



## Structural analysis and recent tectonics in the central Alboran Sea

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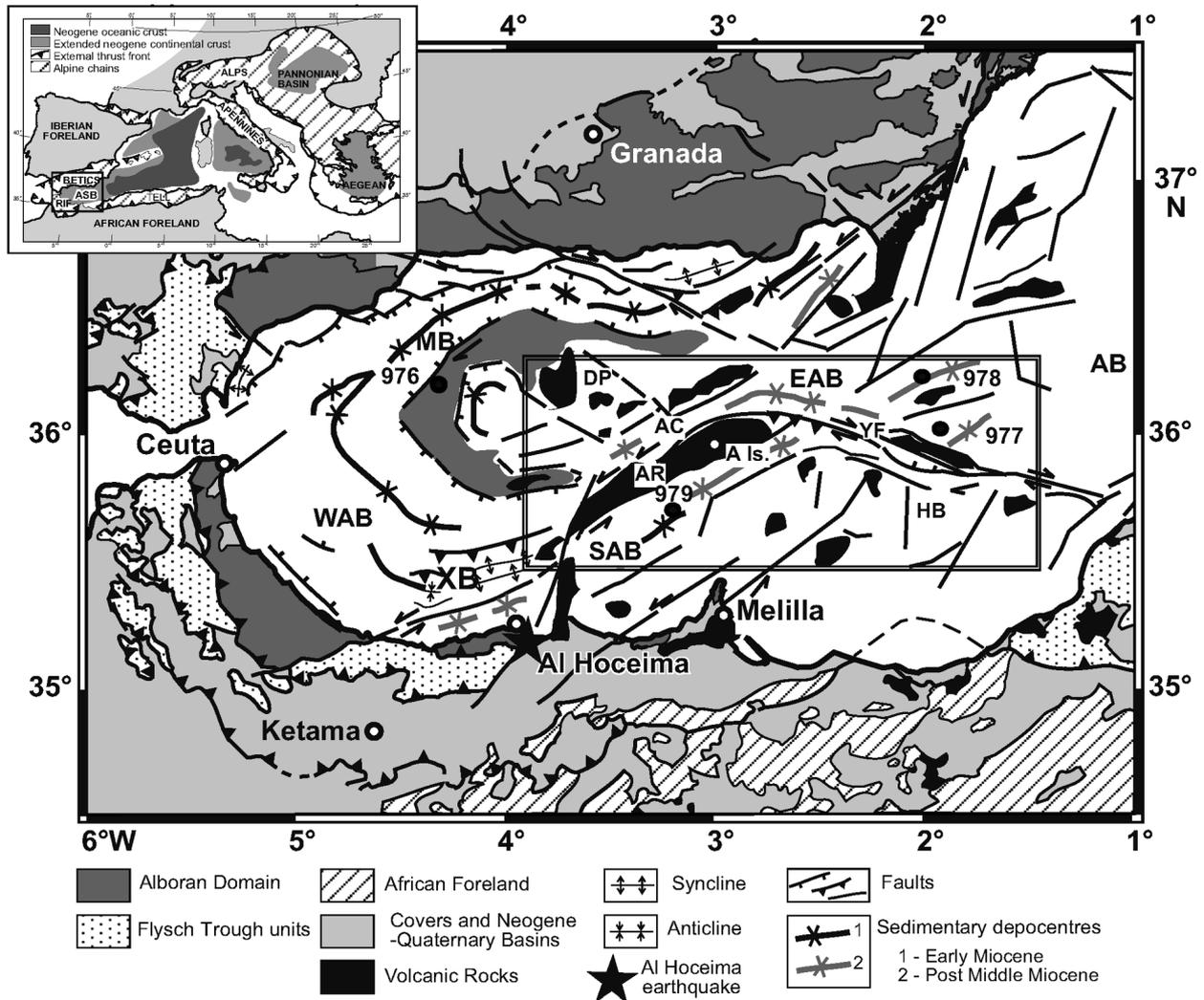
**Abstract:** We analyze the distribution and character of recent deformations in the Alboran Ridge and neighbouring areas of the Alboran Sea (within the Gibraltar Arc System, in the Western Mediterranean). Shallow structure has been analyzed by integrating different geophysical datasets, such as multibeam swath-bathymetry and sub-bottom profiling and comparing with deeper sections shown in multichannel seismic profiles. We explore relationships between upper-crustal structures and shallow seismicity, to decipher the position and nature of active fault segments. Pliocene to recent uplift of the Alboran Ridge has been produced by reverse to strike-slip faulting along NE-SW trending fault-systems that show a transpressive character. Major faults bounding the ridge gradually change their direction from NE-SW to NW-SE and connect with the transtensional Yusuf fault system, which includes the Yusuf Ridge and Basin. Towards the west, the ridge is affected by NNE-SSW trending folds, associated with high-angle faults at depth. These structures define a seismogenic, left-lateral fault zone connected to the south with the Al Hoceima seismic swarm.

**Keywords:** Alboran Ridge, active-fault, strike-slip tectonics, seismic profiles.

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Structural analysis of marine survey data can also be used to investigate the geometry, nature, and tectonic evolution of structures in submerged regions. In this way, we have characterized the recent structure in the major tectonic lineament of the Alboran Sea Basin, the Alboran Ridge and its connection with the Yusuf fault zone, by integrating different geophysical data from marine surveys. The main objective of this work is to reconstruct the structure of faults and folds that deform the most recent sedimentary cover, commonly up to the seafloor. A detailed structural map has been produced for the studied region, finally comparing the geometry, type and age of the faults with the distribution and character of the seismicity in the upper crust. Fault structures and earthquake information have been linked to reconstruct the present-day stress field, which is compared with the overall ongoing convergence between the African and Eurasian plates.

The Alboran Sea Basin is a back-arc basin developed behind the Gibraltar Arc, formed by the Betic and Rif mountain ranges (Fig. 1, inset map). The basin originated from crustal thinning, rifting and basin subsidence, which started during the Early Miocene (~18 Ma) and resumed by the Late Miocene (~8-9 Ma). Miocene extensional tectonics resulted in half-graben structures that accommodate deep depocenters of Miocene sediments, particularly in the West Alboran Basin and in the Málaga Basin (Fig. 1). Subsequent contractive tectonics, producing folding, high-angle faulting and tectonic inversion, occurred from the Late Miocene (Late Tortonian-Messinian, ~5-8 Ma) until Recent (Comas *et al.*, 1992, 1999; Watts *et al.*, 1993; Chalouan *et al.*, 1997; Mauffret *et al.*, 2004, 2007). Contractive tectonics has resulted in roughly N-S shortening of the whole basin, and conditioned the present day structure of the Alboran Basin (Fig. 1).



**Figure 1.** Structural map of the Alboran Sea Basin and surrounding areas (modified from Comas *et al.*, 1999). The studied area is shown within a rectangle. Position of ODP Leg 161 Sites (976 to 979) is noted. Al Hoceima earthquake taken from Akoglu *et al.*, 2006. AB: Algerian Basin; AC: Alboran Chanel; A Is: Alboran Island; AR: Alboran Ridge; ASB: Alboran Sea Basin; DP: Djibouti Plateau; EAB: East Alboran Basin; HB: Habibas Basin; MB: Málaga Basin; SAB: South Alboran Basin; YF: Yusuf fault zone; WAB: West Alboran Basin; XB: Xauen Bank.

In the Alboran Basin we investigate the Alboran Ridge and the Yusuf fault zones (Fig. 1). The Alboran Ridge represents the major, bathymetric high of the Alboran Sea. With a general SW-NE trend, the ridge continues to the SW in the Xauen Bank (Fig. 1). To the east, the ridge connects with the NW-SE Yusuf Escarpment that, in turn, prolongs with the Yusuf Ridge and the Yusuf Basin. These morphological lineaments in the basin seem to be related to major fault systems. The Alboran Ridge currently corresponds with a left-lateral transpressive fault zone, whereas the Yusuf Ridge and Basin have been interpreted as resulting from a right-lateral, transtensive fault system (Álvarez-Marrón, 1999; Comas *et al.*, 1999; Fernández-Ibáñez *et al.*, 2007).

## Dataset and methods

The present study integrates datasets acquired during different geophysical surveys. Multi-channel seismic profiles (MCS), processed down to a depth of 7 s twtt (two-way travel time), acquired during the TECALB (2000) and MARSIBAL I-06 (2006) cruises onboard the BIO Hespérides, have been analyzed to better understand deep structures around and across the Alboran Ridge. Single channel seismic and very high-resolution acoustic sub-bottom profiling (TOPAS: Topographic Parametric Sonar, 0.5-6 kHz frequency), as well as swath-bathymetry (SIMRAD) data were acquired during these surveys. Complementary datasets from the

ALBA cruise (BIO Hespérides, 1992) and swath-bathymetry from the IFREMER-CIESM compilation (MediMap Group, 2005) were combined in an area of the central Alboran Sea to help achieve a bathymetry mosaic of 14,400 km<sup>2</sup> where our structural analysis has been carried out.

Seismic interpretation and depth conversion of seismic profiles have been accomplished using well data (Fig. 1). This study considers logging information from several ODP Sites drilled in the Alboran Sea during ODP Leg 161 (Comas *et al.*, 1996).

### Deep structure

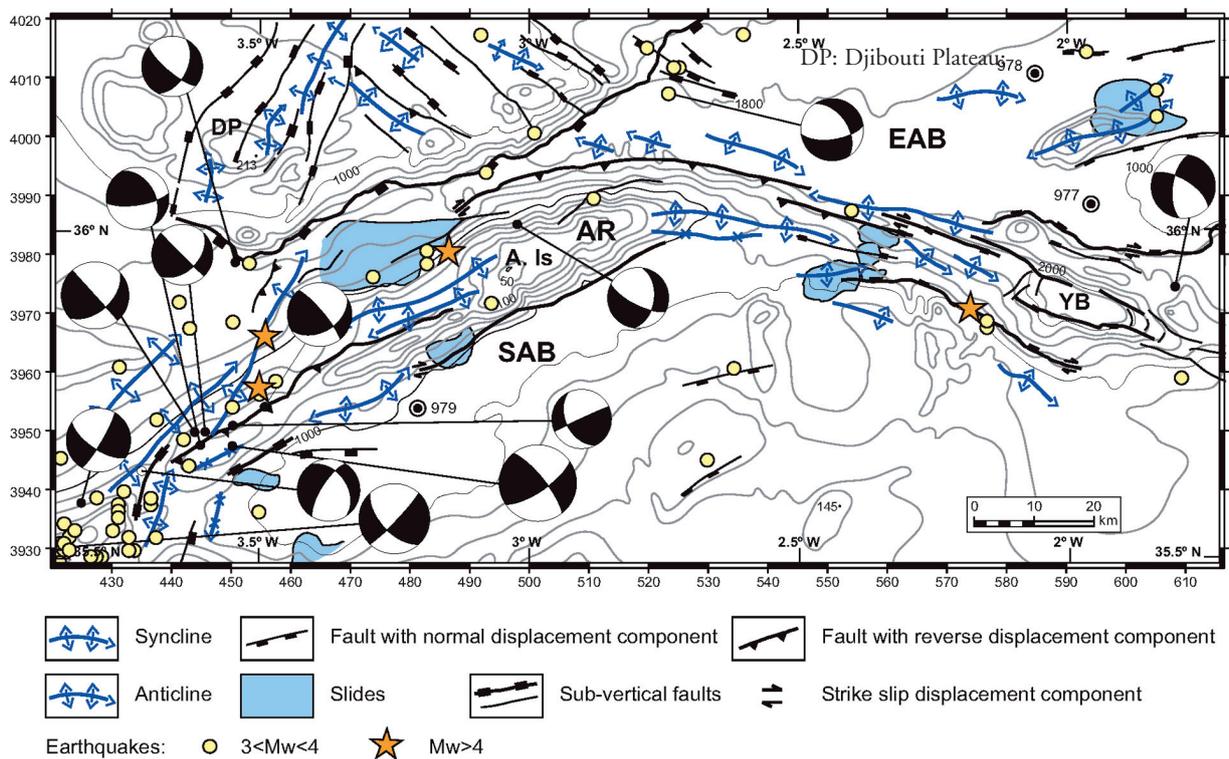
The structure beneath the Alboran Sea, as shown in figure 1, results from the interpretation of a dense grid of MCS profiles including commercial and academic ones (Comas *et al.*, 1999).

The Alboran Ridge, the major NE-SW trending seamount of the Alboran Basin, is imaged in MCS as a large, complex antiform bounded by strike-slip to

reverse fault zones. The resulting structure encompasses uplift, subsidiary folding, and basin inversion. Sediments in the ridge consist of Plio-Quaternary deposits lying on top of the volcanic acoustic basement. Tilted strata at the antiform limbs show significant angular unconformities indicating discontinuous uplift of the Alboran Ridge during the Plio-Quaternary.

The northern escarpment of the Alboran Ridge, adjacent to the Alboran Channel, corresponds to a major left-lateral strike-slip fault zone at depth. At the eastern end of the ridge the master fault shows high-angle dip and a reverse displacement whereas, towards the west, left-lateral strike-slip components dominate. The southern escarpment of the ridge, flanking the South Alboran Basin, corresponds to a near vertical fault zone at depth (Fig. 1).

The Yusuf fault zone to the east is a dextral NW-SE fault system which includes two master normal faults that produce local transtension and forms the Yusuf pull-apart basin. The temporal and spatial relation-



**Figure 2.** Shallow structure and crustal seismicity in the central Alboran Sea. Seismic events ( $M_w > 3$ ) from the USGS (period 1979-2007) and focal mechanisms from moment tensor inversion (Instituto Andaluz de Geofísica database). Position of ODP Leg 161 Sites (977 to 979) is shown. Bathymetric contour lines (in metres) from GEBCO-97 (IOC-IHO). A Is: Alboran Island; AR: Alboran Ridge; DP: Djibouti Plateau; EAB: East Alboran Basin; SAB: South Alboran Basin; YB: Yusuf Basin.

Sector	Folds		Faults	
	Mean orientations <sup>(1)</sup>	N	Mean orientations <sup>(1)</sup>	N
Djibouti Plateau	018 ± 6° and 132 ± 9°	19	024 ± 4° and 126 ± 3°	40
western Alboran Ridge	030 ± 4.5°	25	024 ± 9°	6
central Alboran Ridge	065 ± 1°	7	064 ± 1.5°	9
eastern Alboran Ridge	093 ± 5°	8	092 ± 13°	4
Yusuf Escarpment	122 ± 3°	7	103 ± 6°	27
East Alboran Basin	090 ± 5°	11	092 ± 4°	16

**Table 1.** Fault and fold orientation in the studied region. <sup>(1)</sup>Mean vector (azimuth) is accompanied by a value of 95% of the distribution. N: number of measurements.

ship between the Alboran-Ridge and the Yusuf fault zones remains still unclear.

Post-Messinian deformation involves from the basement up to the Pliocene-to-Holocene sedimentary sequences. However, folding and strike-slip faulting seems to have started from the Late Miocene.

### Shallow structure

Recent tectonic processes in the Alboran Sea Basin are mainly responsible for its complex seafloor physiography. Shallow structures in the central Alboran Sea, around the Alboran Ridge have been analyzed and mapped (Fig. 2). This map shows faults and folds affecting the seafloor and the uppermost hundreds of meters beneath the seafloor (<200 m). Mean structural directions are shown by sectors in table 1. Shallow structures are open folds associated with high-angle faults, which produce seafloor escarpments. High-resolution profiles provide oblique seismic sections showing apparent dips from predominant structures, and we identify fault traces and fold culminations in the bathymetry. Moreover, depth conversions have been done using velocity profiles from ODP well logging.

Recent deformation is heterogeneously distributed and shows different structural styles (Fig. 2). Shallow structures in the Alboran Ridge are open NE folds and parallel, high angle faults (average  $65 \pm 1^\circ$ ). Fold axes are tilted towards the SW and ENE on both sides of the shallow platform surrounding the Alboran Island. Towards the SW (Fig. 2), these structures are cut by an oblique system (NNE-SSW; average  $30 \pm 1^\circ$ ) formed by a fold-and-fault system that continues northwards to the Djibouti Plateau. The northern escarpment of the Alboran Ridge represents a recent reverse fault affecting the seafloor. To the east, the orientation of this fault changes to NW-SE (average from  $93 \pm 8^\circ$  to  $102-122 \pm 1^\circ$ ). The Yusuf fault zone

shows different segments with lateral tips in relay, accommodated by en echelon folds, suggesting transtensive deformation.

### Seismicity and active faults

The distribution and character of the shallow-crustal seismicity (Fig. 2) have been used to constrain the location and nature of active faults. Hypocenter distribution, magnitude, and focal mechanisms allow to determine the position and kinematics of active fault segments. A set of 13 focal mechanisms has been compiled for this study (Fig. 2). Focal mechanisms in the Alboran Ridge mostly correspond to strike-slip (left lateral) to reverse faults. In the East Alboran Basin and the Yusuf region, the scarce focal mechanisms show normal faulting with an important strike-slip component.

Identified slumps and mass wasting structures probably derive from unstable seafloor escarpments conditioned by active faulting. Shallow crustal seismicity occurs along the Alboran Ridge and in the Yusuf region. In the western part of the ridge, a seismic swarm connects southward with the Al Hoceima seismic series. We propose the existence of an active NNE-SSW left-lateral fault zone crosscutting the Alboran Ridge obliquely (Figs. 1 and 2).

Present-day stress field in the region has been calculated by integrating the shallow-fault pattern and focal-mechanism data. The resultant  $S_{Hmax}$  (average azimuth  $11^\circ$ ) in the studied region shows a significant ( $-55^\circ$ ) clockwise rotation of the local stress field with respect to the regional orientation imposed by the ongoing plate convergence between Africa and Eurasia (e.g. DeMets *et al.*, 1994). This sort of rotation reinforced the interpretation that active faults crosscutting the Alboran Ridge represent segments of a weak, strike-slip (left-lateral) fault zone.

## Conclusions

As a whole, seafloor morphology and seismic images from the studied region corroborate that the present-day structural pattern in the Alboran Basin is mainly conditioned by post-Messinian, roughly N-S contractive tectonics. Two main conjugated, NE-SW (Alboran Ridge fault zone) and NW-SE (Yusuf fault zone) strike-slip fault systems and associated folding were developed. These faults resulted in a substantial WSW-ENE elongation of the Alboran Sea Basin and contributed to the westward escape of the Gibraltar Arc front (Fernández-Ibáñez *et al.*, 2007; and references therein).

Seafloor deformations connect with deeper structures. Superficial fold systems are linked with sub-vertical

faults having seismogenic segments. The relationships between faults and seismicity suggest that present-day deformation is concentrated along a NNE-SSW fault-zone crosscutting the Alboran Ridge and connecting southward with the Al Hoceima seismic swarm. This discovered fault zone may therefore represent an area of potential seismic hazard in the Alboran Sea.

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