Morphotectonics and Strain Partitioning at the Iberia-Africa plate boundary from multibeam and seismic reflection data

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Abstract

The Gulf of Cadiz, off SW Iberia and the NW Moroccan margin, straddles the cryptic plate boundary between Africa and Eurasia, a region where the orogenic Alpine compressive deformation in the continental collision zone passes laterally to the west to strike-slip deformation. A set of new multibeam bathymetry, multi-channel and single channel seismic data presented here image the main morphological features of tectonic origin of a significant part of the Gulf of Cadiz from the continental shelf to the abyssal plain. These morphotectonic features are shown to result from the reactivation of deeply rooted faults that changed their kinematics from the early Mesozoic rifting, through the Late Cretaceous-Paleogene collision, to Pliocene-Quaternary thrusting and wrenching. The old faults control deep incised, more than 100km long canyons and valleys. Several effects of neotectonics on deep water seabed are shown. These include: i) the complex morphology caused by wrenching on the 230 km long WNW-ESE faults that produced en echelon folds on the sediments; ii) the formation of up to 5 km wide crescent shaped scours at roughly 4 km water depth by reactivation of thrusts; iii) 10 km long creep folds on the continental slope; and iv) the formation of landslides on active fault escarpments. The present day deformation is partitioned on NE-SW thrusts and WNW-ESE to W-E strike-slip faults and is propagating northwards on N-S trending thrusts along the West Iberia Margin from 35.5ºN to 38ºN, which should be considered for seismic hazard.

Keywords: Gulf of Cadiz; Southwest Iberia Margin. multibeam bathymetry, morphotectonics, seismotectonics, wrench tectonics, strain partitioning, migration of deformation.

1. Introduction

1.1. Scope and objectives

In recent years the Gulf of Cadiz (Fig. 1) has been recognized as a key site to understand a broad spectrum of geological issues, such as: i) the tectonic evolution of the Africa-Iberia plate boundary, the formation of the Gibraltar orogenic arc, the earthquake and tsunamigenic structures, the origin of the catastrophic 1755 Lisbon earthquake and tsunami (Argus et al., 1989; DeMets et al., 1994; Sillard et al., 1998; Maldonado et al., 1999; Kreemer and Holt, 2001; Zitellini et al., 2001; Calais et al., 2002; Gutscher et al., 2002; Sella et al., 2002; Calais et al., 2003; Fernandes et al., 2003; Gràcia et al., 2003; Terrinha et al., 2003; Gràcia et al., 2003a; Medialdea et al., 2004; Nocquet and Calais, 2004; Stich et al., 2006) , ii) the Mediterranean Outflow Water (MOW) and its relation to sedimentation and climate changes (Ambar et al., 2002; Voelker et al., 2006; Hernandez-Molina et al., 2003; Mulder et al., 2003; Somoza et al., 2003); iii) fluid escape and mud volcanism (Pinheiro et al., 2003; Somoza et al., 2003; Van Rensbergen et al., 2005; Pinheiro et al., 2006a), and chemosynthetic ecosystems associated to cold seeps (Niemann et al., 2006).

Behind this diversity of processes affecting the geosphere, the biosphere and the hydrosphere, is a complex geological evolution of the area throughout the Neogene. It is now well established, after various studies based on seismic reflection profiles, sidescan sonar and ground truthing, that the whole area is under compressive deformation. A number of active tectonic structures with high tsunamigenic potential were mapped (Gràcia et al., 2003; Terrinha et al., 2003; Zitellini et al., 2004) and various multilayered complexes of hemipelagic-mass wasting deposits of Holocene and Pleistocene age were imaged and dated (Vizcaino et al., 2006).

The morphology of the northeastern part of the Gulf of Cadiz was described by Hernandez-Molina et al.(2003), Mulder et al.(2003) and Somoza et al.(2003). The morphology of the southern part of this sector is clearly influenced by the tectonomorphic processes associated with the deformation of the Gulf of Cadiz accretionary wedge (Maldonado et al., 1999; Gutscher et al., 2002), as well as gravitational processes (Gutscher et al., 2008), whilst in the northern part the shaping processes are sedimentary, erosive and tectonic, associated with the MOW and to diapiric ridges.

The objective of this work is to describe the morphology of the northwestern part of the Gulf of Cadiz and discuss the morphogenetic processes in relation to the tectonic deformation of the Alpine collision front and the Gloria transform fault. This is done based on the interpretation of an original multibeam bathymetry data and seismic reflection profiles

1.2. Geological setting

During Triassic through Early Cretaceous times the southern and western Iberian margins underwent tectonic rifting, which led to oceanic break-up of the West Iberian Margin from Barremian to Aptian times (Pinheiro et al., 1996). Although the existence of oceanic lithosphere in the Gulf of Cadiz is still a matter of debate (Srivastava et al., 1990; Rovere et al., 2004; Gràcia et al., 2003), some authors postulated the existence of a south Iberia subduction zone that accommodated the Africa-Iberia convergence, from Late Cretaceous-Paleogene through Miocene times (e.g. Srivastava et al., 1990). Accordingly, this process led to the formation of back arc basins and associated tectonic terranes in the western Mediterranean, the formation of the Betic orogen, as well as to the tectonic inversion of the rifted autochthonous south Portuguese and south Spanish margins (e.g. Terrinha, 1998; Maldonado et al., 1999; Rosenbaum et al., 2002; Lopes et al., 2006). Westward-directed thrusting of the Internal Betics domains and orogenic collapse, possibly associated with roll back of the Africa subducted slab, formed the Gibraltar orogenic arc, the Gulf of Cadiz accretionary wedge and lithospheric thinning in the Alboran Sea (Rosenbaum et al., 2002; Faccenna et al., 2004). These tectonic processes led to the formation of an accretionary wedge westward of the Gibraltar arc (Gutscher et al., 2002) or imbricate wedge with a westward directed tectonic transport, and an associated distal olistostrome complex (e.g., Horseshoe Gravitational Unit in Iribarren et al., 2007; Giant Chaotic Body in Torelli et al., 1997) that extends across the Horseshoe Abyssal Plain (fig. 2). The MCS lines reveal a basal decollement horizon of the stacked thrusts of the accretionary wedge near the top of the Cretaceous. Both the accretionary prism and the olistostrome are sealed by sediments of Late Miocene to Lower Pliocene age (Tortella et al., 1997; Torelli et al., 1997; Roque, 2007). The segment of the Azores-Gibraltar Fracture Zone to the east of the Gloria Fault (inset in fig. 1) was described by Sartori et al. (1994) as a diffuse plate tectonic boundary and various plate kinematic models indicate a 4mm/yr rate of NW-SE to WNW-ESE convergence between Nubia and Iberia along this fault (insets in Figs.1 and 7), (Argus et al., 1989; DeMets et al., 1994; Sillard et al., 1998; Kreemer and Holt, 2001; Calais et al., 2002; Sella et al., 2002; Calais et al., 2003; Fernandes et al., 2003; Nocquet and Calais, 2004; Stich et al., 2006). Ribeiro et al. (1996) postulated the formation of an incipient West Iberia subduction zone during Pliocene-Quaternary times, based on the computed NW-SE Present day main compression direction.

N-S to NE-SW faults formed in the Permian during the late Variscan fracturing event (Arthaud and Matte, 1977; Ribeiro, 2002) and they were subsequently reactivated during the Mesozoic rifting, the Mesozoic transient compressive episodes (Terrinha et al., 2002) and the Cenozoic through Present compression (Fig. 2, Dias, 2001; Carrilho et al., 2004).

Offshore, the N-S trending Marquês de Pombal and Pereira de Sousa faults lie on the north to south trending southernmost segment of the West Iberian Margin. These faults were described as active in the Quaternary by Zitellini et al. (1999), Zitellini et al.

(2001), Gràcia et al. (2003) and Terrinha et al. (2003). The uneven surface of the Marquês de Pombal fault scarp is due to widespread slumping and landslides with mass transport distances that exceed 20 km. The Pereira de Sousa fault scarp is also heavily incised and the D. Henrique basin shows a series of radial ridges that consist of turbidite levees transported down slope from the highs that surround it (Gràcia et al., 2003; Terrinha et al., 2003).

WSW-ENE to W-E trending Mesozoic rifting faults were inverted during the latest Cretaceous through early Miocene times (Terrinha, 1998; Lopes et al., 2006).

Duarte et al. (2005) showed the existence of presently active WNW-ESE trending faults in the Gulf of Cadiz and Medialdea et al. (2007) proposed that these faults acted as transfer faults between the Gorringe Bank and the Marquês de Pombal fault across the Horseshoe fault. Onshore southwest Portugal, WNW-ESE trending Lower Jurassic extensional faults were described by Ribeiro and Terrinha (2007). Zitellini et al. (2009) proposed the existence of a Nubia-Eurasia plate boundary based on a set of 600 km long WNW-ESE trending set of strike-slip faults that cut across the Horseshoe Abyssal Plain and Gulf of Cadiz connecting the Gloria Fault and the Tell tectonic zone onshore north-west Morocco.

Earthquake frequency and epicentre location (Fig. 2) show that SW Iberia is an area of moderate seismicity which accommodates the brittle deformation associated with the Nubia-Iberia collision west of Gibraltar, by means of thrusting and strike-slip events of shallow and intermediate depth. However, the existence of historical and instrumental high magnitude earthquakes such as the 1/11/1755 Lisbon earthquake (M=8.5 to 8.9) and the 28/2/1969 (Ms=7.9) event require clarification of the present tectonic setting of the SW Iberia-NW Africa region, and identification of the structures that generate large magnitude earthquakes and tsunami in this area. The Gorringe Bank Fault is a north westwards directed thrust that sits at the northern base of this morphologic feature. This thrust uplifted the seafloor from approximately -5000 m to -24 m, it reached its paroxysmal activity in Miocene times and has accommodated negligible shortening since then (Sartori et al., 1994; Tortella et al., 1997). Although the Gorringe Bank is by far the most conspicuous morphotectonic structure in the study area (Fig. 1), the distribution of seismicity (Fig. 2), numerical models for tsunami wave propagation (Baptista et al., 1998) and the interpretation of MCS lines (Sartori et al., 1994), led various researchers to abandon it as the source of the 1755 Lisbon earthquake.

Recent models proposed the existence of two faults, the Marquês de Pombal Fault and the Horseshoe fault (Gràcia et al., 2003; Terrinha et al., 2003) (Fig. 2) or the Marquês de Pombal Fault and the Guadalquivir Bank fault (Baptista et al., 2003), acting together simultaneously to generate the 1755 event by adding up their rupture areas (Baptista et al., 2003; Gràcia et al., 2003; Terrinha et al., 2003). Alternatively, Gutscher et al. (2002) proposed that the 1755 Lisbon earthquake was generated in the Gibraltar subduction zone imaged on seismic tomography, arguing that this was also the source of the deep 1954 Granada earthquake.

1.3. Data and methods

38.000 km^2 of multibeam swath bathymetry data were acquired in the MATESPRO Survey with a hull-mounted Simrad EM 120 echo-sounder aboard the research vessel NRP D. Carlos I in 3 legs from 14 June to 7 July 2004 (Figs. 3 and 4). The survey was carried out in order to comply with a level 3 hydrographic survey as established by the International Hydrographic Organization. The EM 120 operates at a main frequency of 12 kHz (from 11.25 to 12.6 kHz) with 191 beams covering a 150º degrees fan with a width of 1º. In order to increase data quality the angular value was reduced to 120 degrees and the ping width was of 2 degrees. One Sound Velocity Profile (SVP) was performed every 24 hours and at locations chosen to spatially cover the entire area in order to compensate the effect of the Mediterranean Outflow Water on the sound velocity in the water column regionally. SVP data were acquired down to 2000 m of water depth. From -2000 to -4000 m sound velocity was taken from climatologic profiles provided by the Instituto Hidrográfico of Portugal in this area. Quality control lines were also performed totalizing about 10% of the area; the depth errors found were below 0.3% of the water depth. Bathymetric data filtering and processing was carried using CARIS HIPS software and a 100m grid was generated.

The positioning of the vessel was done with both GPS and DGPS mounted on different parts of the vessel in order to better determinate the position and make the yaw corrections; the errors associated with the navigation positioning were around 5 meters.

The seismic data presented here are of two types: multichannel seismic (MCS) profiles from three previous surveys, ARRIFANO (acronym of Arco Rifano; Sartori et al., 1994), IAM (acronym of Iberian Atlantic Margin; Banda et al., 1995) and VOLTAIRE (acronym of Valuation Of Large Tsunamis And Iberian Risk for Earthquakes) and one single-channel profile acquired during the TTR-14 survey (Training Through Research; Kenyon et al., 2006).

The IAM and ARRIFANO deep MCS have a similar central peak frequency of approximately 30 Hz and the VOLTAIRE MCS has a central peak frequency of approximately 50 Hz. As a result, the vertical resolution in the sedimentary section is of around 20 meters for the IAM and ARRIFANO profiles and of about 15 meters for the VOLTAIRE data, assuming a mean seismic velocity of 2500 ms^{-1} in the sedimentary section (data from bore-holes in Fig. 3 and Gonzalez et al., 1998). The central peak frequency of the single channel TTR profile is around 100 Hz with a corresponding vertical resolution of about 6 meters. Information on acquisition and processing of these profiles is summarized in Table 1.

(Table 1)

The presented seismostratigraphic interpretation was based on the stratigraphy of five industry wells offshore the Algarve Basin (stars in Fig. 1, Lopes et al., 2006), as well as published data from the offshore Guadalquivir Basin (Maldonado et al., 1999).

2. Morphology of the NW part of the Gulf of Cadiz

The MATESPRO multi-beam dataset (Fig. 4) shows a variety of seafloor major morphological features within which smaller scale features indicative of genetic processes discussed elsewhere in this paper are found.

2.1. The submarine sediment drainage system

The drainage system of the study area is subdivided in two groups: a northern one that drains the Portuguese continental margin from north to south, and a southern one that drains the western continental shelf of Spain.

2.1.1. The north to south sediment drainage system

The north to south oriented drainage system consists of a poorly organized network of gullies and canyons. The deeply incised 120 km long São Vicente canyon (Fig. 1) has its head scarp at 70m below sea level (mbsl), cuts across the shelf and slope and ends in the Horseshoe Abyssal Plain. The maximum incision into the sedimentary substratum on the continental slope is of 2 km. This canyon is made up of two segments oriented NE-SW and N-S that collect the sediment from the gullies that incise the shelf and slope

(Figs. 4 and 5). Also note that the flanks of the NE-SW trending segment and the eastern flank of the N-S trending segment display higher degree of incision, whilst the western flank of the N-S trending segment and both flanks of the deepest part of the canyon are smoother. The close up in Fig. 6A shows a submarine landslide near the termination of the canyon. The lack of the mass transport deposit within the canyon is an indication of the activity of the canyon in terms of sediment erosion and transport.

The 70 km long Portimão canyon also has its head scarp in the shelf at roughly 70 mbsl. The canyon cuts across the shelf and slope sedimentary sequence with a maximum incision of 1 km. The canyon terminates abruptly at the meeting point with the Faro canyon and D. Carlos valley that drain east to west. These features have a different physiography, with a flat and broad bottom capable of accommodating larger sediment influx. The Portimão canyon is fairly rectilinear and sits along the Portimão Fault (Terrinha et al., 1999).

The Aljezur and Lagos canyons only incise the continental slope. The NNE-SSW trending Aljezur canyon is short, rectilinear and drains into the Sagres valley. The western flank of the Aljezur canyon displays a series of anastomosed submarine slide scars at approximately 1300 mbsl, at a main morphologic break of the continental slope near the base of the Lagos contourite drift (Fig. 6B).

The Sagres valley collects the east to west draining D. Carlos and Cadiz valleys and the Aljezur and Lagos canyons. The Aljezur canyon and Sagres valley lie on the southern prolongation of an important slope break that can be observed in the low resolution bathymetry (see Figs. 2, 4 and 5) and also on the southern continuation of the Aljezur Fault that cuts across the Meso-Cenozoic Algarve Basin and Paleozoic basement (Fig. 2).

The Lagos canyon has its head scarp roughly at 800 mbsl, where it incises the Pliocene through Holocene Lagos contourite drift.

2.1.2. East to west oriented sediment drainage system

The seafloor of the inner part of the Gulf of Cadiz dips to the west towards the Atlantic Ocean. The seafloor is shaped by a variety of morphological features of various scales, many of which have been described by Mulder et al. (2003), Somoza et al. (2003), Molina-Hernandez et al. (2006), Gutscher et al.(2008).

The most important E-W trending valleys of the study area lie in the prolongation of the sinuous and broader E-W channels that initiate on the Gibraltar Arc owing to erosion and sedimentation by the MOW and to down-slope gravity processes (Hernandez-Molina et al., 2003). In the study area these valleys are broad, with flat gently dipping bottom. The Faro canyon and D. Carlos valley collect the sediment transport from the South Portuguese margins, a large number of gullies, valleys and the Portimão canyon. The D. Carlos valley changes from narrow channel to broad valley downslope from the merge of the Portimão Canyon..

The Cadiz valley lies between the Portimão Bank and the wrinkled surface of the Gulf of Cadiz accretionary wedge. The Sagres valley that lies in the prolongation of the Aljezur canyon establishes the connection between the drainage system located to the east of the Horseshoe Fault scarp and the Horseshoe Abyssal Plain. The Sagres valley displays a corrugate bottom north of the confluence with the Cadiz valley; from this point to the south it has a smooth surface and less dip. The flanks of the Sagres valley display various evidences of gravity slumping (Fig. 6B).

The Horseshoe valley is a roughly rectangular area, 80 km x 50 km, dipping to the west (mean dip of ~0.5º), connecting the Gulf of Cadiz seafloor and the Horseshoe Abyssal

Plain across the Horseshoe Fault scarp (Fig. 1). The valley is limited by the Sagres plateau in the north, the Coral Patch Ridge in the south and the Gulf of Cadiz accretionary wedge in the east. It is cross cut by WNW-ESE trending morphological lineaments described elsewhere in this paper. This wide valley collects the mouths of well developed canyons and valleys that drain the sediments from the north and eastern shelves. The drainage to the Horseshoe Abyssal Plain is poorly developed (Fig. 5) and the Horseshoe fault scarp is being eroded in various segments showing evidences of landsliding (Fig. 6C). These different styles and degrees of maturation of the sediment drainage pattern suggest that this area acts simultaneously as a by-pass and receptacle region for the sediments that are carried from the continental shelves to the Horseshoe Abyssal Plain.

Despite the general low slope of this area, there are NE-SW trending scarps with a maximum height of approximately 150 m (Fig. 7). The flat areas have maximum dips of 3º and slope breaks in which formed convex upwards crescent shaped escarpments.The crescent shaped three-dimensional features measure up to 5km across, are shown in detail in Fig. 7 to occur between 3900 and 4700mbsl, have an internal escarpment up to ~100m high with an internal slope varying from 6º to 27º.

2.2. Plateaus and escarpments

The plateaus in the study area are the Marquês de Pombal, Sagres and Portimão plateaus (Figs. 1, 4 and 5). The Marquês de Pombal plateau is a roughly rectangular surface bound by the NNE-SSW trending Marquês de Pombal reverse fault scarp in the west and by the São Vicente canyon in the east, as described by Gràcia et al. (2003).

The Sagres plateau has an approximately rectangular shape divided by a diagonal NE-SW trending crest. To the west, the Sagres plateau is bound by the Horseshoe reverse fault scarp and the São Vicente canyon and by the Aljezur canyon and the Sagres Valley in the east. In the north this plateau is separated from the mid and upper continental slope and shelf by a rectilinear E-W trending valley that lies in the prolongation of the D. Carlos valley.

The Horseshoe fault scarp is only well developed on its northern segment. The southern part is being eroded (Fig. 6C) by the sediment drainage system described previously.

The southern part of the Sagres plateau dips gently towards the Horseshoe valley. This surface dips approximately 1.5º, is very uneven, has a wavy appearance comprising undulations that vary from hundreds of meters to more than 10 km in length, and 0.5 km to 5 km across (Figs. 4 and 5).

The Portimão plateau is an E-W elongated surface limited by the two prominent escarpments which constitute flanks of the D. Carlos and Cadiz valleys. The northern escarpment is sinuous, whilst the southern one, is fairly rectilinear, trending WNW-ESE, draped by recent sediments carried by the local drainage. The top of this plateau shows circular positive reliefs, the larger one of which has been labeled here as the D. Carlos salt diapir (Figs. 1, 4 and 6D), whose origin is discussed elsewhere in this paper.

2.3. The Horseshoe Abyssal Plain

The extremely flat HAP has general slopes of less than 0.1º sharply contrasting with the slopes of the foot of its boundaries, between 5º and 10º in general.

The foot of the slope of the Gorringe Bank presents a remarkable offset of about 14 km at roughly 11ºW (Fig. 4). This offset lies at the end of a valley that originates at the Gorringe saddle (see fig. 1 for location). It is also clear that the southern flanks of the Gettysburg and Ormonde seamounts display fairly different topographic roughness. The Ormonde southern flank smooth topography resembles the morphological types of the continental slope or of the Sagres plateau, whilst the edges of the Gettysburg and Coral Patch Ridge display a similar wrinkled surface. It is possible that this offset and valley coincide with the ocean-continent boundary proposed by Rovere et al. (2004) at the Gorringe Bank.

The interior of the HAP is only locally perturbed by four elongated groups of hills that rise between 40 m and 200 m above seafloor (Fig. 4 and 6E). The largest of these groups is 16 km in length and the largest individual hill is 6 km long. The hills in each group are aligned along approximately E-W directions and each one of the hills has their crest parallel to NE-SW, approximately. These hills are aligned along the WNW-ESE oriented tectonic morphological lineaments described and discussed elsewhere in this paper.

2.4. Lineaments

Long WNW-ESE trending discrete lineaments of tectonic origin were for the first time revealed in the Gulf of Cadiz sea floor by the MATESPRO multibeam survey (Duarte et al., 2005 and Rosas et al., 2009). These lineaments consist of an aligned series of elongate WNW-ESE trending crests and troughs, more or less continuous, with a typical width of a few hundreds of meters (Figs. 4 and 7). Pervasive sets of E-W linear undulations, up to 8km long, accompany these lineaments (Fig. 7). To the east of the Horseshoe escarpment these lineaments present uninterrupted segments as large as 100 km of length, approximately, while in the Horseshoe Abyssal Plain these lineaments are discontinuous. Altogether, from the Gorringe Bank flank across the Horseshoe Abyssal Plain and lower continental slope of the Gulf of Cadiz, lineaments of 250 km can be identified, from approximately 4870 to 2000 mbsl (Fig. 4). It is worthwhile to note that various mud volcanoes sit on top of the lineaments (Figs. 2 and 4).

3. Structure of the NW part of the Gulf of Cadiz

A structural map of the study area based on the interpretation of the MATESPRO bathymetry and available MCS profiles is presented in Fig. 8. The main faults are here described based on MCS profiles that are quoted from published works or presented here. Fig. 8 also shows a compilation of focal mechanisms and main horizontal compression taken from Ribeiro et al. (1996).

3.1 WNW-ESE to E-W Faults

One of the most prominent features in the north-western part of the Gulf of Cadiz is the above described WNW-ESE to E-W trending set of valleys, escarpments and lineaments (Figs. 4 and 7). The seismic lines that are shown in Figs. 9 to 11 and hereafter described show that all these features are associated with faults, whose geometry and kinematic history are different.

The D. Carlos and Cadiz valleys that bound the Portimão plateau sit on top on two faults, as shown in Fig. 9. According to this the Portimão plateau can be interpreted as a pop-up structure. The D. Carlos valley lies at the south-western edge of the Guadalquivir acoustic basement high that, at the precise location of this seismic profile, bears a WNW-ESE strike as can be seen on the bathymetry (Fig. 4). The drag evident in the sediments of the uppermost sequence and the superficial gravity extensional faults indicate that the northernmost valley flank fault is undergoing extensional deformation at Present. The folds in the Mesozoic through Miocene-Lower Pliocene of the central and northern parts of the Portimão pop-up depict an asymmetry that indicates northwards tectonic transport on top of the acoustic basement fault.

Since it has been known for long that the Guadalquivir Bank is made up of Variscan basement metamorphosed flysch of Carboniferous age (e.g. Ribeiro et al., 1979, Gràcia et al., 2003) the stratigraphy across the northern fault of the Faro valley implies that it played an extensional role during the Mesozoic followed by northwards directed thrusting during the Paleogene through Miocene and resumed extensional movement during Pliocene-Quaternary times.

The southern boundary of the Portimão pop-up block shows both the topography and the Mesozoic through Quaternary sedimentary packages dipping to the south (Fig. 9). The following features are also evident in the seismic line across the southern part of Portimão plateau (Fig. 9), as follows: i) tectonic deformation affects the topmost sediments (Fig. 6F), ii) the pre-Pliocene folds asymmetry is southwards verging, iii) there is no correspondence on the seismic stratigraphy between the pre-Pliocene sediments of the Portimão pop-up and the southern counterpart and iv) the Mesozoic units show a wedge geometry. From these observations it is inferred that, firstly, this boundary of the Portimão plateau is an old fault with opposite dip with respect to the north boundary of the plateau, secondly, this was a northerly dipping extensional fault during the Mesozoic, thirdly, it was inverted with a southwards directed tectonic transport during the Paleogene through Miocene times and, fourthly it is going tectonic deformation at Present.

The southernmost segment of the seismic profile in Fig. 9 cuts across the Cadiz valley and up slope the gently dipping north western part of the Gulf of Cadiz accretionary wedge. The profile shows a sub-horizontal, mildly deformed sequence of sediments covering the chaotic seismic facies of the accretionary wedge or imbricate thrust wedge, as described by Gutscher et al. (2002) and Iribarren et al. (2007), respectively. The base of the chaotic seismic facies unit is made up by coherent high amplitude reflectors here interpreted as Jurassic through Cretaceous syn-rift sediments on top of which detached the thrust wedge. It is worthwhile to note that these sediments are disrupted by vertical discontinuities, with small vertical displacement, that can be followed up into the chaotic body and overlying topmost sequence.

The sub-vertical discontinuity that separates the Portimão plateau from the southern plain is neither compatible with thrusting nor with extensional tectonics (Fig. 9). Alternatively, it is interpreted as a transpressive E-W trending strike-slip fault at Present based on the fact that it displays evidence of shortening structures, folds and north wards and south wards directed thrusts on both sides of the fault. These observations imply that the main compression direction rotated from high angle to low angle with respect to the E-W strike of the faults, which is compatible with the counter-clockwise rotation of the movement of Africa with respect to Iberia in the Cenozoic, from approximately south to north in the Paleogene, to south east to north west in the Miocene to ESE to WNW in the Present (Dewey et al., 1989).

The circular dome protruding the top of the Portimão plateau depicted in the bathymetry is interpreted as D. Carlos salt diapir (Figs. 1, 4 and 10). The salt does not outcrop at the surface but is popping-up underneath the sedimentary cover. The two reverse faults that bound this structure were interpreted as smaller scale structures accommodating internal shortening across the Guadalquivir Bank by Zitellini et al. (2004). This is a clear example where the map view image clarifies specific not fully understood superficial structures in reflection seismics.

The deep structure of the WNW-ESE trending lineaments (Fig. 8) is imaged in the seismic profiles shown in Figs. 9,10 and 11 in the work of Rosas et al. (2008). It can be seen in these seismic profiles that the rectilinear morphologic lineaments overlie vertical discontinuities that are rooted far below the accretionary wedge detachment, i.e. into the Jurassic sediments. These discontinuities cut the Mesozoic into blocks of 3-5 km of width, with small vertical offset and stratigraphic mismatch. The symmetry of the upward drag of the seismic horizons with respect to these discontinuities from the deepest stratigraphic levels across the chaotic facies, the disturbance observed in the cover sediments and the existence of mud volcanoes sitting on top of these lineaments (Figs. 8 and 12), strongly argues in favour of upward injection of fluids along these faults (cf. with Figs. 9 and 11). These characteristics strongly suggest that these discontinuities can correspond to tensile fractures with a strike-slip movement component.

The pervasive set of E-W trending undulations that accompany the E-W to WNW-ESE trending faults are en echelon folds (Fig. 7 and 11), i.e. kinematic indicators that show a dextral strike-slip lateral movement on these faults.

The growth wedge of Mesozoic sediments clearly associated to some of these WNW-ESE trending faults (Fig. 10) is another indication for the deep root of these faults.

3.2. N-S to NE-SW faults

The Aljezur canyon-Sagres valley and the Portimão canyon sit on top of the offshore prolongation of the Aljezur and Portimão faults, respectively (Figs. 2 and 8). Inspection of the seismic profiles confirm the Pliocene –Quaternary activity of these faults that show an important decrease in tectonic deformation after Miocene times (Figs. 12 and 13). The offshore mapping of these faults shows they have continuous segments larger than 100 km in length that, when added together with the onshore segments, they constitute discontinuous steep faults of approximately 200 km long, as happens with the left lateral strike-slip late Variscan faults in the central and northern parts of the Iberian peninsula (Ribeiro, 2002; Arthaud and Matte, 1977), which are also active in the Quaternary (Cabral, 1989).

The Tagus Abyssal Plain Fault is proposed on the basis of the N-S trending sharp morphological scarp that lies to the north of the Gorringe Bank thrust. However, recent unpublished work by Cunha (2008) confirms the existence of this reverse fault that cross cuts Pliocene-Quaternary sediments.

The São Vicente Fault strikes NE-SW (Fig. 14) outcrops along the southeast flank of the São Vicente canyon. It is a southeastwards dipping steep fault, possibly part of the Odemira-Ávila fault (also known as the Messejana dyke), an approximately 600 km long vertical left-lateral late Variscan fault intruded by a basic dyke of Early Jurassic age (Dunn et al., 1998). Pliocene-Quaternary vertical displacement along this fault onshore was described by Cabral (1995).

The NE-SW trending Horseshoe fault was described as an active fault in the Present by Gràcia et al. (2003) and Zitellini et al.(2004), has a cluster of seismicity associated to it (Figs. 1 and 2). Its fault scarp is very well depicted in the MATESPRO bathymetry, from the Coral Patch Ridge well into the South Portuguese continental slope bordering the Sagres plateau. It can be seen that the height of the scarp increases northwards and it is intercepted by WNW-ESE trending faults. At these interceptions the Horseshoe fault scarp is either deflected or offset across the WNW-ESE dextral strike-slip faults and landslides formed (Figs. 4, 5, 6C and 8).

The NE-SW escarpments at the back of the Horseshoe fault host some of the crescent shaped Giant Scours described elsewhere in this work. These scarps sit on top of blind thrusts, as shown in Fig. 15 that appear to be recent reactivation of individual faults from within the Gulf of Cadiz Accretionary Wedge or Gulf of Cadiz Imbricate Unit, after Gutscher et al (2002) or Iribarren et al. (2007), respectively. Single channel seismic line across two of the Giant Scours show that the internal parts of the crescents consist of depressions filled in with upslope prograding sedimentary units. These units develop towards the Giant Scour crescent shaped scarp, which sharply truncates sediments behind it (Fig. 16).

3.3. Chaotic Seismic Units

The MATESPRO bathymetry clearly shows the divide between the wrinkled topography that overlies the Gulf of Cadiz Accretionary Wedge, after Gutscher et al. (2002) and the surrounding smoother areas (Figs. 2 and 4). The MCS profiles shown in Figs. 12 and 15 show the existence of a complex of stacked thrusts underneath the wrinkled surface of the so-called accretionary wedge and also under the smoother topography of the Sagres and Cadiz valleys.

In all seismic profiles it is evident that the complex of stacked thrusts is overlain by a package of sediments that is not involved in the thrust stacking. The thickness of this sedimentary cover is generally around 0.3-05 sec. TWT and the earliest age of these sediments is Early Pliocene after Roque (2007). However, this sedimentary cover is deformed by the E-W to WNW-ESE dextral strike-slip faults and by discrete reactivation of individual thrusts of the stacked thrusts units, as described elsewhere in this work, as well as, by widespread extrusion of mud volcanism, gravitational faulting described by various authors as mentioned before.

A unit of chaotic facies that has neither coherent internal layering nor imbricate fabrics, probably an olistostrome, is shown in Fig. 10. This unit is not involved in the thrust stacking of the accretionary wedge and is overlain by the well layered Pliocene-Quaternary sediments. This olistostrome lies between the Portimão Bank and the wrinkled surface of the Gulf of Cadiz Accretionary Wedge, in the Cadiz valley. It is worthwhile to note that the olistostrome pinches out on top of the Portimão Bank, suggesting that it could have been fed from the uplifted area of the Portimão Bank during the Tortonian phase of compression, i.e. the pop-up of the bank.

4. Discussion

4.1. Morphology and tectonics

4.1.1. The escarpments and seamounts

It was shown in this paper that the E-W trending Portimão Bank formed initially as a graben during Mesozoic times, was subsequently inverted during the Paleogene and Miocene compression and is now, probably since Early Pliocene times, undergoing dextral transpressive strike-slip deformation along its southern boundary, whilst the northern boundary experiences local extension due to a releasing bend formed by the basement fault. Seismicity and focal mechanisms (Fig. 2) attest for the compression at the southern edge of this seamount, preferentially concentrated to the east of the study area where the fault becomes NE-SW trending, i.e. at a higher angle to the main NW-SE oriented compression direction.

The Sagres plateau is bound by the NE-SW trending Horseshoe thrust of Miocene age in the west (Gràcia et al., 2003, Zitellini et al., 2004) and the steeply dipping Aljezur fault in the east. The height of the plateau diminishes towards the south and its morphological expression disappears at the contact with one of the WNW-ESE strike-slip faults. The cluster of instrumental seismicity in Fig. 2 attests for its present day activity (Stich et al., 2007).

The Marquês de Pombal plateau also resulted from tectonic inversion of an N-S trending continent-wards directed extensional fault. The Pereira de Sousa fault is a N-S trending steep Mesozoic rift fault still in activity at Present (Gràcia et al., 2003; Terrinha et al., 2003).

The north westwards directed Gorringe Bank thrust with a paroxysmal activity in the Tortonian (after Tortella et al. 1997; Sartori et al., 1994) is still an active structure as attested by the instrumental seismicity cluster (Fig. 2).

It can be concluded that the escarpments, seamounts and uplifted plateaus of the study area, all formed in association with compressive tectonic events and resulted from polyphase tectonics. The Pereira de Sousa fault escarpment is the only one that owes its morphology mostly to the Mesozoic rifting.

The tectonic shaping processes are still active in the Present, as shown by the on-going formation of very recent features that are indicative of uplift and tectonic instability, such as the popping-up of the D. Carlos salt diapir (Fig. 10), the mass wasting processes, such as submarine slides and various manifestations of soft sediment deformation and mass wasting processes in the Sagres plateau-Aljezur canyon, the São Vicente canyon and the Portimão plateau, Horseshoe Faul scarp, as well as, on the Marquês de Pombal, Gorringe and Pereira de Sousa escarpments as described by Gràcia et al.(2003), Terrinha et al.(2003) and Vizcaíno et al.(2006).

4.1.2. The Giant Scours

The Giant Scours are crescent-shaped depressions with scarps that can reach more than 100 meter in high and slopes up to 27º located in a relative flat area of the Horseshoe Valley that collects the sediments from the Northern and North-eastern parts of the Gulf of Cadiz (Figs. 4, 5 and 7). The scours sit on the edge of folds draping Pliocene to Quaternary thrusting and the frontal depressions are filed up with upslope progradational bodies (Figs. 15 and 16). These bodies can be interpreted as been fed by material withdrawn from the retreating scarps (Fig. 17; Duarte et al., 2007). This scenario requires the existence of continuous scouring and sedimentation at unusual depths by means of bottom currents, possibly of turbidite origin as documented offshore the Shetland Islands and Monterrey East Channel (Kenyon et al., 2000; Kenyon et al., 2006; Fildani et al., 2006). The interaction of bottom and turbidity currents with seafloor morphological features formed by Recent tectonic activity can lead to flux separation and formation of vortexes that cause seafloor erosion and the formation of scours. These processes were proposed for the formation of similar structures in other places and different geological settings between 600m and 3500m water depth (Faugères et al., 1997; Bulat and Long, 2001; Verdicchio and Trincardi, 2006; Fildani et al., 2006). This process could account simultaneously for the formation of the scarp of the scour, the progradational bodies and the maintenance of the scarp, at least as long as the bottom current lasted and the retreating escarpment does not meet an obstacle.

An alternative model is that the Giant Scours could form due to the interaction of along slope bottom currents with the sea floor, such as the North Atlantic Deep Water. This interaction could lead to the formation of giant eddies that could locally erode and amplify pre-existing tectonic escarpments. However, the existence of along slope currents at these depths has not been documented in this area.

Evidences for alternative mechanisms for the formation of these features, such as slide-slump processes caused by slope instabilities or collapse processes associated with fluid escape along major tectonic structures (similar to those of pockmark formation), were not observed on the present dataset despite the evidences for mass wasting processes, and the existence of widespread mud volcanism and fluid migration activity in other areas of the Gulf of Cadiz.

4.1.3. The canyons

The São Vicente and Portimão canyons are by far the deepest incisions on the northern margin of the Gulf of Cadiz and they are underlain and controlled by important steep faults. The Aljezur canyon-Sagres valley system is also controlled by a steep fault. These offshore faults connect with other that were inherited from the late Variscan fracturing, subsequently re-activated during the Mesozoic rifting and Cenozoic tectonic inversion (see Fig. 2).

The MCS profiles shown in this work attest for the Quaternary activity of these faults but also show that the deformation after Miocene times has severely diminished in the case of the Portimão and Aljezur faults.

Gràcia et al. (2003) and Zitellini et al. (2004) showed the important activity of the northern segment of the Horseshoe fault that constitutes the eastern flank of the terminal part of the São Vicente canyon.

The São Vicente and Portimão canyons show important gravity slides on their western flanks. This can be interpreted as caused by the increase of the tilting associated with the west wards directed thrusting of the Marquês de Pombal and Horseshoe faults. Alternatively, in the Sagres valley the sliding can be caused by excavation at the meeting point of this valley with the Cadiz valley.

The minor present day tectonic deformation on the faults that control the localization of the canyons together with the important incision and land sliding close to the active Marquês de Pombal and Horseshoe thrusts can be interpreted as an indication of passive uplift of the continental slope carried on top of these thrusts.

4.1.4. The chaotic bodies

Three bodies of chaotic facies were distinguished in this work, all covered by a unit hemipelagic sediments usually of 0.3 – 0.5 sec TWT. One is referred to as the Gulf of Cadiz Accretionary Wedge (GCAW) by Gutscher et al. (2002) or alternatively as the

Gulf of Cadiz Imbricate Wedge by Iribarren et al. (2007). This body has a strong morphologic imprint on the seafloor morphology (Fig. 12).

A second one, that extends across the Horseshoe Abyssal Plain and Horseshoe Valley, has been considered as a gravitational unit, an olistostrome (e.g. Torelli et al., 1997; Iribarren et al., 2007). It is shown in this paper that this unit (Figs.12 and 15) has imbricate seismic reflections that are interpreted as stacked thrusts, some of which have been recently reactivated forming blind thrusts morphologic scarps where the Giant Scours nucleated. These recent scarps are, however, the only morphologic manifestation on the seafloor surface of this body.

A third body with internal non-organized chaotic facies overlies the first described one, as shown in Fig. 10.

It is shown in this work that the two first described bodies consist of complexes of stacked thrusts and that the GCAW overthrusts the second one to the west (Fig. 10). Considering that these are tectono-stratigraphic units we speculate that only one accretionary wedge (or imbricate wedge) formed during the latest Cretaceous and Paleogene (perhaps through the Early Miocene). This event occurred before the Gibraltar arc formed (when the Internal Betic terranes were still a long way farther east, Fig. 18B). Then, from Early Miocene to earliest Pliocene (or Messinian?) times, when the Gibraltar orogenic arc formed, a part of this accretionary wedge was tectonically reworked forming the present day GCAW and its wrinkled topography (Fig. 18C). From the Pliocene to Present the thrust stacking within the GCAW severely diminished and the WNW-ESE dextral strike-slip faults formed (Fig. 18 d).

From a genetic point of view we consider the first two chaotic bodies as tectonic melanges made up of tectonised olistostromes and tectonosomes (see Camerlenghi and Pini, 2009 for discussion). The third chaotic body is a non tectonised olistostrome.

4.1.5. The WNW-ESE lineaments, strike-slip faults and recent folding

The WNW-ESE lineaments shown by the MATESPRO bathymetry in this paper (Fig. 7) display a series of en echelon folds materialized on the most recent seafloor soft sediments that indicate strain accumulation by means of dextral strike-slip (Fig. 3 and 6). Rosas et al. (2008) using quantitative strain analysis, analogue modelling and MCS data showed that these en echelon folds result from Quaternary reactivation of basement faults.

Inspection of MCS profiles in this paper show that these WNW-ESE faults are deeply rooted into the Jurassic –Cretaceous rift sequences, which is compatible to observations made onshore in the Algarve Basin at the Lower Jurassic of the S. Vicente cape (Ribeiro and Terrinha, 2007).

These faults also serve as conduits for the exhalation of fluidized sediments that form some of the Gulf of Cadiz mud volcanoes (Fig. 2), which is another evidence of the recent activity of the faults and also that they cut through the Gulf of Cadiz accretionary prism. Moreover, as shown on the MCS profile in Figs. 11 and 12, these strike-slip faults allow the escape of fluids from within deep in the Mesozoic sequences, probably at the Hettangian stratigraphic level that hosts the salt in south Portugal and northwest Morocco (Terrinha, 1998).

The strike-slip faults and folding are also active in the Horseshoe Abyssal Plain. However, the scarce morphotectonic features associated to these faults in the Horseshoe Abyssal Plain when compared to the continental slope to the east, suggests a westwards propagation of the recent deformation on the WNW-ESE faults, away from the Gibraltar Arc.

Because i) these faults have only recently been reactivated as strike-slip faults, ii) they strike at only a small angle to the present day trajectory of Africa with respect to Iberia, according to recently reported geodetic models (Fig. 8), iii) their minimum length exceeds 230 km as shown in the presented bathymetry and iv) they cut across the Horseshoe Abyssal Plain and the Gulf of Cadiz accretionary wedge; it is here suggested that they will play an important tectonic role in the new tectonic framework that is presently under development between Iberia and Nubia. As a matter of fact, some of the WNW-ESE faults described here are located within a 600 km x 40 km shear zone proposed by Zitellini et al. (2009) as a segment of the Eurasia-Nubia plate boundary that spans from the eastern tip of the Gloria Fault to the Rif-Tell plate boundary in north-western Morocco (Morel and Meghraoui, 1996).

4.2. Strain partitioning, deformation migration and seismicity

The studied dataset shows that the E-W trending faults were inherited from the Jurassic-Lower Cretaceous rifting and subsequently inverted as reverse faults during the Cenozoic (Fig. 8); the same applies to the NE-SW to N-S trending faults as shown in previous works (Terrinha, 1998; Rovere, 2004; Terrinha et al., 2002; Terrinha et al., 2003; Gràcia et al., 2003a; Ribeiro and Terrinha, 2007). It was also shown that the Gulf of Cadiz accretionary wedge has diminished significantly its activity since latest Miocene times, possibly Early Pliocene, although disperse thrusts that still remain blind underneath the Messinian-Recent sediments are presently reactivated (Fig. 12 and 15).

Based on the presented dataset, we propose that the present day WNW-ESE convergent movement of Africa with respect to Iberia generates deformation in the study area, which is accommodated through partitioning on two approximately orthogonal fault sets, as follows. An N-S to NE-SW striking set of faults that accommodate shortening mainly by thrusting and an E-W to WNW-ESE striking, generally sub-vertical, set of faults that accommodate dextral strike-slip faulting.

The first set comprehend the main thrust faults of the area, Horseshoe Fault, Marquês de Pombal fault and Tagus Abyssal Plain fault (see map of Fig. 2) that extend the Present east to west shortening for approximately 300 km from the South, near the contact with the Coral Patch Ridge (35.5ºN), towards the north, along the West Portuguese Margin until a latitude of 38ºN, as recently shown by Neves et al. (2008).

The second fault set is deeply rooted in Jurassic through Cretaceous rifting faults and were reactivated mainly in the Pliocene-Quaternary as dextral strike-slip faults, which is compatible with the present day movement of Nubia with respect to Iberia. These faults show considerably higher degree of deformation in the east than in the west, which argues in favour of propagation of deformation from east to west.

The thrusting on the N-S Marquês de Pombal fault is recent, as well as, on the Gorringe Bank fault (that had a quiescence period after the Tortonian), on the Tagus Abyssal Plain Fault (Cunha, 2008) and at the N-S trending faults at 38ºN (Neves et al., 2008). Altogether, these observations lead us to argue that the deformation is migrating from the realm of Gibraltar to the west and along the Portuguese West Margin to the north.

Considering the sub-parallel strike of the N-S to NE-SW faults, their common origin in the Permian and reactivation during the Mesozoic rifting and Cenozoic inversion, it is here suggested that this 300 km en-échelon fault zone can have a common detachment, underneath SW Iberia. Since the tomography data presented in Gutscher et al. (2002) suggests that the Horseshoe may penetrate at least till 100 km in the lithosphere, the 300 km long N-S trending fault system should be considered as *firstly*, a possible source candidate for the Lisbon 1/11/1755 earthquake and *secondly*, the propagation of a new front of compressive deformation towards the north along the West Portuguese Margin, which will eventually lead to the nucleation of a West Iberia incipient subduction zone, as proposed by Ribeiro et al. (1996).

Alternatively, even if these faults do not have a common detachment, a complex rupture scenario can be envisaged to explain the large energy released during the 1755 event. Complex seismic ruptures have been documented in other locations, such as, for instance the 1958 Gobi-Altay event which produced 260 km of surface rupture from the segmented main fault with a strike-slip movement and simultaneous rupture of nearby thrust faults (Kurushin et al., 1997), or the Tangshan earthquake of 1976, which was a combination of several ruptures, strike-slip and thrust faults, following each other only a few tens of seconds (Butler et al., 1979). The hypothesis of complex ruptures involving triggering or "domino-effect" is consistent with the majority of the historical documents that report a very long vibration (up to 20-30 minutes) and various sub-events for the 1st November 1755 earthquake (e.g. Martinez Solares, 2001).

We also speculate that the location of recent epicentres in front of the Horseshoe fault in the Horseshoe Abyssal Plain, such as the 1969 event (Ms=7.9) (Fukao, 1973), as well as the Mw=6.0 12/02/2007 and the ML=4.5 21/06/2006 events (Stich et al., 2007), all with an major dip-slip component can be interpreted as an indication of nucleation of new thrusts to the west of the main Horseshoe fault.

The NW-SE S_{Hmax} direction calculated from earthquake focal mechanism is in very good agreement with the Eurasia-Africa convergence direction estimated by the NUVEL-1 model (DeMets et al., 1994). However, recent estimates of this velocity using space geodetic techniques, and considering the Africa plate split into Nubia and

Somalia, give for the Nubia-Eurasia collision a WNW-ESE direction, in the middle of the Gulf of Cadiz (Fig.8). This discrepancy is interpreted as the coupled result of strain partitioning on E-W and NNE-SSW trending faults and aseismic deformation along the plate boundary.

5. Conclusions

The following conclusions are withdrawn.

1. The escarpments, seamounts and uplifted plateaus of the study area, all formed in association with polyphase compressive tectonic events from the late Cretaceous through Present, with the exception of the Pereira de Sousa fault escarpment that owes most of its morphology to the Mesozoic rifting. The Quaternary uplift has generated mass transport deposits (also reported by Gràcia et al. (2003), Terrinha et al. (2003) and Vizcaíno et al. (2006)), kilometric scale soft sediment unstable folds on the continental slope and incision of the canyons.

2. The Giant Scours display erosive and depositional structures that result from vortexes of high-density bottom currents at the edge of scarps formed at the crest of blind thrusts anticlines of Recent age.

3. The chaotic bodies buried under uppermost Miocene – lower Pliocene sediments in the Horseshoe Abyssal Plain and Horseshoe Valley together with the GCAW formed as stacked thrusts (possibly an accretionary wedge) in the Late Cretaceous-Earliest Miocene times before the emplacement of the Gibraltar orogenic Arc. Miocene reactivation of the eastern part of this body originated the GCAW and thrusting of this tectono-stratigraphic unit to the west. The third chaotic body corresponds to a non tectonised olistostrome that seals the most important thrust stacking in early Pliocene times.

4. The WNW-ESE trending lineaments are the superficial expression of steep faults deeply rooted in the Mesozoic substratum and underlying acoustic basement or Paleozoic basement onshore. Segments of these faults acted as rift faults during the Mesozoic and were reactivated in Quaternary times as strike-slip faults that cross cut the NE-SW trending thrusts.

5. The present day NW-wards movement of Nubia with respect to Iberia generates strain partitioning by means of dextral wrenching on WNW-ESE trending steep faults and thrusting on the NE-SW trending fault in the Gulf of Cadiz and Horseshoe Abyssal Plain. Further north, at the base of the continental slope of the southernmost part of the West Iberia Margin, NNE-SSW to N-S westerly dipping thrusts accommodate shortening in an area where wrenching has not been observed, which indicates that westward directed thrusting propagated from the Gibraltar Arc to the west (Horseshoe Fault) and to the north along the Portuguese margin (Marquês de Pombal Fault and Tagus Abyssal Plain Fault).

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Figure captions

Fig. 1. Location and main morphological features of the study area. Inset shows the geotectonic location of the area and the relative motions of the Eurasia, Nubia and North America lithospheric plates in mm/year. Triangles show location of mud volcanoes.

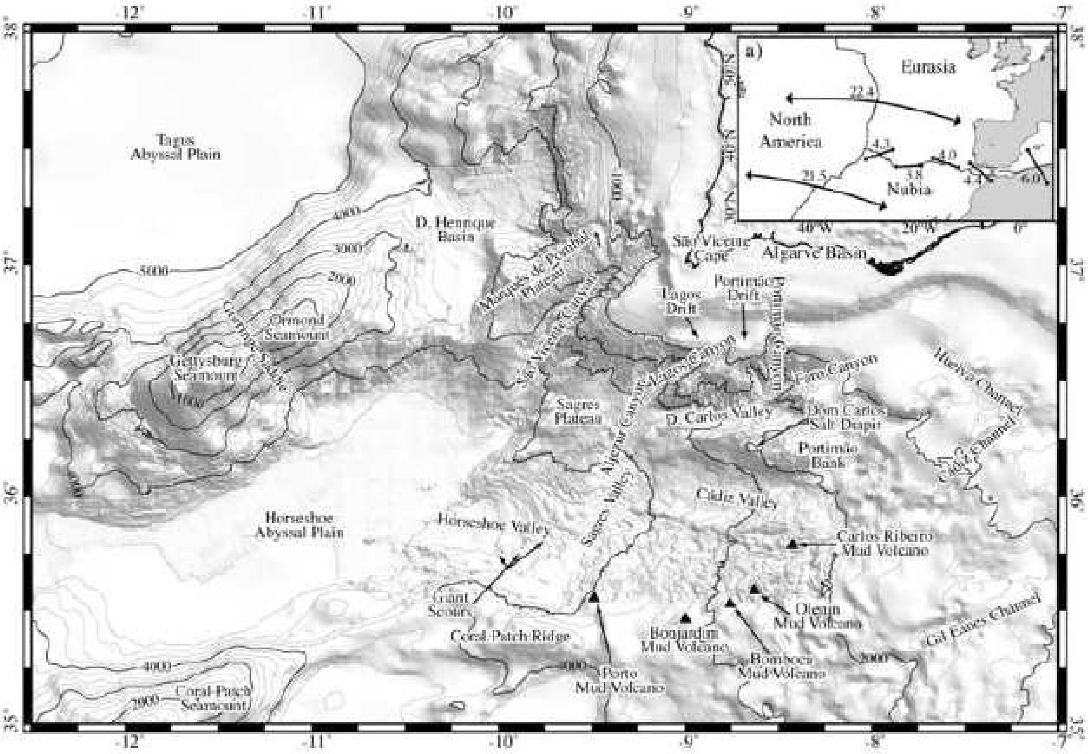


Fig. 2. Seismicity of the study area, the main faults and boundaries of the Accretionary Wedge of the Gulf of Cadiz and Horseshoe Gravitational Unit as mapped in previous works (Sartori et al., 1994; Torelli et al., 1997; Gutscher et al., 2002; Gràcia et al., 2003; Terrinha et al., 2003; Iribarren et al., 2007). AF- Aljezur Fault; AWDF- Accretionary Wedge Deformation Front; GF- Gorringe Fault; HGU- Horseshoe Gravitational Unit; HsF- Horseshoe Fault; MPF- Marquês de Pombal Fault; PF- Portimão Fault; PSF- Pereira de Sousa Fault; QF- Quarteira Fault; Triangles show the location of mud-volcanoes.

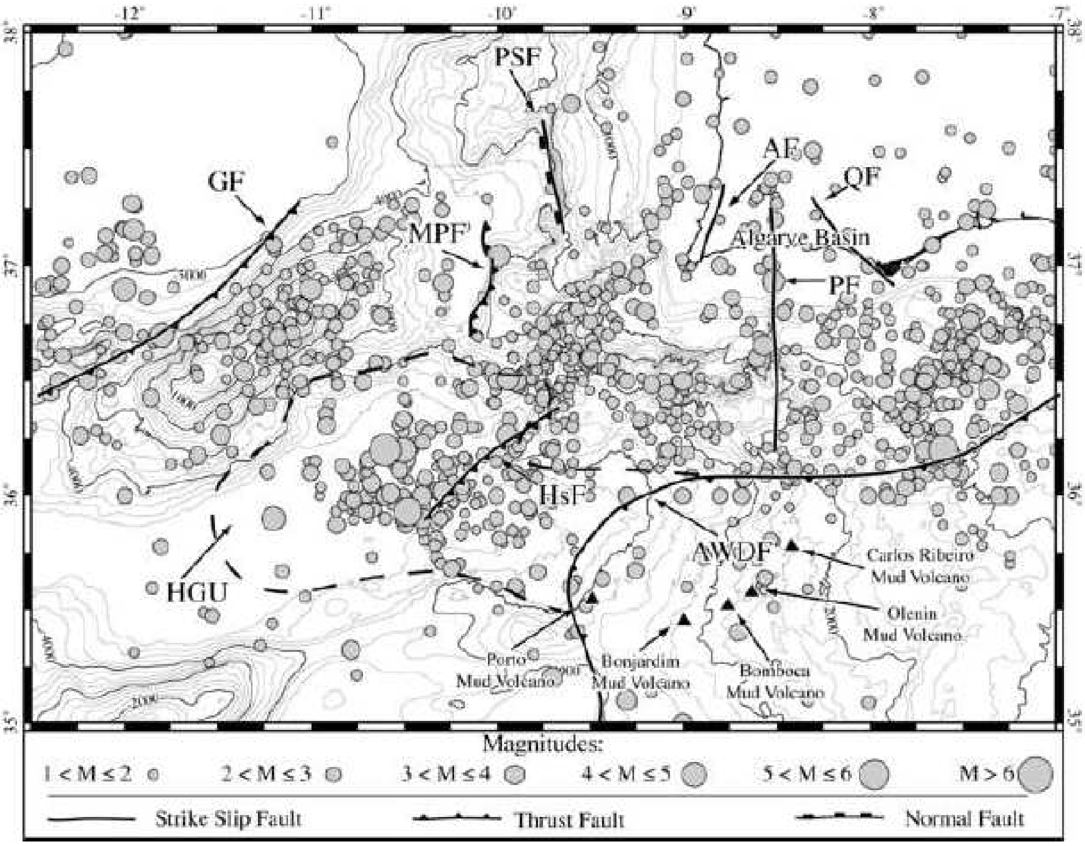


Fig. 3. Map showing the acquisition track lines of the MATESPRO multibeam bathymetry and the position of the seismic reflection lines shown in this work. Circles indicate location of the Sound Velocity Profiles performed. Location of oil prospection wells (stars) is also shown. Altimetry data derived from SRTM (USGS, 2004).

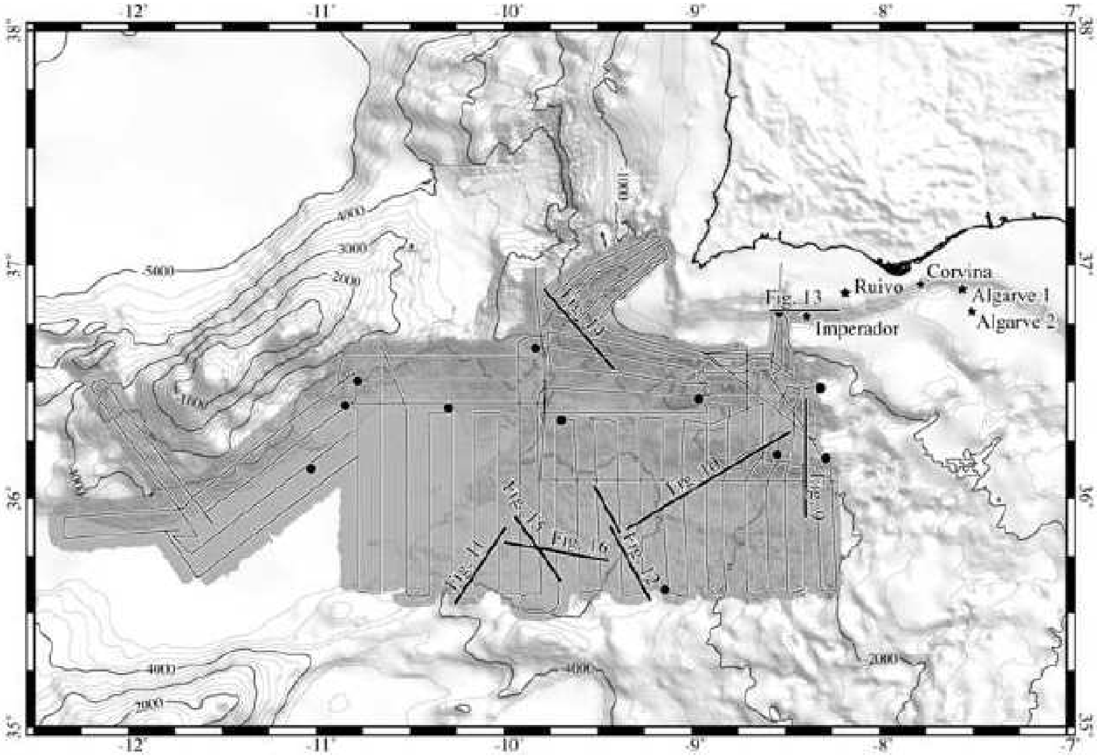


Fig. 4. Multibeam bathymetry map of the MATESPRO study area, offshore SW Iberia. Topography of onshore area also shown as shaded relief with a maximum of 902 m. Mercator projection, datum WGS84. PARSIFAL bathymetry of the Marquês de Pombal area and Pereira de Sousa escarpment published by Gràcia et al. (2003). Bathymetry for other offshore areas and onshore altimetry is taken from Gebco (IOC et al., 2003).

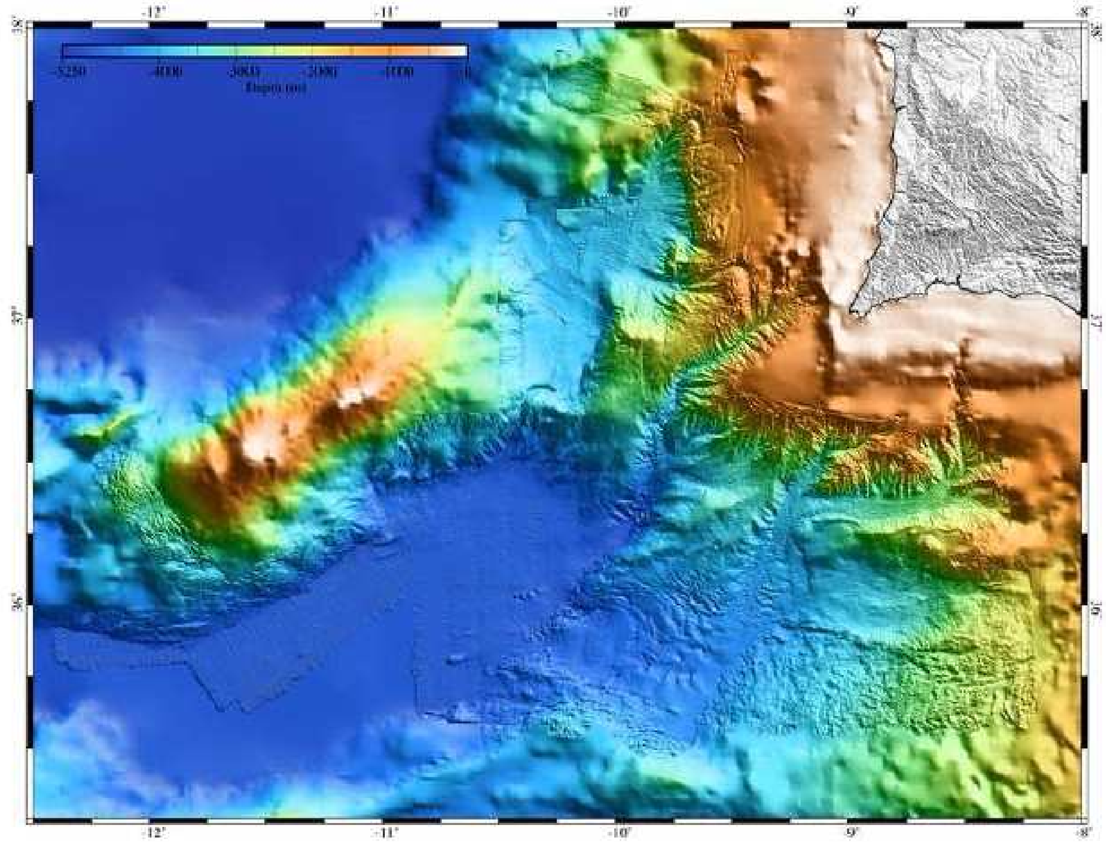


Fig. 5. Interpretative sketch of the morphology of the study area. 6.A to 6.F, location of the features imaged in 3D in Fig. 6.

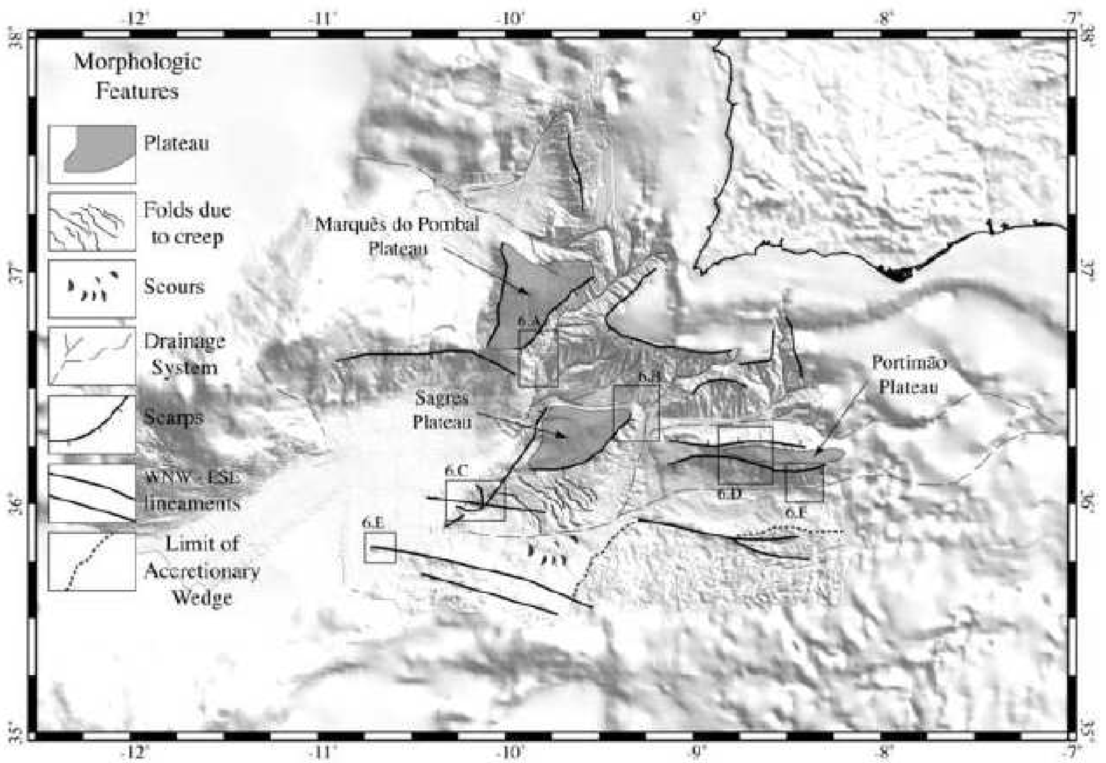


Fig. 6. 3D block diagrams of selected morphologic features of the study area. Images made from MATESPRO multibeam data presented in this work. A) Slide scar on the western flank of the S. Vicente canyon. B) Slide scar on the western flank of the Sagres valley. C) Slide scar on the Horseshoe fault scarp at the intersection with the WNW-ESE trending lineaments. D) D. Carlos salt diapir protruding through the top of the Portimão Bank (cf. with Fig. 10 for internal structure). Note the incisions on both flanks of the plateau, mainly on the northern side. E) E-W oriented hill in the Horseshoe Abyssal Plain sitting on top of one of the WNW-ESE trending lineaments. F) E-W trending channel at the foot of the Portimão Bank, whose structure in depth is imaged in MCS profile in Fig. 9. See text for detailed description.

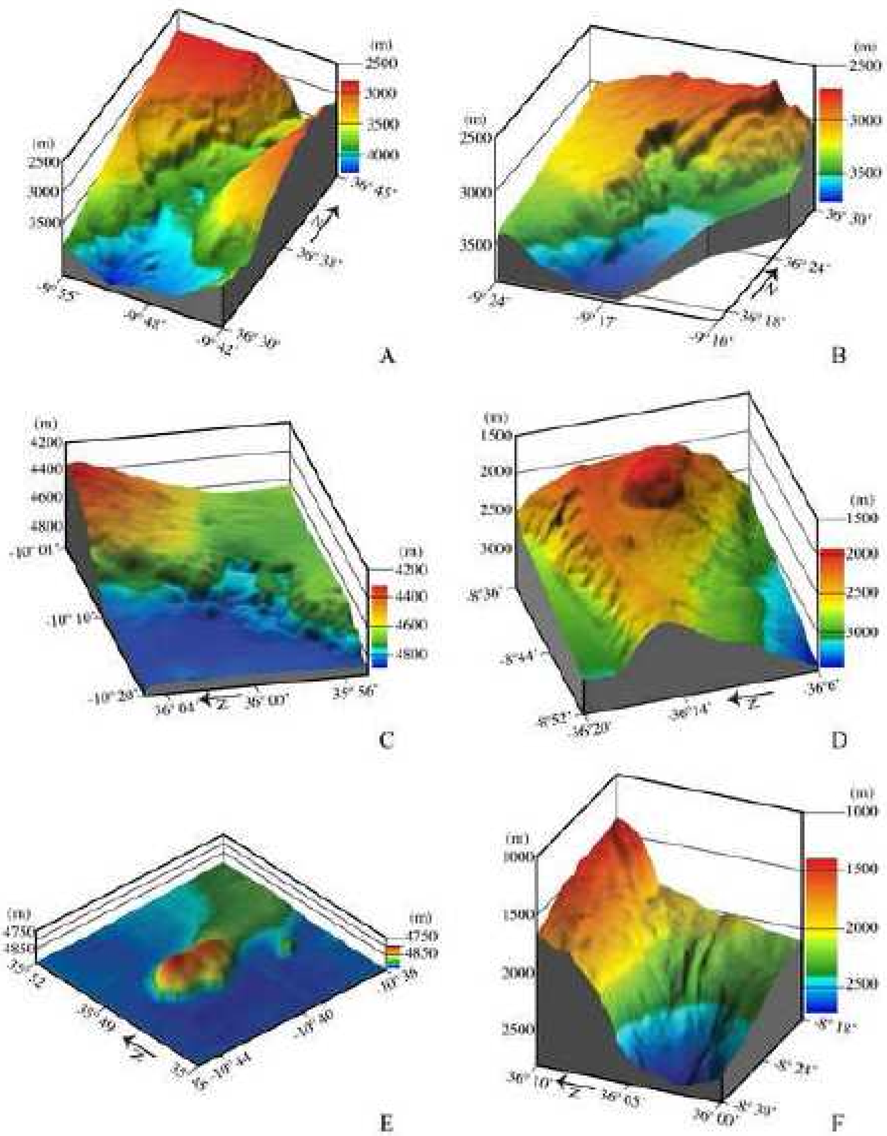


Fig. 7. Shaded relief image (perspective view) of the Giant Scours (GS), L1 and L2 WNW-ESE trending lineaments (interpreted as strike slip faults, max. total length 250km, see Fig. 11) and associated en echelon folds on sea floor recent sediments indicating dextral strike-slip movement component on the faults. Approximate depth 4000m, confer with Figs. 1 and 4. Position of seismic lines in Figs. 11, 15 and 16 is also shown. Detail of the en echelon folds on L1 in the Horseshoe Abyssal Plain is shown in Fig. 6E.

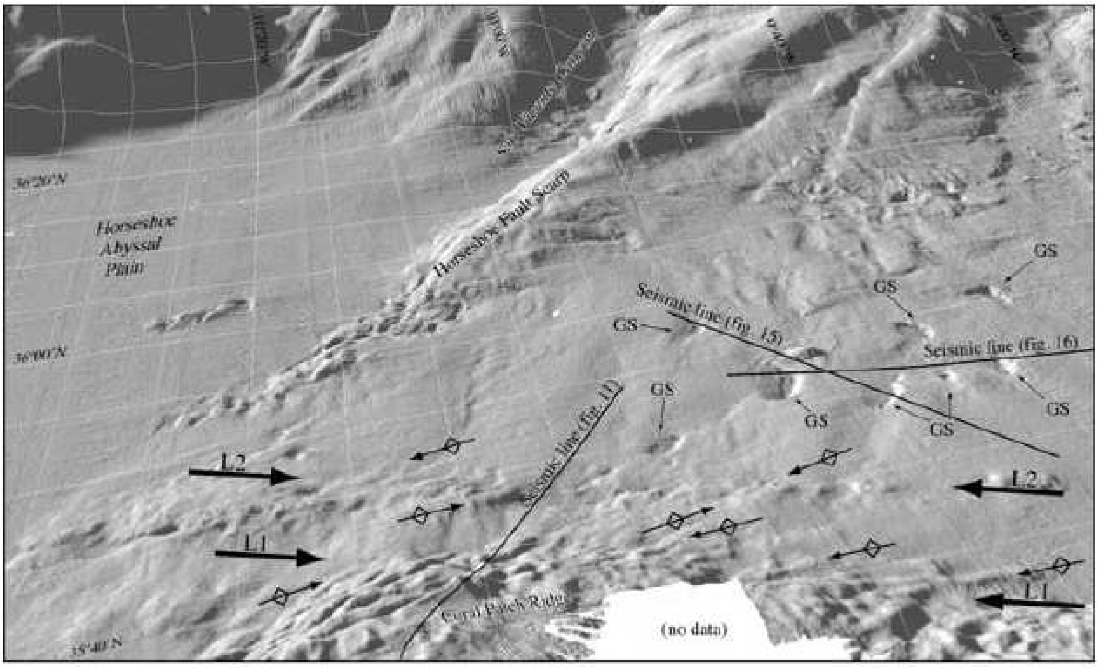


Fig. 8. A) Structural map of the study area with a compilation of stress indicators and focal mechanisms. Stress indicators computed from earthquake focal mechanisms and faults from interpretation of MCS profiles dataset shown in inset b). The size of the stress indicators is proportional to their quality. Note that position of mud volcanoes (white triangles) are in close spatial association with interpreted WNW-ESE dextral strike-slip faults. Fault names from published work as in Fig. 2. PbF- Portimão Bank fault; SVF- S. Vicente Fault; TAPF- Tagus Abyssal Plain Fault.

B) Location of the MCS profiles used in this work.

C) Plate kinematic data taken from various indicated sources indicated in the text. Black star shows position of computed movements of Nubia with respect to Iberia.

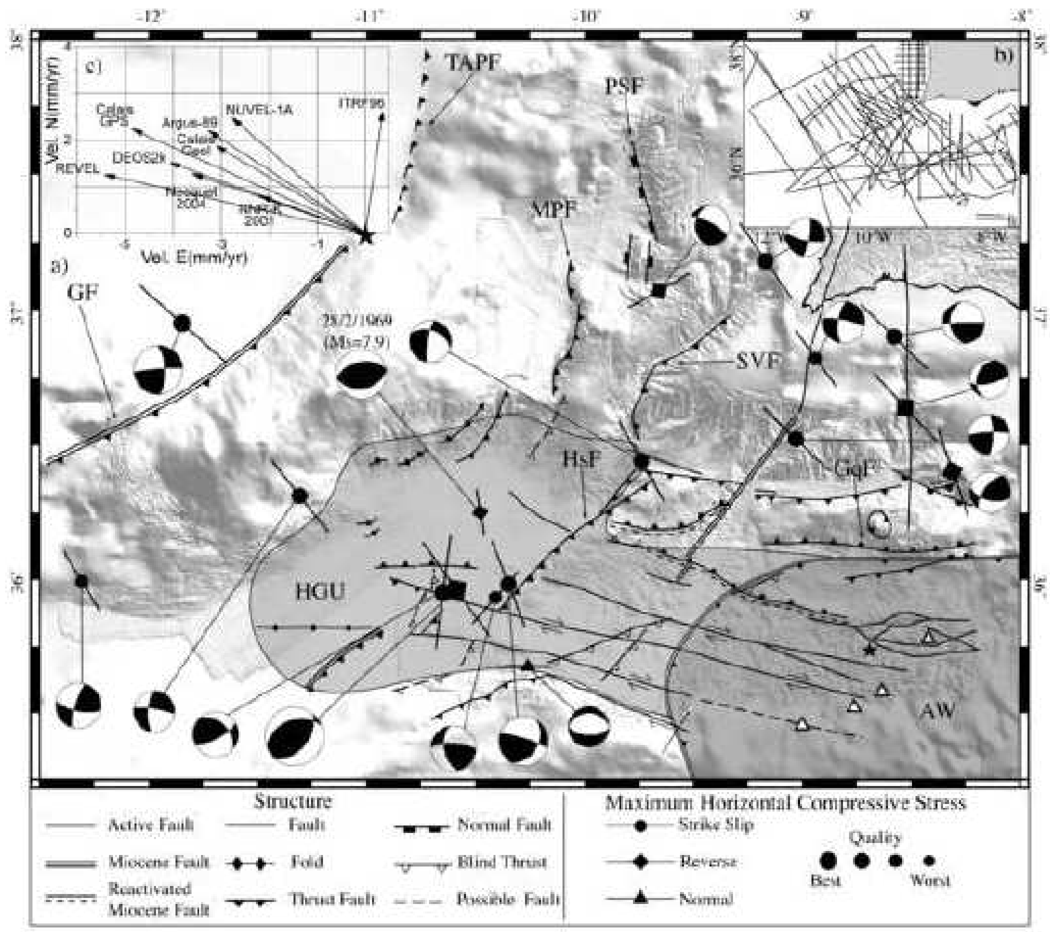


Fig. 9. Multi-channel seismic line VOLTAIRE 3 and line drawing interpretation. The Guadalquivir basement high of Carboniferous age is bound by a NW-SE trending Mesozoic extensional fault, reactivated as a reverse fault (1st movement) that resumed its extensional movement in late Miocene through Present times (see text for discussion, for location of line see Fig. 1). The topographic bulge on top of the strike-slip fault is imaged in 3D in Fig. 6F.

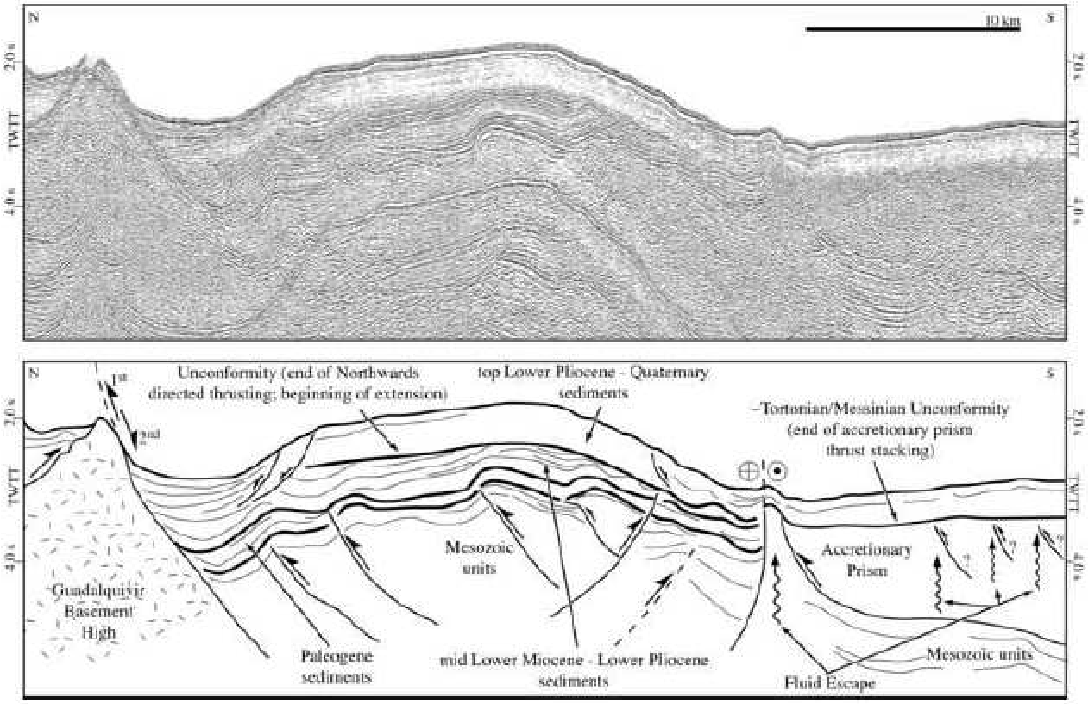


Fig. 10. Segment of multi-channel seismic line ARRIFANO 92-04 and line drawing interpretation. 1st and 2nd movements on main faults are of Jurassic-Cretaceous age and latest Miocene through Present, respectively. For location of seismic line see Fig. 3. The D. Carlos salt diapir 3D topography is shown in Fig. 6D.

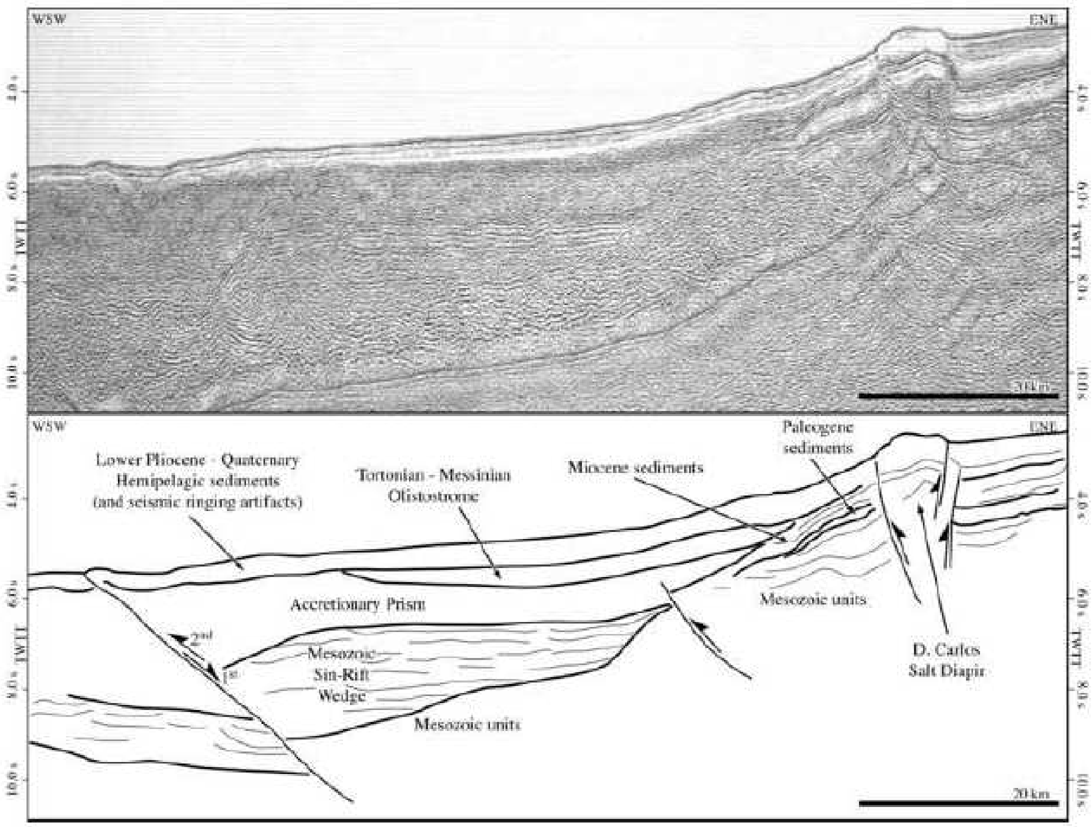


Fig. 11. Segment of multi-channel seismic profile IAM-3 at the contact between the Coral Patch Ridge (CPR) and the Horseshoe valley. Arrows point to folds in recent sediments on the seafloor as imaged on the MATESPRO bathymetry (see Figs. 3 and 7). Note that these faults cut across seismic discontinuity D that outlines the decollement of the seismic chaotic facies.

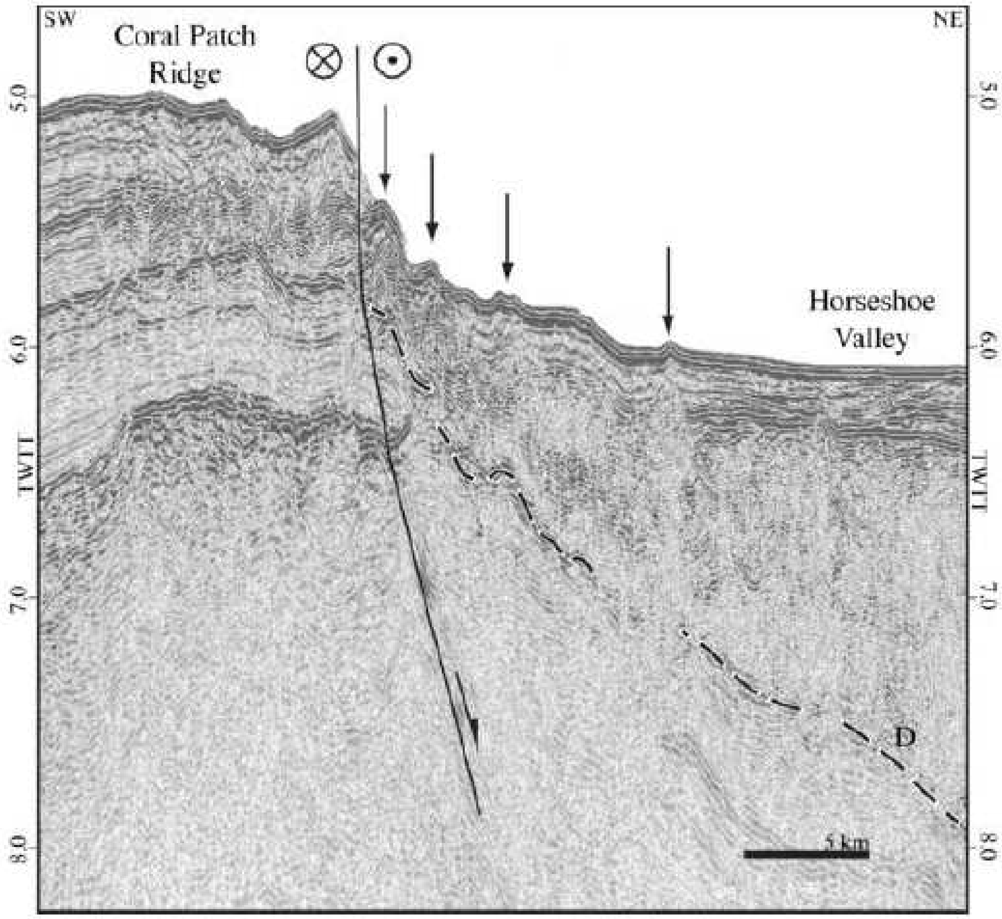


Fig. 12. Segment of multi-channel seismic line ARRIFANO 92-10 showing the deep origin of fluidized sediments breaching through the Mesozoic rift units and accretionary prism. Also note that the most recent unit is not involved in the thrust stacking tectonics of the accretionary wedge (see text for discussion, for location of line see Fig. 3). The steeply dipping north westernmost fault is the Aljezur fault bounding the deposits of the Sagres valley. Note that the chaotic body under the Sagres valley also has imbricated horizons but has no influence on the seafloor morphology (see text for discussion).

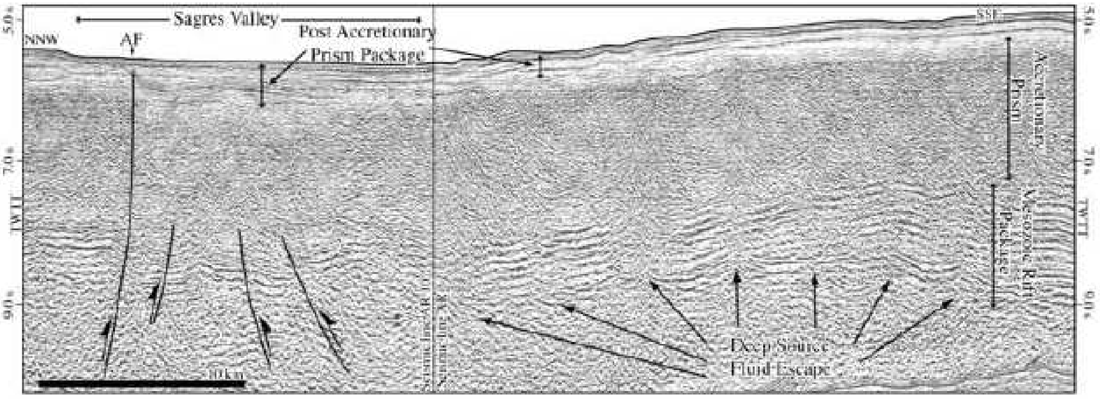


Fig. 13. Segment of multi-channel seismic line perpendicular to the Portimão canyon. Note that the Lower Miocene unconformity (M) truncates the folds that resulted from tectonic inversion on both sides of the Portimão canyon fault. However, mild deformation associated with this fault is visible on the eastern side of the fault and canyon. The salt-wall shown in the east of the profile also affects the recent sediments.

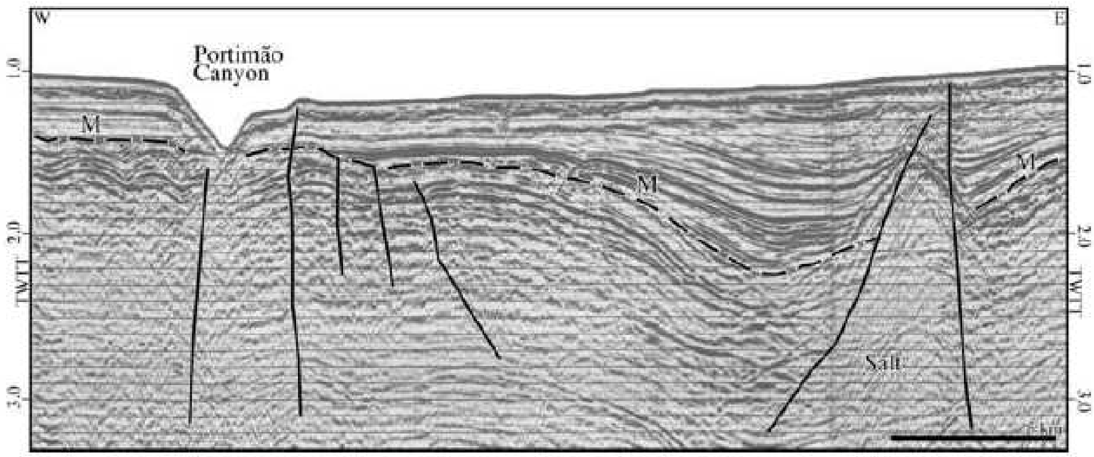


Fig.14. Segment of multi-channel seismic line perpendicular to the S. Vicente canyon. Note the main fault controlling the position of the eastern flank of the canyon. This is a steep fault, possibly en echelon with the Messejana dyke fault (see text for description). Sediments on both sides of the fault are tilted and deformed including seismic reflector S, which is interpreted as a paleo-canyon bottom.

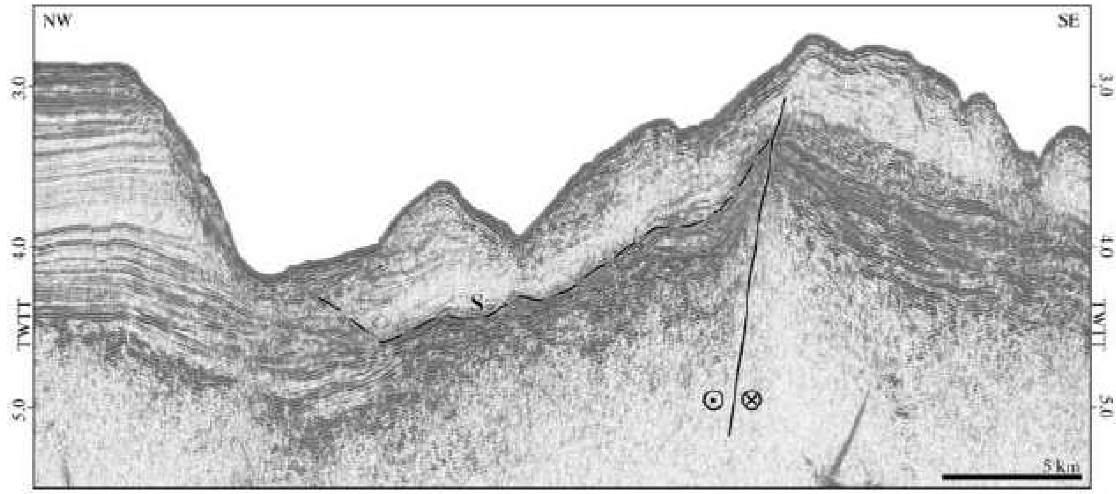


Fig 15. Multi-channel seismic reflection profile across the Giant Scours. For location of the lines see Figs. 3 and 7. Seismic line IAM-4E shows the existence of stacked blind thrusts with present activity underneath the Giant Scours in the Sagres valley.

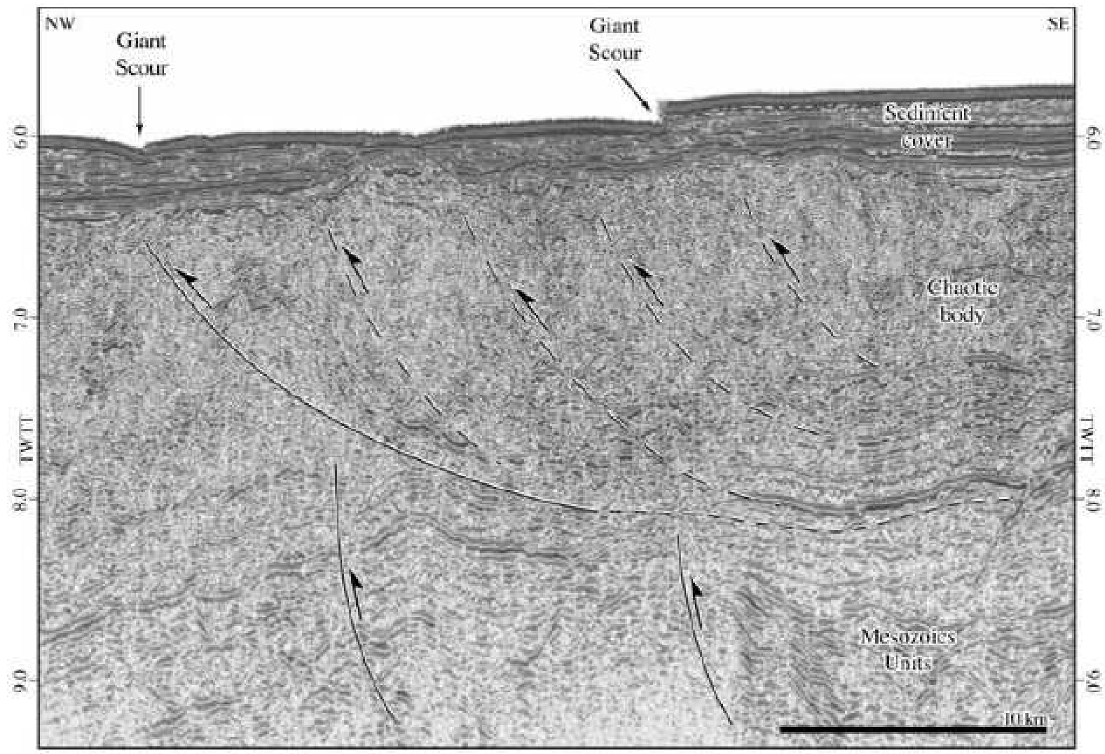


Fig. 16. Single-channel seismic line PSAT246 across two scours and line drawing interpretation. Note the erosive character of the escarpments and the sediments prograding towards the escarpment. For location see Figs. 3 and 7.

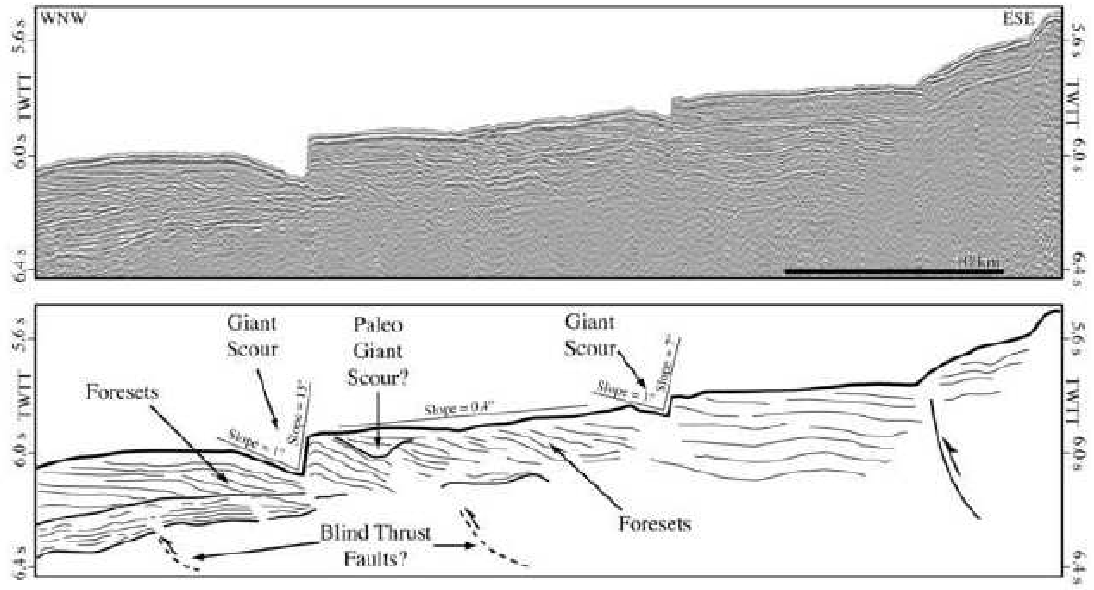


Fig. 17. Sketch of the effect of bottom currents on the retreat of the scarp and simultaneous progressive sedimentation of the progradation foresets. Scarp initially formed by uplift of hanging-wall on top of a blind thrust (see text for discussion).

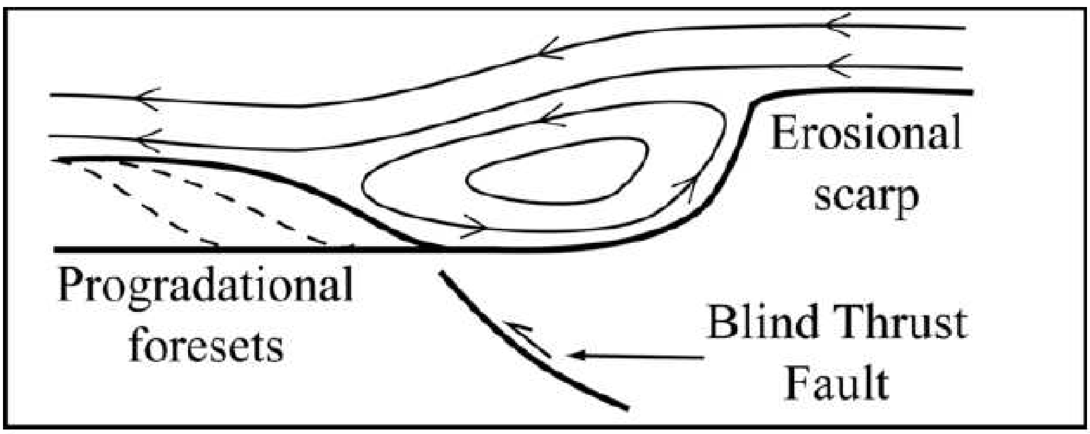
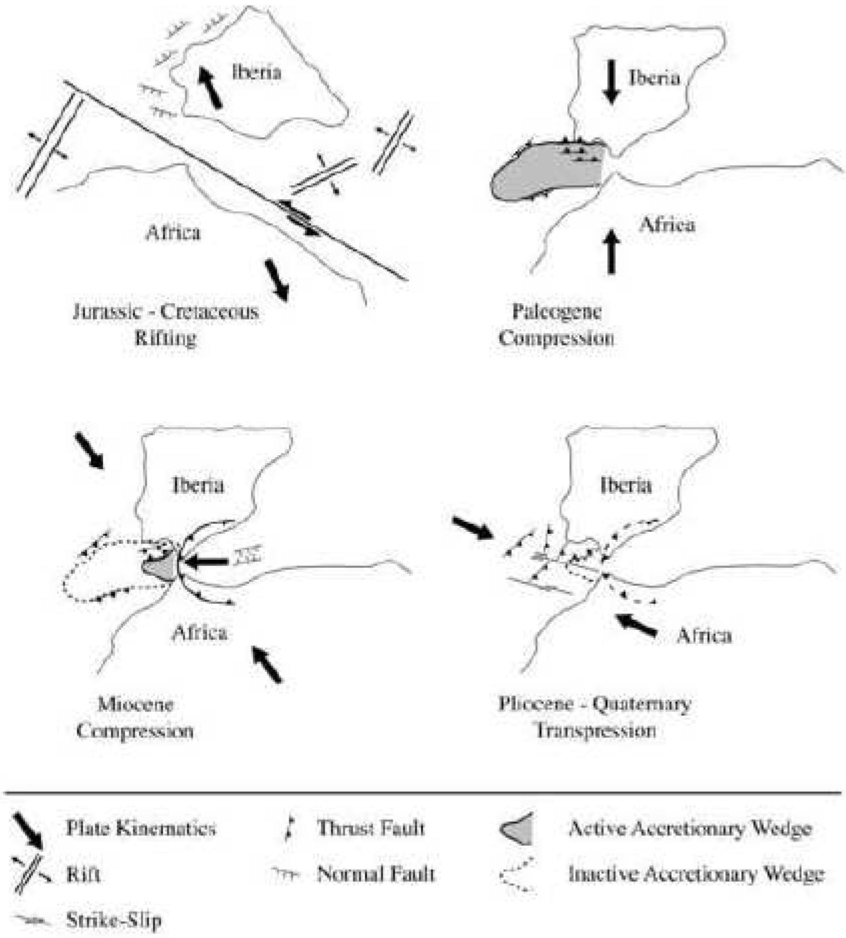


Fig. 18. Schematic tectonic evolution of the structure of the Gulf of Cadiz. In this simplified interpretation it is proposed the formation of an accretionary wedge (or thrust belt) that extended from Gibraltar across the Horseshoe Abyssal Plain during the latest Cretaceous – Paleogene compression. A second accretionary wedge formed (after

Gutscher et al., 2002, or imbricate unit after Iribarren et al., 2007) during the Gibraltar orogenic arc westward overthrusting in Miocene times. In Pliocene-Quaternary times this accretionary wedge severely diminished its activity, the WNW-ESE dextral strike-slip faults formed and westward directed thrust increased along faults on the southern part of the West Portuguese Margin. See text for detailed discussion.



	ARRIFANO	IAM	Voltaire	TTR-14
Year	1992	1993	2002	2004
Vessel	R/V OGS Explora	Geco Sigma	R/V Urania	R/V Prof Logachev
Reference	Sartori et al. 1994	Banda et al. 1995	Zitellini et al., 2002	Kenyon et al., 2006
Seismic source	32 Airguns (80 litres max.)	30 Airguns (125 litres max.)	2 GI guns	1 Airgun (120 bar)
Shooting Interval	50 meters	74 meters	50 meters	10 seconds (aprox 30 metres)
Sample Interval Recorded	1 ms	4 ms	1 ms	1 ms
Number of channels	120	192	48	1

Resampling	4 ms	8 ms	2 ms	1ms (no resampling)
Signal Processing	Spiking deconvolution Spherical divergence correction NMO correction Finite-difference wave-equation migration Time variant bandpass frequency filter	NMO correction Kirchoff migration (constant velocity 1700m/s) AGC, 500 ms time gate	Trace editing Shot delay removal Amplitude recovery Predictive deconvolution Velocity analysis every 200 CMPs NMO correction Stack Band-pass-frequency filtering Time migration using stacking velocities	Static correction Spiking deconvolution Spherical divergence correction Butterworth bandpass filtering (20-60-180-240 Hz)