Marine Geology 209 (2004) 173–198
MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS
www.elsevier.com/locate/margeo

Structure and evolution of the "Olistostrome" complex of the Gibraltar Arc in the Gulf of Cádiz (eastern Central Atlantic): evidence from two long seismic cross-sections

T. Medialdea[a,*], R. Vegas[b], L. Somoza[a], J.T. Vázquez[c], A. Maldonado[d], V. Díaz-del-Río[e], A. Maestro[a], D. Córdoba[f], M.C. Fernández-Puga[c]

[a] *Marine Geology Division, Instituto Geológico y Minero de España, IGME, Ríos Rosas 23, Madrid 28003, Spain*
[b] *Depto. de Geodinámica, Fac. C. Geológicas, Universidad Complutense, Madrid 28040, Spain*
[c] *Facultad de Ciencias del Mar, Universidad de Cádiz, Puerto Real, Cádiz 1510, Spain*
[d] *Instituto Andaluz de Ciencias de la Tierra, CSIC/Universidad de Granada, Granada 18002, Spain*
[e] *Centro Oceanográfico de Málaga, Instituto Español de Oceanografía, Málaga 29640, Spain*
[f] *Depto. de Geofísica, Fac. C. Físicas, Universidad Complutense, Madrid 28040, Spain*

Received 16 June 2003; received in revised form 28 May 2004; accepted 28 May 2004

Abstract

Reflection profiles characterize the structure and the upper Mesozoic to Cenozoic deposits of the Gulf of Cádiz region. Two long ENE–WSW multichannel seismic lines (ca. 400–500 km long) are analyzed to study the evolution of the area from the continental shelf to the Horseshoe and Seine abyssal plains. The huge allochthonous deposits emplaced in this region (the so-called "Olistostrome" of the Gulf of Cadiz) are described in terms of three different domains on the basis of the seismic architecture, the main tectonic features and the nature of the basement, oceanic or continental. The eastern domain extends along the continental shelf and upper and middle slope and corresponds to the offshore extension of the Betic–Rifean external front. It is characterized by salt and shale nappes later affected by extensional collapses. The central domain develops along the lower slope between the Betic–Rifean front and the abyssal plains and is characterized by a change in dip of the allochthonous basal surface and the basement. The allochthonous masses were emplaced by a combined gravitational and tectonic mechanism. The northern boundary of this domain is marked by the occurrence of an outstanding WNW–ESE-trending thrust fault with a strike-slip component, termed here as the Gorringe–Horseshoe fault. The westernmost domain corresponds to the abyssal plains, where the distal emplacement of the allochthonous body takes place; it is characterized by thrust faults affecting both the sedimentary cover and the oceanic basement. The allochthonous masses show a less chaotic character and the thickness decreases notably. These domains represent different evolutionary steps in the mechanisms of emplacement of the allochthonous units. The eastern domain of the allochthonous units was emplaced as part of the pre-Messinian orogenic wedge related to the collision that gave rise to the Betic–Rifean Belt, whereas the allochthonous wedge of the central and western domains were emplaced later as a consequence of the NE–SW late Miocene compression that continues in present times.

Keywords: tectonics; olistostromes; Gulf of Cadiz; Southwest Iberia continental margin; seismic profiles

* Corresponding author. Tel.: +34-91-7287223.
E-mail address: t.medialdea@igme.es (T. Medialdea).

0025-3227/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2004.05.029

1. Introduction

The Gulf of Cádiz region straddles the E–W trending segment of the Eurasian–African plate boundary that extends from Azores to the Mediterranean Sea, between the Gloria Fault and the western end of the Alpine Mediterranean belt: the Gibraltar Arc (Fig. 1). The diffuse nature of this segment of the plate boundary is widely accepted on the basis of the related seismicity, that is characterized by scattered shallow-and intermediate-type earthquakes (Vázquez and Vegas, 2000). Earthquake fault plane solutions (Grimison and Chen, 1986; Buforn et al., 1995; Jiménez-Munt and Negredo, 2003) support the existence of a wide transpression zone ascribed to the slow (2–4 mm/year) oblique NW–SE convergence that initiated in the late Miocene (Dewey et al., 1989; Argus et al., 1989).

The Gulf of Cádiz is also a relevant area, as it comprises the ocean–continent boundaries of the African and Iberian margins, in spite that the exact location of both boundaries is not well known. Most of the Gulf of Cádiz is floored by continental crust that thins to the west (Gónzalez-Fernández et al., 2001), whereas the oceanic crust is found at the Gorringe Bank, Horseshoe and Seine Abyssal Plains (Purdy, 1975; Roeser et al., 2002).

In the wake of the opening of the Central Atlantic, the geodynamic evolution of the Gulf of Cádiz has been ruled by N–S Africa–Eurasia convergence. This plate convergence lasted from mid-Oligocene up to late Miocene times and then continued with slow late

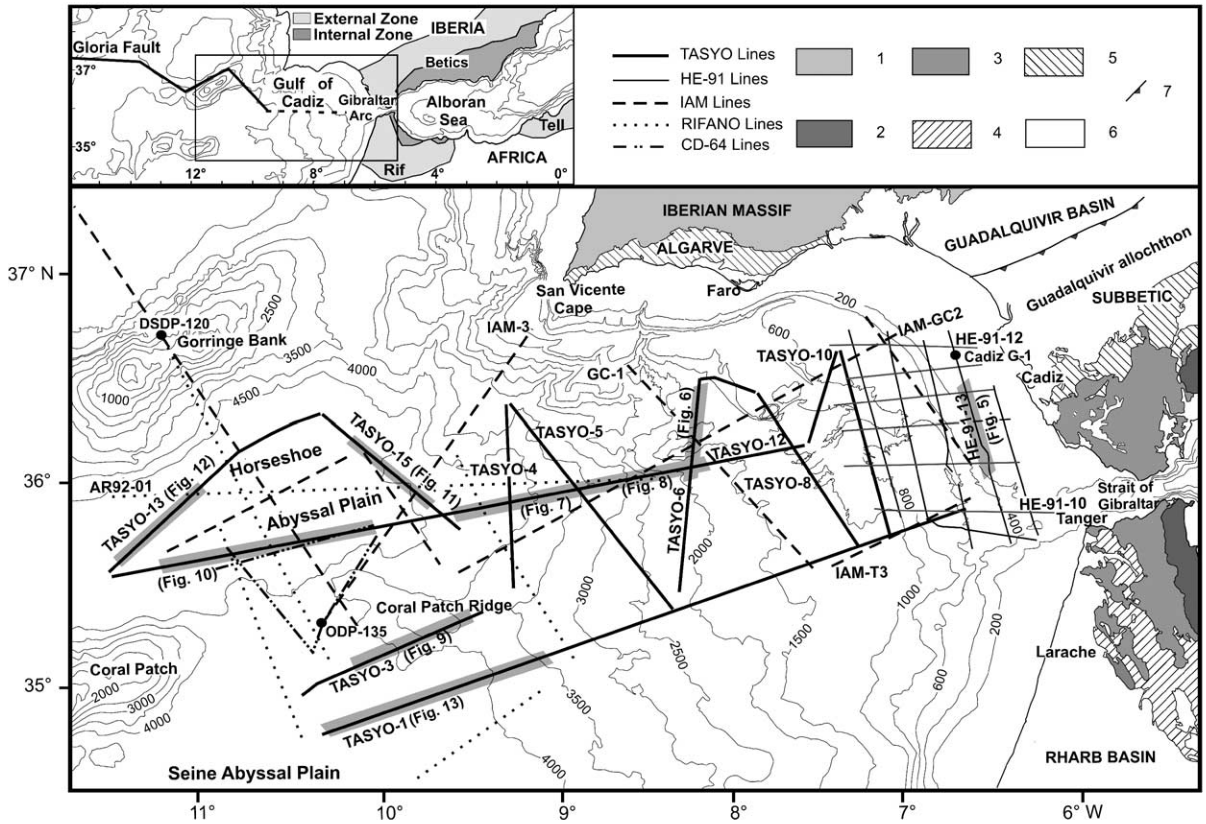


Fig. 1. Location map of Tasyo and HE-91 MCS lines and previous surveys in the Gulf of Cádiz: ARIFANO lines (Sartori et al., 1994; Torelli et al., 1997), IAM lines (Tortella et al., 1997; González-Fernández et al., 2001), CD lines (Hayward et al., 1999). Shaded areas denote the track of seismic lines displayed in the following figures. Inset shows plate tectonic setting with plate boundaries as solid lines. (1) South Portuguese Zone of the Iberian Massif, (2) Complexes of the Alborán Domain, (3) Flysch units, (4) Mesozoic Maghrebian Domain Cover, (5) Mesozoic South Iberian Domain Cover, (6) Neogene–Quaternary Deposits, (7) Guadalquivir Allochthon boundary onland.

Miocene to recent NW convergence (Dewey et al., 1989; Srivastava et al., 1990; Rosenbaum et al., 2002). Westward drift and collision of the Alborán Domain with the north African and south Iberian margins in the early–middle Miocene, caused the development of the Rif and Betic orogen, and as a consequence the radial emplacement of huge allochthonous masses (the so-called "olistostrome unit") on the Guadalquivir Basin (Iberian foreland), Rharb Basin (North African foreland) and Gulf of Cádiz (Perconig, 1960–1962; Flinch and Vail, 1998; Torelli et al., 1997; Maldonado et al., 1999; Gràcia et al., 2003a).

Since the chaotic body was recognized onland in the sixties (Perconig, 1960–1962) and offshore in the following decades (Roberts, 1970; Lajat et al., 1975; Bonnin et al., 1975; Baldy et al., 1977; Malod and Mougenot, 1979; Maldonado et al., 1999), various interpretations have been made to explain the emplacement mechanism of this allochthonous unit (including gravitational processes, debris-flow mechanisms, diapirism and tectonic melange, among others). These interpretations gave rise to different nomenclatures: "Olistostrome", "Guadalquivir allochthon" and "Guadalquivir accretionary wedge". There is, however, a general agreement on the age of emplacement, which has been established as late Tortonian in the Guadalquivir (Perconig, 1960–1962) and Rharb foreland basins (Flinch and Vail, 1998). A similar discussion has been carried on for the offshore prolongation of this unit in the Gulf of Cádiz (Torelli et al., 1997; Tortella et al., 1997; Maldonado et al., 1999; Somoza et al., 1999; Gutscher et al., 2002).

The tectonic setting of the Gulf of Cádiz has been so far ascribed to three scenarios: (a) Maldonado et al. (1999) proposed subduction of the intermediate-type Iberian crust under the Alborán microplate in a western Alborán subduction zone and subsequent deformation of the lower plate in the form of crustal slices (oceanic slices at the Gulf of Cádiz). (b) Gutscher et al. (2002) considered that in the Gulf of Cádiz, these allochthonous masses represent an active accretionary complex related to a narrow east-dipping slab of oceanic lithosphere west of the Gibraltar Arc, under the Alborán Sea. (c) Sartori et al. (1994) suggested that in the distal margin and Atlantic basin plains there is no subduction-related deformation, but the stresses are released across a 200-km area between the Seine Abyssal Plain and the Gorringe Bank, without a defined plate margin. Vázquez and Vegas (2000) also supported a diffuse contractive deformation of the lithosphere due to the African–Iberia convergence. This diffuse deformation occurs at the long-lived Africa–Iberia interface, a "not fully fledged" plate boundary (Vegas, 2001). Both tectonic regimes—subduction and distributed compression deformation—have been related in the same tectonic frame by Vázquez and Vegas (2000).

The objective of this work is to contribute to the knowledge of the main tectonic structures and the evolution of the Gulf of Cádiz within the African–Iberian Tertiary convergence. We analyze two long transects (ca. 400–500 km long) from the Cádiz continental shelf and Strait of Gibraltar to the Horseshoe and Seine Abyssal Plains. These sections have been mainly drawn on the basis of two-long reflection seismic profiles, acquired during the Tasyo cruise. To date, no attempts have been made to explain the evolution of the olistostrome unit from the Guadalquivir Basin to the Atlantic abyssal plains. These cross-sections not only reveal the present tectonics and structure of the region, but also allow us to infer the geological evolution. The long sections are complemented, moreover, with additional Tasyo profiles that show detailed structures (Fig. 1).

2. Geological background

The main geological units that bound the Gulf of Cádiz are: the Algarve Basin in the north part, the South Portuguese Zone of the Iberian Massif, that crops out in southern Portugal, the Guadalquivir foreland basin to the east and the Betic–Rifean orogenic belt, which extends from southern Iberia to Morocco through the Gibraltar Arc (Fig. 1).

The Algarve Basin extends along southern Portugal and the continental margin with an E–W direction. The basement is made up of Devonian and Carboniferous materials, which belong to the South Portuguese Zone, a Variscan SW verging fold-and-thrust belt (Ribeiro et al., 1983). The stratigraphic record of this basin extends from Late Triassic to Quaternary with a hiatus from Cenomanian to Miocene. Nevertheless, Paleogene deposits have been found on the continental shelf, where boreholes have drilled sediments of Paleocene and Eocene age. The evolution of the Algarve Basin within the south Iberian margin is characterized by the Alpine tectonic inversion of the Mesozoic extensional structures (Terrinha et al., 2002).

The Betic belt has been divided in terms of internal and external zones. The former corresponds to the Alborán Domain Complexes and is made up of a stack of nappes mainly composed of Paleozoic to Triassic metamorphic rocks. The external zone (Subbetic units) represent the south Iberian Mesozoic paleomargin, later incorporated into the belt and characterized by thin skinned tectonics. They consist of Triassic to lower Miocene deposits detached and thrusted towards the foreland. The Subbetic is overthrusted by the Flysch of Campo de Gibraltar units, which contains Cretaceous to Miocene siliciclastic deposits, mostly turbidites. These sediments were deposited in a deep trough located between the Iberian margin and the Alborán Domain and later translated and incorporated into the Gibraltar Arc belt (Azañón et al., 2002).

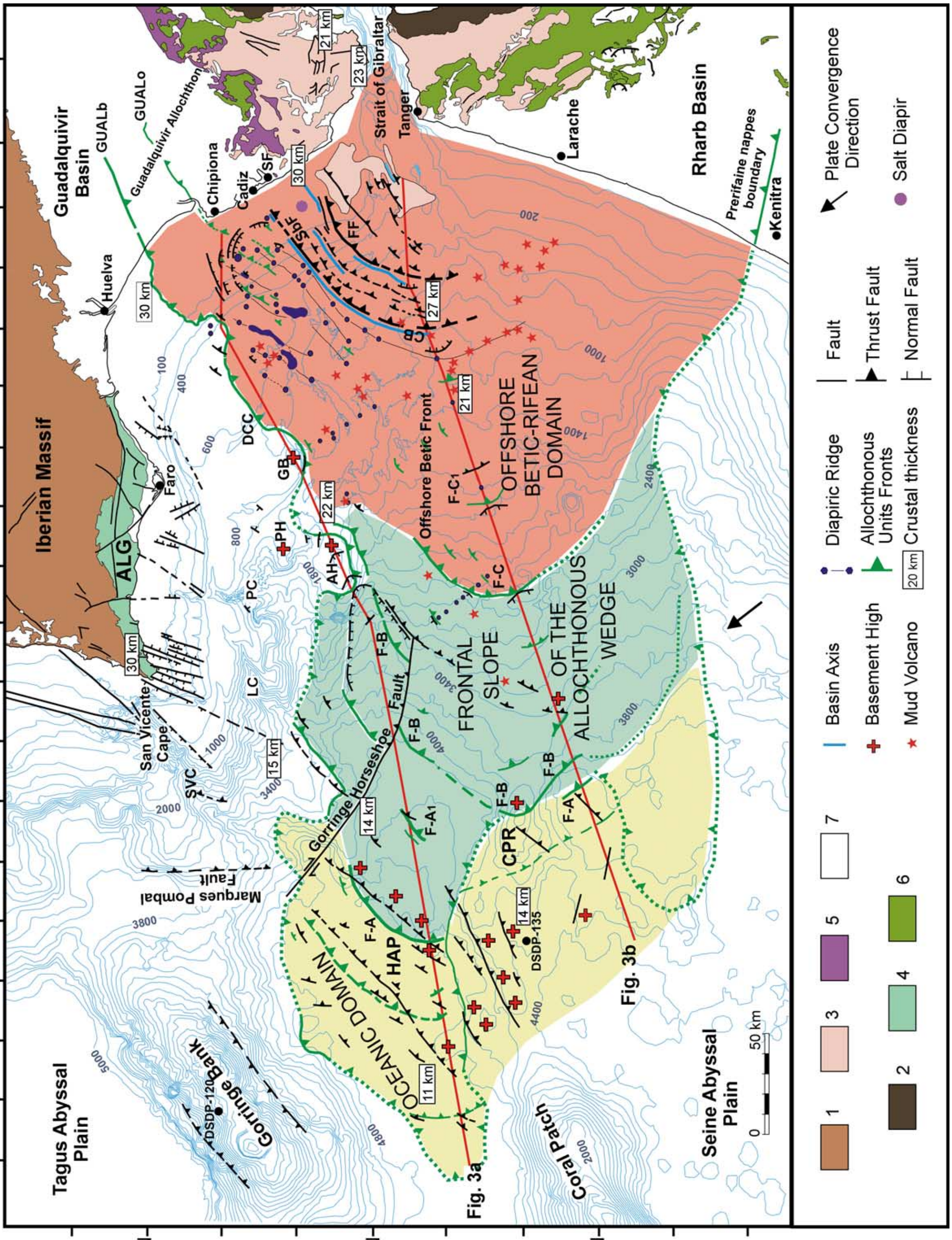
In the Cádiz area, two sectors have been defined onland within the External Zone (Berástegui et al., 1998; García-Castellanos et al., 2002): a southwestern zone of Mesozoic outcrops (lower Jurassic to upper Cretaceous–Paleocene age), and to the north, a body which has been traditionally referred to as the Olistostrome or Guadalquivir Allochthon, constituted by chaotic masses and a frontal Miocene north-verging imbricated wedge. This chaotic body consists of Triassic evaporites and red beds with blocks, mostly of upper Cretaceous to Paleogene limestones. It also involves marlstones ranging from Aquitanian to Tortonian. The southeastern half of the Guadalquivir foreland basin is covered by this allochthonous unit, which near the coast reaches a width of 50 km and a thickness of 2–3 km (Flinch and Vail, 1998). These wedge-shaped allochthonous units extend from the Iberian Peninsula and Morocco (Prerifaine nappes at the Rharb foreland basin) to the Horseshoe and Seine Abyssal Plains.

3. Methodology and data sources

As part of the TASYO Project, a multichannel seismic reflection (MCS) survey was carried out in 2000 in the Gulf of Cádiz aboard the B/O *Hespérides*. During this cruise, 1728 km of MCS seismic profiles were obtained crossing the area in ENE–WSW, NE–SW and NW–SE directions (Fig. 1). Seismic data were acquired by means of a five BOLT airgun array of 22.45 and 34.8 l (line Tasyo-3) of capacity and a TELEDYNE 96-channel streamer of 2.5 km long, and recorded for 10 s at a 2-ms sampling rate. The shot interval was 50 m. Data processing (stacking and time migration) has been performed at the B/O *Hespérides* and the Instituto Andaluz de Ciencias de la Tierra (CSIC). The area was simultaneously surveyed with Simrad EM-12 multibeam echo sounder.

Analysis of these new seismic data allow us to identify several seismic units and map the main tectonic features that have determined the general structure of the margin (Fig. 2). Additional MCS profiles obtained during HE-91 cruise as well as IAM seismic lines have also been analyzed to complement the easternmost part of the Gulf of Cádiz and the Horseshoe Abyssal Plain. The structures and seismic units identified on MCS lines have been tied to other profiles (Fig. 1) previously published by different authors in the area (Sartori et al., 1994; Torelli et al., 1997; Tortella et al., 1997; Hayward et al., 1999). Seismic unit ages have been assigned on the basis of tentative correlations with DSDP 135 and units defined by Maldonado et al. (1999).

Fig. 2. Structural map of the survey area based on interpretation of MCS lines. The map is supplemented in the Portuguese continental shelf with the Carta Geológica de Portugal a escala 1:500,000 (Serviços Geológicos de Portugal, 1992) and in the southwest Portuguese margin, the Marques de Pombal fault has been traced after Terrinha et al. (2003). Bathymetric contours from Tasyo multibeam data and Smith and Sandwell (1997). Crustal thickness after Purdy (1975), Medialdea et al. (1986), González et al. (1998) and González-Fernández et al. (2001). AH: Albufeira basement high; ALG: Algarve Basin; CB: Cádiz Basin; CPR: Coral Patch Ridge; DCC: Diego Cao Channel; F-A, F-A_1, F-B, F-C, FC_1: Fronts of the Allochthonous Units; FF: Flysch Front; GB: Guadalquivir Bank; GUALb: Guadalquivir Allochthon boundary (buried); GUALo: Guadalquivir Allochthon boundary (outcropping); HAP: Horseshoe Abyssal Plain; LC: Lagos Canyon; PC: Portimao Canyon; PH: Portimao basement high; SbF: Subbetic Front; SF: San Fernando; SVC: San Vicente Canyon. (1) South Portuguese Zone (Paleozoic), (2) Complexes of the Alborán Domain (Internal zone), (3) Flysch units, (4) Algarve Basin (Mesozoic), (5) Triassic deposits (External zone), (6) Mesozoic sediments (External zone), (7) Neogene–Quaternary sediments.


Iberian Massif
Guadalquivir Basin
GUALb
GUALo
Guadalquivir Allochthon
Huelva
Chipiona
Cadiz
SF
Faro
ALG
Strait of Gibraltar
Tanger
Larache
Rharb Basin
Prerifaine nappes boundary
Kenitra
Tagus Abyssal Plain
Gorringe Bank
DSDP-120
Coral Patch
Seine Abyssal Plain
DSDP-135
Marques Pombal Fault
Gorringe Horseshoe Fault
San Vicente Cape
SVC
LC
PC
PH
AH
GB
DCC
CB
FF
SbF
Offshore Betic Front
OFFSHORE BETIC-RIFEAN DOMAIN
FRONTAL SLOPE OF THE ALLOCHTHONOUS WEDGE
OCEANIC DOMAIN
HAP
CPR
F-A
F-A1
F-B
F-C
F-C1
Fig. 3a
Fig. 3b
11 km
14 km
15 km
22 km
21 km
27 km
30 km
23 km
37° N
36° N
35° N
11° W
10° W
9° W
8° W
7° W
6° W
0
50 km
1
2
3
4
5
6
7
Basin Axis
Basement High
Mud Volcano
Diapiric Ridge
Allochthonous Units Fronts
Crustal thickness
Fault
Thrust Fault
Normal Fault
Plate Convergence Direction
Salt Diapir

The current structure of the region and its evolution is envisaged through two long ENE–WSW line-drawings (Fig. 3). Both line drawings are chiefly derived from the interpretation of MCS profiles Tasyo-1 and Tasyo-12. Nevertheless, in order to get a more complete image of the region, both Tasyo lines has been linked to MCS profiles IAM-T3 and HE-91-10 and IAM-GC-2 and HE-91-12 lines, respectively (Tortella et al., 1997; González-Fernández et al., 2001). The structure of the lower crust and Moho depth is based on velocity models, where depth has been converted to TWT (González-Fernández et al., 2001), and on other seismic data (Sartori et al., 1994). It should be considered, however, that these conversions might locally produce a distorted image of the crustal geometry.

4. Stratigraphic framework

Five units are differentiated above the acoustic basement. These units range in thickness from: 2–2.5 s (TWT) in the middle continental slope to 2–3.5 s (TWT) in the lower slope, and again to 2–2.5 (TWT) in the basin plains (Fig. 3).

The complete stratigraphic sequence of the sedimentary cover in the Gulf of Cádiz region is constituted by the following units (Fig. 4): (U1) a basal upper Jurassic–lower Aptian unit made up of marls and limestones, onlapping basement irregularities with a mean thickness of 400–600 ms TWT; (U2) an upper Cretaceous–lower Eocene predominantly terrigenous unit (shales with chert layers and limestones at the base) deposited in a deep sea environment (Hayes et al., 1972) and with a fairly constant thickness of 400 ms TWT along the basin plains, that increases towards the slope (600–800 ms TWT); (U3) a unit that has been tentatively attributed to the Upper Oligocene–Miocene according to the stratigraphic position, that was only recognized on the Horseshoe Abyssal Plain and locally at the lower slope with a thickness of about 400 ms (TWT); (U4) the Allochthonous Unit of the Gulf of Cádiz, the so-called "Olistrostrome", (U5) a Miocene–Quaternary Unit. This later unit is composed on the continental shelf and slope of Miocene marly clays and sands, and Pliocene–Quaternary hemipelagic deposits, contourites and turbidite beds (Maldonado et al., 1999). On the southern edge of the Horseshoe Abyssal Plain, DSDP 135 drilled marls and nannoplankton chalk ooze of late Oligocene–early Miocene to Pleistocene age (Hayes et al., 1972).

Due to its specific characteristics (unusual thickness and wide distribution) and the widely discussed mechanism of emplacement, the "olistostrome unit" merits independent attention. In this contribution, these deposits will be called the Allochthonous Unit of the Gulf of Cádiz (AUGC). This denomination avoids genetic implications, since more than one mechanism can be invoked along the evolution of the margin, as it will be farther discussed.

The wedge-shaped AUGC is constituted by a set of superposed sheets. Its thickness ranges from 0 s in the external front to 2.5 s TWT (about 2.75 km assuming a velocity of 2.2 km/s, after González-Fernández et al., 2001). These masses have been seismically characterized by chaotic reflectors and numerous diffractions and hyperbolic reflections. Nevertheless, towards the western external front as the thickness decreases, it is seismically more coherent and less deformed. The allochthonous deposits have been drilled onshore in front of Chipiona (Cádiz G-1 in Fig. 1) where it is made up of marls and anhydrite (Maestro et al., 2003).

The allochthonous masses involve two Miocene units defined in the continental shelf and upper slope by Maldonado et al. (1999): pre-olistostrome unit M1 (Langhian-Serravallian and lower Tortonian) and syn-olistostrome unit M2 (upper Tortonian). Fragments of Mesozoic and plastic Triassic materials and even lower Cenozoic units are also comprised in the AUGC, taking into account seismic and well data (Maestro et al., 2003). On the continental shelf and upper slope the AUGC overthrusts unit M1, composed of grey and green clays, which is responsible of the marly diapirism in the Gulf of Cádiz. Similar data has been reported by Flinch and Vail (1998) in the southern margin of the Guadalquivir foreland basin.

5. Structure of the Gulf of Cádiz from seismic interpretation

The tectonics, seismic architecture, morphostructure and crustal structure of the area will be described and interpreted in terms of three key regions (Figs. 2

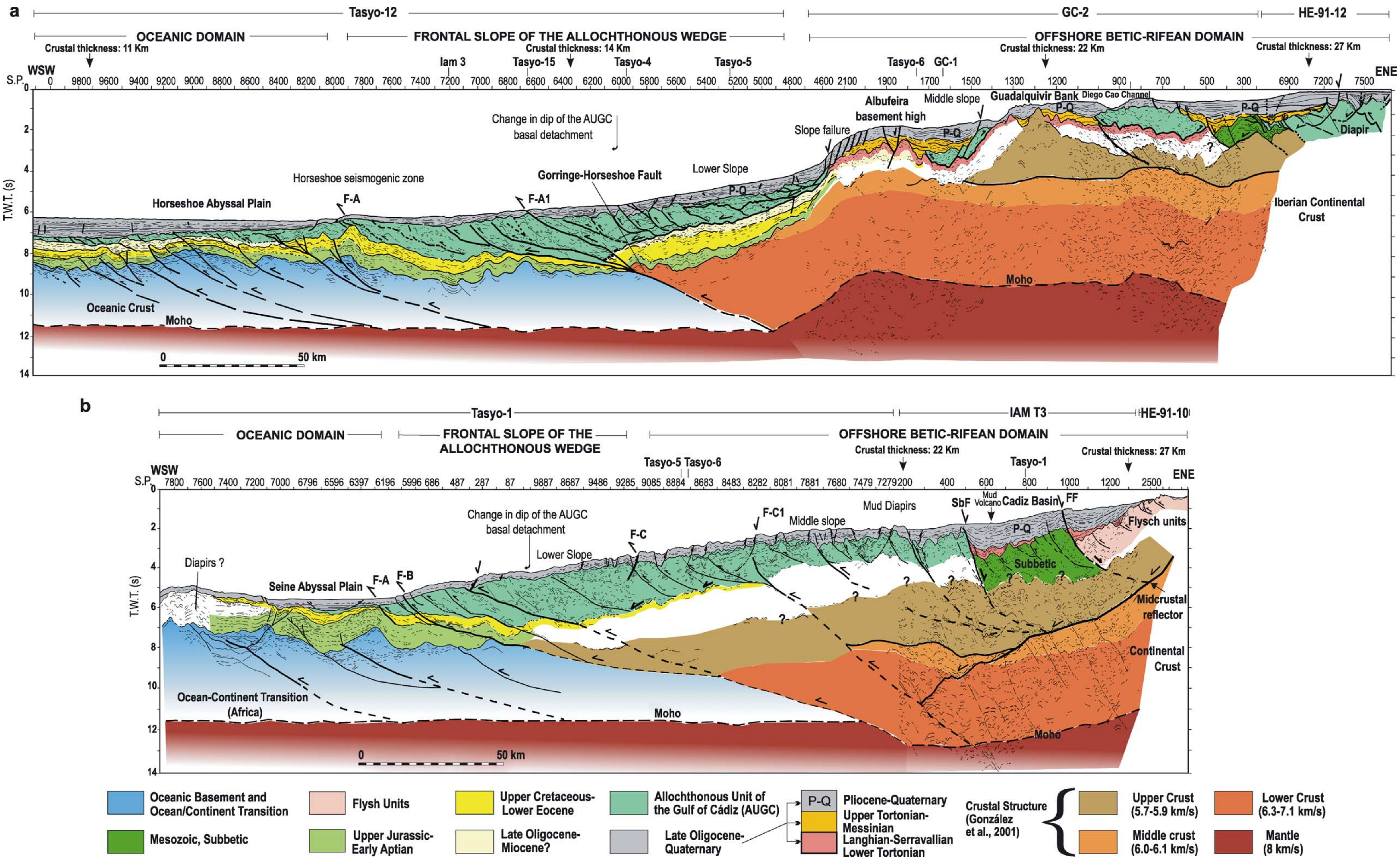


Fig. 3. Two cross-sections along the Gulf of Cádiz composed of line-drawings of MCS profiles Tasyo 12, IAM GC-2 and HE-91-10 (a) and Tasyo 1, IAM-T3 and HE-91-12 (b). Crustal structure from depth to TWT time converted after González-Fernández et al. (2001) is superposed on both sections. Discussion in the text. See Fig. 2 for location.

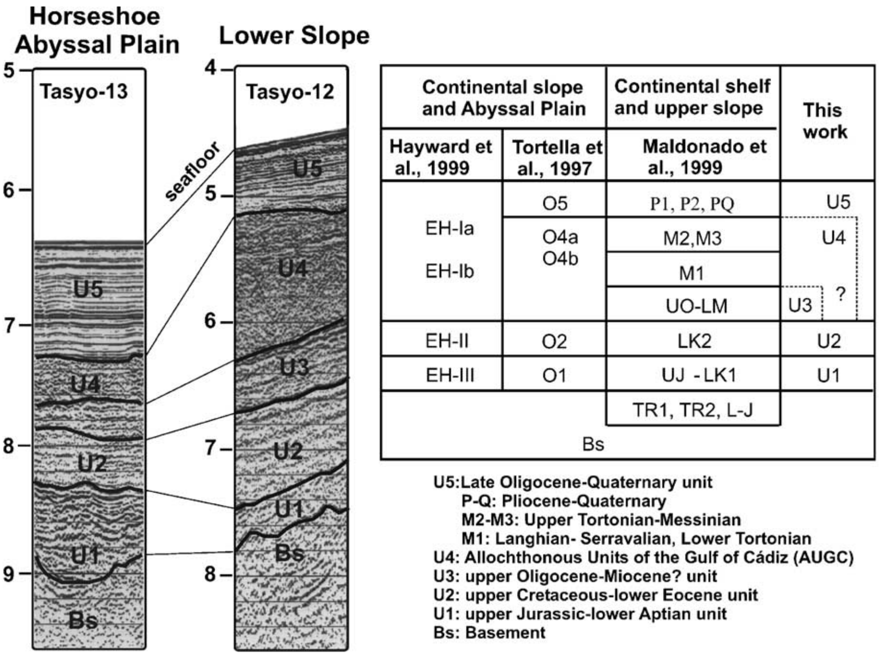


Fig. 4. Stratigraphy of the following MCS profiles at the lower slope and abyssal plain and correlation with seismic units previously defined in the area.

and 3): (1) the easternmost region, which extends along the continental shelf and upper and middle slope, has been named the Offshore Betic–Rifean Domain; (2) the central domain, which includes the Frontal Slope of the allochthonous wedge; and (3) the outer Oceanic Domain, that corresponds to the Horseshoe and Seine Abyssal plains separated by the Coral Patch Ridge, where thrust tectonics affecting the basement is conspicuous. This later domain includes the distal front of the AUGC.

5.1. The offshore Betic–Rifean domain

The northern external boundary is marked by a set of elongated basement highs, named the Guadalquivir Bank, and the Portimao and Albufeira basement highs (GB, PH and AH, respectively, in Fig. 2). These highs are located on the middle slope at 1200–1300 m depth, south of the Algarve Basin, and they correspond to the offshore prolongation of the Variscan basement outcropping in South Portugal (Fig. 2). The Guadalquivir Bank constitutes the only Variscan basement outcrop (South Portuguese Zone of the Iberian Massif) of the margin, where graywackes, shales, quartzites and basic volcanic rocks were dredged (Vegas et al., 2004), although in Fig. 3a it is covered with a thin layer of sediments. These basement highs play an important role in the morphostructure and depositional architecture of the margin, as they trap sediment supplied from the Algarve Basin, act as an obstacle for the advance of the AUGC and influence the development of canyons and channels on the margin. The basement highs overlie a thinned continental crust of 22–23 km (González-Fernández et al., 2001) and their dimension and importance are well expressed by gravity and magnetic anomalies (Dañobeitia et al., 1999).

East and southwards and in the proximity of the Strait of Gibraltar, the Flysch and Subbetic units cross obliquely the continental shelf and upper slope and continue into the Moroccan margin with the Rifean flysch and external units to form the Gibraltar Arc (Fig. 2).

The region is characterized by successive arcuate thrusts corresponding from E to W to the Flysch and Subbetic materials in the internal area and to the AUGC, which continues onland (Figs. 2 and 3b). The Flysch units outcrop extensively close to the Strait of

Gibraltar and overthrust the Subbetic units (Figs. 3a and 5). The Subbetic units include upper evaporitic Triassic units, affected by diapirism, and Mesozoic to Tertiary carbonate and terrigenous deposits (Jurassic to late Oligocene), which overlie the Paleozoic basement. Several diapirs have been identified offshore in this area, as for example a huge diapir close to the Flysch-Subbetic boundary, seaward off San Fernando (SF in Fig. 2), where a salt diapir outcrops. Over the Subbetic and Flysch units, an arcuate basin (Cádiz Basin, CB in Fig. 2) with two marked depocenters located over the fronts of both units is remarkable in Fig. 3b (S.P. 600 and 1100), filled by a middle Miocene–Quaternary depositional sequence of more than 1 s TWT.

West of the Subbetic Front (SbF in Fig. 2), the AUGC develops as a set of superposed units that prograde seawards, reaching progressively further distances along a seaward dipping basal surface (Fig. 3b). The chaotic masses of the northern allochthonous wedge front overlie middle Miocene deposits, as for example close to the Portimao basement high (Fig. 6).

The progressive westward migration of these units is responsible for the convex morphology of the isobaths on the slope, which appear as a fan-shaped body. The AUGC reaches the base of the middle slope at 2400 m water depth, and delineates the external boundary of this domain (F–C in Figs. 2 and 3b). In spite of the chaotic character attributed to the AUGC, the high quality of the seismic data allows us to distinguish the internal landward-dipping reflectors that represent the basal detachments of the successive imbricated bodies (Fig. 3b).

Extensional collapses and roll-over structures are found at the back of the advancing allochthonous sheets (Maestro et al., 2003). These features are

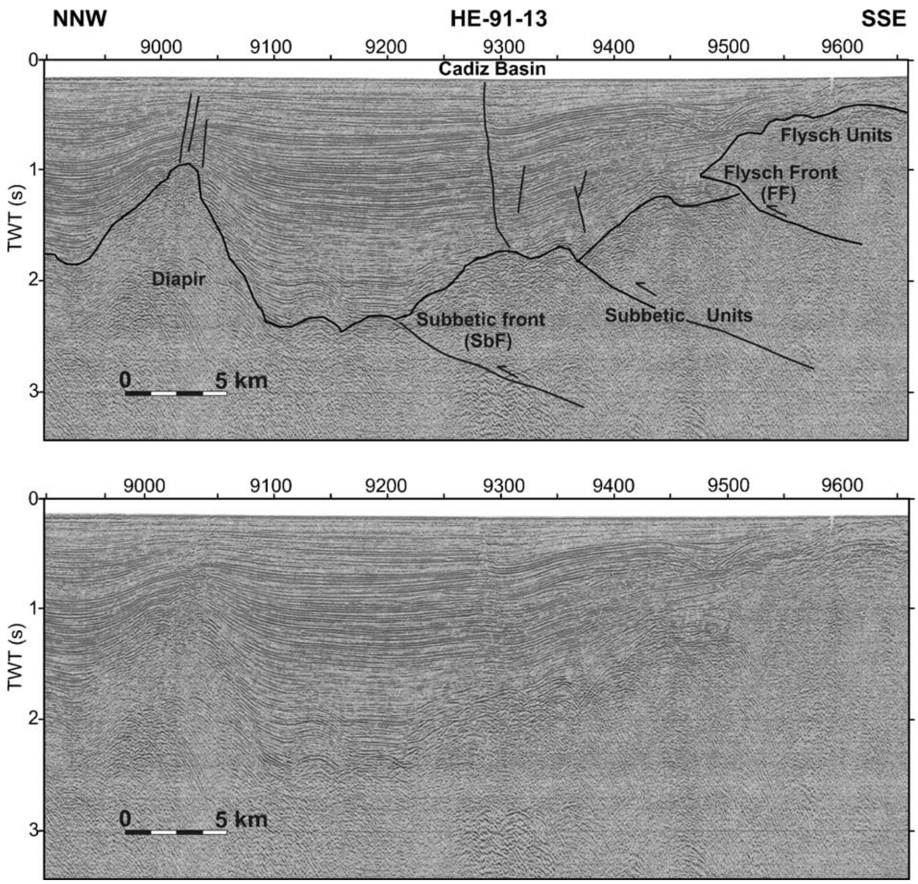


Fig. 5. Interpreted MCS line HE-91-13 and seismic profile across the Flysch and Subbetic units. Discussion in the text. See Fig. 1 for location.

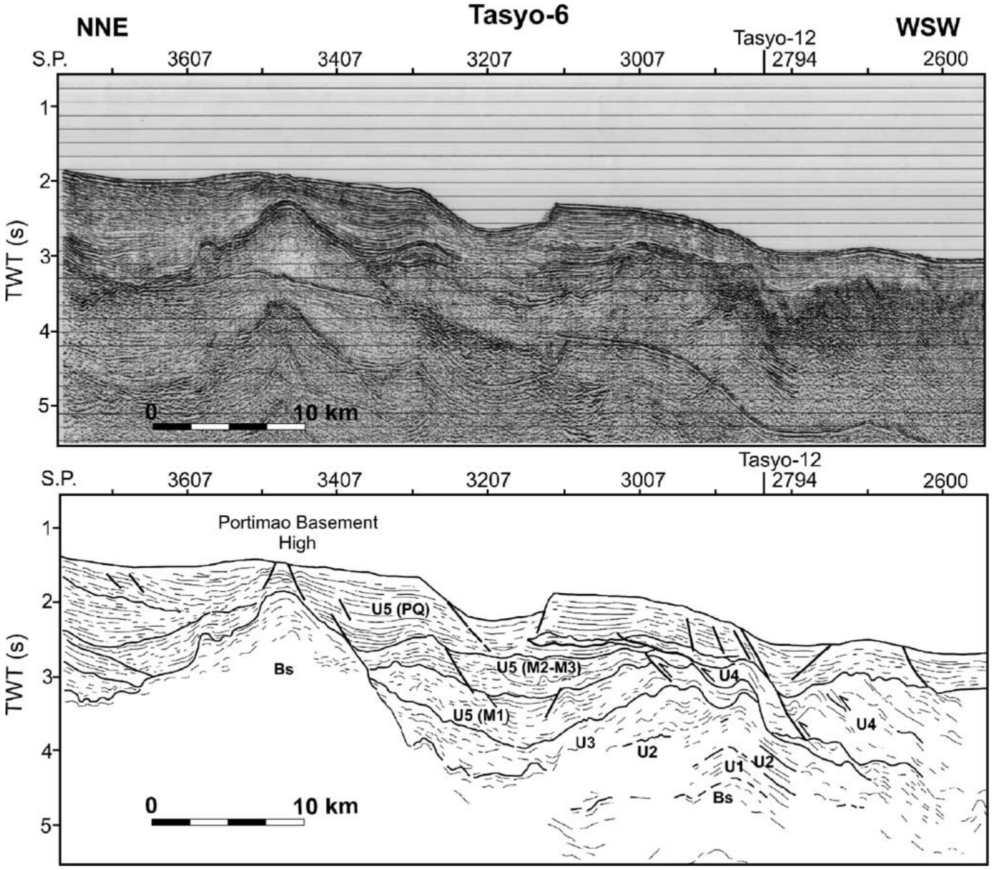


Fig. 6. Detail of the MCS line Tasyo-6 and line drawing in the Portimao basement high area, showing the external front of the AUGC. See Fig. 1 for location and Fig. 4 for seismic units explanation.

represented in Fig. 2, where several listric faults with an arcuate trace merge at the sea floor near the continental shelf break in front of Chipiona.

The irregular and undulating top of the allochthonous unit frequently shows mounded geometries, that can either mark secondary fronts or geometries related to diapirism (Figs. 3 and 5). Extensive mud diapirism and mud volcanism has been reported throughout the Gulf of Cádiz margin (Somoza et al., 2002; Pinheiro et al., 2003). On Fig. 2, the location of the main diapirs and mud volcanoes structures extending from the coast to the lower slope are shown. In the northern Gulf of Cádiz, these diapirs display a NE–SW trend, parallel to the arcuate Subbetic Front and form a set of parallel ridges (Hernández-Molina et al., 2003). South of the Strait of Gibraltar, mud volcanoes followed a NNW–SSE trend.

Near the coast, the 30-km-thick continental crust thins progressively to 21–22 km approximately at 8°W (González-Fernández et al., 2001). Two basement highs that belong to the northern boundary of this domain are represented in Fig. 3a: the Guadalquivir Bank and the Albufeira basement high, located to the SW (Fig. 2), where the upper crust has been defined using wide-angle seismic reflection models. Taking into account that the Guadalquivir Bank is made up of Paleozoic rocks, it is proposed that this uppermost layer represents the South Portuguese Zone. A prominent intracrustal reflector (Fig. 3b), associated with the top of the middle crust at 4 s TWT (approximately 5 km depth) beneath the Cádiz Basin, can be traced down to 10 s TWT (12 km depth) along an 80-km long seaward dipping surface. This crustal boundary separates two blocks (upper and lower crust) with different reflection signatures. There are also groups of upper crustal reflectors rising from this midcrustal region, which could be considered emerging thrusts ramping up into the upper crust from the midcrustal detachment zone.

5.2. The frontal slope of the allochthonous wedge: the transition to the basin plains

The lower slope and rise is characterized by the occurrence of an outstanding WNW–ESE-trending fault, named here as the Gorringe–Horseshoe fault, which lies southeast of the Gorringe Bank and bounds the northeastern margin of the Horseshoe Abyssal Plain (Figs. 2 and 3a). Another feature of this area is the change in inclination of the allochthonous basal surface. The greatest thicknesses of the AUGC are reached in this domain, close to the Gorringe–Horseshoe fault (Fig. 3a).

The internal boundary of this region is well observed south of San Vicente Cape by an abrupt deepening of the basement of 3 s (TWT) from the Albufeira High along 15–20 km, followed by a gentler deepening of 1.5 s (TWT) along 25 km (Figs. 3a and 7).

Three seismic units (U1, U2 and U3) of Late Jurassic to Miocene age underlie the AUGC (Fig. 3a). In contrast to the eastern domain, the AUGC (U4) seems to involve the complete Miocene depositional sequence and constitutes the bulk of the ‘‘infilling’’ of the slope basins. The abrupt deepening of the basement facilitates the gravitational collapse of the allochthonous unit and the overlying sediments (Fig. 3a). As it can be observed in Fig. 7 (S.P. 4500–5500), several allochthonous sheets have slid down due to

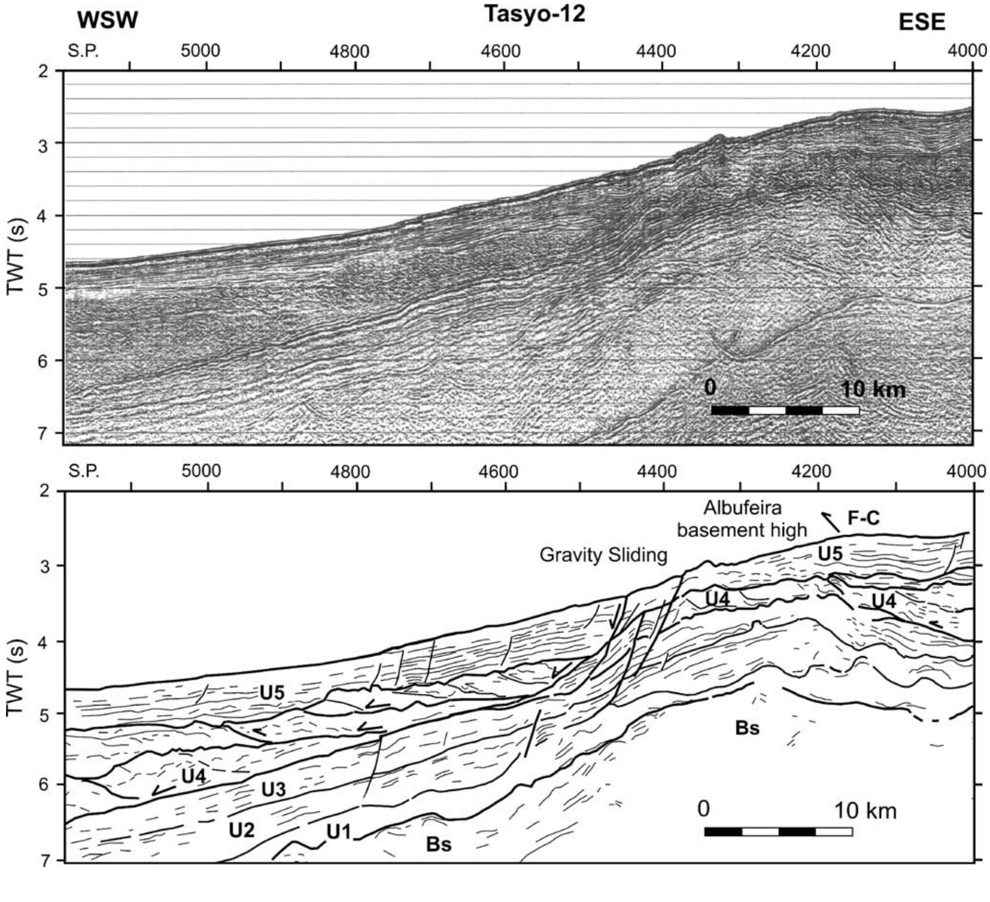


Fig. 7. Segment of MCS line Tasyo-12 and line drawing. Note the slope failure produce by gravity-driven advance of the allochthonous sheets at the base of the Albufeira High. See Fig. 1 for location and Fig. 4 for seismic units explanation.

slope instability and appear superposed at the base of the Albufeira basement high. Extensional structures are produced at the slide head due to the gravitational forces that emplace the slope allochthonous masses. These gravitational faults determine the arcuate trace of the isobaths (Fig. 2).

The Gorringe–Horseshoe fault is an active thrust fault with a right-lateral strike-slip component that has been identified using seismic data and map criteria (Figs. 2, 3a and 8). It is 150 km long and has a NW–SE direction that slightly changes at its eastern end. Neotectonic modelling of this part of the Africa–Eurasia plate boundary carried out by Jiménez-Munt and Negredo (2003) has predicted NW–SE striking faults to have dextral motion and relatively high slip rates (2.8 mm $year^{-1}$). This fault, that has been crossed by two seismic profiles (Tasyo-4 and Tasyo-12), displaces the basement top and seemed to be rooted at the base of the crust, which lies at 12 s TWT at the lower slope (González-Fernández et al., 2001). It is interpreted to be located near the continent–ocean boundary, considering that crustal thickness reaches 14 km (González et al., 1996). We have also re-interpreted this structure in the following seismic profiles (Fig. 1): ARIFANO AR92-01 line, close to CDP 1400 (Torelli et al., 1997) and IAM-3 line, near CDP 4700 (González-Fernández et al., 2001; Tortella et al., 1997).

The Gorringe–Horseshoe fault offsets the unconformity between the basement and the sedimentary cover, but also cuts through the AUGC deposits to the seafloor. This fault produces tilting of the depositional units (which appear northeastward dipping), due to the hangingwall load, lamination of the units and the outward advance of successive imbricates of the allochthonous wedges (Fig. 3a). The Gorringe–Horseshoe fault marks also a change of dip in the basal surface of the AUGC, that passes to verge from oceanward to landward, and induced a change in the mode of emplacement from gravitational to

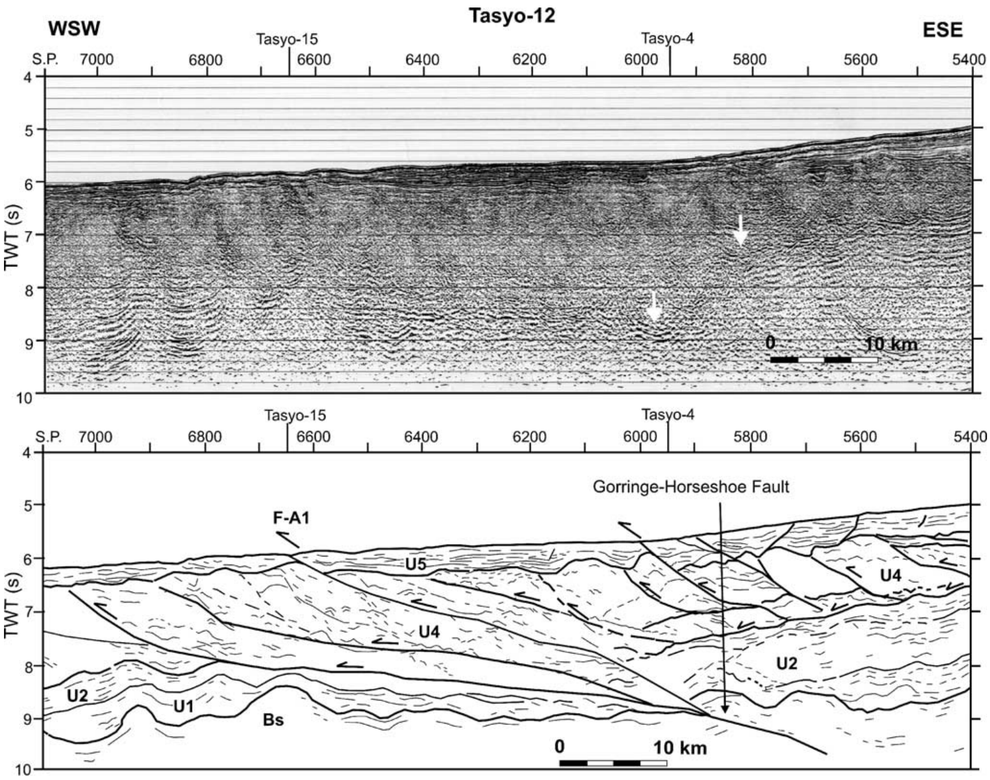


Fig. 8. Segment of MCS line Tasyo-12. Note the Gorringe–Horseshoe fault, which marks a change in the basement dip. Arrows denote the offset produced by the fault. See Fig. 1 for location and Fig. 4 for seismic units explanation.

tectonic (Fig. 3). Previously slid allochthonous wedges of the slope were reactivated and transported seaward as illustrated by some subfronts: (between F-A_1 and F-A in Figs. 2 and 3). The change of the basement dip is also observed in Fig. 3b, close to SP 80, where a fault of similar characteristics has been identified (F-C_1 in Figs. 2 and 3).

The Coral Patch Ridge constrained the seaward migration of the allochthonous wedges and induced the divergence of the migration front, which becomes split into two lobes, one north–westward and another south–westward (Fig. 2). The external front (F–B) of the AUGC pinches out near the top of the Coral Patch Ridge, where it is sealed by only

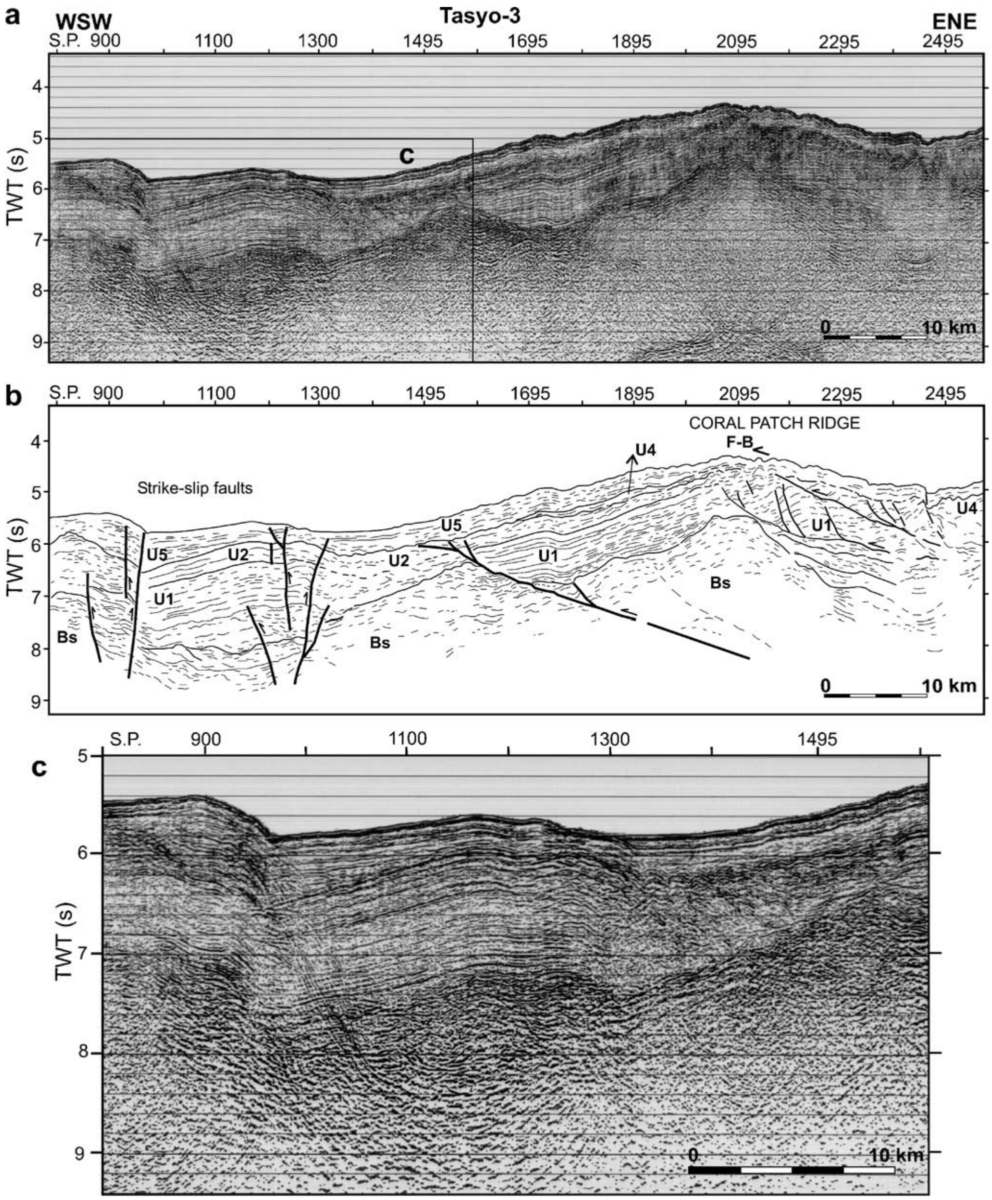


Fig. 9. MCS line Tasyo-3 (a) and line drawing (b) at the Coral Patch Ridge. Discussion in the text. Black box on the MCS line outlines a detailed section (c). See Fig. 1 for location and Fig. 4 for seismic units explanation.

200 ms TWT of Pliocene–Quaternary sediments (Fig. 9).

González et al. (1996) proposed from the interpretation of the IAM-3 wide-angle seismic reflection profile (Fig. 1), a model for the crustal structure of this domain that shows a progressive thinning of the crust from about 30 km close to San Vicente Cape to 15 km (11 km below sea bottom) at 80–100 km from the coast. On the distal margin this thickness is maintained south–westward, close to the Gorringe–Horseshoe fault. In a NE–SW direction, crustal thickness changes from 22 to 14 km (Fig. 2).

5.3. The oceanic domain: the abyssal plains and the Coral Patch Ridge

This region is characterized by active thrust tectonics (Figs. 10 and 11). A slope of 600–700 m marks a change from the distal margin to the flat Horseshoe Abyssal Plain located at 4800 m depth (Fig. 10). The basin plain is bounded by two NE–SW major reliefs: the Gorringe Bank and the Coral Patch Seamount (Fig. 2). The Gorringe Bank is flanked by northwest and southeast-verging thrust faults (Ryan and Hsü, 1973; Mauffret et al., 1989; Le Gall et al., 1997; Galindo-Zaldívar et al., 2003). South of the Coral Patch Seamount, the Seine Abyssal Plain at 4300–4400 m depth is shallower than the Horseshoe Abyssal Plain.

5.3.1. The Horseshoe Abyssal Plain

The depositional sequence in the Horseshoe Abyssal Plain is characterized by upper Jurassic to Miocene sediments (U1, U2 and U3) overlain by an allochthonous wedge (U4) of 400–500 ms (TWT) thick, that thins progressively until it disappears at about 11°50′ W–12°W. In the basin plain, a northwestward-verging thrust system trending NNE–SSW is observed (Figs. 2, 3a, 10 and 11). These thrust faults can be delineated by internal crustal reflectors that extend into the oceanic basement, fold the sedimentary cover and develop seafloor elevations (Figs. 10 and 11). In general, these thrust faults have a small horizontal component, and consequently the crustal shortening accommodated by each fault is minor. The

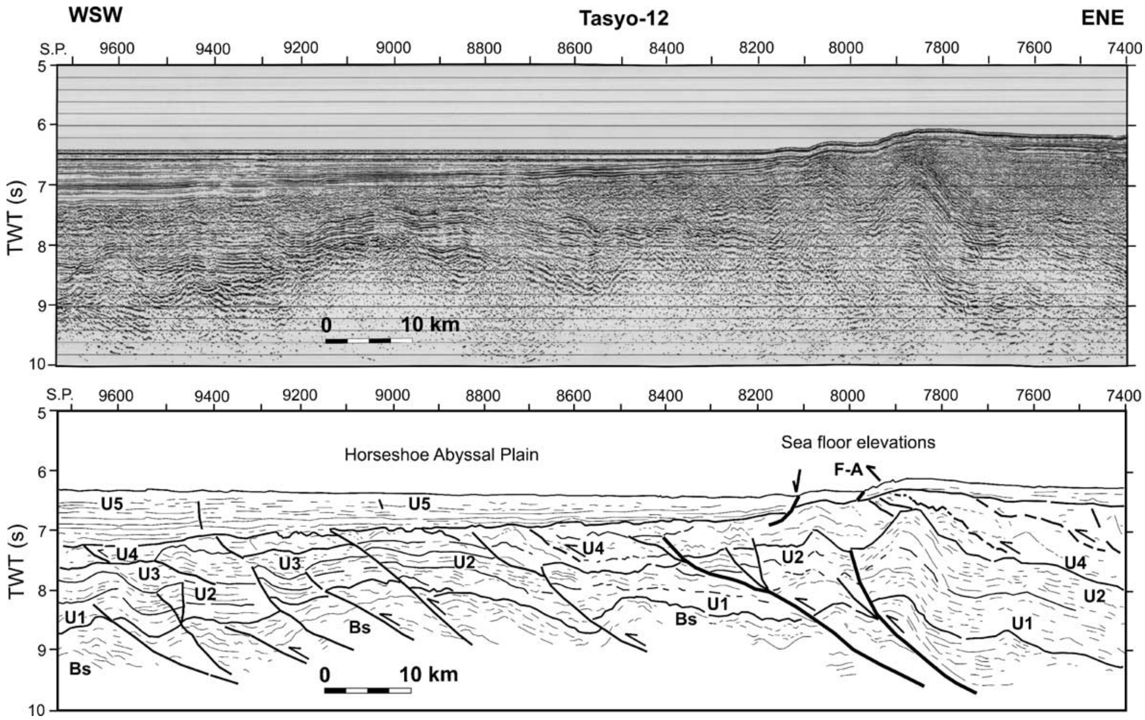


Fig. 10. Western segment of MCS line Tasyo-12 and line drawing showing the thrust belt of the Horseshoe Abyssal Plain. Details of interpretation in text. See Fig. 1 for location and Fig. 4 for seismic units explanation.

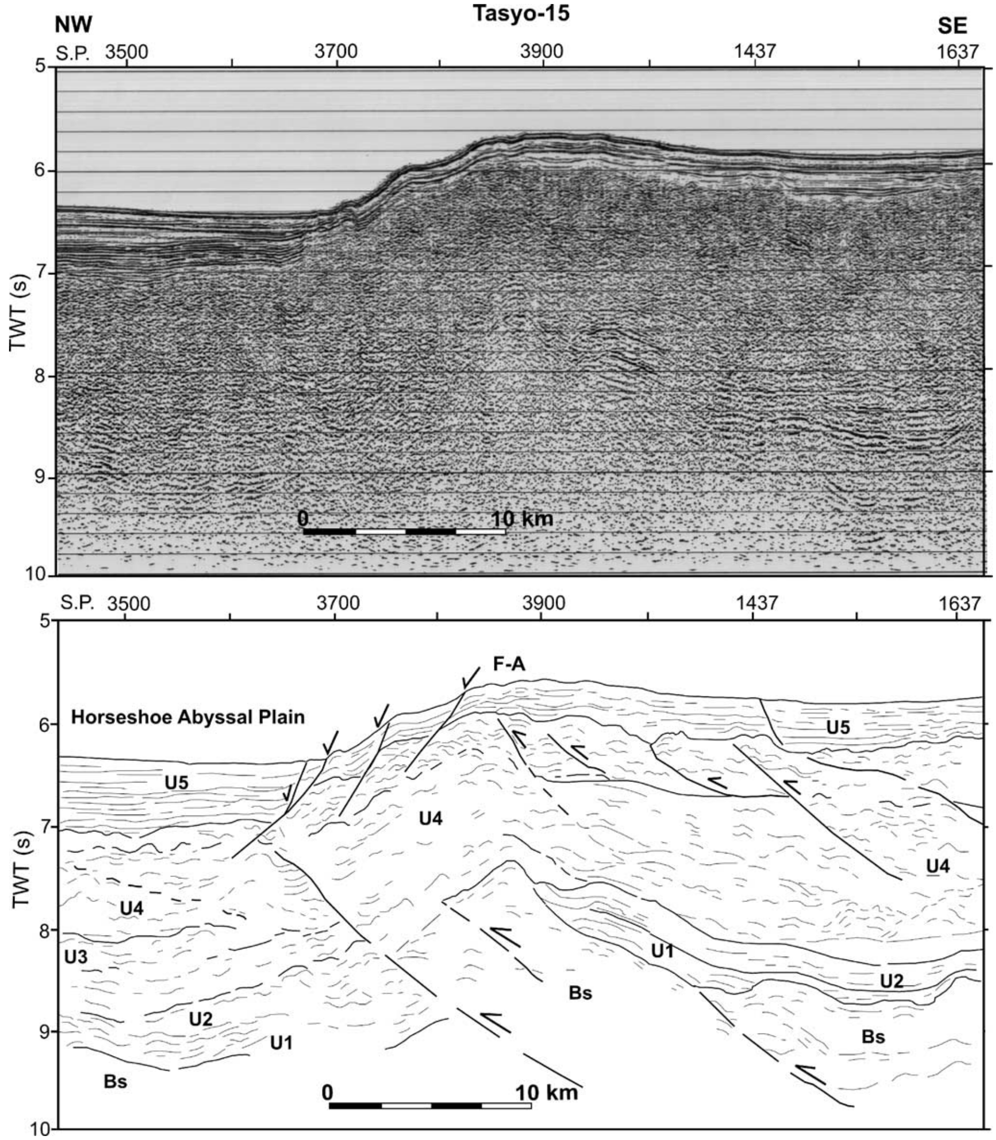


Fig. 11. MCS line Tasyo-15 and line drawing showing the thrust fault that marks the eastern boundary of the Horseshoe Abyssal Plain. Associated recent slides are observed. This thrust fault has also been cut southwards by line Tasyo 12 (Fig. 10, S.P. 7900). Details of interpretation in text. See Fig. 1 for location and Fig. 4 for seismic units explanation.

main vertical offset of the basement is observed at the eastern boundary of the plain, where a thrust fault originates a promontory that rises 600 m over the sea floor (Fig. 11). The geometry of the structures shows high-middle angle in the sediments and tends to flatten to low angles in the basement. It is noteworthy that the thrust faults seem to be rooted at the base of the crust (11.5 s TWT), as it can be observed in the seismic profiles from the IAM Project (MCS line IAM-3, Fig. 1), that registered 14 s TWT (González et al., 1996; Tortella et al., 1997). In fact, the Moho discontinuity has been identified by Sartori et al. (1994) at about 11 s (TWT) near the basin plain.

Shortening is expressed in the sedimentary cover as symmetric folds. These are thrust-related folds and show large amplitude and middle-long wavelength

(12–30 km). The thrust faults also favoured the westward transport of small allochthonous sheets, that progressively become more layered and less chaotic in character (Fig. 10). In this sense, each thrust accounts for a small proportion of the continuous and slow shortening of the oceanic crust and at the same time favoured the basinward transport of the allochthonous materials, which only comprise part of the Miocene deposits. The seafloor elevations developed by the crest of the folds indicate, however, recent tectonic activity (Fig. 10, S.P. 7800–8100).

The thrust belt extends westwards under the Horseshoe Abyssal Plain, where these structures are blind (Fig. 12). The Miocene–Quaternary unit (U5) buried the thrust relief, although its base can be often disrupted by normal faults that accommodate part of the deformation.

5.3.2. The Seine Abyssal Plain and the Coral Patch Ridge

During the Tasyo survey, only the eastern prolongation of the Coral Patch Seamount was surveyed: the

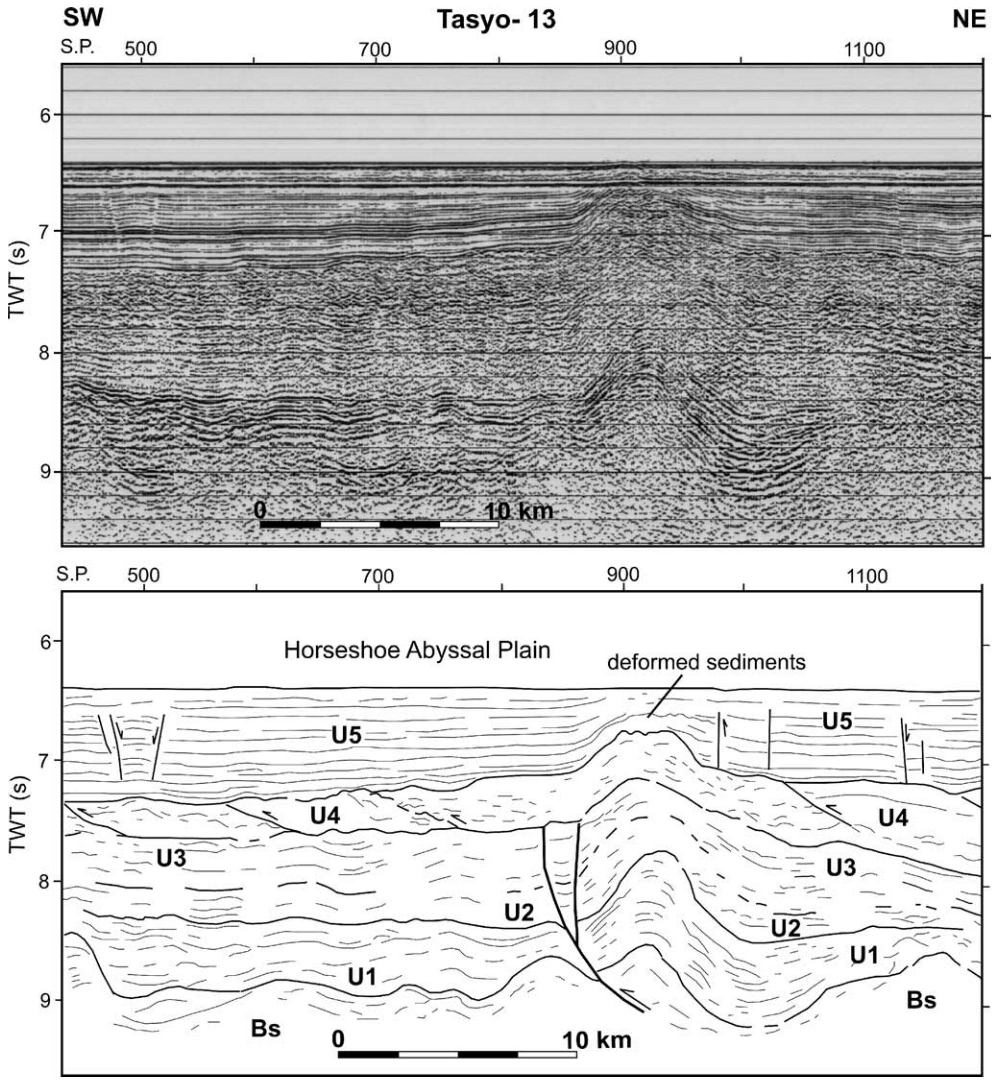


Fig. 12. MCS line Tasyo-13 and line drawing showing a blind basement thrust at the Horseshoe Abyssal Plain. Details of interpretation in text. See Fig. 1 for location and Fig. 4 for seismic units explanation.

Coral Patch Ridge (CPR in Fig. 2), located on the southeastern edge of the Horseshoe Abyssal Plain. This elongated ridge is bounded to the NW by northwestward-verging thrust faults trending ENE–WSW, recently active, that give rise to a step-like morphology of the sea-floor (RIFANO, IAM and AR-92 lines, Sartori et al., 1994; Tortella et al., 1997; Hayward et al., 1999), that progressively rises to 3200 m depth at the top of the Coral Patch Ridge. The direction of the ridge and the faults is slightly oblique to the NE–SW thrust faults of the Horseshoe Abyssal Plain (Fig. 2). In this area, DSDP Site 135 (Hayes et al., 1972) drilled the upper part of an upper Jurassic–Aptian unit (U1, marls and limestones) below an Aptian–lower Eocene unit (U2), that records at the top a change from terrigenous to pelagic sedimentation corresponding to the Miocene–Quaternary deposits (U5).

Some differences must be pointed out related to thrust fault architecture and geometry in the southern Coral Patch Ridge and northern Seine Abyssal Plain. The thrust faults appear to be controlled by pre-existing basement extensional faults. Examples of this tectonic inversion are displayed in Fig. 9 (S.P. 1795) and Figs. 13 and 14b (S.P. 6496–6596), where reactivation of pre-existing extensional faults, that have become thrust faults can be observed, verging to the WSW on seismic profiles. The system has undergone partial inversion, and normally, the pre-existing extensional architecture is not obliterated, even though they may have locally sea floor expression (Fig. 9, S.P. 2095). Only in one case, the basement is clearly displaced about 200 ms (Figs. 13 and 14b, S.P. 6496–6596). These faults are spaced about 15–20 km apart, propagate into the upper units and become steeper and convex upwards, showing the development of shortcuts. The sedimentary cover has also undergone shortening and forms anticlinal and synclinal fold structures, which adapt to the basement morphology. It is difficult to determine the direction of these faults as only two profiles cross the area, but taking into account the stress direction during the Miocene, as well as the bathymetric trend, they could be considered as nearly NNE–SSW structures.

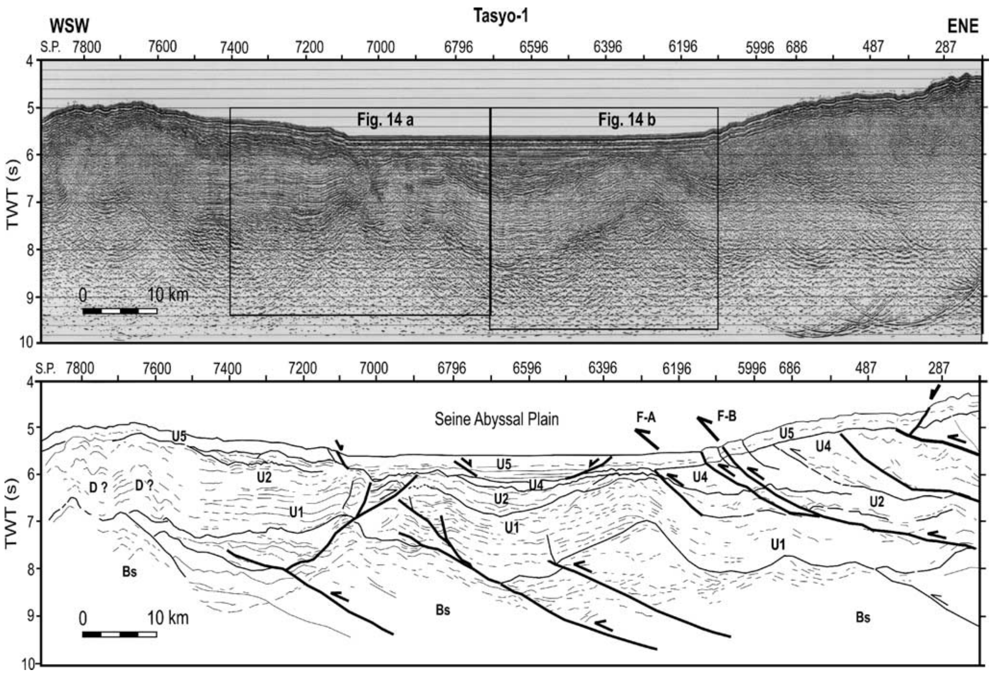


Fig. 13. Western segment of MCS line Tasyo-1 and line drawing. Details of interpretation in text. D: Diapirs. The black boxes on the MCS line outline detailed segments depicted in Fig. 14. See Fig. 1 for location and Fig. 4 for seismic units explanation.

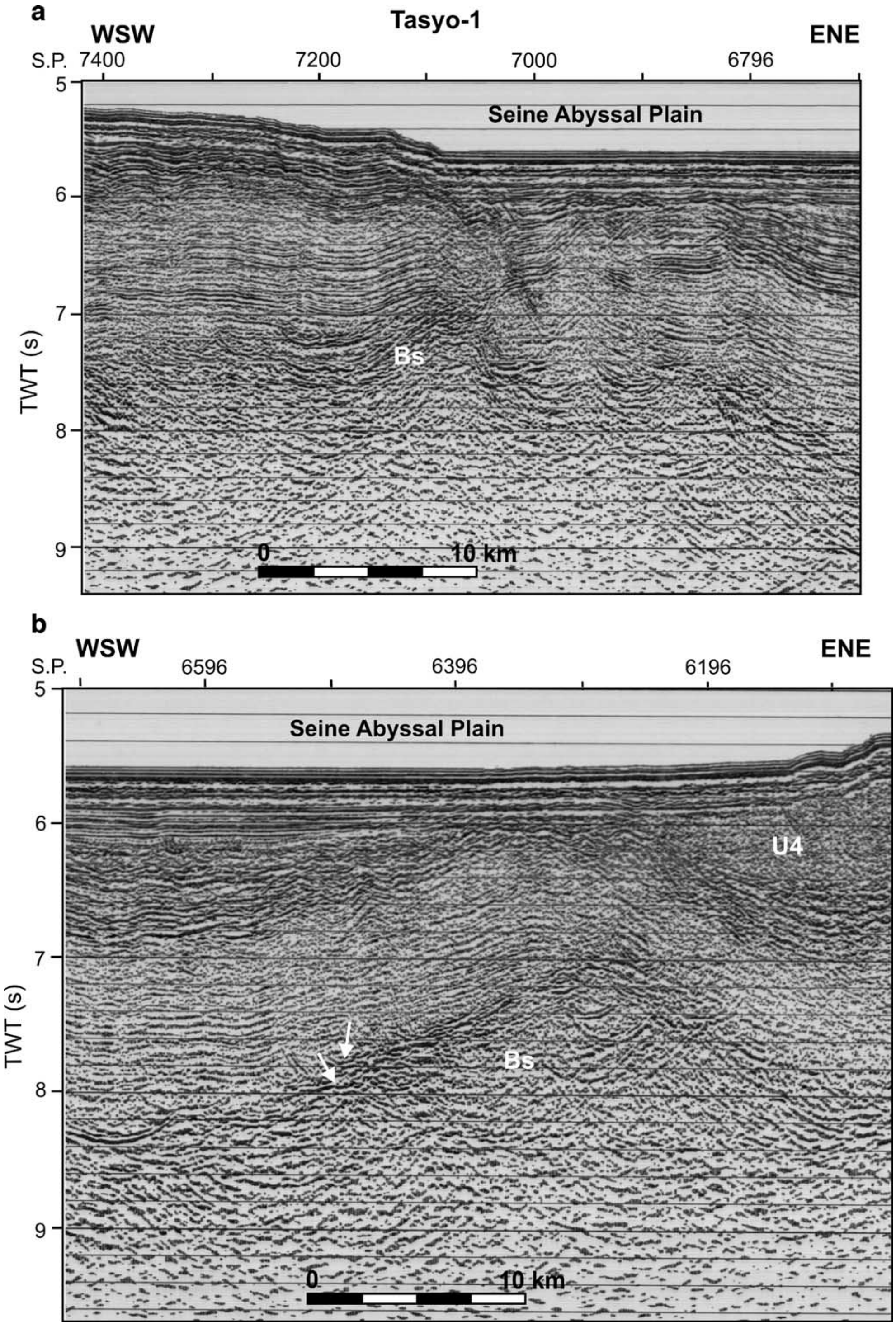


Fig. 14. Two details of MCS line Tasyo-1 shown in Fig. 13. Arrows mark a small basement offset. See Fig. 13 for location.

On the western end of line Tasyo-3, S.P. 900–1300 (Fig. 9), it is interesting to notice the occurrence of faults, verging to the ENE in the seismic profiles and asymmetrical folds affecting the sedimentary cover. On line Tasyo-3 (Fig. 9, S.P. 900–1000), one of these faults produces a vertical offset of 200 ms (TWT) in the sedimentary cover and eventually reaches the sea floor, which appears elevated 150–300 m. It has been interpreted as a strike-slip fault trending WNW–ESE, considering the scarp depicted by multibeam data. Nevertheless, more seismic profiles would be necessary to characterize and map these faults.

Piercement structures that deform the sedimentary cover, and that may have a diapiric origin are observed in the western end of line Tasyo-1 (Fig. 13). In this respect, the diapirism is widely spread in the Moroccan margin and especially close to this area, where it has been related to an early rifting phase (Pautot et al., 1970). The Jurassic–lower Cretaceous unit is thicker and a Triassic evaporitic sequence may not be excluded.

Wide-angle seismic reflection profiles in the Seine and Horseshoe Abyssal Plains show typical oceanic Moho depths of about 11 km below sea level with low upper mantle velocities of 7.3–7.6 km/s (Purdy, 1975). The continent–ocean boundary has been defined from magnetic anomalies and seismic data by Roeser et al. (2002) near the beginning of line Tasyo-1 (Figs. 1 and 3b).

6. Evolutionary steps and tectonic interpretation

The present structure of the AUGC in the Gulf of Cádiz seems to be developed under a NW–SE compressive regime by a three step evolutionary sequence that initiated in the middle Miocene (Figs. 2 and 3). This hypothesis is supported by three successive processes that have been repeated at each step: thrusting, gravitational sliding and/or tectonic transport, and subsequent extensional collapse at the back of the advancing sheets, which in turn facilitates overthrusting. Each step is well represented in each of the three domains, within which the mechanism of emplacement of the AUGC changes from gravitational in the Offshore Betic–Rifean Domain to gravitational and tectonic in the Frontal Slope of the allochthonous wedge, evolving to tectonic in the basin plains (Oceanic Domain). As the compressive regime progresses, the deformation extends westwards from the Offshore Betic–Rifean Domain to the oceanic basin plains. In spite of this basinward migration, deformation continues in the eastern areas of the Gulf of Cádiz, where extensional collapse reaches the sea floor. During these processes, not only different types of crust but deeper crustal layers were progressively involved.

6.1. Thrusting and extensional collapse of the allochthonous wedges in the offshore Betic–Rifean domain

The first evolutionary step is recorded in the Offshore Betic–Rifean Domain (Figs. 2 and 3). The allochthonous units were transported seaward the Subbetic Front along the continental slope as a consequence of the emplacement of the external zones from the middle Miocene to the Tortonian (Berástegui et al., 1998; Maldonado et al. 1999). These chaotic masses were initially extruded by the overthrusting external Subbetic zone. The evaporites and marls acted as a detachment layer along a basal seaward-dipping paleoslope that favoured the development of gravity driven processes. As a consequence, the allochthonous units become progressively imbricated and advance seawards.

The large accommodation space of the Gulf of Cadiz and the paleoslope facilitates the radial expulsion of the allochthonous masses, while in the confined Guadalquivir Basin, these units form a belt restricted to the southern half of the basin. The distribution and extension of the allochthonous units is controlled by the existent paleorelief. Besides, the allochthonous mass advance is restricted by some structural highs that block its movement as for example the Guadalquivir Bank and the Portimao basement high (Figs. 2 and 6). The arcuate or curved shape of the external fronts is also a consequence of the olistostrome advance interaction with obstacles in the basement (Fig. 2).

The diapirism is especially important north of the Subbetic Front (Fig. 2). The enhanced diapirism was probably favoured by the overload and overpressure produced by the Subbetic, including the allochthonous units, as they advanced over a narrow basin, where the Variscan basement occupies an elevated position and constitutes a rigid boundary. Also remarkable is the alignment of a series of diapiric ridges and mud volcanoes along the Subbetic arcuate front trace. This fact confirms the relation between the compressional tectonics and these hydrocarbon fluid venting structures, although extensional processes have also been invoked (Díaz-del-Rio et al., 2003; Somoza et al., 2003).

The advancing sheets gave rise to extensional collapse and roll-over structures on the back (Figs. 2 and 3a), which developed coeval with the thrusting of the successive imbricates (Maestro et al., 2003). The occurrence of evaporites facilitated the collapse. Similar structures have been described on the Prerifaine nappes at the Rharb Basin (Fig. 2) in Morocco (Flinch and Vail, 1998; Service Géologique du Maroc, 1985). The extensional collapse of the Late Messinian and the Pliocene, has been related to the highest rates of basin subsidence (Maldonado et al., 1999). The basinward migration of the allochthonous masses facilitates the development of landward dipping normal faults, which coincide with the previously thrusted Subbetic and Flysch fronts. This process originated the Cádiz Basin (Fig. 3b).

6.2. Gravity and tectonic transport in the frontal slope of the allochthonous wedge

The second step is represented in the Frontal Slope of the allochthonous wedge and it is marked by the development of the Gorringe–Horseshoe fault and the change in dip of the AUGC basal surface and the basement, which indicates tectonic transport favoured by the continuous NW–SE compressive regime. Gutscher et al. (2002) also interpreted that this type of deformation is tectonically driven in this domain by west vergent thrusts rooted in an east-dipping decollement, but located above the acoustic basement.

Fault activity determines the gravity and tectonic transport of new sheets against the slope that previously slid (Fig. 3). Thus, gravitational and tectonic mechanisms of emplacement are superposed. Once more the westward advancing allochthonous sheets facilitate the extensional collapse on the back of the advancing wedges and favour chaotic mass transport. In this context, vertical uplift of the Albufeira basement high, related to reverse faults active at present (Zitellini et al., 2004) would also ease slope failures at its base.

6.3. Thrusting in the oceanic domain

The deformation migrates during the final step to the basin plains, where thrust tectonics prevails. The transport and reactivation of allochthonous sheets (Oceanic Domain) is linked to thrust development, where basement in involved. Each thrust carries the allochthonous masses over and at the same time, increments the dip of the imbricates at the back of the thrust (Figs. 3a and 10, S.P. 7800). Additional sheets are triggered, moreover, along the slopes previously created by the tectonic uplift.

Thrusts that sole out in the basement and become listric at the Horseshoe Abyssal Plain have also been reported by Gràcia et al. (2003b) and Zitellini et al. (2001, 2004). According to Zitellini et al. (2004), movement along the thrust fault that bounds the eastern limit of the Horseshoe Abyssal Plain (termed Horseshoe fault by this authors) (Fig. 2) post-dates the emplacement of the allochthonous body and it is active at present.

Widespread seismic activity has been reported in the Gulf of Cádiz and surrounding areas, where the focal mechanisms show reverse faulting with a strike-slip component and horizontal NNW–SSE compression (Buforn et al., 1995; Negredo et al., 2003). Nevertheless, the analysis of earthquake distribution (Vázquez and Vegas, 2000; Gràcia et al., 2003a; Zitellini et al., 2004) indicates that although the scattered character of the seismicity pattern, shallow to intermediate-depth earthquakes are specially concentrated in the Guadalquivir Bank–Albufeira–Portimao basement highs, in the eastern Horseshoe Abyssal Plain and close to the Gorringe–Horseshoe fault.

In the eastern Horseshoe Abyssal Plain, seismicity pattern is in agreement with the most recent deformation observed on seismic lines, where thrust tectonics seems to be subsequent to accretion of the allochthonous units at the Frontal Slope of the allochthonous wedge. Thus, as seismicity indicates, the present tectonic activity related to Africa–Eurasia convergence is located in the Oceanic Domain.

7. Concluding remarks

The present structure of the Gulf of Cádiz is a result of both the European–African plate convergence motion and the westwards migration of the Betic–Rifean Arc. The emplacement of the huge allochthonous wedges can also be regarded as a result of both. The compressional regime has generated a broad zone of deformation, which is mainly expressed by folds, thrusts faults and thrusts with a strike-slip component (Gorringe–Horseshoe fault), that extend across the slope and reach the basin plains, involving the continental and oceanic basements.

The Gulf of Cádiz region comprises three domains, along which tectonic activity migrates westwards, characterized by its own seismic architecture, tectonics and crustal structure, each one representing an evolutionary step. In this context, the compressive deformation of the allochthonous body and the basement is accommodated in a different manner.

The eastern domain (Offshore Betic–Rifean Domain) represents the seaward extension of the Betic–Rifean front, overthrusted onto the southern Iberian and northern African Mesozoic continental margins. This domain exhibits overthrusted allochthonous wedges that were developed as a result of the emplacement of the orogenic front onto the proximal continental margin. The allochthonous units subsequently collapsed along extensional detachments caused by the seaward gravitational migration of nappes.

The central domain constitutes the zone of transition to the oceanic basins, which contains the transition between the continental and oceanic crust. Within this central domain, the basement accommodates the late Miocene up to Present compressive deformation by several thrusts and the Gorringe–Horseshoe fault. The allochthonous wedges were emplaced in this domain by a combined mechanism of mass gravity sliding and collapse along the slope, and were later tectonically reactivated.

The base of the lower slope is close to the ocean–continent boundary as wide-angle seismic data supports (Purdy, 1975; González et al., 1996). This boundary may act as an inhomogeneity that accommodates deformation produced by the slow convergence. Thus it is consistent that compressive stresses had been resolved through such a weak zone close to the Horseshoe Abyssal Plain by major thrust faults, rooted at the base of the crust (Fig. 3a).

Finally, the westernmost domain corresponds to the African oceanic crust. The generalized compressive regime affected the area in a distributed manner and developed numerous thrusts in the sedimentary cover and oceanic basement. Some thrust faults seem to take up, however, a more important amount of deformation in the eastern Horseshoe Abyssal Plain, and must be responsible for the main shocks in the region. The allochthonous wedges represent the distal extension of this body over the oceanic crust, with a mixed allochthonous–parautochthonous character.

In summary, the allochthonous wedges of the easternmost domain initially originated by the westward migration of the Betic–Rifean orogenic belt over the Atlantic margins of Iberia and Africa. However, these allochthonous units were later reactivated and new wedges were emplaced successively in the central and western domain as a result of NE–SW late Miocene compression, and in relation to basement structures. This evolution may be explained as a consequence of the slow Africa–Iberia convergence, which is accommodated throughout an area that straddles the ill-defined Africa–Eurasia plate boundary.

Acknowledgements

We are very grateful to Emilia Gulmezova for multichannel seismic data processing, Ricardo León for multibeam and GIS data processing and Pablo Rodríguez and Abel Zahinos for seismic acquisition data. We also wish to thank all those who participated in the TASYO cruise, especially the Captain and crew of the B/O *Hespérides*. This research has been funded by the Spanish Marine Science and Technology Programme, under the "TASYO" (CYTMAR 98-0209) and GADES" (REN2002-04117-CO3) projects in the framework of the Spanish–Portuguese agreement for scientific cooperation. This work is a contribution to the ESF EUROCORE-EUROMAR-GINS projects MVSEIS (01-LEC-EMA24F, REN2002-11669-E/MAR) and MOUNDFORCE (01-LEC-EMA06F, REN2002-11668-E). Two anonymous reviewers provide constructive comments that significantly improved the manuscript.

References

Argus, D.F., Gordon, R.G., DeMets, C., Stein, S., 1989. Closure of the Africa–Eurasia–North America plate motion circuit and tectonics of the Gloria fault. J. Geophys. Res. 94, 5585–5602.

Azañón, J.M., Galindo-Zaldívar, J., García-Dueñas, V., Jabaloy, A., 2002. Alpine tectonics: II. Betic Cordillera and Balearic Islands. In: Gibbons, W., Moreno, M.T. (Eds.), The Geology of Spain. Geological Society of London, London, pp. 401–416.

Baldy, P., Boillot, G., Dupeuble, P., Malod, J., Moita, I., Mougenot, D., 1977. Carte géologique du plateau continental sud-portugais et sud-espagnol (Golfe de Cadix). Bull. Soc. Geol. Fr. XIX (4), 703–724.

Berástegui, X., Banks, C., Puig, C., Taberner, C., Waltham, D., Fernández, M., 1998. Lateral diapiric emplacement of Triassic evaporites at the southern margin of the Guadalquivir Basin, Spain. In: Mascle, A., Puigdefábregas, C., Luterbacher, H.P. Fernández, M. (Eds.), Cenozoic Foreland Basins of Western Europe. Geol. Soc. London Spec. Publ. 134, 49–68.

Bonnin, J., Olivet, J.L., Auzende, J.M., 1975. Structure en nappe à l'Ouest de Gibraltar. C.R. Acad. Sc. Paris 280, 559–562.

Buforn, E., Sanz de Galdeano, C., Udías, A., 1995. Seismotectonics of the Ibero-Maghrebian region. Tectonophysics 248, 247–261.

Dañobeitia, J.J., Bartolomé, R., Checa, A., Maldonado, A., Slootweg, A.P., 1999. An interpretation of a prominent magnetic anomaly near the boundary between the Eurasian and African plates (Gulf of Cádiz, SW margin of Iberia). Mar. Geol. 155, 45–62.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the Western Mediterranean. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics. Geol. Soc. London Spec. Publ. 45, 265–283.

Díaz-del-Río, V., Somoza, L., Martínez-Frías, J., Mata, M.P., Delgado, A., Hernández-Molina, F.J., Lunar, R., Martín-Rubí, J.A., Maestro, A., Fernández-Puga, M.C., León, R., Llave, E., Medialdea, T., Vázquez, J.T., 2003. Vast fields of hydrocarbon-derived carbonate chimneys related to the accretionary wedge/olistostrome of the Gulf of Cádiz. Mar. Geol. 195, 177–200.

Flinch, J.F., Vail, P.R., 1998. Plio–Pleistocene sequence stratigraphy and tectonics of the Gibraltar Arc. In: de Graciansky, P.C., Hardenbol, J., Thierry, J., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM Spec. Publ. 60, 199–208.

Galindo-Zaldívar, J., Maldonado, A., Schreider, A.A., 2003. Gorringe Ridge gravity and magnetic anomalies are compatible with thrusting at a crustal scale. Geophys. J. Int. 153 (3), 586–594.

García-Castellanos, D., Fernández, M., Torné, M., 2002. Modeling the evolution of the Guadalquivir foreland basin (southern Spain). Tectonics 21 (3), 1018 (doi: 10.1029/2001TC001339).

González, A., Torné, M., Córdoba, D., Vidal, N., Matias, L.M., Díaz, J., 1996. Crustal thinning in the southwestern Iberia margin. Geophys. Res. Lett. 23 (18), 2477–2480.

González, A., Córdoba, D., Vegas, R., Matias, L.M., 1998. Seismic crustal structure in the southwest of the Iberian Peninsula and the Gulf of Cadiz. Tectonophysics 296, 317–331.

González-Fernández, A., Córdoba, D., Matias, L.M., Torné, M., 2001. Seismic crustal structure in the Gulf of Cádiz (SW Iberian Peninsula). Mar. Geophys. Res. 22, 207–223.

Gràcia, E., Dañobeitia, J., Vergés, J., Bartolomé, R., 2003a. Crustal architecture and tectonic evolution of the Gulf of Cadiz (SW Iberian margin) at the convergence of the Eurasian and African plates. Tectonics 22 (4), 1033 (doi: 10.1029/2001TC901045).

Gràcia, E., Dañobeitia, J., Vergés, J., PARSIFAL Team, 2003b. Mapping active faults offshore Portugal (36°N–38°N): implications for seismic hazard assessment along the southwest Iberian margin. Geology 31 (1), 83–86.

Grimison, N.L., Chen, W.P., 1986. The Azores-Gibraltar plate boundary: focal mechanisms, depths of earthquakes, and their tectonic implication. J. Geophys. Res. 91, 2029–2047.

Gutscher, M.A., Malod, J., Rehault, J.P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. Geology 30 (12), 1071–1074.

Hayes, D.E., Pimm, A.C., Benson, W.E., Berger, W.H., Rad, U.V., et al., 1972. Site 135. Initial reports of the Deep Sea Drilling Project, vol. 14. U.S. Government Printing Office, Washington, pp. 15–48.

Hayward, N., Watts, A.B., Westbrook, G.K., Collier, J.S., 1999. A seismic reflection and GLORIA study of compressional deformation in the Gorringe Bank region, eastern North Atlantic. Geophys. J. Int. 138, 831–850.

Hernández-Molina, J., Llave, E., Somoza, L., Fernández-Puga, M.C., Maestro, A., León, R., Medialdea, T., Barnolas, A., García, M., Díaz-del-Río, V., Fernández-Salas, L.M., Vázquez, J.T., Lobo, F., Alveirinho Dias, J., Rodero, J., Gardner, J., 2003. Looking for clues to paleoceanographic imprints: a diagnosis of the Gulf of Cádiz Contourite Depositional Systems. Geology 31, 19–22.

Jiménez-Munt, I., Negredo, A.M., 2003. Neotectonic modelling of the western part of the Africa–Eurasia plate boundary: from the Mid-Atlantic Ridge to Algeria. Earth Planet. Sci. Lett. 205, 257–271.

Lajat, D., Biju-Duval, B., Gonnard, R., Letouzey, J., Winnock, E., 1975. Prolongament dans l'Atlantique de la partie externe de l'Arc bético-rifain. Bull. Soc. Geol. Fr. 17, 481–485.

Le Gall, B., Piqué, A., Réhault, J.P., Specht, M., Malod, J., 1997. Structure et mise en place d'une ride océanique dans un contexte de limite de plaques convergentes: le banc de Gorringe (SW Ibérie). C.R. Acad. Sci. Paris 325, 853–860.

Maestro, A., Somoza, L., Medialdea, T., Talbot, C.J., Lowrie, A., Vázquez, J.T., Díaz-del-Río, V., 2003. Large-scale slope failure involving Triassic and Middle Miocene salt and shale in the Gulf of Cadiz (Atlantic Iberian Margin). Terranova 15, 380–391.

Maldonado, A., Somoza, L., Pallarés, L., 1999. The Betic orogen and the Iberian–African boundary in the Gulf of Cádiz: geological evolution (central North Atlantic). Mar. Geol. 155, 9–43.

Malod, J.A., Mougenot, D., 1979. L'histoire géologique néogène du golfe de Cádiz. Bull. Soc. Geol. Fr. 21 (5), 603–611.

Mauffret, A., Mougenot, D., Miles, P.R., Malod, J.A., 1989. Cenozoic deformation and Mesozoic abandoned spreading centre in the Tagus Abyssal Plain (west of Portugal): results of a multichannel seismic survey. Can. J. Earth Sci. 26, 1101–1123.

Medialdea, T., Suriñach, E., Vegas, R., Banda, E., Ansorge, J., 1986. Crustal structure under the western end of the Betic Cordillera (Spain). Ann. Geophys. 4 (B4), 457–464.

Negredo, A.M., Bird, P., Sanz de Galdeano, C., Buforn, E., 2003.

Neotectonic modeling of the Ibero-Maghrebian region. J. Geophys. Res. 107 (B11), 2292 (doi: 1029/2001JB000743).
Pautot, G., Auzende, J.M., Le Pichon, X., 1970. Continuous deep sea salt layer along north Atlantic margins related to early phase of rifting. Nature 227, 351–354.
Perconig, E., 1960–1962. Sur la constitution géologique de l' Andalousie Occidentale, en particulier du bassin du Guadalquivir (Espagne meridionale). Livre Mémoire du Professeur Paul Fallot. Mem. Hors-Ser. Soc. Geol. Fr. 1, 229–256.
Pinheiro, L., Ivanov, M.K., Sautkin, A., Akhmanov, G., Magalhães, V., Volkonskaya, A., Monteiro, J.H., Somoza, L., Gardner, J., Hamouni, N., Cunha, M.R., 2003. Mud volcanism in the Gulf of Cadiz: results from the TTR-10 cruise. Mar. Geol. 195, 131–151.
Purdy, G.M., 1975. The Eastern end of the Azores-Gibraltar plate boundary. Geophys. J.R. Astron. Soc. 43, 973–1000.
Ribeiro, A., Oliveira, J.T., Silva, J.B., 1983. La estructura de la Zona Sur Portuguesa. Geología de España, vol. 1. Inst. Geol. Min. España, Madrid, pp. 504–511.
Roberts, D.G., 1970. The Rif–Betic orogen in the Gulf of Cádiz. Mar. Geol. 9, M31–M37.
Roeser, H.A., Steiner, C., Schreckenberger, B., Block, M., 2002. Structural development of the Jurassic Magnetic Quiet Zone off Morocco and identification of the Middle Jurassic magnetic lineations. J. Geophys. Res. 107 (B10), 2207 (doi: 10.1029/2000JB000094).
Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. Tectonophysics 359 (1–2), 117–129.
Ryan, W.B.F., Hsü, K.J., 1973. Gorringe Bank-Site 120. Initial reports of the Deep Sea Drilling Project, Part 1, vol. 13. U.S. Government Printing Office, Washington, pp. 9–41.
Sartori, R., Torelli, L., Zitellini, N., Peis, D., Lodolo, E., 1994. Eastern segment of the Azores-Gibraltar line (central–eastern Atlantic): an oceanic plate boundary with diffuse compressional deformation. Geology 22, 555–558.
Service Géologique du Maroc, 1985. Carte Géologique de Maroc. Echelle 1:1.000.000. Notes et Mémoires 260. Ministère de l'Énergie et des Mines. Editions du Service Géologique du Maroc.
Serviços Geológicos de Portugal, 1992. Carta Geológica de Portugal a escala 1:500000. Serviços Geológicos de Portugal.
Smith, W.H.F., Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings. Science 277, 1957–1962.
Somoza, L., Maestro, A., Lowrie, A., 1999. Allochthonous blocks as hydrocarbon traps in the Gulf of Cádiz. Offshore Technology Conference, OTC, vol. 10889, pp. 571–577.
Somoza, L., Gardner, J., Díaz-del-Río, V., Vázquez, J.T., Pinheiro, L.M., Hernández-Molina, F.J., TASYO/ANASTASYA shipboard scientific parties, 2002. Numerous methane gas-related sea floor structures identified in the Gulf of Cadiz. Eos Trans. AGU 83 (47), 541 and 549.
Somoza, L., Díaz-del-Río, V., León, R., Ivanov, M., Fernández-Puga, M.C., Gardner, J.M., Hernández-Molina, F.J., Pinheiro, L.M., Rodero, J., Lobato, A., Maestro, A., Vázquez, J.T., Medialdea, T., Fernández-Salas, L.M., 2003. Seabed morphology and hydrocarbon seepage in the Gulf of Cádiz mud volcano area: acoustic imagery, multibeam and ultrahigh resolution seismic data. Mar. Geol. 195, 153–176.
Srivastava, S.P., Schouten, H., Roest, W.R., Klitgord, K.D., Kovacs, L.C., Verhoef, J., Macnab, R., 1990. Iberian plate kinematics: a jumping plate boundary between Eurasia and Africa. Nature 344, 756–759.
Terrinha, P.A., Ribeiro, C., Kullberg, J.C., Lopes, C., Rocha, R., Ribeiro, A., 2002. Compressive episodes and faunal isolation during rifting, Southwest Iberia. J. Geol. 110, 101–113.
Terrinha, P.A., Pinheiro, L., Henriet, J.-P., Matias, L., Ivanov, M.K., Monteiro, J.H., Azhmetzhanov, A., Volkonskaya, A., Cunha, T., Shaskin, P., Rovere, M., 2003. Tsunamigenic–seismogenic structures, neotectonics, sedimentary process and slope instability on the southwest Portuguese margin. Mar. Geol. 195, 55–73.
Torelli, L., Sartori, R., Zitellini, N., 1997. The giant chaotic body in the Atlantic Ocean off Gibraltar: new results from a deep seismic reflection survey. Mar. Pet. Geol. 14, 125–138.
Tortella, D., Torné, M., Pérez-Estaún, A., 1997. Geodynamic evolution of the eastern segment of the Azores-Gibraltar zone: the Gorringe Bank and the Gulf of Cadiz region. Mar. Geophys. Res. 19, 211–230.
Vázquez, J.T., Vegas, R., 2000. Estilos diferentes de deformación en el límite de placas entre África y Eurasia, desde el Arco de la Herradura al Mar de Alborán. 2° Asamblea Hispano Portuguesa de Geodesia y Geofísica S03-19, 147–148.
Vegas, R., 2001. The convergent intra-oceanic plate boundary west of Gibraltar (Spain and Portugal): an overview. Workshop on the Geodynamics of the Western part of Eurasia–Africa plate boundary (Azores-Tunisia), San Fernando (Cádiz), Spain. Bol. ROA 3, 167–168.
Vegas, R., Medialdea, T., Muñoz, M., Díaz-del-Río, V., Somoza, L., 2004. Nature and tectonic setting of the Guadalquivir Bank (Gulf of Cádiz, SW Iberian Peninsula). Rev. Soc. Geol. Esp. 17 (1–2), 43–54.
Zitellini, N., Mendes, L.A., Córdoba, D., Dañobeitia, J., Nicolich, R., Pellis, G., Ribeiro, A., Sartori, R., Torelli, L., Bartolomé, R., Bortoluzzi, G., Calafato, A., Carrilho, F., Casoni, L., Chierici, F., Corela, C., Correggiari, A., Della Vedova, B., Gràcia, E., Jornet, P., Landuzzi, M., Ligi, M., Magagnoli, A., Marozzi, G., Matias, L., Penitenti, D., Rodríguez, P., Rovere, M., Terrinha, L., Vigliotti, L., Zahinos-Ruiz, A., 2001. Source of the 1755 Lisbon earthquake and tsunami investigated. Eos Trans. AGU 82 (26), 285–291.
Zitellini, N., Rovere, M., Terrinha, P., Chierici, F., Matias, L., BIGSETS Team, 2004. Neogene through Quaternary tectonic reactivation of SW Iberian passive margin. Pure Appl. Geophys. 161 (3), 565–587.