QUATERNARY TECTONICS INFLUENCE ON THE ADRA CONTINENTAL SLOPE MORPHOLOGY (NORTHERN ALBORAN SEA)

Influencia de la tectónica cuaternaria sobre la morfología del talud continental de la región de Adra (Mar de Alborán septentrional)

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Resumen: El análisis de un mosaico batimétrico y de perfiles sísmicos de alta resolución ha permitido definir la geomorfología tectónica del Margen de Adra, sector norte del Mar de Alborán. Se han identificado cuatro tipos morfológicos relacionados con estructuras tectónicas: (i) Crestas longitudinales (N50-70); (ii) Escarpes lineales (N30, N55, N130, N165, N-S); (iii) Depresiones tectónicas (N130, N165, N-S), y (iv) Líneas de cambio de la pendiente (N130). Este esquema morfoestructural se relaciona con un cabalgamiento ciego (NO-SE) en el sector NO, y en el oriental con la falla de desgarre siniestra de La Serrata (NE-SO). Entre estas dos estructuras se ha desarrollado un sistema de fallas de desgarre diestras (NO-SE) que incluye a la Falla de Adra, y un corredor NNE-SSO constituido por fallas secundarias NNO-SSE. Además se han observado fallas inversas menores N-S que pueden ser consecuencia de la interferencia de los principales sistemas de fallas de la región con el Banco de Chella.

Palabras clave: Geomorfología, Fallas, Tectónica, Cuaternario, Mar de Alborán.

***Abstract**: The analysis of multibeam bathymetric data and high resolution seismic profiles has allowed us to define the tectonic geomorphology of the Adra margin, northern Alboran Sea. Four geomorphic tectonic-related structures have been analyzed: (i) Longitudinal ridges (N50-70); (ii) Linear scarps (N30, N55, N130, N165, N-S); (iii) Tectonic depressions (N130, N165, N-S), and (iv) Lines of changes in the slope gradient (N130). In the northwestern sector morphostructure is related to a blind thrust (NE-SW), which folds Quaternary units, and in the eastern sector is linked to the NE-SW sinistral strike slip fault of La Serrata (NE-SW). Between these two structures, a NW-SE dextral strike-slip fault system, including the Adra Fault, and a NNE-SSW highly deformed corridor constituted by secondary NNW-SSE faults have been developed. Minor high angle N-S reverse faults can be related to secondary deformation features, due mainly to the interference of Chella Bank and the regional main fault systems.*

***Key words**: Geomorphology, Faults, Tectonics, Quaternary, Alboran Sea.*

INTRODUCTION

The Alboran Basin is located in the backarc extensional domain of the Gibraltar Arc which is constituted by the Betics-Rif thrust and belt systems, the westernmost Mediterranean Alpine Compressive Belt. The Gibraltar Arc was generated by the westward migration of the Alboran Domain in relation to the westward retreat of a subduction slab. The basin is underlined by a thinned continental crust and their basement is basically constituted by the Internal Units of the Betics-Rif system and a volcanic complex of Middle and Upper Miocene in age (Comas et al., 1999).

This region shows an intense deformation during Pliocene and Quaternary as a consequence of the NNW-SSE oblique convergence between the plates of Eurasia and Nubia, which is characterized by the absence of a well defined plate boundary, the generation of a broad deformation area and strain partitioning (Stich et al., 2010). Basin seafloor physiography is controlled by this inversion tectonics (Martínez-García et al., 2013) which has produced the radial tilting of the continental margin basement to its interior and the development of several inverted structures as the Alboran Ridge. Besides there are several tectonic seafloor features as linear scarps, small ridges and longitudinal or rhomb-shaped depressions that evidence the contemporary varied and active tectonics (Ballesteros et al., 2008; Vázquez et al., 2008).

Local seismicity shows a large number of events that have mostly low to moderate magnitudes, lower than M5. However two areas have been affected by high magnitude earthquakes: the Al Hoceima region in the African margin which recently suffered two strong seismic events (M6.0 in 1994 and M6.3 in 2004), and the Adra region, in southern Iberia, where a M6.1 earthquake has been produced in 1910. The focal earthquake solutions in the Alboran domain range from pure thrust to strike slip and normal faulting (Stich et al., 2010, and therein).

These factors highlight the importance of understanding the contemporary tectonics and the earthquakes role in the Alboran basins architecture. The aim of the present paper is to characterize the seafloor tectonic geomorphology and the Quaternary tectonics on the continental slope close to Adra. In this area, a main NW-SE Quaternary fault has been defined by Gràcia et al. (2012) which proposed as the seismogenetic fault of the 1910 Adra earthquake.

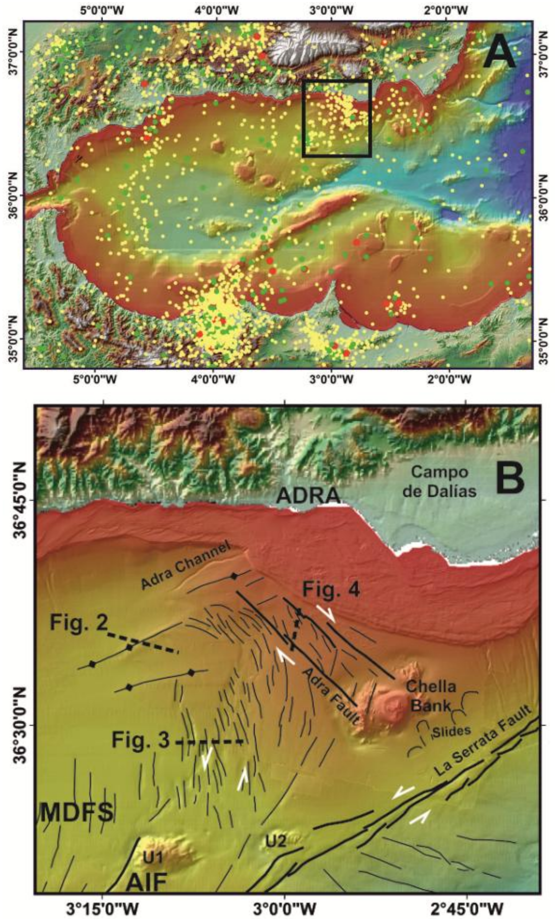

Figure 1: Earthquake location of magnitude >3 in the Alboran Sea (1990-2010) region taken from the IGN data base (Yellow: M=3-4; Green: M=4-5; Red: M>5) on the EMODNET bathymetric model. The frame corresponds to the study area. B. Structural map of the Adra continental margin and location of Figures 2, 3 and 4 (dotted lines). AIF: Al Idrissi Fault; MDFS: Motril-Djibouti Fault System.
Figura 1: A. Distribución de terremotos de magnitud superior a 3 en la región del Mar de Alborán (1990-2010) tomada de la base de datos del IGN (Amarillo: M= 3-4; Verde: M= 4-5; Rojo: M>5) sobre el modelo batimétrico de la base de datos EMODNET. El recuadro corresponde a la zona de estudio. B. Mapa estructural del margen continental de Adra y localización de las Figuras 2, 3 y 4 (líneas de puntos). AIF: Falla de Al Idrissi; MDFS: Sistema de fallas de Motril-Djibouti.

DATA

A multibeam bathymetry data set which includes surveys acquired with MB 300, 3002 and 710 Kongsberg echosounders, and very high resolution parametric profiles acquired with TOPAS PS18 and ATLAS-PARASOUND sounders have been used. Data was obtained along several surveys developed in the Alboran Basin aboard of the R/V Vizconde de Eza (ALBORAN 1, 2, 3; 500 VIVIENDAS), R/V BIO Hesperides (SAGAS), R/V Sarmiento de Gamboa (SAGAS bis, MONTERA 0412), R/V Angeles Alvariño (INDEMARES-Seco de Los Olivos_1013). The bathymetric compilation has been done with ArcGis, as well as hill shade, slope, aspect and curvature analysis. Seismic data interpretation has been performed with IHS Kingdom software. As a marker for the determination of fault offsets on Late Pleistocene-Holocene units, it has been used a seismic horizon correlated to well ODP977 where it was dated in 36 ky (Martrat et al., 2004).

RESULTS

The Adra continental slope sector is a smooth promontory breaking the general trend of the margin physiography; this fact is favoured by the presence of three volcanic buildings in the area, located at 27km to SSE, 41km to the S and 46 km to the SSW of Adra (respectively Chella Bank, U2 and U1 in Fig. 1). The Chella Bank, called Seco de los Olivos by fishermen, rises 500m (580-80m water depth). The other two highs rise 100m (U2, 950-850m water depth) and 340m (U1, 920-580m water depth) respectively. These submarine hills are related to morphostructural changes in the margin. From the Chella Bank to the east, the margin shows a general ENE-WSW to NE-SW trend and to the west, the trend is NW-SE; however westwards of Adra the margin shows again a general ENE-WSW trend.

Morphology of the area has a high complexity that results from the interplay between tectonic structures and sedimentary processes, mainly contouritic and mass movements that are out of the present aim. Four seafloor elements related to tectonic structures have been differentiated: longitudinal ridges, linear scarps, tectonic depressions and lines with changes in the slope gradient.

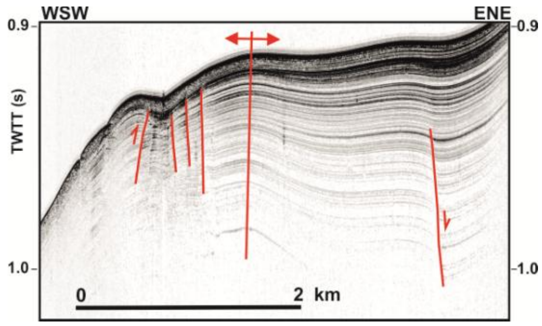

Figure 2: High resolution seismic profile on longitudinal ridges (see Fig. 1B for location) related to folds anticlines.
Figura 2: Perfil sísmico de alta resolución mostrando las crestas longitudinales (ver Fig. 1B para situación), relacionadas con pliegues anticlinales.

i) Longitudinal ridges. Three smooth asymmetric ridges of N50-60 are located to the northwest of the studied area (Figs. 1B and 2). From north to south, they have around 7, 13 and 20km length, 30, 75 and 40m of relief northwards, and the gradients of northern flanks are steeper (3.5, 4.5 and 2.5º) than southern ones (2, 2 and 1.5º) which are close to average gradient of the slope. The northern ridge controls the location of the Adra Channel and the surficial expression of the second one is controlled by two high angle inverse faults, which produce offsets up to 9ms in the upper part of the ridge (Fig. 2). They are interpreted as anticlines folds which affect Quaternary units and deform the seafloor.

It has been located three N55 compressive ridges to the SE of Chella Bank at an instraslope position; they have 8-12km length, 0.5-1.2km width, 5-30m of relief and up to 8º associated gradients. These steeper ridges are part of the surficial expression of the sinistral strike slip fault of La Serrata (Estrada et al., 1997), so called Carboneras Fault (Gràcia et al., 2006), and are push-up swell structures. Two of them appear associated in successive compressive relays and are connected to the third one by means of linear scarps. Their surficial structure is fractured by several reverse high angle faults with up to 16ms offsets on most recent Quaternary units.

ii) Linear scarps with varied directions (N30, N55, N130, N165, N-S) and dimensions have been differentiated (Figs. 1B and 3, Table 1). A N30 scarp has differentiated to the SSW of Chella Bank, related to a normal fault which offsets up to 26ms, and joints towards the SW to La Serrata alignment. The N55 scarps are located to the E and SE of Chella Bank (offset), and are associated to La Serrata Fault. The N130 scarps are located to the NW of Chella Bank, related to the Adra Fault and especially in its western termination, and mostly correspond to oblique reverse faults with up to 14ms offsets. The N165 scarps are concentrated in a NNE-SSW corridor which runs to the unnamed secondary hills to the western of Chella Bank; they are generated mainly by normal faults although reverse displacements have been also observed. The displacement reaches up to 15ms offsets on most recent Quaternary units. Finally, the N-S scarps are frequents on the Chella contourite Drift to the W of Chella Bank and their geometry are lightly irregular.

LINEAR SCARPS				
Direction	Length (km)	Relief (m)	Gradient(º)	Gradient trend
N30	8	30	4-5	SW
N55	15	15	6	SE
N130	2.5-5.5	5-15	4-5	SW / NE
N165	3-5	20-40	5-7	W / E
N-S	3.5-6.5	5-15	3	W / E
TECTONIC DEPRESSIONS				
Direction	Length (km)	Relief (m)	Scarps Gradient(º)	Width (km)
N-S	3.8-6.3	10-25	3	2.5
N165	3-5	20-40	5-7	1.5
N130	2.5-3.5	10-25	4-7	1.5-1

Table 1. Morphometric characterization of linear scarps and tectonic depressions identified in the Adra margin.
Tabla 1: Caracterización morfométrica de los escarpes lineales de origen estructural y depresiones tectónicas identificados en el margen de Adra.

iii) Tectonic depressions. They are longitudinal depressions bounded by two linear scarps, which are related to normal or reverse faults. They have different trends and dimensions (Table 1) and are preferentially located along a NNE-SSW corridor of 5km of width which extends towards the NNE from the hill U2 until the Adra Fault, their trend change from this hill from N-S to NNW-SSE and them to NW-SE. The two first groups correspond to normal faulted depressions (8-40ms offsets), but the third group are bounded by reverse faults with 5-16ms offsets on most recent Quaternary units (Figs. 1 and 3) which produce an asymmetrical configuration.

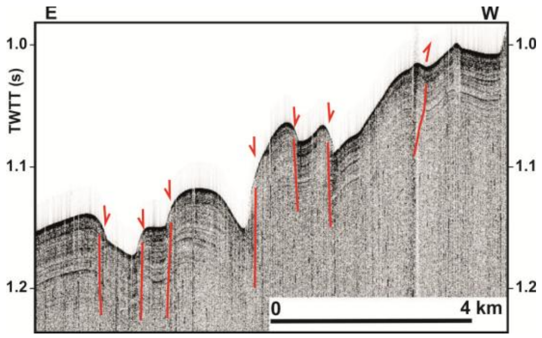

Figure 3: High resolution seismic profile on linear scarps and tectonic depressions (see Fig. 1B for location).
Figura 3: Perfil sísmico de alta resolución sobre los escarpes lineales y las depresiones tectónicas (ver Fig. 1B para situación).

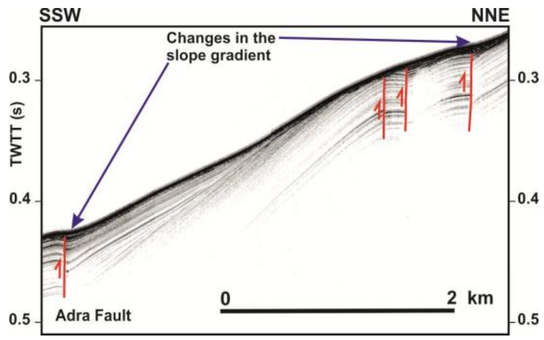

Figure 4: High resolution seismic profile on lines with changes in the slope gradient related to the Adra fault system (see Fig. 1B for location).
Figura 4: Perfil sísmico de alta resolución sobre líneas de cambio de pendiente relacionados con el sistema de fallas de Adra (ver Fig. 1B para situación).

iv) Lines with changes in the slope gradient. When the structure has not a main vertical component, the tectonic offsets of seafloor do not always appear well defined, and they could be hidden by the regional gradient of the slope or obliterated by sedimentary processes. In these cases, only linear changes in the gradient maybe observed that could be related to smooth minor scarps or ridges. At least three N130 lines with changes in the slope gradient have been differentiated between Adra and the Chella Bank (Figs. 1B and 4). From SW to NE, the first one have 22km length and is divided in two segments with a relay configuration, the second one have 10km length, and the third one around 8km, but in the two last cases could be obliterate by the Chella contouritic drift and biogenic constructions at the foot of the upper slope. The separation of these faults varies from 3.5 to 1.5km. A clear compressive component is observed on recent Quaternary units with 3 to 9 ms offsets and a vertical component that deforms seafloor (Fig. 4).

DISCUSSION AND CONCLUSIONS

Morphostructural interpretation of bathymetric and seismic reflection profiles allows defining the Late Quaternary tectonics which is responsible of seafloor deformation features observed.

The smooth asymmetric crests at NW sector are interpreted in relation to folded anticlines in high resolution seismic profiles that deform until the seafloor. The deeper structure corresponds to a main NE-SW blind thrust verging to the NW (Comas et al., 1999; Vázquez et al., 2008) that affects at least the Quaternary base; however, Quaternary units are also fractured by high angle reverse faults. This blind reverse fault could in part absorb the compressive regional deformation. The folds of Quaternary units must be linked eastwards to the onland folds defined in Campos de Dalías (Marín-Lechado et al., 2005).

In the eastern sector, the main deformation is related to La Serrata NE-SW sinistral strike slip fault whose seafloor expression varies from longitudinal ridges, to linear faulted scarps and other aligned elements, such as depressions and displaced markers towards the NE (Gràcia et al., 2006). The main longitudinal ridges are interpreted as transpressive pushups bounded by high angle reverse faults. They are just located to the SW of Chella Bank and close to the secondary volcanic hills; their presence could increase the strength of the crust and concentrate compressive deformation in the fault.

Between these two main features, it has been located several structures westwards of Chella Bank. The most important is the NW-SE family of faults, includes the Adra Fault which has been interpreted as a dextral strike slip fault (Gràcia et al., 2012). These faults produce changes on the slope gradient, inflection lines and minor scarps, which are define from the geomorphic analysis of bathymetry. The Adra Fault is divided in two relay segments, the SE one affecting the Chella Bank. These faults show a compressive vertical component which it is not enough to produce a clear positive morphology on the seafloor. Among these faults there are minor scarps and gradient inflection lines of NNW-SSE to N-S trends which are associated to minor reverse faults and anticlines, but normal faults have been also observed. This configuration could be related to development of R and R' Riedel shears in a dextral strike-slip system. Three submarine slides are located towards the SE of Chella Bank (Fig. 1). They are developed from the Chella Bank in favour of the regional slope, but their NW-SE trend and location in the probable prolongation of the NW-SE strike slip faults through the Chella Bank, could be also an evidence of the modern activity of these faults.

Finally two set of structures are located to the west of Chella Bank between the dextral Adra and the sinistral La Serrata strike slips faults. One set corresponds to a NNE-SSW high deformed corridor constituted by secondary NNW-SSE (N-S to NW-SE) normal and reverse faults, their geometry could be explained in part as a flower shear zone, probably makeup by the interference produced by the slope gradient. The main fault does not affect the seafloor and must be related to the Motril-Djibouti NNE-SSW sinistral strike slip system, whose eastern boundary could correspond to the prolongation of the Al-Idrissi Fault. The other set corresponds to minor high angle N-S reverse faults located mainly on the Chella drift. They developed normal to the dihedral bisector between the two main strike slips faults. Therefore, they could be related to a secondary compressive deformation event, normal to the escape tectonics. The presence of the Chella Bank and their interference to the main fault systems of the region could favour the deformation in this dihedral position.

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