

# THE TECTONIC STRUCTURE OF THE ALBORAN MARGIN OF MOROCCO

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**Abstract:** We utilized a very dense seismic survey mainly performed by the oil companies completed by academic data to perform a depth to basement map of the Morocco margin of the Alboran Sea. The eastern area is characterized by several volcanic edifices that are related to the late Miocene Alboran arc. However, the volcanism persisted after the Messinian in the Gourougou volcano and the Chafarines Island. The Tortonian to Messinian activity of the Nekor fault system is characterized by normal faulting with a NE-SW trend. A tilt of the Messinian surface suggests a 1.5 km uplift of the coast since 5.33 Ma. In the Al Hoceima offshore region we identify the major left-lateral El Idrissi fault zone that probably crosses the Alboran Sea. The Xauen Bank is formed by the early Miocene sedimentary layers of the West Alboran Basin uplifted by compression with an estimated shortening of 3.5 km since the Messinian (0.65 mm/yr). The Jebha Fault was mainly active during the early Miocene. The tomography, the magmatism, and the tectonics suggest that the Alboran Arc collided with the Iberian Plate during the late Tortonian, followed by a clockwise rotation of the central Alboran basin. Although the Alboran basin is clearly affected by E-W motions we think that the eastwards subduction zone is dead since the late Miocene.

**Key Words:** Alboran Sea, active tectonics, structural map

**Resumen:** Hemos utilizado una densa malla de líneas sísmicas procedentes de compañías petroleras, completada con perfiles sísmicos académicos para construir un mapa de profundidad del basamento en el margen marroquí del Mar de Alborán. El sector oriental de este margen está caracterizado por la presencia de varios edificios volcánicos relacionados con el Arco de Alborán durante el Mioceno superior. Sin embargo, el volcanismo ha persistido hasta después del Messiniense en el volcán de Gourougou y las islas Chafarinas. La actividad del sistemas de fallas de Nekor desde el Tortonense al Messiniense se caracteriza por fallas normales de dirección NE-SW. La superficie Messiniense se encuentra basculada, indicando un levantamiento de la costa de 1,5 km durante los últimos 5,33 Ma. En la región marina de Al Hoceima hemos identificado el sistema de falla de Al Idrissi que probablemente atraviesa el Mar de Alborán. El Banco de Xauen está formado por las secuencias sedimentarias del Mioceno inferior de la Cuenca Oeste de Alborán, que se encuentran levantadas por la compresión, estimándose un acortamiento de 3,5 km desde el Messiniense (0,65 mm/a). La falla de Jebha fue activa principalmente durante el Mioceno inferior. Los datos tomográficos, el magmatismo y la tectónica indican que el Arco de Alborán colisionó con la placa Ibérica durante el Tortonense superior, estando seguida por una rotación horaria de la cuenca central de Alborán. Aunque la cuenca de Alborán está claramente afectada por movimientos E-W, creemos que la subducción hacia el Este cesó en el Mioceno superior.

**Palabras Clave:** Mar de Alborán, tectónica activa, mapa estructural

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The Alboran Sea is one of the marine areas of the Mediterranean Sea that has been the most studied because it is the best illustration of the structural complexity of the Mediterranean Region. The central part has a thinned crust whereas the surrounding emerged lands have a thickened crust beneath the Betics in Spain and slightly thickened below the Rif in Morocco. These two cordilleras result from Miocene

compressional deformation more or less coeval to the thinning by extension of the Alboran Sea (Comas *et al.*, 1999). Moreover, the Alboran Sea, located presently between the Eurasia and Nubia (Africa) convergent plates, should be a compressional zone. However, the seismicity and the GPS measurements suggest an E-W extension and strike-slip motions (Stich *et al.*, 2006; Serpelloni *et al.*, 2007). Several hypotheses have been

proposed to explain the structure of the Alboran Sea: extensional collapse of thickened continental lithosphere (Platt *et al.*, 2003), delamination process (García-Dueñas *et al.*, 1992; Calvert *et al.*, 2000), and retreating subduction towards the west (Lonergan and White, 1997; Rosenbaum and Lister, 2004). In order to constrain the geological and geophysical framework a multidisciplinary approach has been performed by several groups: gravimetric, magnetic, and seismic surveys (Willet, 1991; Comas *et al.*, 1992; Watts *et al.*, 1993) and ODP Leg 161 (Comas *et al.*, 1999). The tomographic studies show a probable (cold) slab dipping toward the east (Gutscher *et al.*, 2002; Faccenna *et al.*, 2004; Spakman and Wortel, 2004). The present tectonic situation in the Alboran sea is mainly illustrated by the seismicity (Stich *et al.*, 2003a; Buforn *et al.*, 2004; Akoglu *et al.*, 2006; Biggs *et al.*, 2006; Cakir *et al.*, 2006), the GPS observations (Fadil *et al.*, 2006; Stich *et al.*, 2006; Serpelloni *et al.*, 2007) and the seafloor multibeam map (Gràcia *et al.*, 2006; Ballesteros *et al.*, 2008). The present study is based on a very dense seismic grid on the Morocco and Spanish margins. At the difference of the others papers that utilized a small part of these data (Bourgois *et al.*, 1992; Morley, 1993; Chalouan *et al.*, 1997) we contoured the depth to acoustic basement in the general tectonic framework of the Alboran Sea and we use the CMT determinations of the earthquake focal mechanisms that enlighten the present tectonics of this complex region. This study is an expanded version of a paper published in 2007 (Mauffret *et al.*, 2007) with several additions of seismic data on the Spanish margin provided by the Instituto Geológico y Minero de España (IGME) in a very nice web site (<http://www.igme.es/internet/sigeof/>).

### Physiographic setting

The general bathymetry of the Alboran Sea is well known (IOC-UNESCO, 1981) and has been completed by a multibeam map in the Almería Bay region (Gràcia *et al.*, 2006) and more recently a map covering the Economic Zone of Spain (Ballesteros *et al.*, 2008). To the East this area is limited by the Algerian Basin where lies the 2600 m deep bathyal plain. The boundary between the two regions is dotted by several highs: Maimonides, Yusuf Ridge, El Mansour Seamount, Alidade and Cabliers banks (Fig. 1). This last bank, the Provençaux Bank and another unidentified bank that we named Pytheas Bank, formed a supposed volcanic caldera (Gierman *et al.*, 1967). The backbone of the Alboran Sea is the Alboran Ridge that trends NE-SW and is flanked by two depressions: the Alboran Channel to the North and the South Alboran Basin to the South. An apparent continuity between the Alboran Ridge and the Tofino and Xauen banks to the southwest, the presence of several volcanic edifices in Morocco and Spain and large NE-SW strike-slip faults (Carboneras, Jebha faults) suggested that a Trans-Alboran Shear Zone crossed the region (Hernandez *et al.*, 1987; de

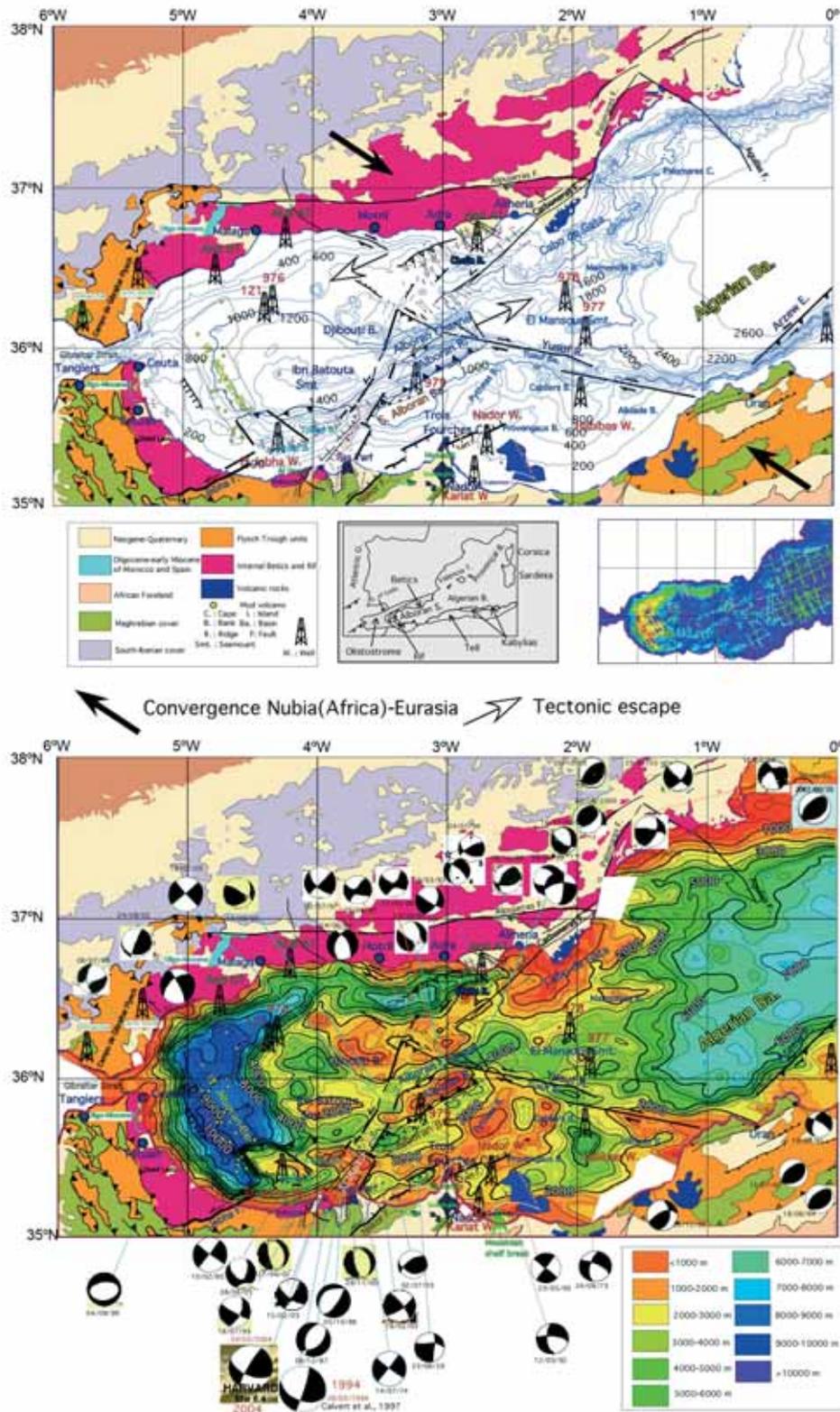
Larouzière *et al.*, 1988). Nevertheless, we will show that the Tofino and Xauen banks are offset relative to the Alboran Ridge and that the connection of this ridge with the Jebha Fault is not evident. The (Ville de) Djibouti and Ibn Batouta banks (Chalouan *et al.*, 1997) are two prominent seamounts that are located in the eastern flank of the Western Alboran Basin. This 1400 m deep basin is protruded by several mud volcanoes and diapirs (Mulder and Parry, 1977; Comas *et al.*, 1992; Pérez-Belzuz *et al.*, 1997; Talukder *et al.*, 2003).

### Geological and tectonic settings

The Alboran Sea is surrounded by the Betic and Rif orogens (Michard *et al.*, 2002 and references therein). The internal Betics and Rif are formed by unmetamorphosed Palaeozoic and Mesozoic rocks terranes (Malaguides and Ghomarides) overlying metamorphic terranes: Nevado-Filabrides in Spain, Alpujarrides and Sebides in Spain and Morocco respectively. These rocks form also the basement of the Alboran Sea as shown by ODP results (Comas *et al.*, 1999). The Internal Betics and Rif and the Alboran Sea are referred as the Alboran Domain or Alboran Plate (Andrieux *et al.*, 1971). There is now a large consensus in the geologic community to group the Alboran, the Kabylas, the Peloritans in Sicily and Calabria in South Italy in a large landmass named AlKaPeCa (Bouillin, 1986), located in the south of the Eurasia margin and east of the present Alboran Sea. This feature was separated from Eurasia by an ocean (Michard *et al.*, 2002; Guerrero *et al.*, 2005) or was directly adjacent to that continental margin (Rosenbaum *et al.*, 2002; Jolivet *et al.*, 2003; Rosenbaum and Lister, 2004). The westwards Miocene displacement of the Alboran Plate (Andrieux *et al.*, 1971) and the coeval westwards compressional deformation (Frizon de Lamotte *et al.*, 1991; García-Dueñas *et al.*, 1992; Martínez-Martínez and Azañón, 1997) are also largely accepted by the geologic community.

The volcanic rocks obtained on land and offshore by dredging and diving surveys (Duggen *et al.*, 2004; Gill *et al.*, 2004), industrial (Jurado and Comas, 1992) and ODP (Comas *et al.*, 1999) wells can be divided into two types: the oldest one (33.6 to 17.4 Ma) is located in the western part of the area, mainly around Malaga, and the youngest (11.8 to 6.6 Ma) is localized in a large stripe from Spain (Cabo de Gata through Alboran Island, Yusuf Ridge, El Mansour Seamount) to Morocco (Trois Fourches, Ras Tarf and Gourougou). The Malaga dikes are related to the Oligocene-early Miocene rifting (Torres-Roldán *et al.*, 1986; Duggen *et al.*, 2004, 2005) of the West Alboran Basin whereas the late Miocene calc-alkaline and shoshonitic volcanic rocks seems to belong to a volcanic arc (Duggen *et al.*, 2004).

The late Miocene and the present tectonics is controlled by large strike-slip faults that are conjugate (right-lateral for the NW-SE and left-



**Figure 1.-** General setting of the Alboran Sea. Upper scheme: compilation of the bathymetric map of the International Bathymetric Chart (IOC-Intergovernmental Oceanographic Commission, 1981) and onshore geological setting (Comas *et al.*, 1999, Frizon de Lamotte, 2004; Crespo-Blanc and Frizon de Lamotte, 2006). Offshore tectonic map from Comas *et al.* (1999) and the present study. Inset map, on the centre: general framework around the Alboran Sea. Inset map, on the right: track map of the seismic profiles used in this study. Lower scheme: depth to basement map of the Alboran Sea from seismic study. Contour interval 500 m. The present tectonic situation in the Alboran sea is mainly illustrated by the seismicity (Stich *et al.*, 2003a; Buforn *et al.*, 2004; Akoglu *et al.*, 2006; Biggs *et al.*, 2006; Cakir *et al.*, 2006), the present motions of the tectonic plates are compiled from the GPS observations (Stich *et al.*, 2006; Serpelloni *et al.*, 2007).

lateral for the NE-SW faults) and governed by a NW-SE compression related to the convergence between Nubia (Africa) and Eurasian plates (Calais *et al.*, 2003; McClusky *et al.*, 2003; Stich *et al.*, 2006; Serpelloni *et al.*, 2007) although the stress tensor deduced from the focal mechanism analysis is NNW-SSE in the Alboran Sea (Stich *et al.*, 2006; Serpelloni *et al.*, 2007) (see later). To the East, the right-lateral Aguilas and the left-lateral Palomares faults may form an arc indenter (Coppier *et al.*, 1989). However, the Alpujarras Fault may have a seaward extension in the Palomares Canyon (Fig. 1) and cut the Palomares Fault. The dextral strike-slip Alpujarras Fault could be a transfer fault between two extensional basins (Martínez-Martínez *et al.*, 2006). This fault and the sinistral Carboneras Fault may be also the boundary of a triangular block escaping towards the West (Martínez-Díaz and Hernández-Enrile, 2004). The present activity of the Carboneras Fault is clearly recorded on the sea floor by a multibeam survey (Gràcia *et al.*, 2006). We will suggest a possible connection between the Carboneras Fault and a large fault zone named here El Idrissi fault (Fig. 1) that offset the Alboran Ridge. The Yusuf Fault is a right-lateral strike-slip fault (Mauffret *et al.*, 1987; Álvarez-Marrón, 1999) that is conjugate of the left-lateral Carboneras Fault. The Alboran Ridge is a compressional structure flanked by two reverse faults (Bourgeois *et al.*, 1992; Woodside and Maldonado, 1992). A seismic profile crossing the northwest scarp of the ridge did not show any evidence of compression and displayed normal faults in the sedimentary layers that infill the Alboran Channel (Watts *et al.*, 1993; Ballesteros *et al.*, 2008). However, this profile crossed the northwest extension of the Yusuf fault that cut the northwest tip of the Alboran Ridge and the normal faulting that is active at Present is attributed to a horsetail of the Yusuf Fault (Willet, 1991) although it crosses the Alboran Channel and offset the north-western flank of the channel (Ballesteros *et al.*, 2008).

### Geophysical setting

The Alboran Sea has been surveyed with several geophysical techniques: refraction (Hatzfeld, 1978), magnetic (Galdeano *et al.*, 1974; Willet, 1991), gravimetric (Willet, 1991; Galindo-Zaldívar *et al.*, 1998; Torné *et al.*, 2000), heat flow (Polyak *et al.*, 1996), seismic (Mulder and Parry, 1977; Gensous *et al.*, 1986; Willet, 1991; Bourgeois *et al.*, 1992; Comas *et al.*, 1992; Morley, 1993; Watts *et al.*, 1993; Calvert *et al.*, 1997; Chalouan *et al.*, 1997), geoid anomaly (Fullea Urchulutegui *et al.*, 2006), general tomography (Calvert *et al.*, 2000; Piromallo and Morelli, 2003; Faccenna *et al.*, 2004; Spakman and Wortel, 2004) and local tomography (Morales *et al.*, 1999; Gurría and Mezcuca, 2000; Serrano *et al.*, 2003).

The refraction (Hatzfeld, 1978) and the gravity modelling (Torné *et al.*, 2000) suggest that the crust is continental and approximately 18-20 km thick. The thinnest crust (15-17 km) of the Alboran Sea is located in the Alboran Channel (Willet, 1991). However, the refraction studies are old and imprecise (D. Hatzfeld, oral communication) and the crust maybe thinner than 20 km beneath the West Alboran Basin where a recent seismic survey shows that the sedimentary cover is as thick as 12.5 km. The crust thins towards the east and is oceanic beneath the Algerian Basin (Comas *et al.*, 1997; Booth-Rea *et al.*, 2007).

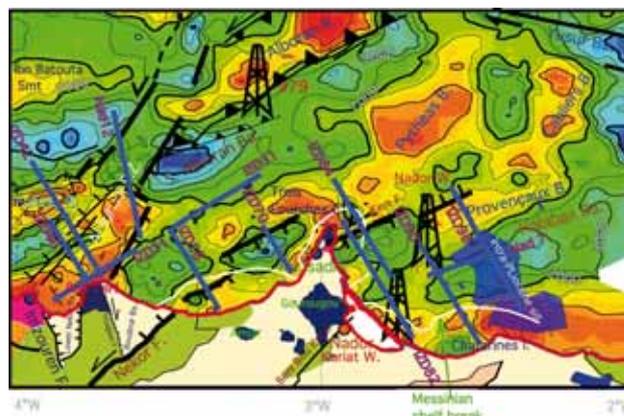
A large magnetic anomaly (more than 500 nannoteslas peak to peak) on the aeromagnetic map (Galdeano and Rossignol, 1977) that trends NE-SW, is located in the centre of the Alboran Sea. It is related to the seamounts that flank the Alboran Channel to the northwest (Willet, 1991; Galindo-Zaldívar *et al.*, 1998) and not to the Alboran Ridge. A similar magnetic anomaly but offset to the southwest relative to the previously described anomaly is located above the Ibn Batouta seamounts.

The heat flow data show (Polyak *et al.*, 1996) a general increase of the thermal regime from west to east and the data in the Algerian Basin confirm the oceanic nature of the crust.

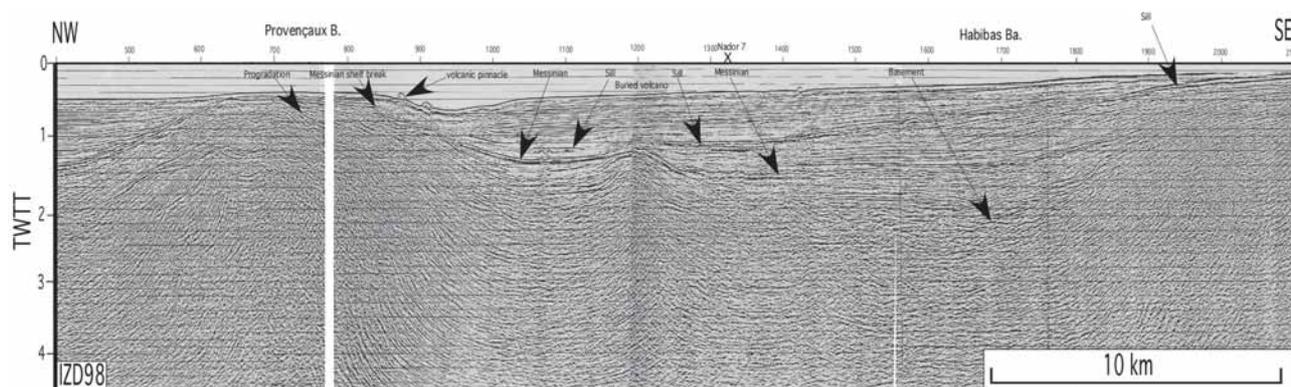
The tomography (Calvert *et al.*, 2000; Piromallo and Morelli, 2003; Faccenna *et al.*, 2004; Spakman and Wortel, 2004) shows a low velocity (warm material) in the upper mantle beneath the Alboran Sea but a high velocity (cold body) in deeper levels, up to 600 km. The geoid (Fullea Urchulutegui *et al.*, 2006) and the gravity modelling (Torné *et al.*, 2000) suggest a thin lithosphere (60-90 km) beneath the Alboran Sea and a lithosphere as thick as 130-160 km under the Gibraltar Strait (Iribarren *et al.*, 2007).

### Description of the Moroccan margin

We will progress in our description of the southern margin of the Alboran Sea from East to West. We use the term Messinian for the prominent reflector that is



**Figure 2.-** Depth to basement and structural map of the Trois Fourches area. Location of the profiles in blue.



**Figure 3.-** Seismic profile in the eastern part of the Trois Fourches Cape (location in figure 2). This profile exhibits an intra- Pliocene sill, north of the Chafarines Islands.

often an unconformity and marks the boundary between the Pliocene and the Miocene sequences. The acoustic basement is made of volcanic and metamorphic rocks, or deformed sedimentary layers.

The main results of the multichannel (Mulder and Parry, 1977; Bourgois *et al.*, 1992; Comas *et al.*, 1992; Morley, 1993; Watts *et al.*, 1993; Calvert *et al.*, 1997; Chalouan *et al.*, 1997) and single channel (Gensous *et al.*, 1986; Willet, 1991) seismic surveys will be later discussed in detail. An isopach map of the western Alboran Sea, mainly focused on the Spanish margin has been already presented (Soto *et al.*, 1996).

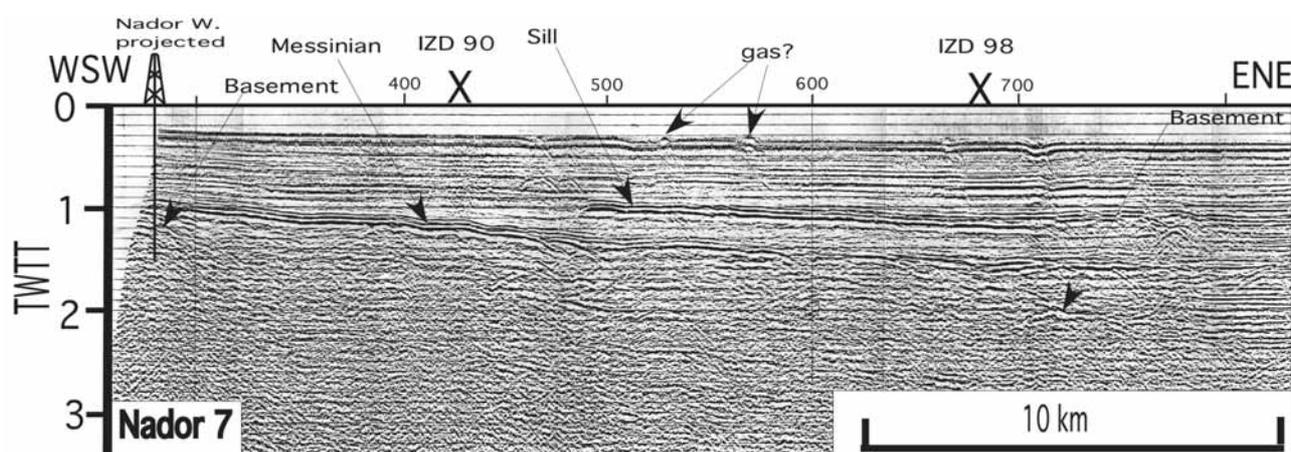
#### Eastern volcanic province

The contact between the eastern region and the Algerian Basin has been described in several publications (Mauffret *et al.*, 1992; Álvarez-Marrón, 1999; Booth-Rea *et al.*, 2007) and has been sampled by two ODP holes that recovered several volcanic pebbles. A diving survey also sampled Tortonian volcanic rocks on the Alboran Ridge, Yusuf Ridge, and Al Mansour Seamount (Duggen *et al.*, 2004; Gill *et al.*, 2004). They are calc-alkaline rocks of Tortonian age (9.32 to 8.7 Ma). The volcanic rocks of the Cap des Trois Fourches have the same age (9.8 Ma) (Hernandez and Bellon,

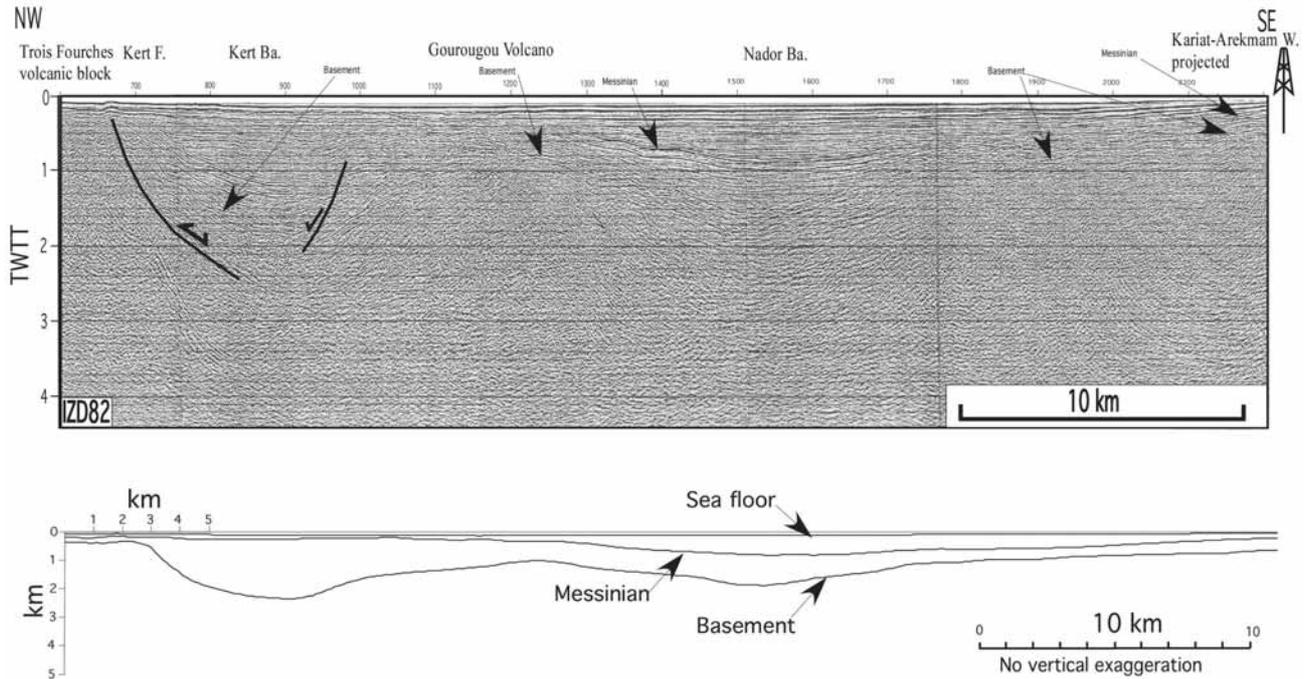
1985) whereas the Gourougou volcano shows an evolution through time from calc-alkaline (9-6.6 Ma), shoshonitic (7-5.4 Ma) to alkaline (4.7-2.6 Ma) (Hernandez and Bellon, 1985; El Bakkali *et al.*, 1998; El Azzouzi *et al.*, 1999; Roger *et al.*, 2000).

In the offshore region (Fig. 2), the volcanic rocks form the basement of several banks (Provençaux, Cabliers, Pytheas). The Pytheas Bank is 4 km wide and 15 km long elongated in the N-S direction. The Cabliers Bank, 6 km wide, 12 km long, has the same trend. The El Mansour seamount is the largest volcanic edifice: 8 km wide, 21 km long and 3.4 km high from the basement to the summit. These volcanic edifices are comparable to the Gourougou volcano, with a diameter of 12 km and 900 m high (El Bakkali *et al.*, 1998). The group Pytheas-Cabliers-Provençaux banks has been assimilated to a caldera (Gierman *et al.*, 1967). However, the distance between the Pytheas and Cabliers banks is more than 30 km and the depression is infilled by 1 km of Pliocene-Quaternary and 1 km of Miocene sediments. The largest calderas are 10-15 km wide and 0.3-0.5 km deep (Cole *et al.*, 2005). Therefore, the caldera hypothesis is unlikely.

A buried volcanic edifice with an important step of the Messinian surface (shot point 1200, Fig. 3) is located along the flank of the Habibas Basin. Some



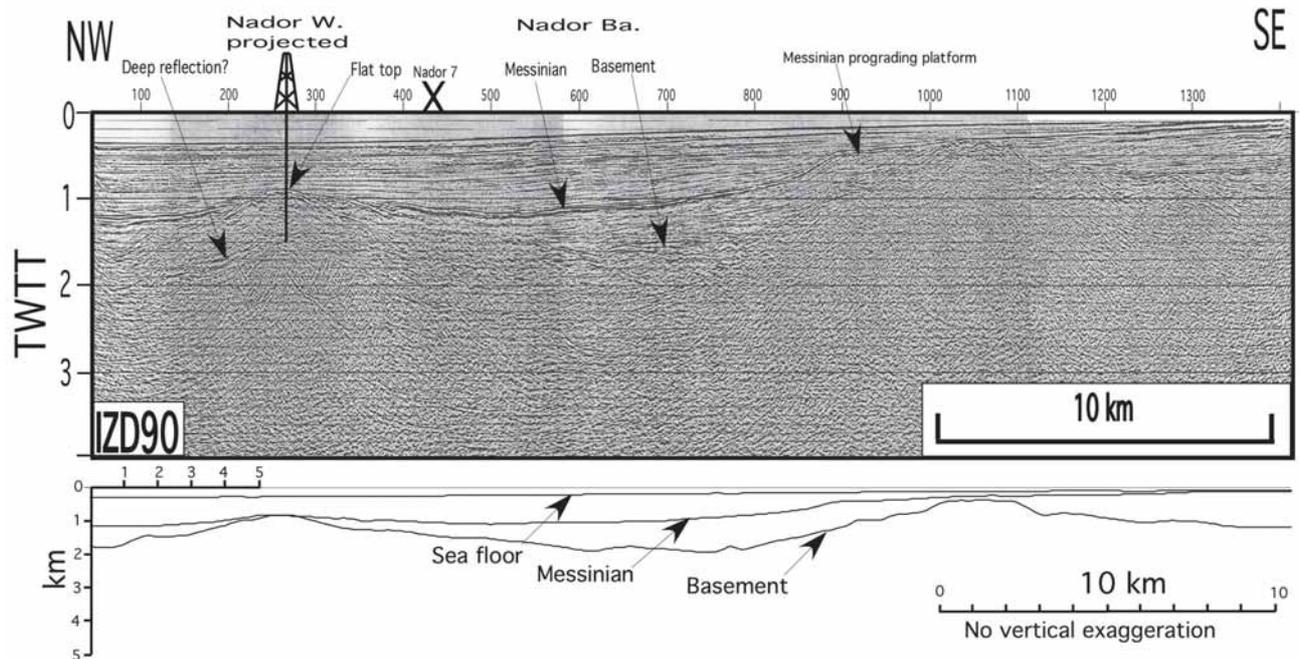
**Figure 4.-** Seismic profile located in figure 2, showing the western boundary of the intra Pliocene sill off the Chafarines Island. In the western end of the profile Nador well is projected.



**Figure 5.-** Seismic profile crossing the Kert Basin and offshore extension of the complex Gourougou volcanic edifice. Location in figure 2. Kariat Arekham well projected on the southern end of the profile.

volcanic pinnacles may protrude the sea floor where it is deeper than 150 m (Fig. 3) but the top of the banks are flat under water depths shallower than 150 m because they are eroded by the waves. The basement is overlain by a sedimentary layer that presents a progradation beneath the Messinian erosional surface that looks like a continental platform with a shelf break on the Provençaux Bank (Fig. 3). Therefore, the sedimentary layer looks like the Messinian-Tortonian carbonate platform described in the Melilla region

(Cornée *et al.*, 2006). The volcanic basement has probably the same age. However, south of the Provençaux Bank, a volcanic sill lies in the Pliocene above the Messinian surface (Fig. 3). The sill is evident in figure 4 where the deformations in the sedimentary layers and the sea floor are caused maybe by fluids and gas related to this sill. The complete seismic grid of this area allows us to trace the surface covered by this sill that is probably related to the Chafarines Island as is shown by the extension of the sill on the continental



**Figure 6.-** Seismic profile crossing the Nador Basin, location in figure 2, showing the Messinian paleo-shelf border (Messinian prograding platform). The Messinian paleo-shelf break is drawn in figure 2 (white line). The Nador well is projected. Flat tops suggest Messinian guyot in this area.

shelf near this island (Fig. 3). Unfortunately there is no any petrographic study of this probable Pliocene volcanic island because it is a Spanish military base and a former penitentiary. The aeromagnetic map shows a very large magnetic anomaly that trends E-W, composed by three magnetic maxima (Demnati, 1972). The first is located on the Gourougou volcano, the second around the Kariat Arekmam well and the third on the Chafarines Island. In the Kariat Arekmam area a local seismic tomography detected a body with a high velocity at 5 km depth that is probably formed by late Miocene volcanic rocks (Serrano *et al.*, 2003). The Kariat Arekmam well drills 164 m in the Pliocene before to reach the Messinian marls (164-320 m). Between 320 and 456 m the well sampled cineritic marl and tuffs, Messinian in age. The hole bottomed in an andesite between 456 and 681 m depth (Wernli, 1988). The depth to basement map (Fig. 2) shows, as the magnetic map, the E-W trend between the Kariat Arekmam well and the Chafarines Island whereas the Gourougou volcano is slightly offset to the NW and flanked by the Nador Basin to the southeast (Fig. 5). The Messinian surface is shallow on the continental shelf and the volcanic basement can be correlated with the 456 m deep volcanic rocks drilled in the Kariat-Arekmam well (Fig. 5). However, the basement in this region could be not entirely volcanic and the Nador well drilled a basement made of shists and quartzite beneath a 740 m thick Quaternary-to-early Pliocene sedimentary layer (Fig. 6). This metamorphic basement has been drilled as deep as 2705 m, probably because several reflections can be observed on the original seismic profile where is placed the hole. These shists and quartzite rocks probably belong to the same metamorphic terranes that outcrop south of the vulcanites located on the Cap des Trois Fourches Cape. However, according to a completely different interpretation of this well (Morley, 1993), the basement has never been reached and the well drilled through clastic and sedimentary rocks, dated 16-11 Ma by K-Ar method, that are slightly metamorphosed by the volcanic activity. The acoustic basement, drilled though almost 1 km, has been confused with a sedimentary layer and we prefer the first interpretation that fits with the on-land study (Negro *et al.*, 2007).

#### *Structure of the Eastern Province*

In the figure 2 two orientations are evident: an E-W to ENE-WSW trend located in the south of the studied area and an N-S trend in the north. The E-W trend has been already described for the Gourougou-Chafarines volcanic system. North of this structure the Habibas Basin (Fig. 3) shows an E-W orientation and then a N-S trend along the Cabliers Bank (Fig. 1). This more than 4 km deep basin has been drilled by the deep-sea (923 m) Habibas well (Kheidri *et al.*, 2000). The metamorphic basement (4496 m depth) is covered by 843 m of Tortonian-Serravallian, 325 m of Tortonian, 1271 m of

Messinian marine at the base with some gypsum and halite at the top, and 571 m of Pliocene-Quaternary layers. The second important basin of this area is the Kert Basin (Figs. 5 and 7). This depression is limited to the north by the Kert Fault that was a left-lateral fault during the early Tortonian formation of the basin (Morel, 1987; Wernli, 1988; Morel, 1989). However, the Kert Fault had an extensional component during the late Tortonian-Messinian (Morel, 1989) and the Kert Basin shows a graben configuration (Figs. 5 and 6) with the Gourougou volcano in a hanging wall position. The Kert fault may have recently moderate reverse motion as suggested by the deformation of the sea floor (Fig. 5). On the northern side of the Trois Fourches structure, the early Messinian layers beneath the erosional surface present a downlap configuration (Fig. 7). However, if the post Messinian tilt ( $5.5$  to  $4^\circ$ ) is removed, the downlap configuration is less evident. Therefore, the current dip of Messinian sediments may result by the addition of an initial down-slope and a Pliocene tilting. The Trois Fourches volcanic block shows an arched shape of the Messinian surface with 0.7 km difference in level (Fig. 7), suggesting an uplift of the block. This uplift cannot be related to the formation of the volcanic feature that is older than the Messinian (9 Ma; Hernandez and Bellon, 1985), but some relief had probably persisted during the Messinian. On land, the Messinian carbonate platform and reefs with a progradation to the south between the Trois Fourches volcanic edifice and the Gourougou volcano have been described by different authors (Roger *et al.*, 2000; Rouchy *et al.*, 2003; Cornée *et al.*, 2006; Van Assen *et al.*, 2006; Garcia *et al.*, 2007). With the progradation towards the north we can conclude that the Trois Fourches volcanic centre was an island during the early Messinian, surrounded by a carbonate reef platform. The Messinian continental shelf is evident in the south (Fig. 6) and shows an embayment (Fig. 2) where the Trois Fourches Island was separated from the continent by a deep basin that will be filled during the late Miocene-Pliocene by the Gourougou volcano (Münch *et al.*, 2001). The change of direction from NE-SW to N-S is observed between the Provençaux Bank and Cabliers Bank. The Pytheas Bank shows the same structural orientation, evident on the bathymetric map (Fig. 1) and the depth to basement map (Fig. 2).

#### *The Messadit Basin*

An E-W high forms a westwards extension of the Trois Fourches volcanic centre. This high is flanked towards the NE by a 4 km deep basin (Fig. 2). This basin has been already illustrated in a publication (Watts *et al.*, 1993). A dense seismic grid allows us to precise the structure of this Messadit Basin. A clear fan-shaped configuration can be observed in the deep layers that are probably deposited during a rifting event (Fig. 8). This syn-rift sequence has been tilted and the tilt of the break-up unconformity can be estimated to 1.2 km. The Messadit Basin is limited to

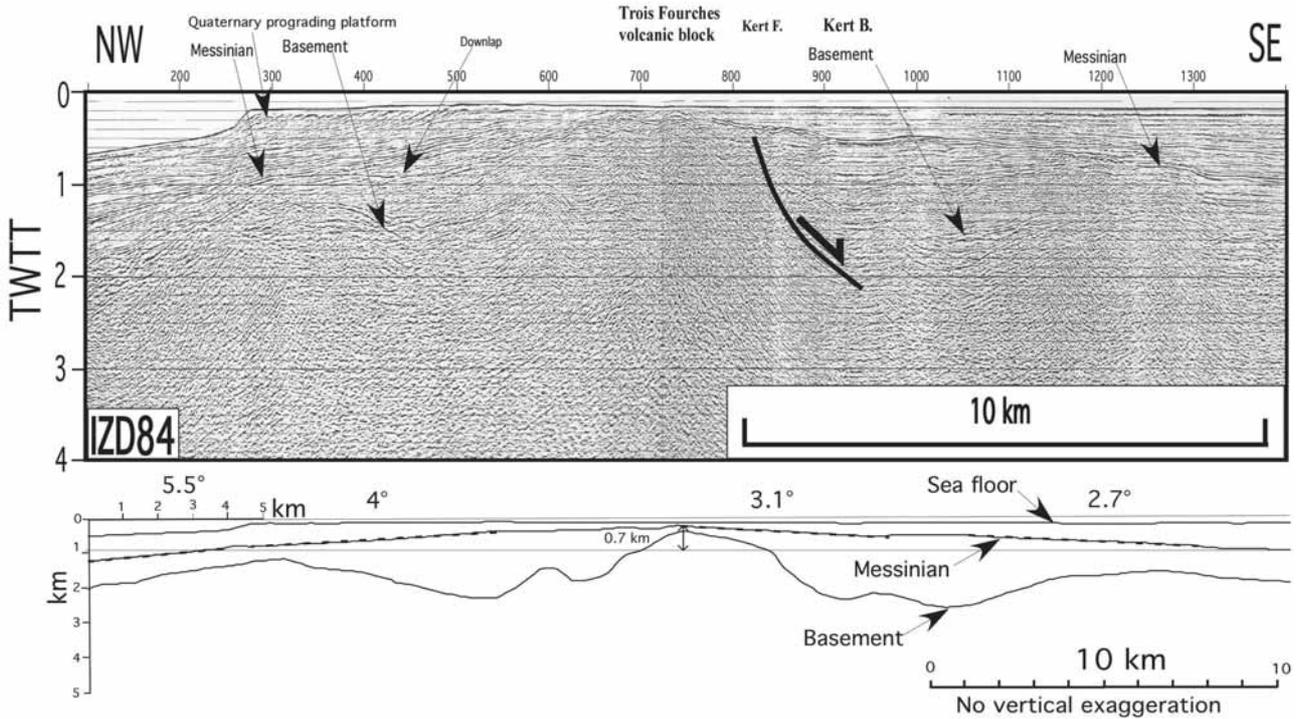


Figure 7.- Seismic profile crossing the offshore extension of the Trois Fourches volcanic complex. The quaternary forced regression prism shows paleo-shore rising to more than 100 m below present day sea level.

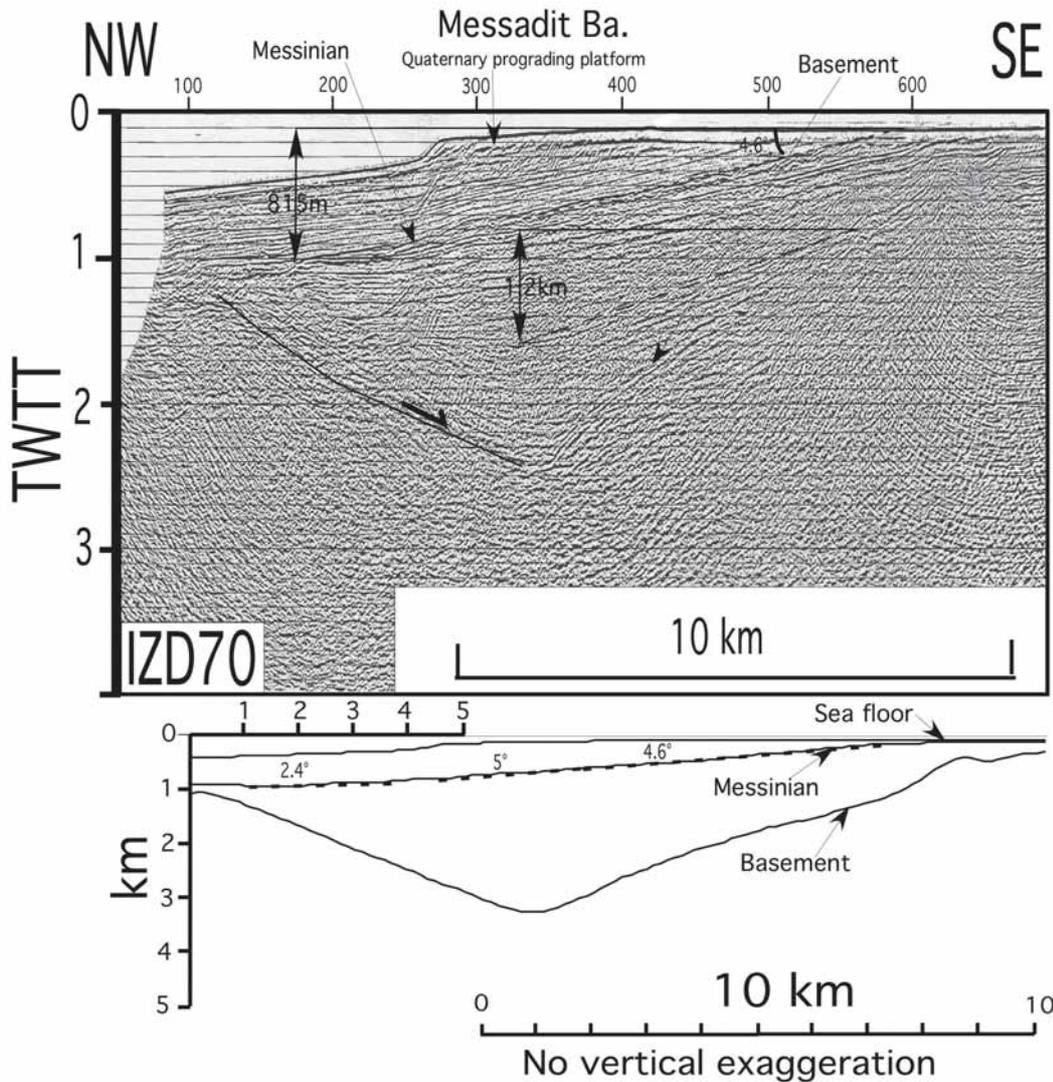


Figure 8.- Seismic profile crossing the Messadit Basin, west of the trois fourches Cape. Note the tilting of the Messinian erosional surface illustrating the vertical movements since 5.3 Ma on this area. Location of the seismic line in figure 2.

the north by a ridge that is the footwall of the graben (Fig. 2). The  $4.6^\circ$  tilting of the Messinian unconformity is evaluated to 815 m and this lower estimation is related to the erosion on the continental shelf. The tilted Pliocene layers are overlain by a small Quaternary progradation continental shelf (Gensous *et al.*, 1986).

#### The Boudinar Basin and the Nekor Fault

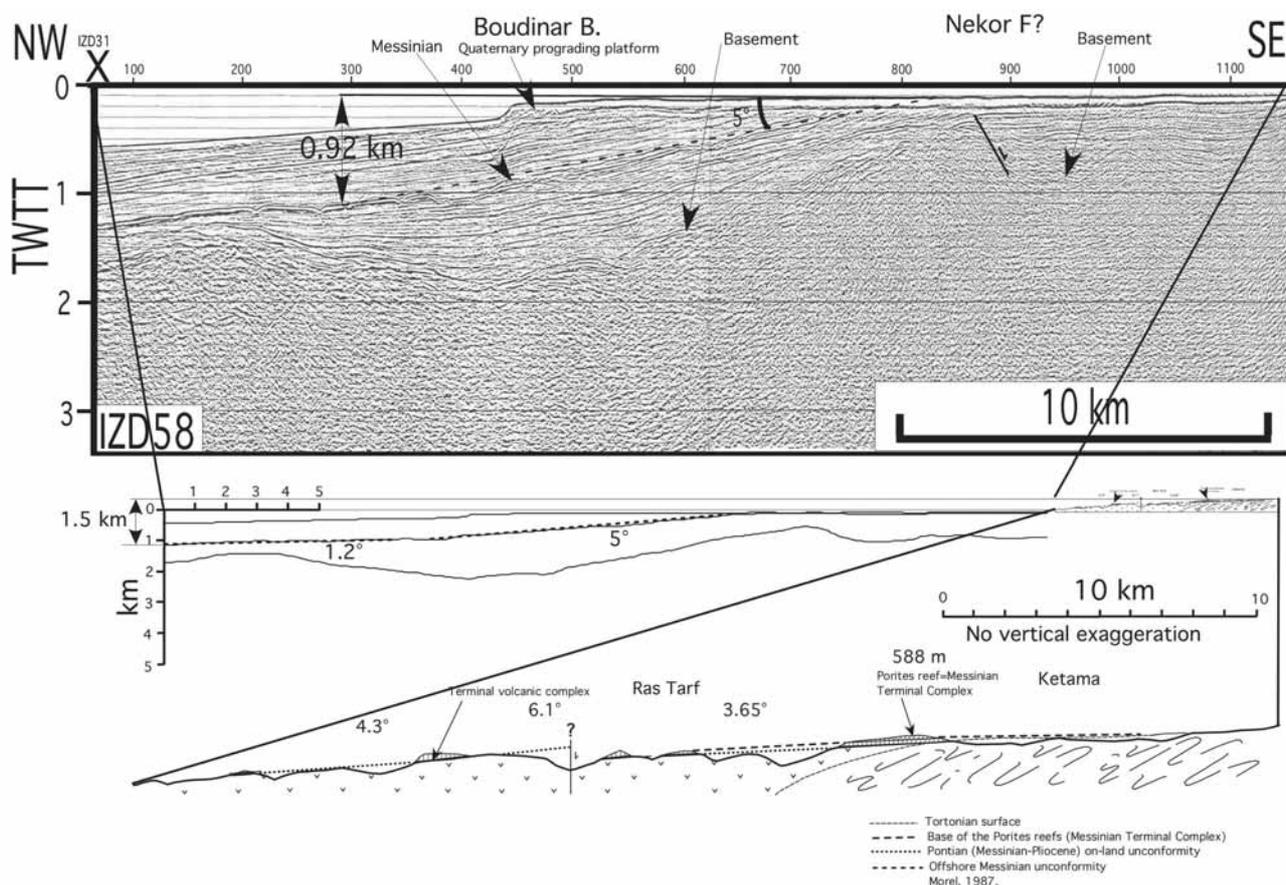
The Boudinar Basin is offset to the NW relative to the Messadit Basin and these two basins are not connected. The triangular-shaped Boudinar Basin is limited to the southeast by the prominent Nekor Fault (Frizon de Lamotte, 1987; Asebriy *et al.*, 1993; Michard *et al.*, 2006). A large magnetic anomaly, maybe related to the Beni Malek serpentinised peridotite (Michard *et al.*, 1992), is parallel (NE-SW) to the Nekor Fault (Demnati, 1972). The aeromagnetic map does not show the extension of this anomaly in the offshore area. The ultramafic body has not been identified by the tomographic studies because the peridotite slices are maybe too shallow to be seen in the 5 km tomographic level (Serrano *et al.*, 2003).

The Nekor Fault is correlated to the Kert Fault in some publications (Bourgois *et al.*, 1992; Asebriy *et al.*, 1993). However, the detailed study of this area (Morel, 1987) and the present study (Fig. 2) do not show any evidence of this connection. The Nekor Fault was a

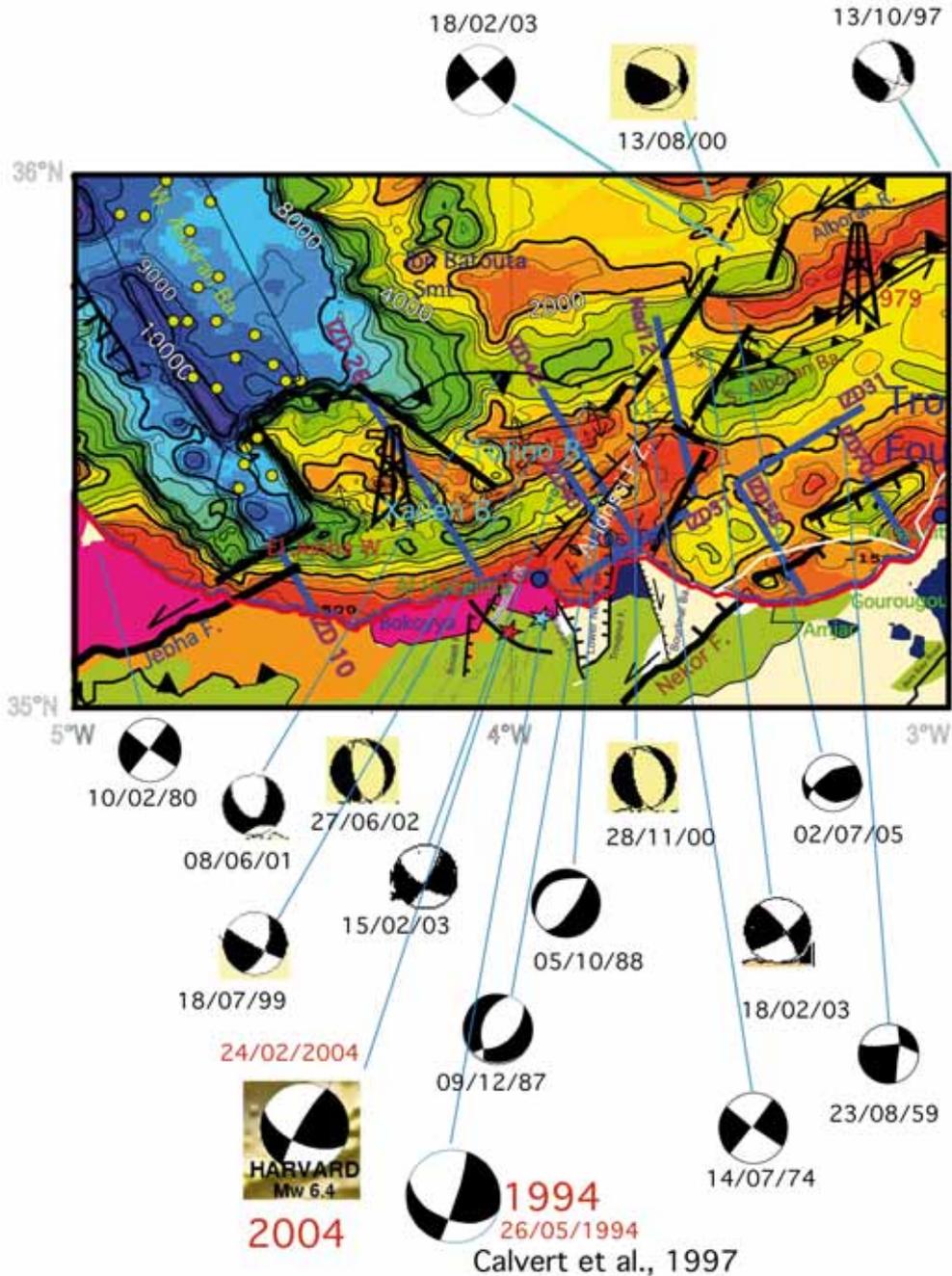
major left-lateral strike-slip fault during the early Tortonian (Morel, 1989). During the late Tortonian and the Messinian the fault was normal and controlled the sedimentation of the Boudinar Basin. A normal fault is in strike with the Nekor Fault (Figs. 2 and 9) but the throw is opposite (facing southeast). In the other hand, the three basins Boudinar, Messadit and Kert are clearly right-lateral offset (Fig. 2) and we will show in the discussion that the Nekor Fault has probably a complex geometry. Offshore, the southeastern flank of the Boudinar Basin is not faulted and we observe the same geometry as in the Messadit Basin: a tilted graben with a fan-shaped configuration dipping to the northwest (Fig. 10). The Messinian surface presents the same dip ( $5^\circ$ ) as the surface in the Messadit Basin. A detailed study of the Ras Tarf shows (Morel, 1987) that different surfaces merging or cutting each other [Tortonian, base of the Messinian reef Terminal Complex, "Pontian" (Messinian-Pliocene boundary) erosional surface] present a similar tilt ( $3.65^\circ$  to  $6.1^\circ$ ) and the Messinian reefs are 588 m high. A 1.5 km difference in altitude is observed between these reefs and the Messinian erosional surface in the basin.

#### Ras Tarf, Al Hoceima Region and Al Idrissi F. Z.

The Ras Tarf volcanic structure has been dated 12-13 Ma by K-Ar technique (Hernandez and Bellon, 1985). However, the lavas are intercalated in Messinian



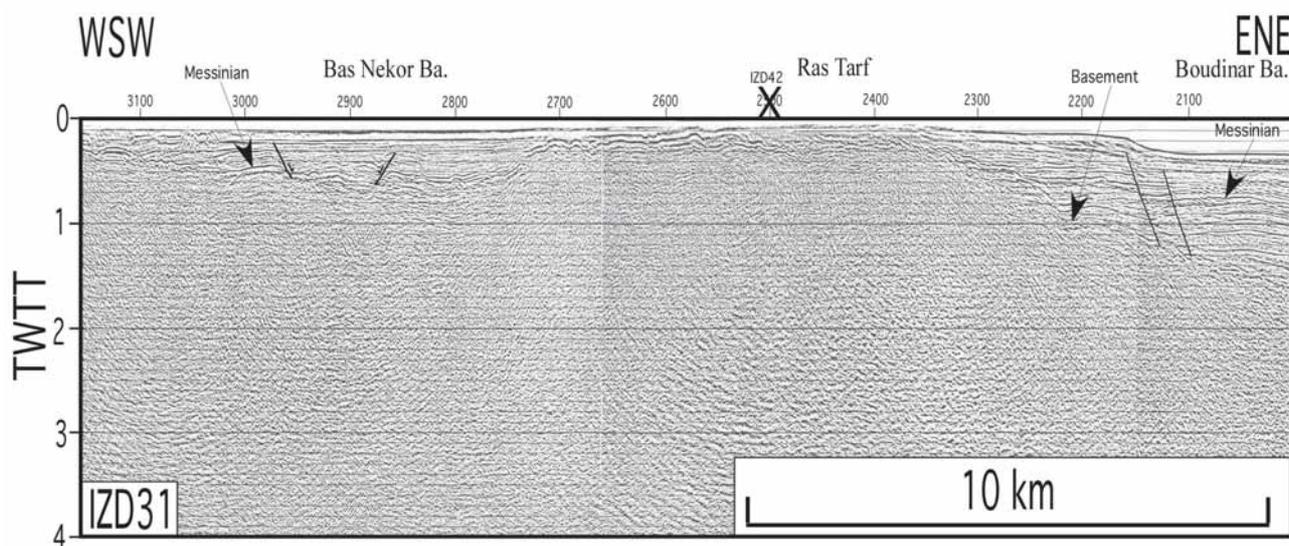
**Figure 9.** Seismic profile crossing the Boudinar Basin and the possible offshore extension of the Nekor Fault. This profile shows the offshore tilting of the Messinian surface and its onshore extension (compilation from Morel, 1987).



**Figure 10.-** This figure is a zoom of figure 2 showing in details Al Idrissi fault zone, Tofino and Xauen banks.

layers and consequently the Ras Tarf would be younger than 12 Ma (Morel, 1987). The Ras Tarf Peninsula separates the Boudinar Basin and the Bas Nekor Basin (Fig. 11). Several normal faulting are observed in this basin and off the Al Hoceima Region (Calvert *et al.*, 1997). The normal faults, that trend NNE-SSW, are dipping west and east with a horst and graben configuration. We name this disturbed region the Al Idrissi F. Z. A small horst is uplifted (Fig. 12) and forms a 400 m high knoll to the NE that merges with a large plateau (Fig. 13). Off Ras Tarf volcanic complex the tilt is more pronounced (6 ° and 11°, Fig. 12) than in the Boudinar Basin, and the progradational body maybe

Messinian or early Pliocene. The profile shown in figure 13 crosses a high that is the southwestern extension of the Alboran Ridge, separated by a saddle and offset (Fig. 10). It is known (Gensous *et al.*, 1986; Bourgois *et al.*, 1992; Watts *et al.*, 1993; Comas *et al.*, 1999) that the Alboran Ridge is a 28 km wide anticline and the Messinian is tilted in both sides of the ridge. This disposition allows us to estimate the shortening of the Alboran Ridge to 2.8 km. The 13 km wide high shown in figure 13 is limited by reverse faults with double vergence. The shortening is evaluated to about 4 km. This high is flanked by two basins. The western basin that is an extension of the West Alboran Basin, and is located between the Ibn Batouta and Tofino



**Figure 11.-** Seismic profile crossing the Bas Nekor Basin, the Ras Tarf volcanic edifice and the Boudinar Basin. Observe the recent normal faulting (NNW-SSW) in the two basins.

seamounts (Fig. 10). The eastern basin is the South Alboran Basin that is up to 4.5 km deep at its western termination. The reverse faults and folds that limit the Alboran Ridge close the ODP 979 area (Comas *et al.*, 1999) are more pronounced towards the southwest (Willet, 1991) and the South Alboran Basin corresponds to a syncline where the deformation is the most intense. In summary the Al Idrissi F. Z. is intensively deformed with normal faults to the south and left-lateral strike-slip faults that offset the Alboran Ridge to the north. Right-lateral, NW-SE conjugate faults probably also offset the Al Idrissi F. Z.

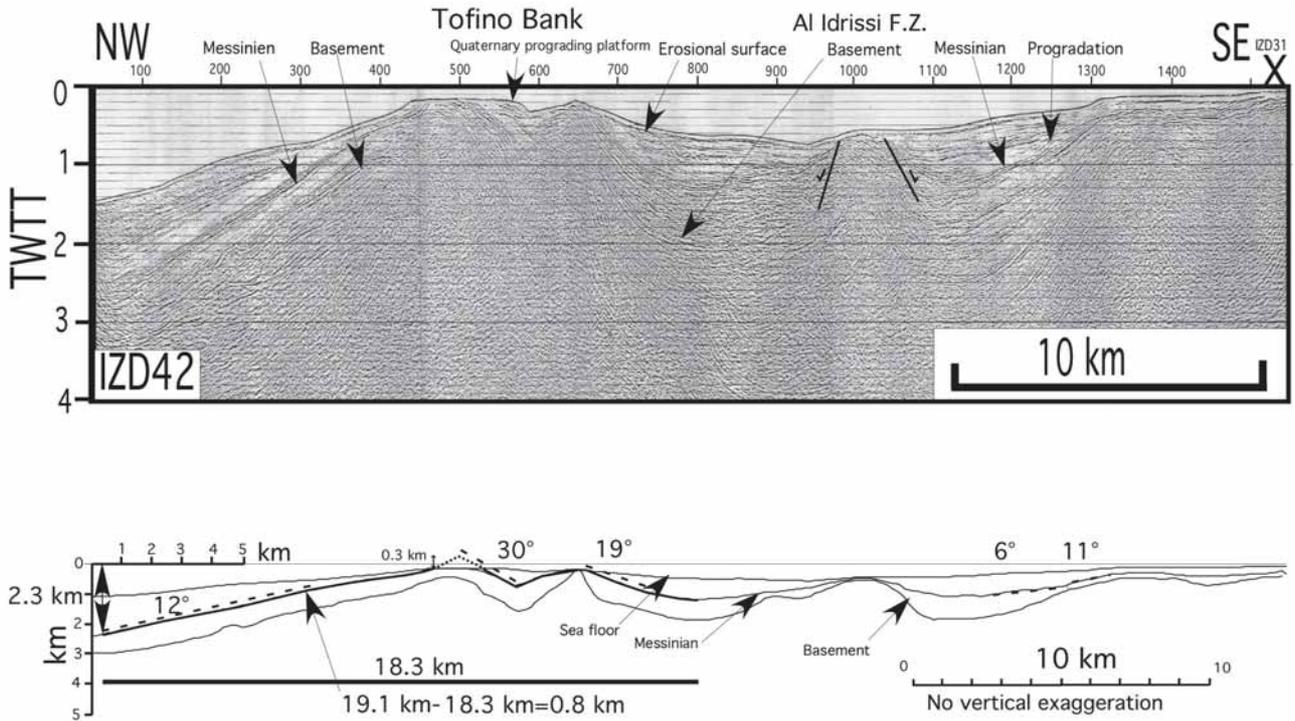
Two large earthquakes have hit this town. The first shock occurred the 26 May 2004 (Calvert *et al.*, 1997; El Alami *et al.*, 1998; Bezzeghoud and Buforn, 1999; Thio *et al.*, 1999; Buforn *et al.*, 2004). The second shock struck the city the 24/02/2004 (Aït Brahim *et al.*, 2004; Jabour *et al.*, 2004; Stich *et al.*, 2005). The INSAR studies (Akoglu *et al.*, 2006; Biggs *et al.*, 2006; Cakir *et al.*, 2006) show that the first earthquake was located on a NNE-SSW fault whereas the second one occurred on a fault that trends NW-SE. The focal mechanisms (CMT Harvard; IAG, Instituto Andaluz de Geofísica; EMSC, European Mediterranean Seismological Centre; SED, Swiss Seismological Service) suggest that the first fault was a NNE-SSW transtensive left-lateral strike-slip fault and the second a NW-SE conjugate transtensive right-lateral fault. Several studies of the micro-seismicity and aftershocks with a temporary network of seismological stations have been performed before and after the 1994 earthquake (Hatzfeld *et al.*, 1993; Calvert *et al.*, 1997; El Alami *et al.*, 1998). Deformation appears to be distributed in a shear zone with several strike-slip and normal faults that trend NNE to N-S. One cluster of micro-earthquakes trending N-S is located south of lower Nekor Basin (Hatzfeld *et al.*, 1993), the second cluster of aftershocks that trend NNE-SSW is located in the

vicinity of the Boussekkour Fault-Al Hoceima (Calvert *et al.*, 1997; El Alami *et al.*, 1998).

Offshore only one determination (02/07/2005, SED) shows a reverse motion on the southwestern tip of the Alboran Ridge (Fig. 10). The other part of the Alboran Ridge is devoid of moderate earthquakes, except one (13/10/1997) with a normal motion, whereas the seismic profiles crossing the ridge show a compression that is maybe inactive at present. Two focal mechanisms (14/07/1974; Bezzeghoud and Buforn, 1999; 18/02/2003, EMSC) with a strike-slip component are detected on the high located southwest of the Alboran Ridge (Fig. 13). A third determination in the same area (28/11/2000, IAG; Stich *et al.*, 2003a) is relative to a normal fault with a strike-slip component. Two focal mechanisms at the same place (9/12/1987 and 5/10/1988; Bezzeghoud and Buforn, 1999) suggest NNE-SSW normal faulting where we found normal faults with the same orientation. Two mechanisms (08/06/2001 and 27/06/2002) are normal and one (15/02/2003) shows a strike-slip component (Stich *et al.*, 2003a) on the Tofino Bank area, although the compression is evident on the seismic profiles (see below).

#### Tofino Bank

The offset between the Alboran Ridge and the Tofino Bank is evaluated to 28 km (Fig. 10). The Tofino Bank is formed by two anticlines that trend E-W with a shortening estimated to 0.8 km (Fig. 12). The northern anticline is eroded (0.3 km) whereas the southern one is deeper than the waves' action and slightly eroded. An erosional surface dipping to the south is observed as deep as 400 m (Fig. 12). This surface was originally at the same level as the continental shelf and the southwards dipping is related to the subsidence in the syncline and the correlative uplift of the anticline (Gensous *et al.*,



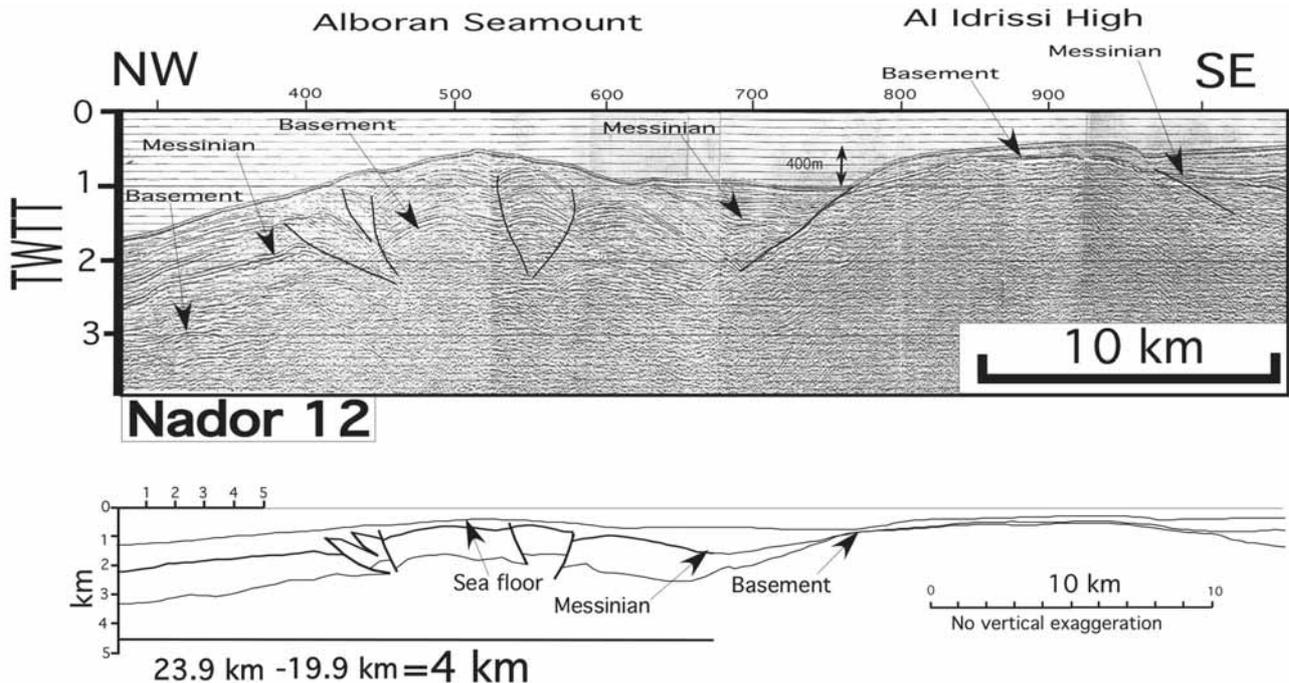
**Figure 12.-** Seismic profile crossing the Tofino Bank and the Al Idrissi Fault Zone. Two eroded anticline are forming the Tofino Bank (Gensous *et al.*, 1986). 0.8 of N-S shortening has been estimated on this area. Discussion in the text.

1986). The erosional surface is probably placed between the Pliocene and the Quaternary that is represented on the top of the Tofino Bank by a progradational unit (Gensous *et al.*, 1986).

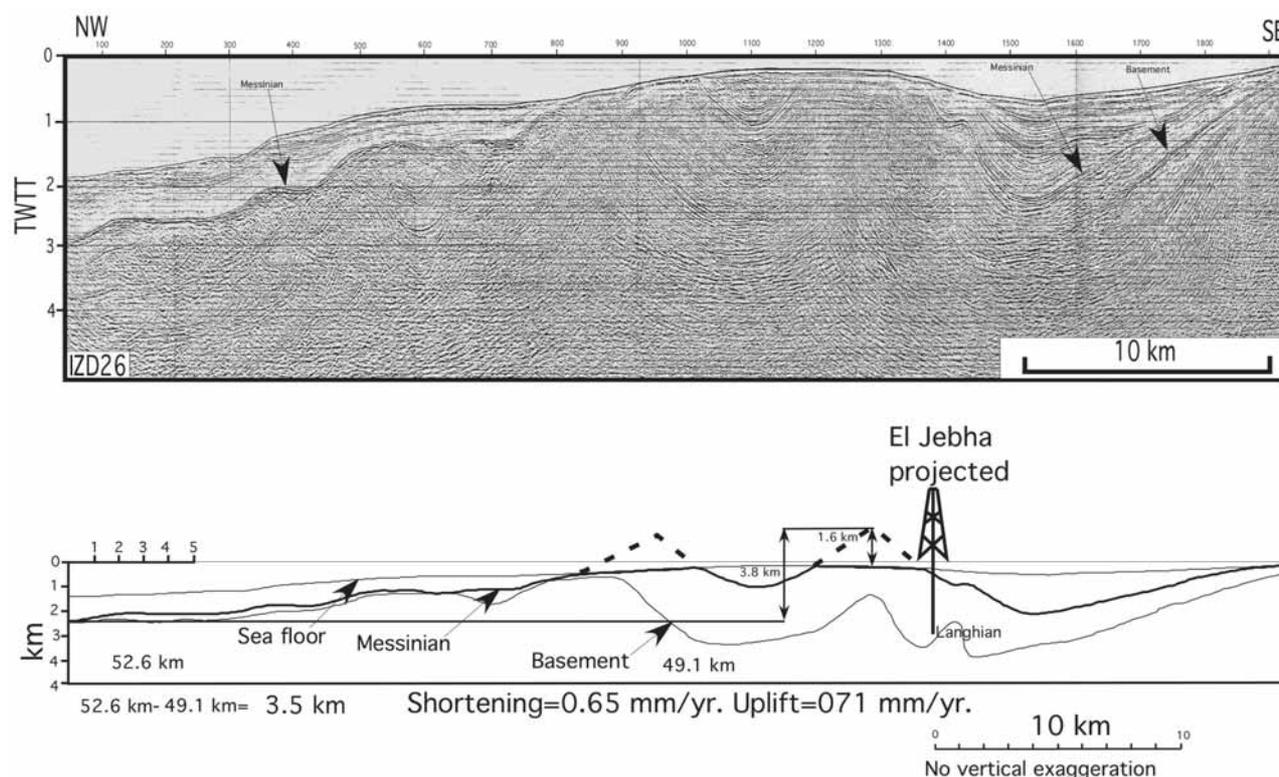
*Xauen Bank*

This bank has been drilled by the El Jebha well (Fig. 14) that was described in detail (Morley, 1993;

Chalouan *et al.*, 1997). The Messinian (213 m) to the base of the Tortonian (1962 m) sediments corresponds to claystone, turbiditic sandstone and volcanic clasts. From 1962 m to 2696 m the Serravallian and Langhian layers are composed by bathyal claystones with rare thin turbiditic sandstone intercalations. Early Miocene microfaunas observed at the base of the well maybe reworked (Chalouan *et al.*, 1997). It is evident that



**Figure 13.-** Seismic profile crossing the southern extension of the Alboran Ridge and the Al Idrissi High. A shortening of 4 km has been estimated for the Alboran seamount area.



**Figure 14.-** Seismic profile crossing the Xauen Bank. Two anticlines forming this structure are deeply eroded (1.6 km) and the shortening has been estimated (3.5 km) with an average rate since the Messinian of 0.65 mm/yr. The uplift of 3.8 km corresponds to a rate of 0.71 mm/yr.

the sedimentary layers drilled on the Xauen Bank was originally deposited in the very deep West Alboran Basin then uplifted by the compression on the bank. The shortening is evaluated to 3.5 km with two main anticlines that trend E-W. The erosion cut (1.6 km) the top of the folds and the uplift measured from their top the Messinian of the deep basin is estimated to 3.8 km (Fig. 14). The Xauen Bank is separated from the West Alboran Basin by a N-vergent thrust system located to the north of the bank, whereas the eastern and western flanks are limited by abrupt NW-SE scarps that are probably right-lateral strike-slip faults (Fig. 10).

#### West Alboran Basin

The West Alboran Basin has been described in detail in several publications (Mulder and Parry, 1977; Bourgois *et al.*, 1992; Morley, 1993; Chalouan *et al.*, 1997; Comas *et al.*, 1999). The presence of mud diapirs in the early Miocene West Alboran Basin disturb the sedimentary layers and conceal the deep part of the basin (Mulder and Parry, 1977; Campillo *et al.*, 1992; Pérez-Belzuz *et al.*, 1997; Talukder *et al.*, 2003). The folds of the Xauen Bank have been confused with mud diapirs (Morley, 1993). The depth to basement is more than 10 km (Figs. 1 and 10) and a recent industrial seismic survey shows that the basement can be as deep as 12.5 km. The southern boundary of the West Alboran Basin with steep scarps in the basement map and left-lateral offset (Fig. 10) corresponds to the Jebha Fault that guided the

displacement of the Internal Zone during the early Tortonian (Morel, 1989). Although a recent reactivation is described on-land (Benmakhlouf *et al.*, 2005) with right-lateral motion and thrusting to the southeast, the seismic profiles do not show any evidence of present activity in the Pliocene-Quaternary sedimentary layers (Fig. 15). We will discuss (see later) the real signification of the Jebha Fault. The depth to basement map (Fig. 1) shows an embayment off the Tetuan Basin then the scarp that limits the West Alboran Basin is offset to the west and the trend changes, just like the coast, from NNW-SSE to N-S. This trend is also observed off the Gibraltar Strait (Fig. 1).

#### Discussion

##### Eastern volcanic province

The Cabliers-Provençaux banks and Pytheas Bank are trending N-S in their northern portion and they turn NE-SW and are related to Gourougou and the Cap des Trois Fourches volcanic complex respectively. The Alboran Volcanic Arc was probably N-S oriented during its early to middle Miocene travel toward the west, and then the arc may have turned clockwise because the late Miocene collision was more pronounced in the Betics range than in the Rif. The NE-SW and E-W trend are probably related to the left-lateral tear or STEP faults that limit the volcanic arc to the south (Spakman and Wortel, 2004; Govers and Wortel, 2005). The Arzew Escarpment, on the Algerian Margin, probably

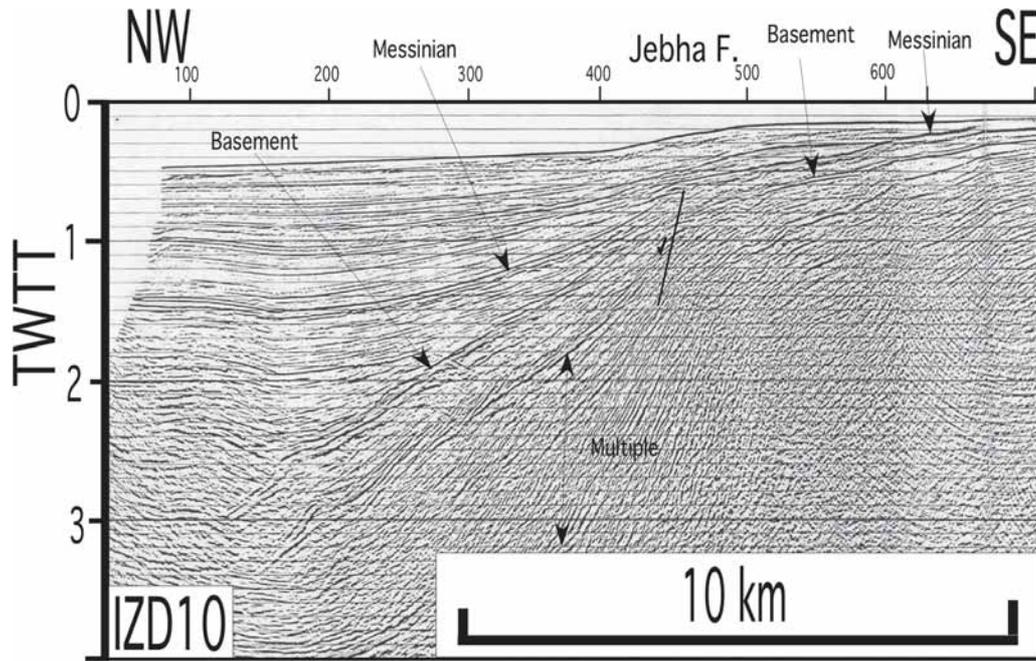


Figure 15.- Seismic profile crossing the offshore extension toward the NE, of the Jebha Fault, sealed by the Messinian unconformity. See the text for explanation.

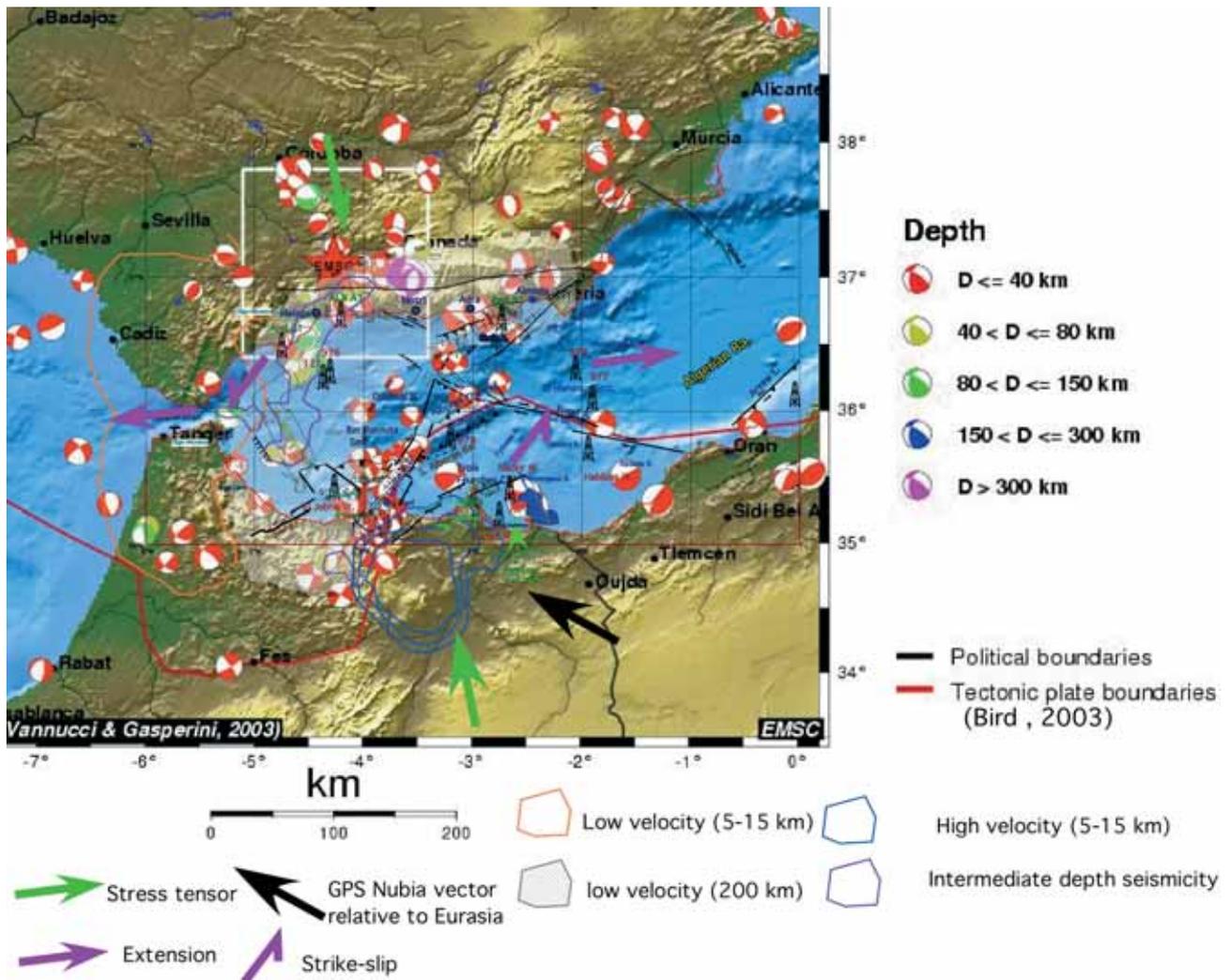


Figure 16.- General tectonic framework of the Alboran Sea, superimposed with focal mechanisms of the Alboran area (after Vannucci and Gasperini, 2003) and the plate boundary proposed by Bird (2003). Stress tensor and GPS Nubian vector relative to Eurasia from Stich *et al.* (2006) and Serpelloni *et al.* (2007).

belong to the same system (Domzig *et al.*, 2006) but a present activity of the Arzew Fault cannot be excluded (Mauffret, 2007). The Gourougou-Kariat Arekmam-Chafarines Island volcanic structure shows an E-W trend on the aeromagnetic map (Demnati, 1972).

The persistence of the volcanism up to late Pliocene in this region can be explained by a slab window that is inferred in the Melilla-Oran region at the contact between the volcanic arc and the tear faults (Maury *et al.*, 2000; Faccenna *et al.*, 2004). The motion along the NE-SW and E-W faults was left-lateral during the westward motion of the volcanic arc. The motion can be opposite (right-lateral) on the E-W structure during the present motion between the Eurasia and Nubia (Africa) plates as shown by the Yusuf Fault.

#### *Nekor and Kert F. Z.*

The Kert Fault (Fig. 15), the Nekor Fault and the three associated basins Kert, Messadit and Boudinar basins are related to the early Tortonian (Morel, 1987, 1989) left-lateral faulting along tear faults. In these areas an E-W stretching accompanying a middle Miocene exhumation of metamorphic rocks is followed by brittle normal faulting until the Messinian (Negro *et al.*, 2007). A clear offshore extension of the Nekor Fault has not been found but a strike-slip fault may have a scissor expression. However, it is clear that the Nekor and Kert faults and the three associated basins belong to the same system (Morel, 1987) and are the superficial expression (flower structure) of a deep, early Tortonian fault that affected the whole crust. Moreover, the same complexity can be observed in the southern extension of the Nekor Fault on land (Asebriy *et al.*, 1993). A low velocity zone is located offshore in the tomographic 5 km-deep slice (Serrano *et al.*, 2003) and could be correspond to the Messadit Basin. A low velocity from 0 to 11 km has been also identified by tomography above the same region and the Boudinar Basin (Gurría and Mezcuca, 2000). SE of the Nekor Fault in another tomographic study (Calvert *et al.*, 2000) a prominent positive velocity anomaly is imaged between 5 and 30 km (Fig. 16). However, the anomaly is very large and maybe connected to the Al Idrissi F. Z instead of the Nekor Fault. The seismicity of the Al Hoceima region demonstrates that the Nekor Fault is not active at Present (Hatzfeld *et al.*, 1993).

#### *Jebha Fault*

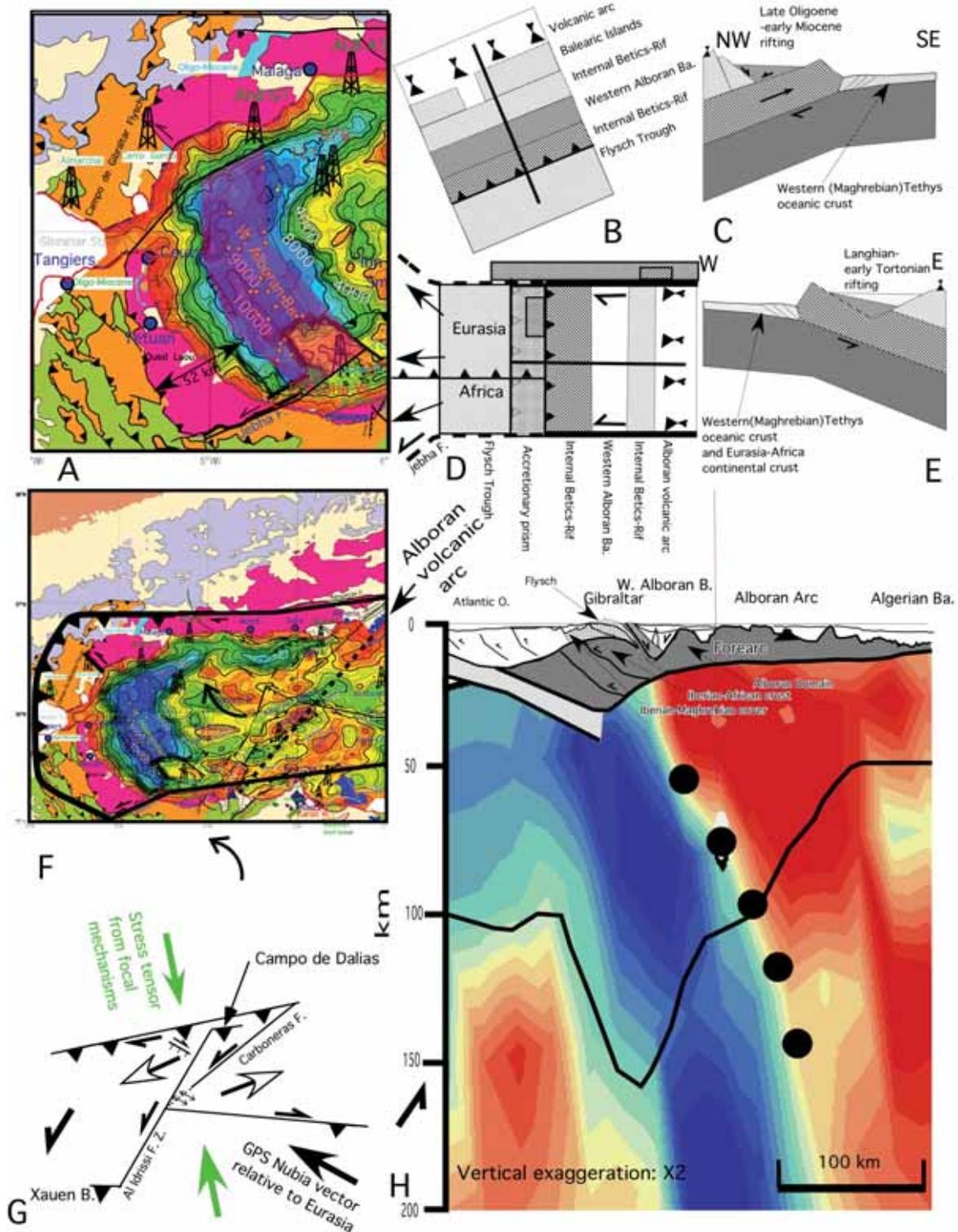
A Trans-Alboran Shear Zone has been proposed (de Larouzière *et al.*, 1988) with several positions, the most popular being the junction of Jebha Fault, Alboran Ridge and Carboneras Fault (Maldonado *et al.*, 1992). However, the first proposition (Leblanc, 1990) was to link the Carboneras Fault to the Jebha Fault during the Burdigalian, whereas it is suggested in more recent publications (Woodside and Maldonado, 1992; Meghraoui *et al.*, 1996; Fernández-Ibáñez *et al.*, 2007)

that the Jebha Fault is active today. A fault can be traced beneath the Messinian erosional surface but it is sealed by this unconformity (Fig. 15). A left-lateral strike-slip faulting is proposed during the early Tortonian (Morel, 1987). However, it is evident from the depth to basement map (Fig. 17A) that the Jebha Fault is the southwestern boundary of the early Miocene West Alboran Basin. The Xauen Bank forms a nose made of deformed sediments of the deep basin but the limit of the basin in line with the Jebha Fault can be observed on the northwest side of the bank. In fact the main left-lateral displacement (about 50 km) of the Jebha Fault has been dated as old as Burdigalian (Olivier, 1981). A late Oligocene-Burdigalian, E-W extension has been described (Ouazani-Touhami and Chalouan, 1995) in the northern Internal Rif. If the Internal Zone is displaced 52 km to the northeast (Fig. 17A) the early Miocene West Alboran Basin is filled. Moreover, the northern tip of the Internal Rif is in strike with the western end of the Internal Betics and the southern boundary of the Internal Rif becomes adjacent to the Bokkoya Massif close to Al Hoceima. However, the Jebha Fault could be active on land in transpression during the Messinian-lower Pliocene (Morel, 1989; Benmakhlof *et al.*, 2005). In the Gibraltar Arc area the fan pattern of the tectonic transport (Fig. 17D) suggests an arc formation during its curvature, similar to a piedmont glacier formation (Balanyá *et al.*, 2007). This disposition may explain the counter-clockwise of the Jebha Fault relative to a E-W tear fault during the final docking of the Alboran Plate (Figs. 17D and 17F). This emplacement of the arc was coeval with a clockwise rotation of Spain and a counter-clockwise rotation of Morocco (Platt *et al.*, 2003). Therefore, it is unlikely that the Jebha Fault is an extension of the Alboran Ridge.

#### *Al Idrissi F. Z.*

The position of the two major earthquakes (1994 and 2004) of Al Hoceima is not very precise and they do not correspond to a known fault, although the Boussekour fault is a good candidate for the 1994 earthquake (El Alami *et al.*, 1998; Akoglu *et al.*, 2006). However, the superficial manifestations of the earthquakes are open fissures (Aït Brahim *et al.*, 2004) that are probably related to blind faults. Moreover, the micro-seismicity studies (Hatzfeld *et al.*, 1993) and the aftershocks studies (El Alami *et al.*, 1998) demonstrate (Calvert *et al.*, 1997) that two, N-S to NNE-SSW trending main fault zones are concerned by the seismicity in the Al Hoceima region: one SSE of the town and the other, south of the Bas Nekor Basin. Therefore, a blind fault zone located at about 10 km depth and trending NNE-SSW, may have superficial manifestations on a large surface. This fault zone may be offset by dextral conjugate faults that trend NW-SE as shown by the fault related to 2004 event (Akoglu *et al.*, 2006; Biggs *et al.*, 2006; Cakir *et al.*, 2006).

On a shallow tomographic study (Serrano *et al.*,



**Figure 17.-** Regional geological sketch map of the Betic-Rif orogen indicating major geological features in the Alboran Basin: **A)** extensional formation of the West Alboran Basin, with a displacement of 52 Km along the Jebha Fault during the early Miocene (Leblanc, 1990). **B)** Structural sketch map (modified from Mauffret *et al.*, 2004, 2007): West Alboran Basin is interpreted as an extensional fore-arc basin that was located between the Balearic volcanic arc and Tethysian subduction zone. See explanation in the text. **C)** Cross section of the late Oligocene early Miocene Tethysian subduction zone, with exhumation of high-pressure metamorphic rocks in the Mediterranean (after Jolivet *et al.*, 2003). **D)** Westward displacement of the Alboran Plate over the African and Iberian plates. **E)** Cross section of the middle to late Miocene subduction zone, with a new extension phase in the West Alboran fore-arc basin (after Mauffret *et al.*, 2007). **F)** Oblique trend of the late Miocene volcanic arc crossing the East Alboran Basin (Duggen *et al.*, 2004), related to a clockwise rotation during the western migration of the Alboran Plate, between the African and European plates. The Gibraltar Arc is related to the fan pattern of the tectonic transport according to Balanyá *et al.* (2007). **G)** General structural sketch showing the importance of the actual Al Idriiss and Carboneras fault zones in relation with plate motions in the Alboran Sea area. See explanation in the text. **H)** Cross section showing lithospheric structure beneath the Alboran Basin (Medialdea *et al.* 1986; Torné *et al.*, 2000; Gutcher *et al.*, 2002), superimposed on a tomographic image (Wortel and Spakman, 2004).

2003) a positive velocity anomaly is located on the high, north of Ras Tarf, corresponding to the Al Idrissi F. Z. The cluster of Al Hoceima earthquakes is located in the transition between fast and slow anomalies (Serrano *et al.*, 2003). The cluster is not only located in the Al Hoceima area but extends offshore (Figs. 10 and 16). The focal mechanisms are mainly related to strike-slip and normal faulting and the cluster include the areas where the reverse faulting is demonstrated by the seismic profiles (Tofino Bank, Fig. 12).

This bank is 28 km left-laterally offset from the main Alboran Ridge (Fig. 10). A prominent magnetic anomaly can be correlated to the Ibn Batouta Seamount. A similar anomaly but offset to the northeast with the same 28 km displacement, is observed on the seamounts that flank the Alboran Channel to the NW (Willet, 1991; Galindo-Zaldívar *et al.*, 1998).

In a first hypothesis it is suggested that the El Idrissi Fault Zone belongs to the plate boundary proposed (Bird, 2003) between Eurasia and Nubia (Africa) plates (Fig. 16) and is interrupted by the Alboran Ridge that may be the northern boundary of the Nubia (Africa) Plate. A southward displacement of a Rif Block in Morocco with respect to the Nubia plate is inferred from GPS observations (Fadil *et al.*, 2006) and a left-lateral motion of this Rif Block along the Al Idrissi F. Z. maybe proposed. This block may belong to the Eurasia Plate (Fig. 16) (Bird, 2003; Vannucci and Gasperini, 2003). However, the present motion in this area is not well constraint by the GPS data and if a southward motion is suggested (Fadil *et al.*, 2006; Serpelloni *et al.*, 2007), a westward displacement is also proposed (Fernandes *et al.*, 2007). A clear boundary of the Eurasia and Nubia (Africa) plates is not well defined and a diffuse zone is yet preferred. Moreover, the offset of the Ibn Batouta Seamount and the seamounts that limit the Alboran channel to the northwest suggest that the fault has a northern extension and crosses the channel. Therefore, the first hypothesis is unlikely and a second hypothesis will be examined.

It is suggested that the Al Idrissi F. Z. has a northern extension. Two focal mechanisms in the Alboran Channel (13/08/00 and 18/02/03; Fig.10) show pure strike-slip and strike-slip with a normal component respectively. These two earthquakes have a NW-SE, left-lateral nodal plane compatible with the N30E Al Idrissi F. Z. The southwestern boundary of the Djibouti Bank is limited by a prominent fault (Pérez-Belzuz, 1999) that is in strike with Al Idrissi F. Z. A recent multibeam survey enlightens (Ballesteros *et al.*, 2008) this area. The Al Idrissi F. Z. is interrupted by a NW-SE prominent fault that shows strike-slip and reverse components (Pérez-Belzuz, 1999). This fault is a northwest extension (Ballesteros *et al.*, 2008) of the NW-SE Yusuf Fault that crosses the Alboran Channel. The southeast side of the Carboneras fault is occupied by short en echelon structures (Fig. 17G) that trend northwest-southeast. These structures are probably folds related to the left-lateral Carboneras fault or to a

blind fault associated to the main fault (Gràcia *et al.*, 2006). This blind strike-slip fault can be related to the Al Idrissi F. Z. trough a restraining bend. North of the Yusuf Fault, graben and normal faults trend NE-SW (Ballesteros *et al.*, 2008). The Campo de Dalías-Adra area (Fig. 17G) presents many similarities with the Al Hoceima region, with NW-SE normal and right-lateral strike-slip faulting (Rodríguez-Fernández and Martín-Penela, 1993; Stich *et al.*, 2001, 2003b; Martínez-Díaz and Hernández-Enrile, 2004; Marín-Lechado *et al.*, 2005, 2007). The NNW-SSE compression and the E-W extension are coeval and the blocks between the main faults (Alpujarras, Carboneras, Al Idrissi, Yusuf) undergo a tectonic escape (Martínez-Díaz and Hernández-Enrile, 2004; Martínez-Martínez *et al.*, 2006) towards the west but also to the east and the Alboran Island area is the centre where all the large faults are converging.

The diffuse SW-NE band of strike-slip earthquakes that crosses the Alboran Sea (evident on the figure 3 of Fernández-Ibáñez *et al.*, 2007 and in figure 16) may represent an embryonic fault (Negredo *et al.*, 2002), although a careful analysis shows that the stripe is not so diffuse and the fault is active and not nascent. In fact we reactivate a fault already suspected a long time ago (Dillon *et al.*, 1980; El Alami *et al.*, 1998). However, the trace of this fault was based on few seismic profiles whereas several multichannel lines, focal mechanisms and multibeam surveys are now available.

In summary the Al Idrissi F. Z. is a left-lateral strike-slip zone that crosses the Alboran Ridge and the Alboran Channel. This fault can be followed up to the northwest extension of the Yusuf Fault. To the north the Al Idrissi F. Z. maybe connected to the Carboneras Fault through a restraining bend or/and a blind fault that may extend up to the Campo de Dalías-Adra region (Fig. 17G).

#### *Tofino and Xauen Banks*

Three tectonic compressional pulses have been defined in this area (Chalouan *et al.*, 1997). The two first events, with a NNE compression, late Tortonian and early Pliocene in age, affect the north and west of the Xauen Bank. The third is between the Quaternary and the Pliocene, with a compressional stress N150 E to N-S, affects the northern margin of Morocco with the formation of a syncline south of the banks and the uplift of the banks with a northern vergence of the folds and thrusts that limit the banks to the north. It is suggested (Chalouan *et al.*, 1997) that the E-W to ESE-WNW folds are controlled by a deep Jebha Fault located beneath the bank. However, it is unlikely, as previously discussed, that the Jebha Fault is connected with the Alboran Ridge. 3.5 km of post-Messinian shortening have been calculated on the eroded two anticlines that form the Xauen Bank and the syncline that separates the bank from the land. With a 5 mm/yr of convergence between the Nubia (Africa) and Eurasia

plates, 26.5 km of shortening can be expected since the Messinian (5.3 Ma). Thus the compression is dispersed between the Betics, the Spanish margin, the Xauen Bank where about 13% of the compression is absorbed, and in the Rif and Atlas in Morocco. Therefore, a small part of the 28 km of displacement of Tofino Bank with respect to the Alboran Ridge along the Al Idrissi F. Z. is absorbed by the banks, but a deep decollement, about 10 km deep or even at the Moho level, may dip southward beneath the banks whereas the former normal fault that dipping north from the continent acts as a backstop between the coast and the banks (Chalouan *et al.*, 1997). A 10 km-deep decollement is also observed along the Spanish margin (Marín-Lechado *et al.*, 2005) and this decollement maybe continuous and transmit the compression from Spain to the Atlas (Frizon de Lamotte *et al.*, 2004). The Tofino Bank and the Xauen Bank have not the same composition. The core of the first bank is volcanic whereas the second is mainly made of deformed sedimentary layers as demonstrated by the El Jebha well (Morley, 1993). Moreover, this bank is not visible on the free-air gravity map (Willet, 1991) at the difference of the Tofino Bank.

#### *Uplift of the land*

A prominent tilting occurred at the Pliocene-Quaternary boundary with a deepening of the margins basinward and uplift of the margins onshore (Gensous *et al.*, 1986; Docherty and Banda, 1995). The Quaternary prograding platform is related to the forced regression during the glaciations (Gensous *et al.*, 1986). We can see (Fig. 6) a 0.7 km high Messinian arch on the Trois Fourches Block. However, it is difficult to differentiate between the initial slope of the Messinian level towards the basin and the late Pliocene tilting. In the Messadit Basin (Fig. 8) the difference of the Messinian from the shelf to the basin is 0.8 km. The Messadit Basin is a graben that has been tilted during the late Pliocene event. The top of the syn-rift infill was probably horizontal and the tilt is about the same as the Messinian. We compare (Fig. 9) the tilt of the Messinian surface and the polyphased surface of the Ras Tarf (Morel, 1987). The Porites reef that belongs to the Messinian Terminal Complex is uplifted to 588 m and the tilt varies from 3.6° to 6.1°. Offshore the tilt is 4.6° (Figs. 8) and 5° (Fig. 9). A difference of 1.5 km is observed between the deep basin and the top of the Messinian Reef Complex (588 m, Fig. 9). This difference is the conjunction of an initial slope, an uplift of the coast and a deepening of the basin. The same tilting is observed on the Alboran Ridge, the Tofino and Xauen banks. On the Xauen Bank 1.6 km of erosion has been estimated on the top of an anticline (Fig. 14) and the top of this eroded anticline is 3.8 km higher than the Messinian surface in the deep basin. The Xauen Bank is probably part of the West Alboran Basin uplifted by compression and the top of the bank may have been during the Messinian as the same level as the

basin. An uplift of 0.71 mm/yr is calculated since the Messinian that is similar to the 0.6 mm/yr of uplift proposed by Chalouan *et al.* (1997). However an uplift of 1.2 km seems to be appropriate for the whole region and the corresponding rate is 0.2 mm/yr. The uplifted Quaternary terraces in Morocco and Algeria suggest a rate of 0.11-0.26 mm/yr (Meghraoui *et al.*, 1996; Morel and Meghraoui, 1996). In Spain, a Quaternary rate of 0.2 mm/yr has been calculated in the Gibraltar area (Zazo *et al.*, 1999) whereas a rate of 0.2-0.28 mm/yr is estimated for the uplift of the Betic Cordillera (Braga *et al.*, 2003). The tilting and the uplift of the upper margin and the deepening of the basins imply a deepening of the Alboran Sea from coast to coast since the late Miocene. On the eastern Morocco, east of the Trois Fourches Cape the Messinian shelf break is located 1 km south of the present shelf break. West of the cape the Messinian continental shelf has been eroded after the tilting.

#### *Tectonics and deep structure of the Alboran Sea*

A zoom of the West Alboran Basin is shown in figure 17A. This basin is infilled by late Oligocene-early Miocene syn-rift sediments as thick as 5 km (Comas *et al.*, 1992, 1999; Mauffret *et al.*, 2007). The early Miocene basin is limited to the south by the extension of the Jebha Fault and to the north it extends along the Spanish coast up to the Motril Basin (Soto *et al.*, 1996; Comas *et al.*, 1999). In fact all the tectonic features in this area: the Gibraltar Arc, the Miocene West Alboran Basin, and the DSDP 121-ODP 976-Ibn Batouta High present a horseshoe shape that can be explained by the formation of the arc limited by two main tear faults. The 60 km-wide West Alboran Basin is almost undeformed on the Moroccan side except some Oligocene-Miocene syn-rift sediments south of Gibraltar Strait (Feinberg *et al.*, 1990), whereas the equivalent Spanish basins (Malaga and Motril basins) which trend E-W, are much narrower than the West Alboran Basin, a large part being uplifted and integrated to the continent.

A rifting of the West Alboran Basin in a fore-arc position south of the Balearic Islands has been proposed (Mauffret *et al.*, 2007). This rifting may occur (Figs. 17B and 17C) during exhumation in a subduction channel of the HP-metamorphosed Sebtides and Alpujarrides (Bouybaouene *et al.*, 1995; Michard *et al.*, 2002; Jolivet *et al.*, 2003; Chalouan and Michard, 2004).

After the Burdigalian collision of the Kabylia with Africa occurred, the arc reoriented its rollback towards the west (Faccenna *et al.*, 2004) above an E-W tongue of oceanic Tethys crust located between Eurasia and Africa (Spakman and Wortel, 2004; Mauffret *et al.*, 2007). This tongue was narrow and maybe already partly closed by the approaching Eurasia and Africa plates (Faccenna *et al.*, 2004). In such environment the accretionary prism may have included large pieces of

continental fragments in the Flysch Trough main unit deformed in the accretionary prism (Fig. 17D). Conversely, some pieces of the Alboran Plate may have been dragged and abandoned to the adjacent plate. This tectonic scenario shows many similarities with the present situation of the Caribbean Plate, relative to the North and South America plates, where the slow convergence is almost normal (E-W) to the Lesser Antilles subduction zone (N-S) and partly hidden beneath the Barbados accretionary prism (Müller *et al.*, 1999).

The Maghrebian Flysch tectonic wedge, including large pieces of continental rocks, may have been pushed towards the west during the roll-back and may form the 30 km thick crust (Medialdea *et al.*, 1986; Torné *et al.*, 2000) that is located in the Gibraltar Strait area. The Gibraltar Strait maybe compared to the Barbados Island where old series (Eocene) are located on top of the Lesser Antilles prism (Masclé *et al.*, 1985). A low velocity layer, 10 km thick, has been attributed to the Campo de Gibraltar Flysch (Medialdea *et al.*, 1986). This low velocity is confirmed between 0 and 11 km and 11-24 km by a local tomographic study (Gurría and Mezcuá, 2000). However, the well Cerro Gordo reaches the Cretaceous limestone attributed to the Subbetic Domain as shallow as 1266 m beneath the Aljibe Maghrebian Flysch (Lanaja, 1987; Crespo-Blanc and Frizon de Lamotte, 2006). Nevertheless, this well is located northwest of the Gibraltar Strait and the Flysch may thicken just beneath the strait area. In this southern region the well Almarchal drilled 3465 m of Eocene-Oligocene (Maghrebian Flysch) with a late Cretaceous tectonic slice (Subbetic), sandwiched between 810 and 880 m Flysch (Lanaja, 1987). Therefore, the 30 km thick crust of the Gibraltar area may have been thickened by repetition of Flysch series and thrusts into the Iberian-African crust. A 30 km thick crust is observed also beneath the northern Morocco directly south of Gibraltar (Tadili *et al.*, 1986).

A thick crust and a thick lithosphere (130 km) beneath the Gibraltar Strait is confirmed by all the geophysical methods: tomography (Calvert *et al.*, 2000), gravity (Torné *et al.*, 2000), refraction (Medialdea *et al.*, 1986), geoid (Fullea Urchulategui *et al.*, 2006). However, the tomographic cross section of the Gibraltar Strait (Spakman and Wortel, 2004) suggests (Fig. 17H) that the thick lithosphere with a low velocity may represent a cold and old oceanic lithosphere of the Atlantic Ocean dipping beneath the hot and young Alboran Domain (Thiebot and Gutscher, 2006). A westwards retreat of the Alboran subduction zone is corroborated by several independent methods and well illustrated by the tomography (Faccenna *et al.*, 2004; Spakman and Wortel, 2004). However, the general tomography is blind between 0 and 50 km and the intermediate depth seismicity is active between 50 and 150 km but does not show (Fig. 17H) an evident correlation with the shallow seismicity (Bufoin *et al.*, 1997, 2004). Therefore, the slab is probably detached

since the late Miocene and an active subduction at Present (Gutscher *et al.*, 2002; Thiebot and Gutscher, 2006) is unlikely.

The sketches D and E in figure 17 show the E-W travel of the Alboran Plate (Andrieux *et al.*, 1971). During this journey, from the Langhian to the early Tortonian, a second rifting occurred with an E-W extension in the West Alboran fore-arc basin (Mauffret *et al.*, 2007). The normal faults may have the same N-S trend as the Alboran Volcanic Arc that has been defined by Duggen *et al.* (2004). The Alboran Plate was separated from the Eurasia and Africa by tear or STEP faults (Spakman and Wortel, 2004; Govers and Wortel, 2005). Along the STEP faults a clockwise rotation is observed in Spain and a counter-clockwise rotation in Morocco (Platzman *et al.*, 1993; Saddiqui *et al.*, 1995; Feinberg *et al.*, 1996; Platt *et al.*, 2003). However, these rotations were mainly active before the late Tortonian during the westwards motion of the Alboran Plate and the late Miocene to Recent rotations in Spain are mainly related to strike-slip faulting (Mattei *et al.*, 2006).

A low velocity zone located at 200 km depth according to a general tomography study (Spakman and Wortel, 2004) shows a crescent shape with a N-S orientation beneath the Alboran Sea that turns to NE-SW beneath the Betics in southern Spain (Fig. 16). The collision of the westwards migrating Alboran Plate and the Eurasia (Iberia) probably occurred in the Eastern Betics with a stalling of rollback and the formation of the Betic orogen that is much larger than the Rif orogen and the westwards motion slow down along the northern boundary (Spakman and Wortel, 2004) whereas it is yet fast along the southern boundary. Consequently a clockwise rotation of the Alboran Volcanic Arc (Cabo de Gata-Ras Tarf) may occur with a coeval integration to the continent of the northern part of the West Alboran Basin [Oligo-Miocene syn-rift series (Durand-Delga *et al.*, 2003) and the Oligocene-early Miocene dikes in the Malaga region (Torres-Roldán *et al.*, 1986; Duggen *et al.*, 2004)].

In addition a N-S stripe of intermediate depth seismicity (50-150 km) (Bufoin *et al.*, 1997; López-Casado *et al.*, 2001; Bufoin *et al.*, 2004) shows also a curve towards the east in the vicinity of Malaga. This boomerang shape (Figs. 16 and 17F) may explain the complex geometry of the intermediate depth seismicity with a main eastwards almost vertical dip (Bufoin *et al.*, 1997) and a southern dipping interpreted as a continental subduction of the Iberia beneath the Betics and the Alboran Sea (Morales *et al.*, 1999) that is probably related to the present collision in the Malaga region. The clockwise rotation of the Alboran Domain maybe also related to a drag (Stich *et al.*, 2006) due to the Nubia (Africa) counter-clockwise rotation relative to Eurasia with coeval E-W extension (Fig. 17F). This clockwise rotation in the Al Hoceima region and the central domain of the Alboran Sea is corroborated by a

recent study of the stress field (Fernández-Ibáñez *et al.*, 2007).

On a map (Fig. 16) from EMSC of the focal mechanisms in the Alboran area (Vannucci and Gasperini, 2003) the general tectonic framework of the Alboran Sea is superimposed with the low and high velocity areas deduced from tomography (Calvert *et al.*, 2000; Spakman and Wortel, 2004). In addition it is drawn the Nubia vector relative to Eurasia observed on GPS measurements (4.8 mm/yr in a WNW-ESE direction) and the stress tensor with a NNW-SSE compression (2.3 mm/yr of shortening), W-E extension (2.1 mm/yr) and NE-SW left-lateral strike-slip (Stich *et al.*, 2006; Fernández-Ibáñez *et al.*, 2007; Serpelloni *et al.*, 2007). The sketch (Fig. 17G) shows that tectonic framework of the Alboran area is governed by the stress tensor derived from focal mechanisms and stress field (Fernández-Ibáñez *et al.*, 2007) and not by the convergence motion of Nubia (Africa) Plate relative to the Eurasia Plate.

## Conclusions

The Morocco margin is less involved than South Spain in the collisional process between the Eurasia and Nubia (Africa) plates. Consequently, several tectonic features are undeformed, in particular the southern West Alboran Basin whereas the same structures are highly deformed and integrated to the continent compared to the northern part of the Alboran Sea. A clockwise rotation of the Alboran Domain is proposed with a free southern boundary and a boomerang shape of the northern collisional boundary. However, the Morocco Margin undergoes an uplift related to the compression although mountain building is less developed than in Southern Spain. All the geophysical and geological studies suggest a westwards migration of the Alboran Domain although all consequences of such motion are not totally integrated in the models. Extensional collapse of thickened continental lithosphere or delamination process are not needed if the extension occurred during the Miocene in an eastern area not surrounded by thickened crust but in a fore-arc behind a subduction zone that can roll-back towards a free face. The Nekor and Jebha faults are probably inactive since the late Miocene and they do not belong to a Trans-Alboran Shear Zone. However, a left-lateral fault zone crosses the Alboran Sea from Al Hoceima to Adra and is maybe connected to Carboneras Fault. The Alboran Sea looks like a complex pull-apart that forms a zigzag relay between a northwestern boundary (Gulf of Cadiz) and a southeastern boundary (Algeria) and a diffuse boundary in the Alboran Sea between the Nubia (Africa) and Eurasia is yet preferred. The thick lithosphere beneath the Gibraltar Strait may have been confused with a cold oceanic lithosphere dipping eastwards slab although almost vertical. However, the westwards rollback of the Alboran subduction zone probably died in the late

Miocene and a continental collision is now occurring. The Alboran region is a buffer area between the converging Eurasia and Nubia (Africa) plates. It is in the way to be integrated to the Eurasia Plate.

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