Active faulting offshore SE Spain (Alboran Sea): Implications for earthquake hazard assessment in the Southern Iberian Margin

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Received 17 May 2005; received in revised form 30 October 2005; accepted 7 November 2005
Available online 27 December 2005
Editor: V. Courtillot

Abstract

The southern margin of the Iberian Peninsula hosts the convergent boundary between the European and African Plates. The area is characterised by low to moderate magnitude shallow earthquakes, although large historical events have also occurred. In order to determine the possible sources of these events, we recently acquired swath-bathymetry, TOBI sidescan sonar and high-resolution seismic data on the Almería Margin (Eastern Alboran Sea). The new dataset reveals the offshore continuation of the NE–SW trending Carboneras Fault, a master fault in the Eastern Betic Shear Zone, and its associated structures (N150 and NS faults). These structures are active since they cut the Late Quaternary sedimentary units. The submarine Carboneras Fault zone is 100 km long, 5–10 km wide, and is divided into two N045 and N060 segments separated by an underlapping restraining stepover. Geomorphic features typically found in subaerial strike-slip faults, such as deflected drainage, water gaps, shutter ridges, pressure ridges and “en echelon” folds suggest a strike-slip motion combined with a vertical component along the submarine Carboneras Fault. Considering the NNW–SSE regional shortening axis, a left-lateral movement is deduced for the Carboneras Fault, whereas right-lateral and normal components are suggested for the associated N150 and NS faults, respectively. The offshore portion of this fault is at least twice as long as its onshore portion and together they constitute one of the longest structures in the southeastern Iberian Margin. Despite the fact that present day seismicity in the Almería margin seems to be associated with the N150 to NS faults, the Carboneras Fault is a potential source of large magnitude ($M_w$ ~7.2) events. Hence, the Carboneras Fault zone could pose a
1. Introduction

The present-day crustal deformation of the southeastern Iberian margin, which includes the Iberian Peninsula and adjacent offshore Mediterranean region, is driven mainly by the NW–SE convergence (4–5 mm/yr) between the African and Eurasian plates [1,2] (Fig. 1). This convergence is accommodated over a wide deformation zone with significant seismic activity south of the Iberian Peninsula [4,12,13]. Seismicity is mainly characterised by low to moderate magnitude events. Nevertheless, large destructive earthquakes (MSK Intensity IX–X) have occurred in the region, as has been revealed by historical records [8,14] (Fig. 1). This may pose significant earthquake and tsunami hazards to the coasts of Spain and North Africa.

The Neogene and Quaternary faulting activity in the southeastern Iberian Margin is dominated by a large left-lateral strike-slip system of sigmoid geometry referred to as the Eastern Betic Shear Zone (EBSZ) [15,16]. The active fault system stretches over more than 450 km from Alacant to Almería, and includes, from north to south, the Carrascoy, Bajo Segura, Alhama de Murcia, Palomares and Carboneras faults [e.g. 15,17]. The Carboneras Fault and terminal splays of the EBSZ extend further into the Almería margin in the Alboran Sea [e.g. 18–20], towards the area where the submarine epicentres of the historically recorded earthquakes of Almería (1522), Dalías (1804), and Adra (1910) are located [8,9,21] (Fig. 1). Despite the potential contribution of the Carboneras Fault zone to the earthquake and tsunami hazards, little is known of its detailed shallow structure and geometry offshore.

In order to investigate the offshore prolongation of the Carboneras Fault and associated seismogenic structures, we carried out a high-resolution marine geophysical survey of the Almería Margin in the NE Alboran Sea (Fig. 1). The main objectives of this study are 1) to image and characterise the seafloor geomorphology and the geometry of active tectonic structures identified offshore Almería (Spain), such as the submarine continuation of the Carboneras Fault zone; 2) to study how these structures affect the present-day phys iography of the Almería Margin, such as the drainage system of the Almería Canyon; 3) to investigate how they accommodate the present-day strain regime along the Eurasian-African plate convergence; and 4) to highlight the relevance of the Carboneras Fault to seismic hazard assessment of south Iberia, bearing in mind that high magnitude earthquakes with long recurrence intervals ($10^4$ years) have been documented in the EBSZ [11].

2. Geological and geodynamical setting of the southeastern Iberian Margin

The Betic and Rif Cordilleras linked by the Gibraltar Arc constitutes the westernmost end of the Mediterranean Alpine ranges at the boundary between the African and European plates (Fig. 1). The Betic Cordillera is an ENE–WSW–trending fold-and-thrust belt composed of the External Zone, Mesozoic to Tertiary sediments on top of the Variscan basement, and the Internal Zone (or Alboran domain), consisting of a thrust stack of metamorphic complexes (Fig. 1) [e.g. 16,22]. Superimposed onto the previous structure, Neogene to Quaternary sediments fill the intramontane basins, limited by E–W and NE–SW faults [23]. Middle Miocene to Pleistocene calc-alkaline through K-rich volcanic rocks crop out in the Cabo de Gata area and also in submarine structures, such as the Alboran Ridge [24] (Fig. 1).

Active deformation in the southeastern Iberian Margin is revealed by earthquake mechanisms derived from moment tensor inversion, covering both onshore and offshore regions [4–7] (Fig. 1). In the central Betics and southern Spain, focal mechanisms are heterogeneous and faulting style ranges from normal to reverse, whereas along the EBSZ and Alboran Sea, strike-slip faulting dominates [6] as corroborated by geological and geophysical data [11,15,17–19,25,26] (Fig. 1). Regional seismicity in the Ibero-Maghrebian region is diffuse and does not clearly delineate the present-day European-African plate boundary [4,13]. In the southeastern Iberian Margin, instrumental seismicity is characterized by continuous, shallow seismic events of low to moderate magnitude ($M_w\leq5.5$) [4,6,8].

Although large earthquakes (MSK Intensity > VIII) are relatively infrequent, they have occurred in the
Historical and archaeological records of events suggest that this region has been affected by at least 50 destructive earthquakes over the past 2,000 years, providing evidence of a significant seismic hazard [21]. The town of Almería was devastated by earthquakes in 1487, 1522 (IX MSK), 1658 (VIII MSK), and 1804 (IX MSK), and Vera was destroyed in 1518 (IX MSK) and 1863 (VII MSK) [4,8,21] (Fig. 1). These events have been attributed to motion along the Carboneras and Palomares fault systems [27]. On the other hand, the 1910 Adra Earthquake (mechanism plotted in gray) occurred offshore (Fig. 1) probably generated by N120–N130 trending faults consistent with moment tensor calculations [9].
At a regional scale, the Carboneras Fault system is straight and continuous: its northern end links with the NS trending Palomares Fault [15,17,18,27,28], and its southern end, to the east of the town of Almeria and near Cabo de Gata, enters the Mediterranean Sea [15,18,20] (Fig. 1). The Carboneras Fault is probably the largest brittle structure in the EBSZ, and it could link with other faults to form the Trans-Alboran Shear Zone, connecting the Betics with the North African Rif [18]. The exposed portion of the Carboneras Fault zone is about 50 km long [27,29]. Three main segments (northern, central, and southern) have been distinguished along the Carboneras Fault on land based on relationships between geomorphic and tectonic features [30]. Paleostress analysis indicates that the Carboneras Fault has been affected by a rotation in the maximum horizontal stress direction from NW–SE to N–S, which took place at the end of the Miocene [31]. Keller et al. [27] suggested that since the Burdigalian, left-lateral strike-slip motion has been in the range of 30–40 km and vertical offset in the range of 5–6 km.

The study area is located in the Adra-Almeria Margin, comprising the offshore continuation of the Carboneras Fault and associated structures to the NE Alboran Sea (Fig. 1). The Almeria continental shelf is narrow (4–6 km) along much of this margin. Its main geomorphic features have been recently revealed by swath-mapping in the frame of the Program of Spanish Continental Shelf Cartography (ESPACE) [32]. This margin is characterised by deeply incised canyons with a complex pattern of tributary valley systems [33]. The Almeria Canyon drains from the shelf edge to the deep-sea fan deposits in the Alboran Basin, which exceeds 2000 m in depth [34,35]. The lowermost part of the Almeria Canyon was incised using the MAK-1 sidescan sonar system disclosing individual elements of its channel morphology [36]. The Plio-Quaternary sedimentary architecture of the NE Alboran Sea, based on sparse single-channel seismic profiles, shows a cyclical pattern of deposition with alternating terrigenous input into the basin related to sea-level oscillations [34,35]. Deep multichannel seismic reflection data together with commercial wells and ocean drilling revealed the regional tectonic-sedimentary evolution and crustal structure of the margin and the eastern Alboran Basin [19,20,26,37–39].

3. Data and methods: The HITS cruise

The present study results from an integration of different types of data: deep-towed sidescan sonar backscatter, swath-bathymetry, and high-resolution seismic profiling, acquired during the HITS cruise (“High Resolution Imaging of Tsunamigenic Structures of the Southern Iberian Margins”) on board the Spanish RV Hespérides (Fig. 2). High-resolution sidescan sonar data were collected using the Towed Ocean Bottom Instrument (TOBI) [40] from the National Oceanography Centre, Southampton (UK) as part of the programme European Access to Seafloor Survey Systems (EASSS III). The TOBI sidescan survey consisted of six parallel tracks, 6-km wide swath insonifying most of the area bounded by latitude 36°17′–36°40′N and longitude 3°05′–2°10′W (Fig. 2b). The acoustic response (intensity of the backscattered signal) depends on the incidence angle, roughness/topography and on the nature of the seafloor. Reflective surfaces, such as high relief areas, rock outcrops and landslides are depicted as light-grey to white, whereas less reflective surfaces, such as low-relief and fine-sediment covered areas, are dark-grey. Acoustic shadows are black. The TOBI sidescan data, with an along-track resolution of 6 m [40] enabled us to recognise the seafloor superficial features in detail.

The swath-bathymetric data were collected by using the Simrad EM12-S multibeam system covering an area of about 35 × 100 km (Fig. 2a). Data gaps have been filled using the Simrad EM300 bathymetric grid acquired by the “Instituto Español de Oceanografía” for the Spanish Fisheries Office. Water depth ranges from 80–100 m at the top of the banks and shelf break down to more than 1800 m at the base of the slope. Simultaneously acquired and amounting to about 450 km of profiles, high-resolution (1–5.5 kHz) Simrad TOPAS (TOposgraphic PArametric Sonar) seismic profiler provides detailed stratigraphic information on the uppermost tens of metres below the seafloor (50 to 80 m at an assumed sediment velocity of 1.5 km/s). These data provide new insights into the control of neotectonic structures over the Plio-Quaternary sedimentary architecture of the margin. The seismic units recognised in the high-resolution profiles correspond to Quaternary-age sediments based on correlation with oil exploration wells and single-channel seismic reflection profiles of the Almeria Margin [19,20,35,36]. Similar high-resolution methodologies proved to be useful in exploring submarine earthquake geology in other active areas along the Eurasian-African plate boundary, such as the Marmara Sea [41] and the southwestern Iberian Margin [42].

4. Results

The main morphostructural elements of the Almeria Margin are identified in Fig. 2a. They correspond to 1) the Almeria Canyon and Channel, a meandering turb-
dite system confined between large topographic highs, 2) a dense tributary valley network, 3) a N045–N060 prominent lineation, which corresponds to the submarine continuation of the Carboneras Fault, and 4) the Cabo de Gata, Sabinar, and Chella Banks.

4.1. The Almería Canyon and Channel

A high-resolution map of the northern part of the Almería Canyon is illustrated in the TOBI image (Fig. 3a). The northern Almería Canyon is more than 3 km wide (talweg width of 380 m) and shows abrupt west flanks (up to 300 m high), well developed meanders and terraces (Fig. 3a). Some portions along its path show high reflectivity, probably due to the presence of coarse-grained talweg deposits. The net direction of the Almería Canyon is roughly parallel to the submarine continuation of the Carboneras Fault, located further west (Fig. 3a). To the west and to the east of the Almería Canyon there is a network of tributaries,
Fig. 3. (a) TOBI sidescan sonograph of the northern part of the Carboneras Fault zone and Almería Canyon. The canyon talweg deepens from 550 to 1050 m from the top to the bottom of the image, with a mean slope of 2% and sinuosity of 1.51. Thick dashed line depicts location of (b). TVS: Tributary Valley System. (b) High-resolution seismic profile TA6 across the northern part of the Almería Canyon and Carboneras Fault. Vertical scale in m is calculated by applying a velocity of sound propagation in water of 1500 m/s. Vertical exaggeration ~40.
corresponding to the Dalias and Gata Tributary Valley Systems [33], respectively. The denser Dalias Tributary Valley System is composed of tens of linear gullies and channels, which depart from the shelf edge, mostly following the straight-line slope of the margin, trending N150 to N170. At their intersection with the Carboneras Fault lineation, the tributaries show abrupt changes in stream direction (e.g. gullies A to D, Fig. 3a).

A high-resolution seismic profile crossing the northern part of the TOBI image illustrates the shallow structure and architecture of the upper stratigraphic units (Fig. 3b). To the west, the Dalias Tributary Valley System depicts channel-levee systems and gullies showing different degrees of incision, ranging from a few metres to 45 m deep. The profile shows a gentle upwarp which is bounded to the west by the Carboneras Fault. It also shows how the Carboneras Fault cuts and folds the sedimentary succession up to the most recent units. A thick (~18 m) mass-wasting deposit characterised by chaotic seismic facies is located at the base of the surface break, and is thinly draped by the uppermost sedimentary units (Fig. 3b). To the east are the northern Almeria Canyon and the Gata Tributary Valley System, depicting well stratified reflectors incised by channel-levee complexes.

The southern part of the Almeria Canyon runs from 36°31’ to 36°26.5’N, as revealed by the TOBI sidescan sonar mosaic and the swath-bathymetric map (Figs. 2a and 4a). The southern Almeria Canyon is narrower (average width of 1.5 km) and rectilinear, showing a net N038 trend. Several terraces are identified on the western flank of the canyon. The lower part of the Dalias Tributary Valley System drains into the southern Almeria Canyon, where some sections of the gullies are rectilinear, developed along N150 trending lineations (Fig. 4a). One of these lineations is visible at depth on a high-resolution seismic profile crossing the southern part of the Almeria Canyon (Fig. 4b). The lineation corresponds to a transparent-facies high-angle zone which separates areas where the stratified units show contrasting thicknesses, dipping attitudes and local angular relationships. This lineation is interpreted as a NE-dipping normal fault which deforms the whole

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**Fig. 4.** (a) TOBI sidescan sonograph of the southern part of the Almeria Canyon and the Almeria Channel. In the southern part of the Almeria Canyon, the talweg deepens from 1030 to 1220 m with a gentle slope of 1.8%, yielding a low sinuosity of 1.05. The Almeria Channel shows a high sinuosity of 1.95, with the talweg deepening from 1220 m to more than 1630 m and an average slope of 3.8%. TVS: Tributary Valley System. Thick dashed lines depict the locations of (b) and (c). (b) High-resolution seismic profile TA3 across the Almeria Canyon, where the ~N150 trending fault is imaged. C-L: Channel-levee system. (c) High-resolution seismic profile TA1 across the Almeria Channel. Vertical scale in m is calculated by applying a velocity of sound propagation in water of 1500 m/s. Vertical exaggeration ~40.
sedimentary succession up to the surface, favouring the development of a rectilinear channel of the Dalías Tributary Valley System (Fig. 4b). The prolongation of this fault towards the southeast reaches the Almería Canyon, and probably facilitates the sharp and straight morphology of one of its meanders. The faults striking N150, where Dalías Tributary Valley System gullies develop, are designated by the general term of “N150 faults” (Figs. 3a and 4a).

The Almería Channel is the tight meandering agradational channel-levee turbidite system [34–36] located downstream from the canyon, characterised by a relatively high acoustic backscatter (Fig. 4a). The new full coverage high-resolution dataset reveals the following features. Four large abandoned meanders are observed on the eastern flank of the channel, while narrow terraces and outside meander furrows are identified on its western flank (Fig. 4a). South of 36°22’N, the Almería Channel changes orientation from a general NS to N120 trend and varies in sinuosity, general morphology and infill (Fig. 4a). Towards the lower part of the image, the channel narrows, is less deeply incised, and shows an asymmetric transverse profile, with higher levees on its western flank (Fig. 4b). Incised into well-stratified, non-disturbed sedimentary units, chaotic facies at the axis of the channel are interpreted as the effect of coarse-grained bedload (Fig. 4b). At the eastern end of the profile, transparent irregular deposits overlie the stratified units of the Almería Channel, corresponding to a landslide deposit sourced southwest of the Sabinar Bank (Fig. 4c).

4.2. The Carboneras Fault zone

The swath-bathymetric data allow us to identify a more than 70 km long and 5 km wide lineation striking N045–N060, which corresponds to the surface expression of the Carboneras Fault (Figs. 2a and 5a). We distinguish two main segments along the lineation: the northern (33 km long, N045-trending), and the southern (26 km long, N060-trending). Between these two segments of the Carboneras Fault there is an area of complex morphology formed by a narrow (<1 km) slightly up-slope concave arcuate ridge (referred to as ridge AR) which defines an elongated depression to the northwest and is flanked by an abrupt escarpment to the southeast (Figs. 2a and 5b profile TA3).

North of 36°36’N, the northern segment of the Carboneras Fault is rectilinear showing a NW-facing escarpment evidenced by the sharp backscatter contrast on the TOBI sonograph, up to 10 m high (Fig. 3a). From 36°36’ to 36°31’N, the Carboneras Fault intersects the Dalías Tributary Valley System producing a sharp deflection of its channels and gullies (Figs. 2, 3a and 5a). For instance, Gully D is deflected towards the southwest at the Carboneras Fault and follows this lineation for more than 2 km (Fig. 3a). Then, it bends sharply at a right-angle towards the southeast following, for more than 4 km, the superficial trace of a N150 high-angle fault. Similar geometries and trends are displayed by gullies A, B and C (Fig. 3a). The southern segment of the Carboneras Fault shows a step-like morphology to the west (Fig. 5b, profile TA1), which gradually passes to a subdued irregular ridge to the east (referred to as ridge SR, profile TA2 in Fig. 5b). East of ridge SR, the seafloor shows a series of 10–15 km long and ~6 km wide undulations consistently trending N120–130 (Fig. 5a). Based on the TOPAS seismic profiles (Fig. 5b), these are interpreted as widely spaced folds affecting the sedimentary succession (Fig. 6).

The succession of six high-resolution seismic profiles across the Carboneras Fault lineation, from the shelf to the base of slope, illustrates how its shallow structure varies along-strike (Fig. 5b). Near the shelf area, well stratified units are folded and cut by subvertical faults which separate blocks of different stratigraphy and structure forming a positive flower structure (Fig. 5b, profile BA8). In the area intersecting the Dalías Tributary Valley System, the distinction of faults is less clear-cut owing to the gully and channel incisions which mask the structure at depth. However, the general geometry of the Carboneras Fault zone also coincides with a seafloor upwarp (Fig. 5b, profiles TA4 and TA5). Profile TA3 crosses ridge AR where stratified units are folded in anticline which we interpret as a pressure ridge. To the west, a small basin is underlain by a gently folded thick stratified succession. This basin is separated from ridge AR by tightly spaced high-angle faults, some of which appear to be reverse (Fig. 5b, profile TA3). East of ridge AR, a 30 m high escarpment coinciding at depth with a high-angle fault limits with gently folded strata. Towards the base of the slope, profiles TA2 and TA1 also show folded elevated areas limited by subvertical discontinuities interpreted as faults (Fig. 5b).

4.3. The Chella and Sabinar banks

Prominent highs, such as the Chella, Sabinar, Pollux and Cabo de Gata spur dominate the physiography of the margin (Figs. 2 and 5a). They are composed of a Neogene volcanic basement topped by carbonate platforms [19,24]. The banks, shallowing up to 80 m, are
Fig. 5. (a) Slope map overlain on top of the 3D swath-bathymetry data of the Carboneras Fault zone, view from the southwest. The white thick lines depict location of profiles (BA8 to TA8) presented on (b). (b) Succession of high-resolution seismic profiles across the Carboneras Fault zone, from the shelf to the base of the slope depicting along-strike morphostructural variability. AR: arcuate elevated ridge, SR: subdued ridge. Vertical scale in m is calculated by applying a velocity of sound propagation in water of 1500 m/s. Vertical exaggeration ~40, except for profile BA8, which is ~55.
tens of kilometres in diameter and several hundred metres higher than their surroundings, and are easily identified on the TOBI sidescan image as very high reflectivity areas (Fig. 2b). On the Chella Bank, the circular shape of the old-volcanic edifice is distinguishable (Fig. 2). Moats mainly developed on the eastern flank of the Chella Bank and the northern flank of Sabinar provide evidence of contour currents. Of especial interest is the presence of deeply carved scars to the south of the Sabinar and Pollux banks, suggesting dismantlement of the margin by large and complex mass movements (Fig. 5a). The scars, up to 200 m of headscarp height, cover an area of about 20 km² with run out distances of more than 10 km. Steep slopes (up to 25%, Fig. 5a) and friable lithologies of the volcanic edifices may favour large mass movements along this part of the margin. Localized individual slide lobes are observed on the western flank of the Sabinar Bank and on the southern flank of the Chella Bank. To the west of the Chella Bank we identify several NS morphological ruptures on the seafloor, showing prominent normal fault scarps, based on swath-bathymetry and high-resolution seismic profiles (Fig. 5a).

5. Discussion

5.1. Interplay between submarine channels and faults: Control on the sedimentary architecture of the Almería Margin

According to the bathymetric and high-resolution seismic data, the superficial expression of the Carboneras Fault zone mainly consists of an upwarped narrow area, bounded by subvertical faults at depth. The elevation of the seafloor associated with this structure is responsible for the deflection of the Dalias Tributary Valley System. Deflections to the southwest are interpreted as the result of drainage-blocking produced by the Carboneras Fault seafloor upwarps, which act as shutter ridges (see Section 4.1, Fig. 6). As pointed out by [43], the deflection of streams should be approached with caution when determining the direction of lateral displacement along directional faults. Despite the misleading impression of dextral fault “bayonets” (offset drainage), the consistent deflections to the southwest should be interpreted as resulting from the relationship between the direction of the Carboneras Fault drainage-
blocking and the general slope of the margin. Along the Carboneras Fault lineation, water gaps, the place where drainage cuts through strike-slip faults between shutter ridges [44], allow deflection of the gullies to the southeast. In this case, the mode of deflection is conditioned not only by the general slope of the margin but, in some cases, by the structural depressions coinciding with faults trending N150, which locally constitute preferential paths for the submarine drainage (Figs. 3a and 6).

Gullies and channels of the Dalias Tributary Valley System in the northern part of the Almeria Canyon are seafloor features present throughout the sedimentary succession on high-resolution seismic profiles. They maintain their morphology and position over time, suggesting that these tributary valley systems are stable features at least during the Quaternary, and that no lateral migration of the submarine drainage network is produced where the general slope conditions are maintained.

5.2. Structural model of the Carboneras Fault zone in the Alboran Sea: Evidence for strike-slip displacement

There are several lines of evidence supporting that the submerged portion of the Carboneras Fault described here is a strike-slip fault. Swath-bathymetry and high-resolution seismic profiles show a considerable variation in the three-dimensional structural geometry along the strike of the fault (Fig. 5), analogous to those that have been documented in strike-slip faults exposed on land [44]. For instance, the submarine Carboneras Fault displays several geomorphological characteristics, such as systematically deflected gullies, shutter ridges, water gaps and incised channels parallel to the main structure (Fig. 6). The shallow structure of the Carboneras Fault consists of a series of upward-splaying subvertical faults defining positive flower structures in cross section (Fig. 5b), as previously inferred by [20,35]. These high-angle faults probably coalesce at greater depths and constitute part of a single large-scale directional fault zone 5 to 10 km wide. This is a typical geometry found in the shallow structure of large strike-slip systems [44].

In agreement with evidence found onland [e.g. 15,27,29,30], there are structures which may indicate that the submarine Carboneras Fault is a strike-slip fault with a sinistral sense of motion (Fig. 6). Firstly, the series of widely spaced obliquely trending folds (N120–N130) observed in the southern segment are compatible with the structural geometries predicted under left-lateral shear deformation. Secondly, ridges AR and SR show a series of undulations with “en echelon” arrangement observable in the 10-m contour bathymetric map (Fig. 6). These elevated and folded areas correspond to pressure ridges: Ridge AR is formed at an underlapping restraining stepover between the southern N060 and northern N045 segments of the Carboneras Fault, whereas ridge SR is placed in an overlapping restraining stepover. Both structures (Ridges AR and SR) reveal a geometrical pattern in agreement with a left-lateral strike-slip component on the Carboneras Fault.

It is possible to find elongated hills along pure strike-slip faults depending on the lateral displacement of topographic features [44]. Nevertheless, in the case of the Carboneras Fault, when the general slope of the margin and the left-lateral movement along strike are considered, it is not possible to attribute the blocking and deflection of the Dalias Tributary Valley System drainage to pure sinistral strike-slip deformation. This would bring deeper portions of the margin across the fault, thereby locally increasing the slope, which would be inconsistent with the observed drainage-blocking. This is our explanation for suggesting that the Carboneras Fault is also affected by a vertical slip component, as has been pointed out for the onland segments by [21,30].

Along the strike of the Carboneras Fault, we identify changes in the dip direction of the fault escarpment, which produces variations in the relative upthrown and downthrown blocks (Figs. 5b and 6). Thus, along the northern segment, the fault escarpment faces towards the NW, opposite to the general gradient of the margin but following the same arrangement of uplifted blocks as the Carboneras Fault on land and on the continental shelf (Fig. 7). In contrast, along ridge AR and the southern segment, the main fault escarpment faces to the SE, increasing the margin slope (Fig. 5b). This arrangement suggests a “scissors” structure [44] illustrated in map view in Fig. 6. However, the distinction in the sense of throw between normal and reverse vertical components together with the detailed structure of the Carboneras Fault at depth can only be resolved by using deeper penetration seismic reflection systems.

5.3. The Carboneras Fault zone in the context of the Eurasia-Africa plate convergence

Deformation associated with Eurasia-African plate convergence in the Alboran Region is distributed over a broad area encompassing the EBSZ, Betics, Alboran Ridge, Moroccan Rif and Tell-Atlas in Northern Algeria [4,12,13]. The convergence rate estimated by [1,2] is about 4–5 mm/yr following a NW–SE direction.
Recently published geodetic models based on GPS velocities from the western Mediterranean [45,46] predicted a relatively slower (2.5 to 5 mm/yr) and more oblique motion (20° counter-clockwise rotation in the direction of convergence) of the present-day African and Eurasian plates [45].

The new data presented show that the submarine portion of the Carboneras Fault and associated faults are active given that they affect all the sedimentary sequences, cutting and folding the upper and recent units, which according to [20,35] are of Late Holocene age. Studies along the Carboneras Fault onland indicate 5–10 m of vertical offset across Tyrrhenian marine terraces with no evidence of large lateral offset [30]. The central onland segment, known as La Serrata, consists of two main parallel fault traces bounding a 1 km wide horst (Fig. 7), where stream-channels older than 100 kyr are left-laterally offset by 80–100 m [30]. These authors suggest that the slip history of the onland Carboneras Fault during the last 100 kyr appears to be one of vertical uplift rather than strike-slip movement, with maximum vertical slip rates in the order of 0.05–0.1 mm/yr [30]. In contrast, based on neotectonic modelling, the onland Carboneras Fault zone might accommodate about 0.7 mm/yr of sinistral strike-slip motion [47,48]. Our findings on the submarine segments of the Carboneras Fault do not disagree with the above suggestions. However, the lack of reliable chronological markers prevents us from estimating the vertical and strike-slip rate components.

A local shortening along an approximate NNW–SSE axis is suggested by the regional stress field derived from earthquake focal mechanisms inversions in the Alboran Sea and southeast Spain [6,7]. This direction also coincides with the most compressive horizontal stress orientation and regime predicted by neotectonic
modelling based on thin-sheet finite element [47,48]. Considering the N NW–SSE shortening axis, we can assume the strain regime of the newly identified structures: the Carboneras Fault may have a left-lateral component, the N150 faults would move as right-lateral, and the NS faults located to the west of the Chella Bank would have a predominantly normal component (Fig. 6). The geometrical relationship between the left-lateral Carboneras Fault and the N150 to NS normal faults identified in the area is compatible with the model of block tectonics presented by [25] to explain the neotectonic structures of the southern Almería province. In their model, predominantly extensional structures (such as the NS and N150 faults) accommodate the deformation produced by squeezing the wedge located between the dextral strike-slip Corredor de las Alpujarras and sinistral Carboneras fault zones (Fig. 7). The combined movements of these large strike-slip fault zones would induce a westward tectonic escape [25].

Moment tensor solutions for small and moderate earthquakes in the Alborán Sea show a predominant left-lateral strike-slip motion. They mainly correspond to the Alborán Ridge series of 2003, which follow a N055 nodal plane [6,7] (Fig. 1). Focal mechanisms and epicentre locations also indicate that the newly identified structures to the south of Adra and Campo de Dalias (i.e. N150, NS faults) are active and consistent with the present-day extensional strain pattern of this area [6,21,25,48] (Figs. 1 and 7).

The Carboneras Fault zone corresponds to the transpressional southern end of the EBSZ. The new marine geophysical data reveal that the morphological expression of the Carboneras Fault zone terminates against a topographic high at 36°17.3′N–3°03.5′W on the Alborán Sea (Figs. 5 and 6). This suggests that, in contrast to previous works [e.g. 18], the Carboneras Fault may not extend as a large continuous fault zone connecting the Eastern Betics with the Jebha and Nekor Faults in the North-African coast, calling into question the “Trans-Alborán Shear Zone”. Instead, we propose that strain along the offshore Carboneras Fault zone is transferred to the parallel structure located about 20 km to the south, which flanks the Alborán Trough (Figs. 1 and 7).

5.4. Seismicity and active faulting offshore Almería region: Implications for seismic hazard assessment in the Southern Iberian Margin

Present day seismicity in the southeastern Iberian Margin shows swarms of small to moderate magnitude ($M_w<5$) shallow earthquakes [49] which are more concentrated to the north and east of the Chella Bank (Fig. 7). This seismicity seems to be associated with the secondary N150 to NS faults, suggesting moderate faulting in the region. Based on epicentre relocation, these structures also seem to be the source of the shallow (4.8 to 6.5 km) and moderate ($M_w$ 4.8 to 5.1) Adra earthquake swarms, the most intense earthquake activity recorded recently in this region, which occurred between December 1993 and January 1994 [25,49]. Slope instability features (landslide headscars, detached blocks, and debris flow deposits), which are present on the bank flanks, could also be associated with seismic and paleo-seismic activity of this margin. The unstable nature of the volcanic edifices together with the moderate magnitude seismic activity recorded in the area could account for the triggering of submarine landslides observed on the banks, especially the steep southern flanks of the Sabinar and Pollux Banks (Figs. 5–7).

As regards the Carboneras Fault zone (onshore and offshore), only few epicentres are placed along its trace. However, this does not mean that little seismological hazard should be attributed to the Carboneras Fault. For instance, the location of the Almería (MSK intensity $>IX$) and Adra (MSK intensity $>VIII$ and $M_w=6.1$ [49]) historical events (Fig. 1) fall relatively close (considering location uncertainties) to the submerged trace of the Carboneras Fault as mapped in the present study (Fig. 7). This suggests that the Carboneras Fault is a possible source of these events, especially the 1522 Almería Earthquake and Tsunami (7). Considering that tsunamis are not expected from pure strike-slip motion, the occurrence of a tsunami in 1522 [8] may indicate a large landslide, but possibly also, a dip-slip component on the submarine portion of the Carboneras fault, in line with our interpretations. Calculation of the relationship between magnitude and intensity for the most important historical earthquakes in the Ibero-Maghrebian region assigns a magnitude $m_b$ 5.8–6.0 to the 1522 Almería Earthquake [50].

In addition, a detailed macro- and micro-structural analysis of clay-bearing fault-gouges in the northern segment of the Carboneras Fault yields some insight into its mechanical seismic behaviour [29,51]. It shows a wide heterogeneous deformation zone with low permeability layers in the fault gouge, containing lenses of fractured permeable rocks that may trigger large periodic seismic events against a background of fault creep in the surrounding materials [29]. The onland Carboneras Fault has been suggested as an analogue for the San Andreas Fault around Parkfield (California), where
geophysical observations of the fault suggest a large zone (1–2 km) of deformation with fault creep and $M_w=6.0$ recurrent earthquakes [29].

The Carboneras Fault zone is by far the longest, continuous fault mapped in the southeastern Iberian margin (50 km onshore, plus more than 100 km offshore) (Fig. 7) and, therefore, it would be the best candidate to generate large magnitude earthquakes. For instance, assuming a surface rupture length of 70 km following a $\sim$N045 trend (this would include the assumed “non-gouged” southern segment onshore, the shelf, and the northern offshore segment of the Carboneras Fault, Fig. 7) and using the empirical relationships of [52], a moment magnitude of $\sim7.2$ is obtained. The southeastern Iberian Margin corresponds to the most seismically active and hazardous Spanish region. It is considered to have a moderate seismic hazard, between 0.8 and 1.6 m/s$^2$ mean peak ground acceleration for a return period of 475 year, i.e., with 10% probability of exceedance in 50 years [53]. This correlates well with the values obtained in a recent probabilistic seismic hazard assessment in terms of Arias intensity for different soil conditions in southeast Spain [54]. However, as these models are mainly based on instrumental and historical earthquake catalogues, a reevaluation of the previously calculated seismic and tsunami hazard in the region taking into account the offshore segments of the Carboneras Fault could significantly increase the suggested hazard.

Finally, a paleoseismic approach is required to provide an assessment of the seismic hazard associated with the Carboneras Fault, especially when considering high magnitude earthquakes and probably long recurrence intervals ($10^4$ years) [11,55]. Future work on the Carboneras Fault will be devoted to the imaging of deep structure and to the identification and dating of geological markers of the fault offshore, and to geophysical surveying and trenching onshore. This will be helpful in determining the past activity and seismic parameters of the Carboneras Fault (geometry, slip rate and recurrence interval).

6. Conclusions

1. New marine geophysical data (swath-bathymetry, deep-towed sidescan sonar TOBI and high-resolution seismic data) from the Almería Margin show that the superficial expression of the Carboneras Fault consists of an upwarped 5–10 km wide deformation zone. This is bounded by subvertical faults at depth that trend N045 to N060 and extend for more than 100 km. The drainage system of the margin is deflected by the Carboneras Fault upwarp, and is locally conditioned by secondary structures trending N150.

2. The submarine Carboneras Fault displays geomorphic features and tectonic structures usually found on strike-slip faults onland, such as deflected drainage, shutter ridges, water gaps, pressure ridges and positive flower structures. A narrow underlapping restraining stepover separates the 33 km long northern segment trending N045 from the 26 km southern segment trending N060. Obliquely trending folds (N120–N130) and “en echelon” pressure ridges suggest a left-lateral shear deformation along the Carboneras Fault. In addition, drainage blocking produced by the northern segment of submarine Carboneras Fault indicates a vertical slip component.

3. The submarine portion of the Carboneras Fault and associated faults cut and fold the most recent sedimentary units of Late Holocene age, showing that they are active structures. Considering the NNW-SSE shortening axis, the Carboneras Fault may have a left-lateral component, the N150 faults would move as right-lateral, and the NS faults, located to the west of the Chella Bank would have a predominantly normal component. These structures are consistent with the model of block tectonics suggested by [25]. The morphological expression of the Carboneras Fault zone ends in a structural high in the Alboran Sea, in contradiction to the alleged continuous fault zone connecting South Spain with North Africa, known as the “Trans-Alboran Shear Zone”.

4. Present-day seismicity in the Almería margin shows swarms of small to moderate magnitude shallow earthquakes [49], which are more concentrated to the north and east of the Chella Bank and may be associated with the secondary N150 to NS faults. This moderate seismicity may have triggered the submarine landslides observed on the flanks of the banks. The submerged portion of the Carboneras Fault is at least twice as long as its subaerial portion. The onshore and offshore segments together constitute one of the longest faults in the southeastern Iberian Margin. Despite the low instrumental seismicity along its trace, the Carboneras Fault is a potential source of large (up to moment magnitude $\sim7.2$) events such as the 1522 Almería Earthquake. Seismic and tsunami hazard assessment for southeast Iberia and African margins would significantly increase if the offshore segments of the Carboneras Fault were considered.
Acknowledgements

The authors acknowledge the support of the MCYT Acción Especial HITS (REN2000-2150-E), European Commission European Access of Seafloor Survey Systems EASSS-III programme (HPRI-CT99-0047), Spanish national Project IMPULS (REN2003-05966MAR), ESF EuroMargins WESTMED project (01-LEG-EMA22F and Acción Especial REN2002-11230E-MAR), and funding by Generalitat de Catalunya, research group SGR2001-0081. We thank the captain, crew and technical staff on board the R/V Hespérides and the TOBI Team from the National Oceanography Centre (Southampton, UK) for their assistance throughout the data collection. We also thank Juan Acosta (IEO, Madrid) for providing us with supplementary bathymetric data from the program “Fisheries Cartography of the Alboran Sea”. We are indebted to Miquel Canals (Univ. Barcelona) for valuable suggestions during the preparation of the cruise and Tim Le Bas (NOC, UK) for assisting two of us (O.G. and J.G.) during the processing of TOBI data. We benefited from fruitful discussions during the revision of this article with Ana Negredo (UC, Madrid) and Daniel Stich (INGV, Bologna). The latter is also acknowledged for providing focal mechanisms for Fig. 1. We wish to thank Milène Cornier (LDEO, USA) and three anonymous reviewers whose constructive criticism enabled us to improve our original manuscript.

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