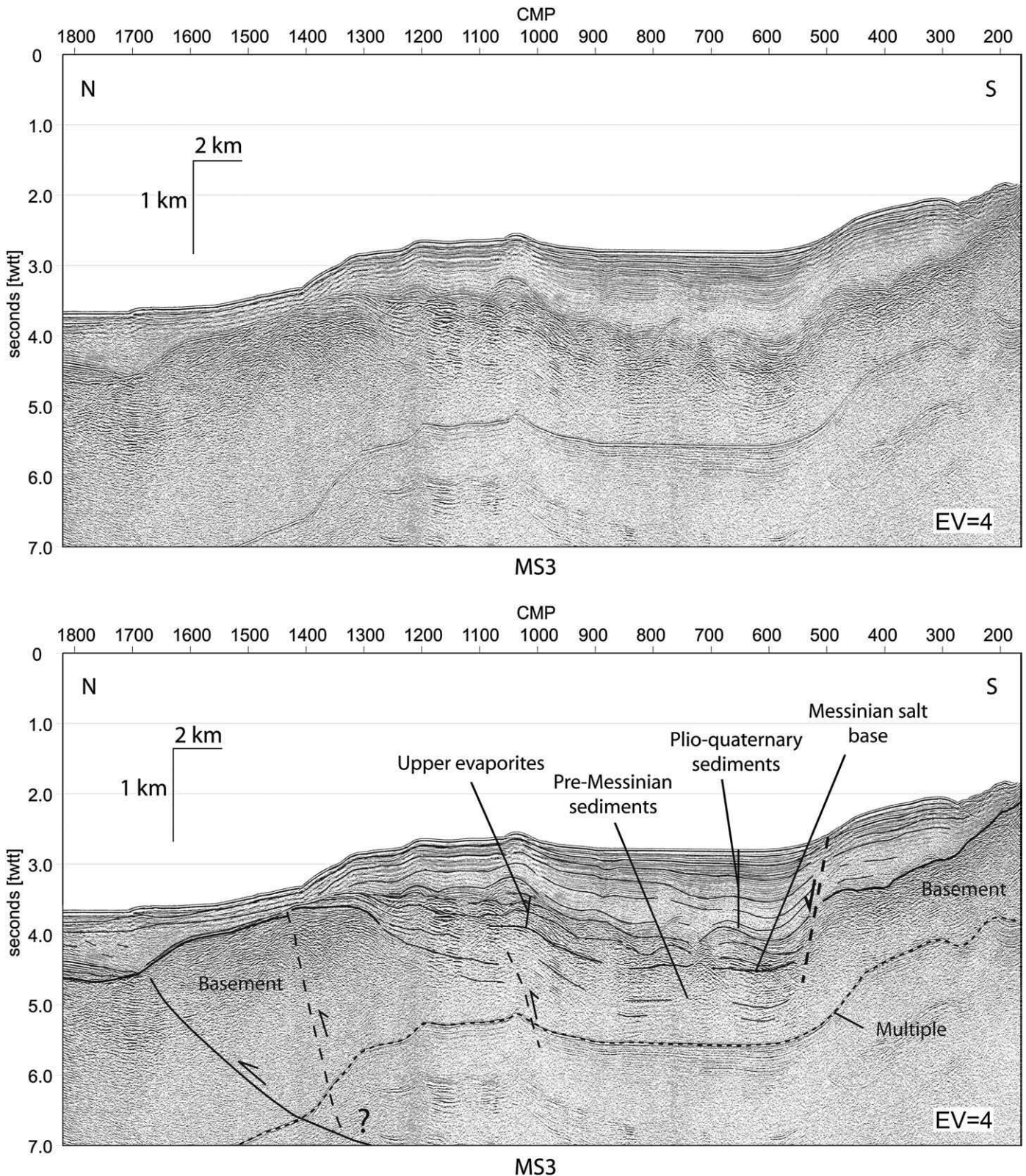


Fig. 8. Multichannel seismic line MS3 (MARADJA'2003) across the western part of the Khayr al Din bank showing that the uplift and tilt of the bank is controlled at depth by a blind and south-dipping thrust. Note a slight flexure in the sedimentary pile above the thrust, which is assumed to be the surface expression of the fold seen on Lines MS1 and MS2 (Figs. 6 and 7 respectively). See position of Line on Fig. 1.

fluid escapes with no tectonic displacement. This along-strike low remains all along the top of the bank, on the rim of the slope break (Figs. 1 and 4). On the inset of the seismic section MS1 (Fig. 6), this topographic low corresponds at depth to a sharp stop of the reflectors,

which may be caused by a vertical fault shifting the basement. However, the activity of this fault and its significance (gravity-driven scarp? Normal fault accommodating internal deformation?) are unclear. Many other smaller pockmarks (several tens of meters in

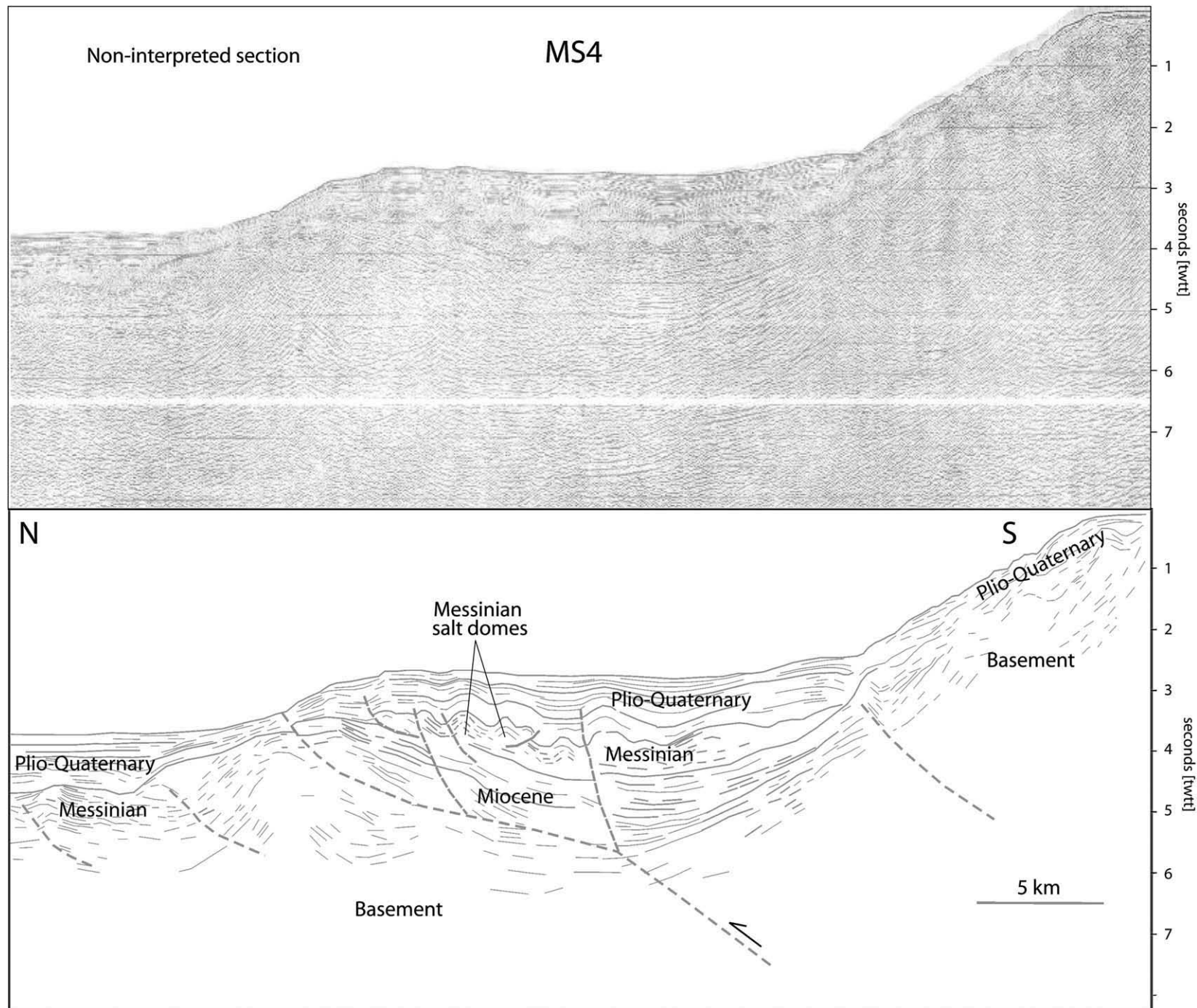


Fig. 9. Deep multichannel seismic line MS4 (360 channels) with interpretation below (line drawing). See position of Line on Fig. 1. Reproduced under permission by Sonatrach.

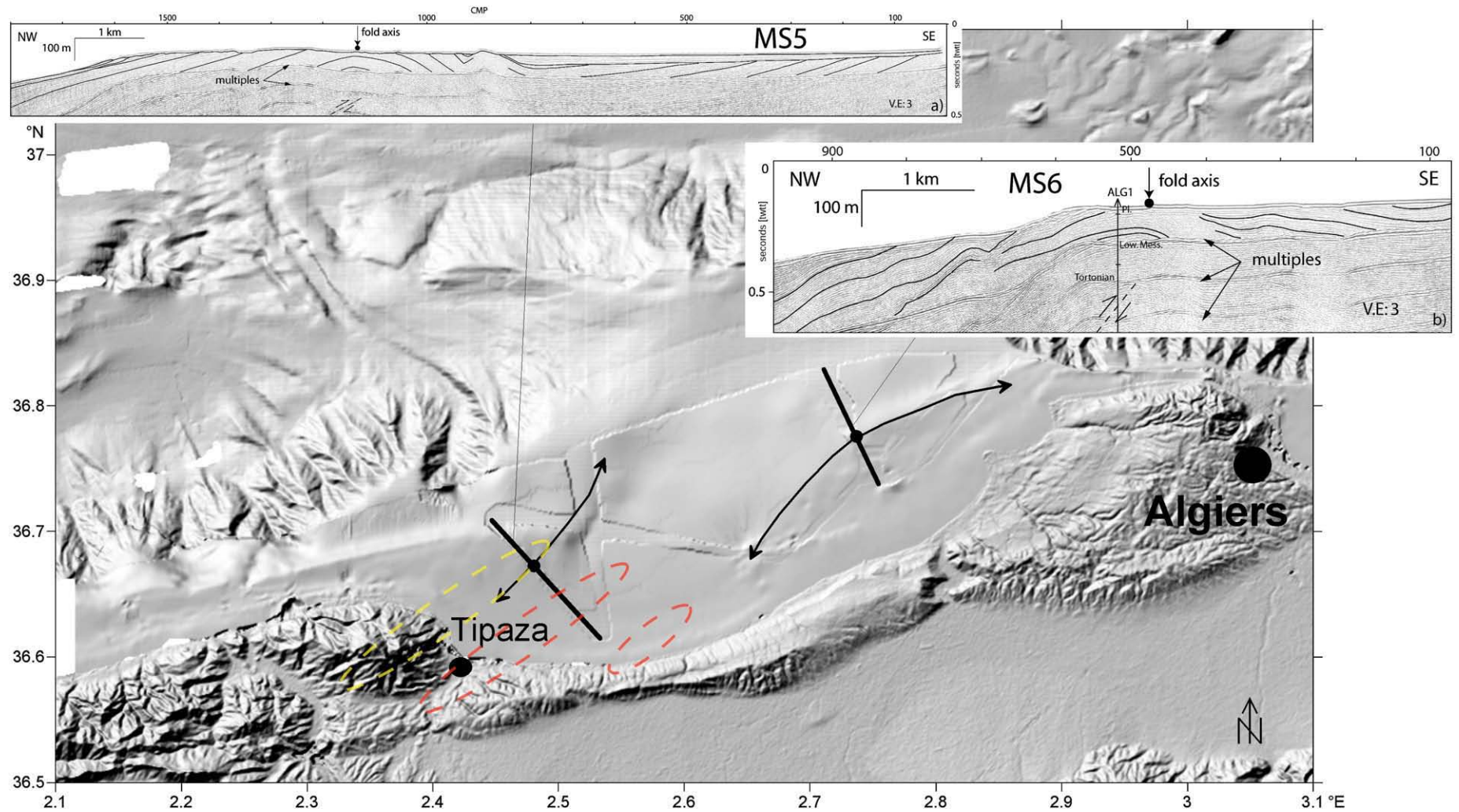


Fig. 10. Morphological map of the Tipaza-Algiers area, with seismic cross sections (vertical exaggeration = 3) across the offshore part of the Chenoua fold (MS5, a) and the Ain Benian fold (MS6, b). The ellipses are the mean axes of the three clusters of events revealed during the Tipaza-Chenoua 1989 (in yellow) and 1990 (in red) events (Meghraoui, 1991; Sebaï, 1997; Maouche, 2002; Bounif et al., 2003; Harbi et al., 2004). The black dots correspond to the anticlines axis, which is roughly at the location of the ALG1 borehole (located on Fig. 2) for seismic Line MS6.

diameter) are evidenced on the 25 m resolution DEM all over the bank, but the resolution of seismic data does not allow a clear identification of the corresponding fluid escape paths.

5.3. The Khayr al Din fault-related fold at the foot of the margin

What is the meaning of the topographic bulge at the foot of the KADB? On the seismic section MS2 (Fig. 7), it appears as a wide anticline which also presents proto-faults (fractures in the Plio-Quaternary cover without significant shifts) in the overlying growth strata. Note that it is also identified as a buried fold further east on MS1 line (Fig. 8). This fold is asymmetric: it depicts a steeper northern flank (backlimb), which favours a probable control by a reverse fault dipping southward underneath the bank. Although the fault is blind, the slicing of the lower Pliocene (and possibly the Messinian Upper Evaporites) layers, regularly faulted (Fig. 7), and more importantly, the progressive tilting of Plio-Quaternary layers supports the hypothesis of an active thrust fault dipping to the south beneath the continent. Although Messinian salt migration may have occurred seawards, possibly initiating the formation of the small faulted blocks observed, this later process is unable to explain either the overall bulge shape of the structure in map view and cross section, or the shifts observed in the infra-Pliocene units. Contouritic deposits can also be discarded because the Messinian sediments are clearly uplifted and deformed, and because we do not generally observe sediment thickness variations apart from the fan shape deposition typical of a structural tilt. However, between CMP 100 and 500, a significant increase of sediment thickness between 4.2 and 4.4 seconds twtt depth could be due to contourites.

The thickness variations of the sequences on both flanks of the fold suggests that the incremental folding was carried at different rates through time. Indeed, the layers below the pointed reflector (reflector R on Fig. 7) depicts a constant thickness across the fold, which implies that tectonic uplift was not effective at that time (pre-growth or pre-tectonic strata). Conversely, the more recent layers above depict a clear fan shape deposition pattern close to the foot of the slope, which indicates syn-tectonic growth strata and a local subsidence on the backlimb of the fold which is still active today (Fig. 5a). Note that further west (Lines MS3 and MS4, Figs. 8 and 9), the tectonic style of this fold evolves along strike: there, the basement is closer to the surface, suggesting a change in the rheology. The fold becomes hardly recorded within the thin Plio-Quaternary layer, however a shallower blind thrust is identified below by the tilting of sediments overlying this part of the block.

A number of moderate-size earthquakes appear to have occurred in the vicinity of this fold and further south (Fig. 2), which could be associated to this south-dipping fold-tip fault at depth. The relatively low abundance of earthquakes may be either due to the relatively poor coverage of this offshore area by seismological networks or to very slow convergence rates and therefore very long recurrence periods.

6. Discussion

6.1. Interpretation of the main fold at the foot of the KADB

6.1.1. Potential size of the fault

If we consider that the fault lies there and extends along the northern flank of the KADB (from 1.8°E to 2.6°E), it implies an approximate surface length of 80 km of the active fault. Indeed, the Sonatrach seismic line (Fig. 9) and our own seismic data (Figs. 7 and 8) confirm the presence of a large reverse fault all along the bank. Following empirical relationships from Wells and Coppersmith (1994), such a structure would be theoretically able to generate earthquakes of magnitude up to 7.32 ± 0.28 , which represents a serious threat for nearby cities like Algiers or Tipaza and Cherchell. Over the long term, this fault would be responsible for the recent (Plio-Quaternary) large-scale uplifting (an tilting) of the northern end ("nose") of the Khayr al

Din Bank, which is considered here as a previous tilted block of the Neogene passive margin.

6.1.2. Fold growth geometry and rate

From the profile shown in inset on Fig. 7 and the architecture of growth strata, it appears likely that this fold results from fault-tip folding (i.e., folding at the tip of a blind thrust) rather than fault-bend folding (Suppe, 1983), because there is apparently no transfer of slip from a deeper to a shallower detachment level near the surface. If this is true, it would indicate that this structure is linked to a relatively immature fault. However, it is not straightforward to determine whether this tip-fault folding corresponds to a specific model, such as: (1) a fault-propagation fold, which assumes conservation of bed length and thickness (Suppe and Medwedeff, 1990), (2) a slip gradient fold, which does not require fault propagation and assumes conservation of area but not of bed length (Wickham, 1995), (3) a detachment fold, which assumes a changing bed length and forelimb angle (Dahlstrom, 1990), or (4) a trishear fold; which assumes a triangular shaped zone of distributed shear (Allmendinger, 1998). It is beyond the scope of this paper to discriminate between these models, because of the lack of geometrical constraints at depth. In the following, we will merely neglect internal deformation of the beds (a case that corresponds to models 1 and 4), so that using a specific pre-growth strata as a measure of shortening rate will provide a minimum value on this rate.

Using the reflector R (Fig. 7, inset) as a marker of the onset of main tectonic deformation, we may estimate the shortening rate across the fold, between the two pins (the bulge between CMP 0 and 500 is likely to be due to contouritic deposits because the underlying sediments, around 4.5 stwt, are not deformed). Dividing its length by the present-day horizontal distance across the fold, we obtain a shortening factor of $5.6 \pm 0.5\%$ corresponding to a total horizontal shortening of 570 ± 50 m. Using the mean Upper Quaternary sedimentation rates found at the foot of the slope in nearby regions (West of Tenes, and Algiers), 0.5 mm/yr (Giresse et al., in press), we estimate an age of 1.15 ± 0.30 Ma for this reflector, taking into account uncertainty on velocity (e.g. Réhault et al., 1984). This age fits well with the position of the R reflector, located within a layer characterized by a typical Quaternary facies (Réhault et al., 1984). Consequently, we obtain a horizontal shortening rate of 0.49 ± 0.14 mm/yr for this fold over this period. If we assume that the folding is entirely driven at depth by a single fault and that the long term strain rate (>1 Myr) computed here is the similar at shorter time scale, we hypothesize a slip rate (considering a mean dip for the fault of $47 \pm 7^\circ$, by analogy with the nearby fault activated during the 2003 Boumerdes earthquake, see e.g. Bounif et al., 2004; Delouis et al., 2004; Meghraoui et al., 2004; Yelles et al., 2004) of 0.72 ± 0.14 mm/yr.

6.1.3. Kinematic implications

Recent kinematic studies in North Africa (e.g., Nocquet and Calais, 2004; Serpelloni et al., 2007) propose a shortening rate across the NNW/SSE Eurasia-Africa plate boundary of 5–6 mm/yr at the longitude of Algiers. From available neotectonic studies, 1.0–2.3 mm/yr could be accommodated during the Quaternary across the Tell-Atlas (Meghraoui et al., 1996), therefore we may expect at least 2.7 mm/yr left for the accommodation by active structures offshore Algeria. On the other hand, a recent GPS profile from Nubia to Iberia in the Algiers area reveals that 1.6 ± 0.6 mm/yr of horizontal shortening in the relative plate convergence strike may occur offshore (Serpelloni et al., 2007). Although these rates are poorly constrained, we therefore anticipate a substantial amount of shortening (between 1.0 and 2.7 mm/yr) being accommodated by offshore structures on the Algerian margin. As we find a horizontal shortening rate of ~ 0.5 mm/yr for the Khayr al Din fold, we propose that about one third of the ~ 1.6 mm/yr found by Serpelloni et al. (2007) is possibly taking up on the single Khayr al Din fault, the remaining being accommodated within the Khayr al Din bank and over other unknown offshore structures, further north.

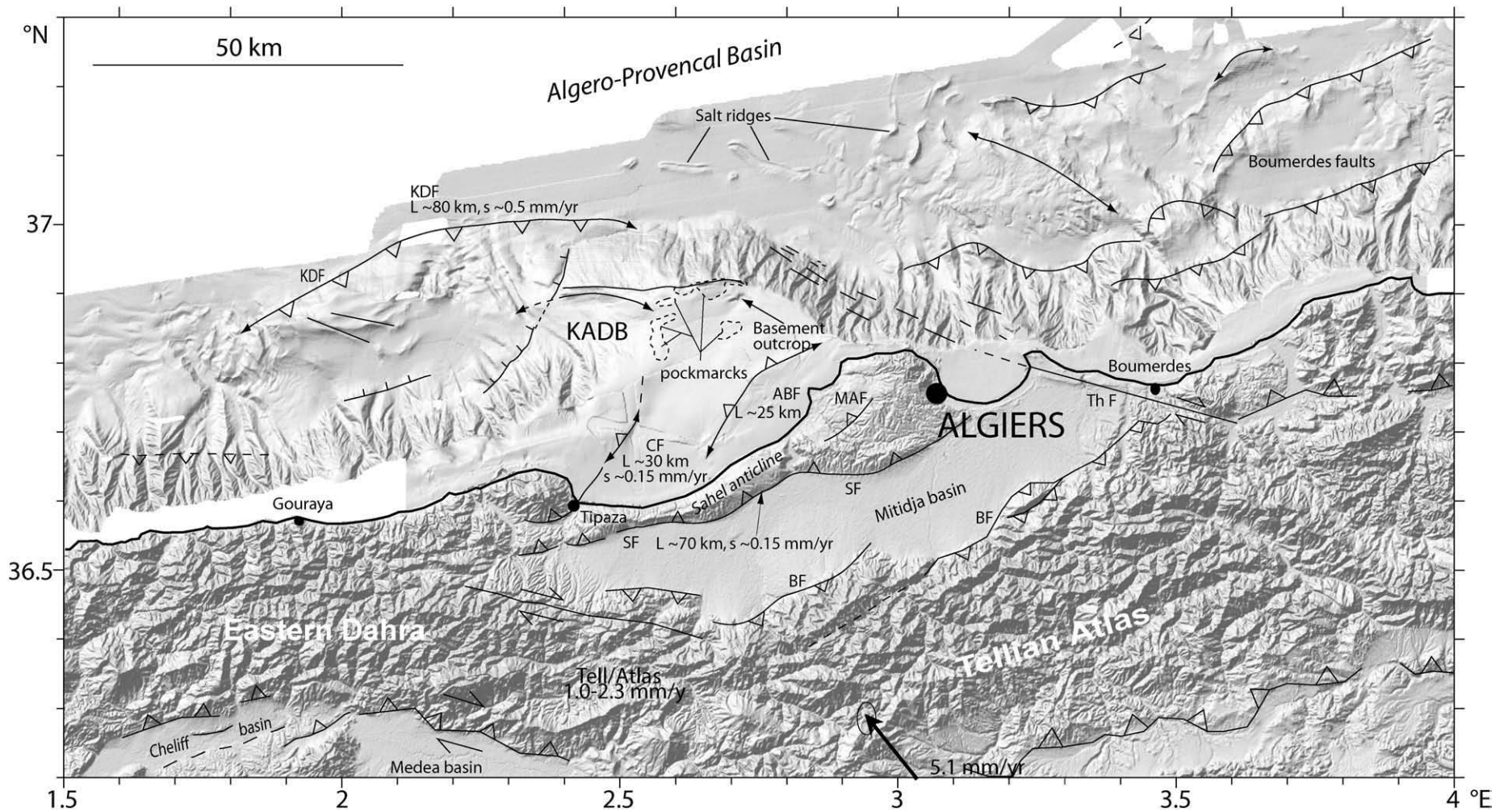


Fig. 11. General marine and onland tectonic framework of the Algiers region. The arrow with the circle represents the direction of convergence from Africa towards Europe (Nocquet and Calais, 2004). L= length of the fault, s= horizontal shortening rate of the fault from bibliography (onland and coastal faults) or from seismic profiles. KDF: Khayr al Din fault MAF= Mahelma fault. ThF: Thenia fault. BF: Blida fault. SF: Sahel fault. ABF: Ain Benian fault. CF: Chenoua fault.

6.1.4. Offshore prolongation of the Thenia Fault

Our observations do not provide any evidence for an offshore tectonic activity in the prolongation of the Thenia fault. However, one must remind that the relatively large sedimentation rates in the area of the bay of Algiers may overcome the slip rates of slow faults, as expected in the case of the Thenia fault (Boudiaf, 1996; Boudiaf et al., 1998). Therefore, although some seldom epicenters (Fig. 2) are reported in the area mainly after the Bouterdes earthquake of May 2003, the activity of this part of the slope remains questionable. The slight topographic anomalies identified do not depict a continuous trend and may correspond to structural heritage or, more preferably, to very slow and short fault segments, possibly accommodating the slight differential movement between the region of Bouterdes and the Khayr al Din Bank. Note that a more pronounced seismic activity is found inside the deep basin, below the Algiers deep-sea fan (Fig. 2), in correspondence to a large fold reported there (Babonneau et al., 2007).

6.2. Possible origin of vertical movements

A large part of the slope height (more than 2 km) of the northern Khayr al Din bank is likely to result from the Miocene rifting which gave birth to opening of the Algerian basin, because: (1) this slope is located at the ocean-continent transition, where the rifting process is assumed to have produced large, kilometer-scale, topographic high through normal faulting; (2) the tilted blocks of passive continental margins typically display the same slope pattern (steep oceanward, gentle continentward) which are rift shoulders during the rifting stage; (3) the height of the scarp is inconsistent with reasonable velocity rates expected regionally during the compressional, more recent, tectonic evolution; (4) the long wavelength tilting of the Algiers massif (Fig. 4) is observed at the easternmost end of the Khayr al Din fault and at about 30 km from it across strike (Fig. 1), which makes a direct correlation of the tilting with the recent Khayr al Din fault unlikely; (5) the pronounced erosional surface seen on the top of the block (Fig. 6), just below the Plio-Quaternary layer, demonstrates that this block had already acquired his high position at Messinian times, preventing from linking the whole slope to the Plio-Quaternary activity of the Khayr al Din fault; and (6) recent marine terraces deposited above the massif and in the surroundings are significantly less tilted than the regional topography (Meghraoui et al., 1996; Maouche, 2002). However, part of the topographic signal (probably minor) could also result from the recent activity of Khayr al Din fault, as suggested by the tilting of coastal Quaternary terraces and of Plioquaternary strata above the western part of the KADB (Figs. 8 and 9). Seismic lines shown in this paper demonstrate that the deformation linked to the Khayr al Din fault is recent, still active, and affects mostly the foot of the slope by creating a 100 m topographic high corresponding to an anticline (Fig. 7). It remains

to clarify which structure is responsible for the uplift of vertical terraces along the shoreline: the Sahel, Khayr al Din and/or Chenoua/Ain Benian faults-related folds? Comparing uplift rates of marine terraces to their position relative to these faults should allow one to infer, at least qualitatively, ratio of vertical slip rates on the faults. In this respect, the slip rate seems to be faster along the Khayr al Din fault as uplift rates of the Tyrrhenian terraces increase northward, away from the Sahel anticline. The recent tilting of the western KADB, inferred from the fan-shape geometry of Plio-Quaternary sedimentary sequences (Figs. 8 and 9) suggest vertical slip rates along the Khayr al Din fault at least similar to the Sahel fault and probably higher. They now need to be quantified by precisely mapping, identifying and dating marine terraces between Ain Benian and Tipaza.

In summary, several important indications for reverse faulting activity have been found on the KADB. The main fault (with largest displacement and extent), the Khayr al Din fault, seems to be located at the foot of the bank, as illustrated by a fold with a cumulative uplift of ~100 m (Figs. 4 and 7). Although we were not able to image precisely the fault as it is the case in other marine active regions, the geometry of the sediments above the bank and the position of the basement indicate that it may have several branches organised in flats and ramps, as also found in the Bouterdes area, west of Algiers (Déverchère et al., 2005). Further arguments are also found through the several breaks recognized on the slope, or through the differential uplift accompanied with minor steep faults at the top of the bank. In addition, from its geographical location, this major fault is potentially the fault responsible for the Gouraya 1891 (I=XI) earthquake.

6.3. Revision of previous structural sketches and geodynamical implications

The KADB appears as a large structure limited on its northern and southern flanks by long, active fault-related folds of opposite vergence and by a sharp WNW-ESE transition to the deep basin on its eastern flank (Fig. 1). We summarize in map view (Fig. 11) and in cross section (Fig. 12) the main active structures of the area. If we admit, as proposed by most kinematic reconstructions, that the Kabyle blocks collided in a NW-SE direction with the African passive margin during Miocene times (Bouillin, 1986; Schettino and Turco, 2006), then the KADB can be understood as a previous tilted block born at the northern boundary of the Internal Zone that accommodated the drift of this part of the Kabyles during the roll-back process. The fault geometry and kinematics proposed here (Figs. 8 and 9) are strikingly different from previous interpretations. Firstly, we did not observe a significant role of strike-slip or normal faults at the tip of or across the Khayr al Din fault, contrary to what is proposed by Mauffret (2007): for instance, the NW-SE Thenia fault and its offshore prolongation do not clearly demonstrate

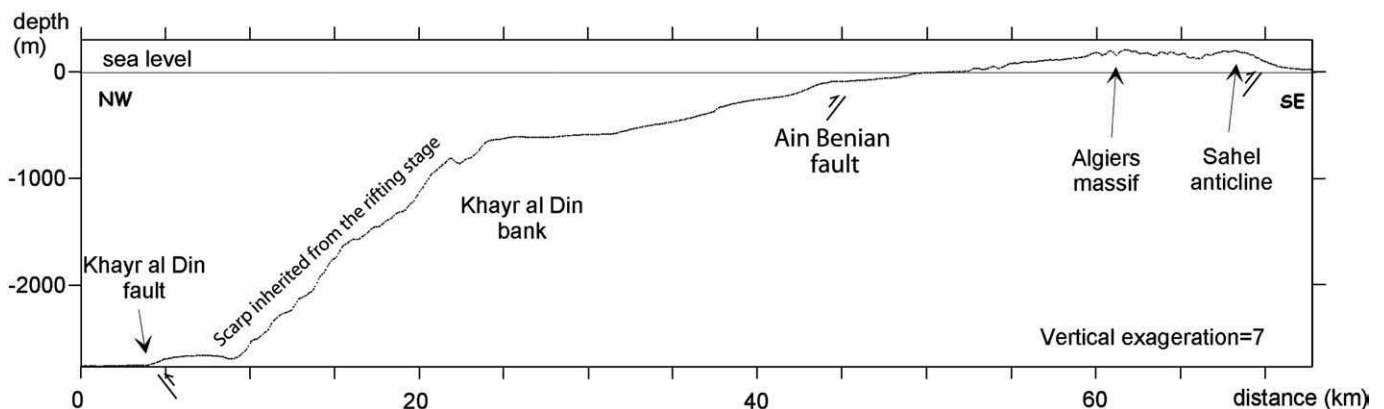


Fig. 12. Synthetic N-S topographic profile across the margin and the coastal area (location on Fig. 1), showing slope breaks and fault positions, and depicting the main faults and folds projected from this study and from previous works on land.

recent tectonic movement. We therefore consider this fault zone as a previous transfer structure of the margin, which depicts in the recent stress field a series of weakly active short segments, therefore constituting a wide relay zone which progressively accommodates the relative movements between the Boumerdes-Zemmouri fault zone and the Khayr al Din main fault (Fig. 11).

Secondly, the dips and relative importance of the faults mapped here clearly discard the proposition from Yielding et al. (1989) of a simple inversion of previous normal faults of the margin. Instead, we propose that the main slope at the northern boundary of the KADB (Figs. 11 and 12) is a dead normal fault of the tilted block, and that the recent stress field determines the progressive focussing of strain at the foot of the margin, resulting into the recent uplift of the Khayr al Din bank, and the birth of a new fault of opposite vergence at the ocean-continent transition, in a backthrust position (Fig. 13). This geometry differs from the one reported in the 2003 Mw 6.8 Boumerdes earthquake area, characterized by a succession of ramps and flats that develops from the coastline towards the ocean (Déverchère et al., 2005). The anomalous steepness of the slope breaks observed in the Khayr al Din area (Fig. 14) may be caused by a steepening of normal faults within the new compressional stress field. In our interpretation, the apparent pop-up aspect of the overall structure (Fig. 13; Déverchère et al., 2005) merely results from a progressive swap of the plate limit from the Late Miocene, north-dipping suture zone located onshore, towards the Quaternary, south-dipping main Khayr al Din fault located offshore. A similar overall pattern is likely to occur in the Lesser Kabylies further East, where a system of active faults and folds have been recently described off the Annaba bay (Kherroubi et al., 2009).

At a more regional scale, the KADB can be understood in a way similar to what is described by Piqué et al. (1998) as the “Maghreb indenter”. Whereas the overall sedimentary tilting observed in a N-S direction (Figs. 8 and 9) is interpreted here as the effect of this compressional reactivation, the progressive deepening of the KADB from East to West observed both in the morphology (Fig. 1) and in the basement depth (Figs. 6–9) is likely to result from the imprints of the lateral escape of the Alboran blocks towards the West (Piqué et al., 1998), which would have led to an increasing obliquity, producing up to a pure strike-slip type margin, or “STEP” fault (e.g. Govers and Wortel, 2005).

6.4. Consequences for seismic hazard in the Algiers region

In coastal areas such as the Algiers Wilaya, seismic hazard assessments have to consider both onshore and offshore seismogenic sources. Previous studies have suggested possible sources offshore the Algiers region. In a probabilistic seismic hazard assessment of the Algiers region, GEOMATRIX (1998), for instance, considered two offshore seismic source zones: the continental shelf/slope area and the deep Mediterranean, with maximum magnitudes of 6.75 (0.2 probability), 7.0 (0.6 prob.) or 7.25 (0.2 prob.). However, lack of data on these sources prevents from reliable estimates of their seismogenic capability and associated hazard. Data from the MARADJA cruise fill this gap by allowing to identify potentially critical seismogenic structures and to precise their seismotectonic characteristics (geometry, style of faulting, slip rates) and the seismic hazard that they may generate.

According to the relationship that link average displacement to moment magnitude for all faults (Wells and Coppersmith, 1994), an earthquake of maximum magnitude Mw 7.3 would produce an average displacement of 1.8 ± 1.7 m. If we consider the slip rate hypothesized here (i.e. about 0.7 mm/yr), the minimum return interval of such an event would be ~ 2500 ($\pm 90\%$) years. Similarly, the Sahel fault would theoretically be able to produce earthquakes with similar maximum magnitude and average displacement. Considering uplift of Plio-Quaternary terraces on the Sahel anticline at a rate of 0.15 mm/yr (Maouche, 2002; Fig. 12) and a reasonable dip of 45° , slip rate on the Sahel fault would be of 0.2 mm/yr, and minimum return interval of a Mw 7.3 event would then be 7500 ($\pm 90\%$) years. Although associated to very large uncertainties, these values show, at least qualitatively, that the Khayr al Din fault may generate strong earthquakes at higher rate than the Sahel fault. The difference would be that return period could be shorter for the Khayr al Din fault with regard to its faster slip rate, which possibly makes it the most critical structure in terms of seismic hazards in the Algiers region.

We should not forget, however, that the proposed magnitudes are maximum theoretical values which consider that all cumulated strain is released by strong earthquakes (i.e. no microseismicity or aseismic creeping). Further studies of seismic cycles on these structures would be required to precise this point. Still, despite very large uncertainties, these values show that the Khayr al Din fault represents a serious threat for the

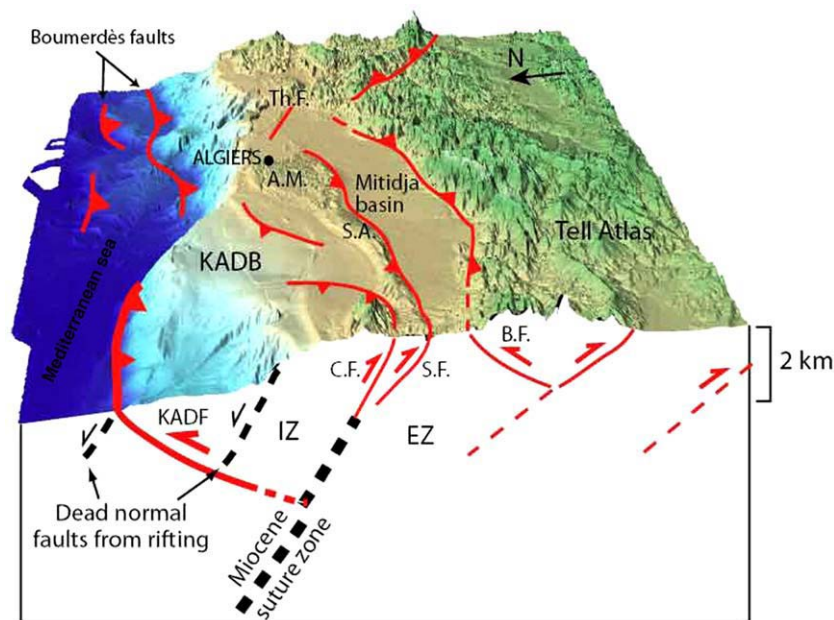


Fig. 13. Tentative 3D view of the marine and terrestrial Digital Elevation Models showing our interpretation of the tectonic framework and fault geometry at depth in the offshore/onshore Algiers region. The black dashed line (suture zone) is assumed to be mostly inactive (see text for details). KADB: Khayr al Din bank, KADF: Khayr al Din fault, Th.F.: Thenia fault, A.M.: Algiers Massif, S.A.: Sahel Anticline, S.F.: Sahel fault, C.M.: Chenoua Mount, C.F.: Chenoua fault, B.F.: Blida fault, IZ: Internal Zones, EZ: External Zones.

Algiers urban area. They suggest that seismic hazard generated by the Khayr al Din fault may even be higher than by the Sahel fault, which was previously considered as one of the most critical seismogenic structure for the Algiers area : possible magnitudes on the Khayr al Din fault are slightly higher (as may consequently be signal durations), with shorter return intervals (i.e. faster slip rate) and, because of its southeastward dip, it can generate events which epicentres could be close to the western extension of the Algiers urban area.

7. Conclusions

The data collected during the Maradja 2003 survey allow us to improve our understanding of the effect of the collision between the African and Eurasian plates, demonstrating that the Algerian margin is the location of active deformation processes, expressed offshore by north-verging faults. This major offshore shortening occurs mostly at the foot of the slope and uplifts the continental domain, as demonstrated by the topographic and structural features presented in this study. The seismic activity generated by the offshore active faults could also be responsible for the tsunamis recorded in the past in this region.

West of Algiers, the Khayr al Din bank constitutes a relic of the Kabylian basement, and shows local internal fracturation and deformation. At its top, two active folds (Ain Benian and Chenoua), both controlled by north-dipping faults, have been also evidenced. These folds were the location of moderate earthquakes in the past, thus providing direct evidence for fault-controlled folds. However, the largest active fault of the region is the fault-tip fold located at the foot of the Khayr al Din bank, which, by its length (80 km), constitutes a new major threat for the Algiers region, as earthquakes of magnitude 7.3 could be generated by this structure. The past destructive earthquakes of 1365, 1716 or 1891 might have been generated on this structure. In addition, others geohazards, like tsunamis and turbidity currents, possibly associated with this fault, must also be considered, and would need further studies.

The discovery of such a large blind fault at the foot of the margin requires an update of the general tectonic framework of the region. Actually, the Khayr al Din fault, which has a northern vergence – opposite to the one of the Internal Zones/External Zones suture – from its length and position, relatively to the other faults of the area, should be the major fault of the region, the others being backthrusts, or at least more superficial thrusts (Fig. 13). Therefore, we propose that we are witnessing the onset of a new tectonic pattern, through the play of a Quaternary major fault system verging to the north at the foot of the margin, a process which suggests the very first stage of subduction initiation.

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