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Tertiary tectono-sedimentary characterisation of the Algarve margin (SW Iberia)

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ABSTRACT

The study of the Algarve margin on the basis of multichannel seismic profiles, tied with stratigraphic data from five exploration wells, illustrates the regional Cenozoic seismic stratigraphy and tectonics. Six seismic units (B to G), bounded by unconformities, form the Cenozoic cover that range in age from the early Paleocene to Quaternary. A stratigraphic correlation between the sedimentary record of the near Portuguese and Spanish areas is proposed, based on interpreted unconformities on seismic data considered to be related to main tectonic events that affected Iberia. This study provides a synthesis of the geodynamic evolution of the Gulf of Cadiz Portuguese margin in the context of the Africa-Eurasia plate boundary.

Key words: Algarve margin, basin analysis, seismic stratigraphy, tectonics, Tertiary

Caracterización tectonosedimentaria del Terciario del margen del Algarve (suroeste de Iberia)

RESUMEN

El presente estudio del margen del Algarve basado en perfiles de sísmica de multicanal, junto con los datos estratigráficos de cinco sondeos de exploración, contribuye al conocimiento de la estratigrafia sísmica y de la tectónica de la región. Seis unidades sísmicas (desde B hasta G) constituyen el conjunto cenozoico y su edad varía desde el Paleoceno inferior hasta el Cuaternario. Se propone una correlación del registro sedimentario de áreas próximas españolas y portuguesas, basada en la existencia de discordancias presentes entre las unidades sísmicas. El estudio sintetiza la evolución de este margen del Golfo de Cádiz en el contexto del límite de placas entre África y Eurasia.

Palabras clave: análisis de cuencas, estratigrafia sísmica, margen del Algarve, tectónica, Terciario

Introduction

The Algarve margin, located in the southwestern margin of Iberia, forms, together with the Spanish southwestern margin, the northern margin of the Gulf of Cadiz (Fig. 1). Its complex geodynamic evolution, particulary during the Cenozoic, results from the convergence between Africa and Iberia along the eastern segment of the Azores-Gibraltar fracture zone (AGFZ) (transpressive context) and the westward migration of the front of the Gibraltar arc (e. g. Sanz de Galdeano, 1990; Ribeiro *et al.*, 1990). From a detailed interpretation of multichannel seismic (MCS) profiles, and gravity and seismological analysis, the Cenozoic of the Algarve Continental margin has been studied, mainly in what concerns: i) its seismic stratigraphy, ii) its main structural features and iii) its tectono-sedimentary evolution in the context of the Africa-Eurasia plate boundary (Lopes and Cunha, 2000; Lopes, 2002).

Seismic units, main active structures and geologic evolution

Seven main seismic units were identified and their age has been interpreted on the basis of the five commercial wells drilled in the margin, namely from their biostratigraphic data (*Imperador-1*, 1976; *Ruivo-1*, 1975; *Corvina-1*, 1976; *Algarve-1*, 1982; *Algarve-2*, 1982), of the geometrical position in relation to the front of the Gibraltar Olistostrome and of the correlation to the near Portuguese and Spanish basins (Fig. 2). These units are bounded by six main reflectors, respectively designated from H_6 to H_1, that mark basinwide angular or erosional unconformities.

Unit A. This unit is the acoustic basement and comprises Hercynian basement and the Carnian to Lower Cretaceous sedimentary succession.

Unit B (late Campanian to middle Eocene). The Unit B is best developed in the eastern sector of the

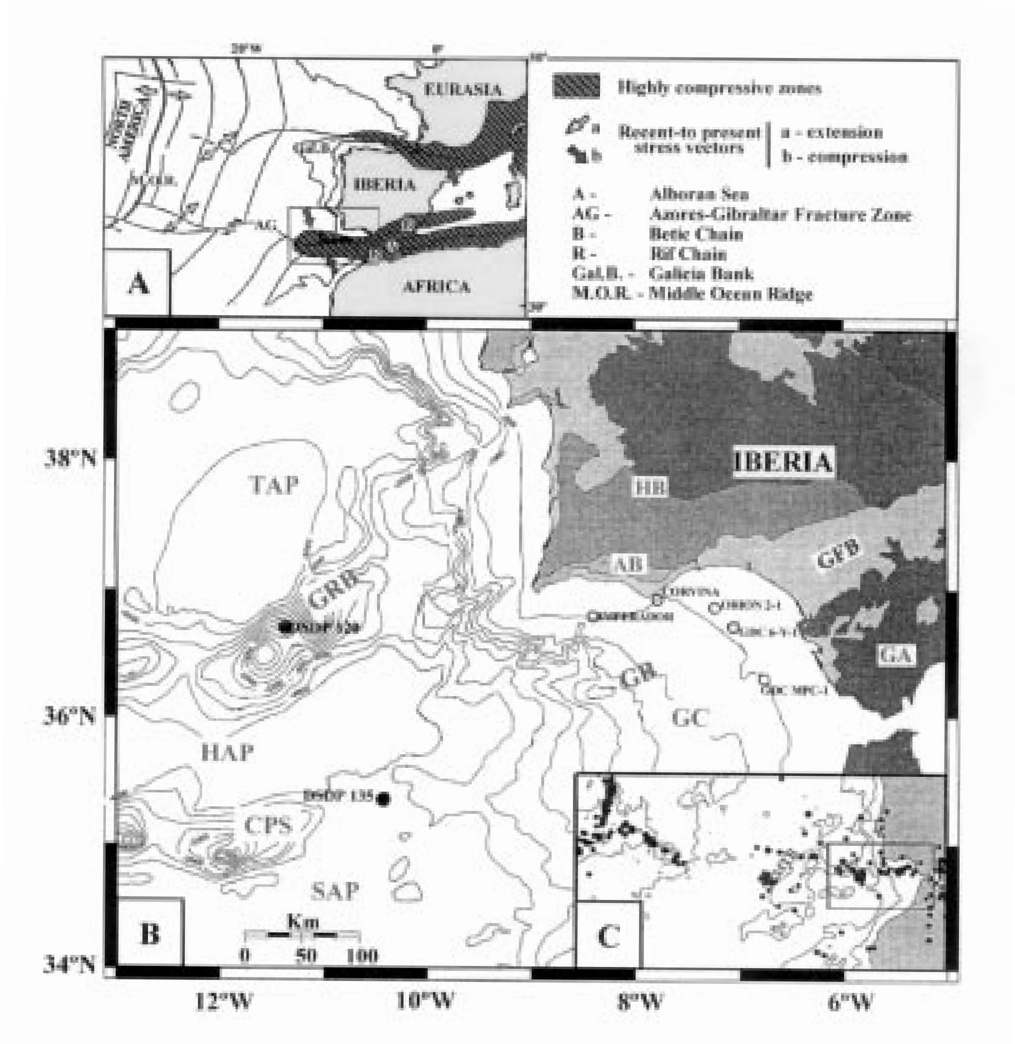

Fig. 1. (A) Present-day stress field at the periphery of the Iberian microplate (adapted from Olivet, 1996). (B) Geological setting and simplified bathymetry of the Gulf of Cadiz and surrounding areas. AB: Algarve Basin; CPS: Coral Patch Seamount; GA: Gibraltar Arc; GB: Guadalquivir Bank; GC: Gulf of Cadiz; GFB; Guadalquivir Foreland Basin; GRB: Gorringe Bank; HAP: Horseshoe Abyssal Plain; HB: Hercynian basement; SAP: Seine Abyssal Plain; TAP: Tagus Abyssal Plain; closed dots: DSDP (Deep Sea Drilling Project) sites; open dots: some exploration wells (adapted from Le Gall *et al.*, 1997; Tortella *et al.,* 1997). (C) Location of the earthquakes with magnitude >3 in the Azores-Alboran region (adapted from Buforn *et al.,* 1988)

Fig. 1. (A) Campo de esfuerzos actual en la periferia de la microplaca Ibérica (adaptado de Oliver, 1996). (B) Marco geológico y batimetría simplificada del Golfo de Cádiz y sectores adyacentes. AB: Cuenca del Algarve; CPS: Seamount del Parche Coralino; GA: Arco de Gibraltar; GB: Banco del Guadalquivir; GC: Golfo de Cádiz; GFB: Cuenca de antepaís del Guadalquivir; GRB: Banco de Gorringe; HAP: llanura abisal de la Herradura; HB: basamento hercínico; SAP: llanura abisal de Seine; TAP: llanura abisal del Tajo; puntos negros: lugares de perforación del DSDP (Deep Sea Drilling Project); puntos blancos: algunos sondeos de exploración (adaptado de Le Gall et al., *1997; Tortella* et al., *1997). (C) Localización de los terremotos de magnitud >3 en la región Azores-Alborán (adaptado de Buforn* et al., *1988)*

Algarve margin. The geometries and seismic character of this unit reflect intense post-sedimentary deformations. Well data (*Algarve-1* and *Algarve-2*) show that the upper part of the Unit B is composed of marine grey dolomites intercalated with marly limestones and micritic limestones. At the base of Unit B, marls and sandstones occur.

Unit C (upper Eocene to lowermost Miocene). Unit C is recognized in all the study area, overlying the acoustic basement. This unit displays a general onlap filling external configuration. The general geometry, seismic facies and well data (*Imperador*, *Ruivo-1*, *Corvina* and *Algarve-1*) documenting micritic limestones, suggest that this unit consists of marine deposits of a carbonate shelf developed over the entire margin. Seismic data show that the Late Eocene to Oligocene evolution of the Algarve margin is marked by an intense and widespread halokinesis activity. Salt and fault-controlled (thin-skinned) subsidence influenced the thickness and lateral distribution of Unit C.

Unit D (Aquitanian to lower Tortonian). Unit D is a widespread wedge geometry filling depressions sequence. The seismic facies and its vertical variation suggest that Unit D has a carbonate character downwards, passing upwards to a more siliciclastic character. Moreover, this facies evolution seems do not occurs basinwards, where the carbonate character is predominant. Halokinesis was relatively moderate during the deposition of Unit D.

Unit E (upper Tortonian to Messinian). The begin of the deposition of Unit E is coeval to the emplacement of the Gibraltar Olistostrome in the area during middle Tortonian (Bonnin, *et al.*, 1975; Lajat *et al.*, 1975; Auzende *et al.*, 1981; Malod, 1982; Sanz de Galdeano, 1990; Flinch *et al.*, 1996). Well data (Imperador, Ruivo and Corvina) indicate that this unit is composed of slope sands and clays. From seismic profiles, three subunits can be identified: subunit E0 is the Gibraltar olistostrome; subunit E1 has been also only recognized in the southeastern Algarve margin, near the front of the olistostrome; subunit E2 is a widespread sequence overlaying, by an erosional unconformity, either subunits E0 and E1 (southeastern Algarve margin) or Unit D. During the deposition of Unit E, the generalized NW-SE compressional regi-

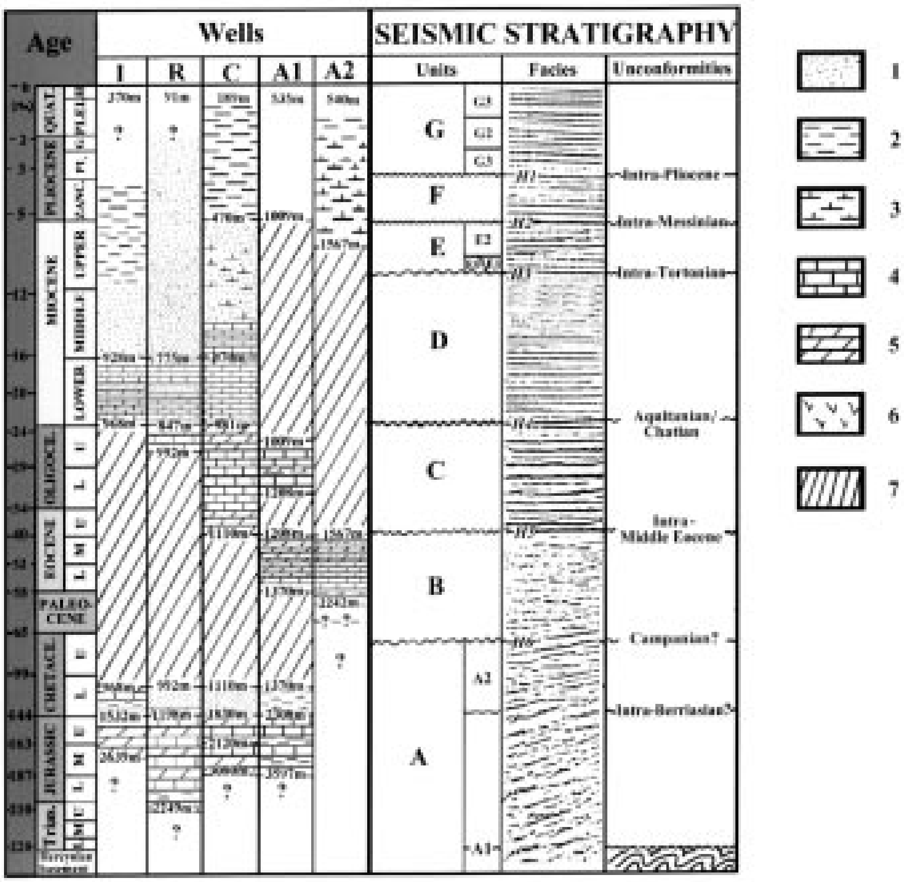

Fig. 2. Seismic stratigraphy, main unconformities and wells of the Algarve offshore. I: *Imperador-1*; R: *Ruivo-1*; C: *Corvina-1*; A1: *Algarve-1*; A2: *Algarve-2*. Wells lithologies: 1: sands; 2: clays; 3: silts; 4: limestones; 5: dolomites; 6: evaporites; 7: hiatus

Fig. 2. Estratigrafía sísmica, principales discordancias y sondeos en la zona de offshore del Algarve. I: Imperator-1*; R:* Ruivo-1*; C:* Corvina-1*; A1:* Algarve-1*; A2:* Algarve-2. *Litologías de los sondeos: 1: arenas; 2: arcillas; 3: limos; 4: calizas; 5: dolomías; 6: evaporizas; 7: hiato*

me induced the tectonic inversion of most of the previous structures. In the eastern domain of the Algarve margin, thin-skinned reverse-thrust faults were reactivated and a N60ºE axis trend depocentre began to develop. Widespread halokinesis also occurred, with reactivation of the previous salt structures and emplacement of some salt diapirs.

Unit F (Zanclean). The deposition of Unit F was characterized by a decreasing halokinesis. Salt diapirism is more located and piercing, forming small rim sinclines. From the wells data, the main lithologies are clays and sands with interbedded sandy clays. Across the area, the underlying depocentres were progressively filled by this unit. On the other hand, a strong and generalized subsidence occurred south and southeastwards, forming a N60ºE trending axis depocentre, probably caused by the NW-SE to NNW-SSE compressive regime. The thickness is variable and is controlled by the underlying fault and salt structures.

Unit G (Piacenzian to Recent). The Unit G is a widespread sequence located between the Unit F and the sea bottom. Its exhibits rather variable seismic facies both upwards in the stratigraphic sequence and laterally across the study area. All the wells show this unit consists of clays and sands, representing hemipelagic deposits, turbiditic sands and current-drift deposits. Detailed interpretation of the seismic profiles allowed the identification of three subunits: G1, G2 and G3. Basinwards, the deposition of the subunits G1 and G2 is marked by a strong subsidence along a roughly N60ºE trending axis. Just before the deposition of the subunit G3 the decreasing halokinesis ends, most of the underlying structures become inactive and the depocentres were progressively filled.

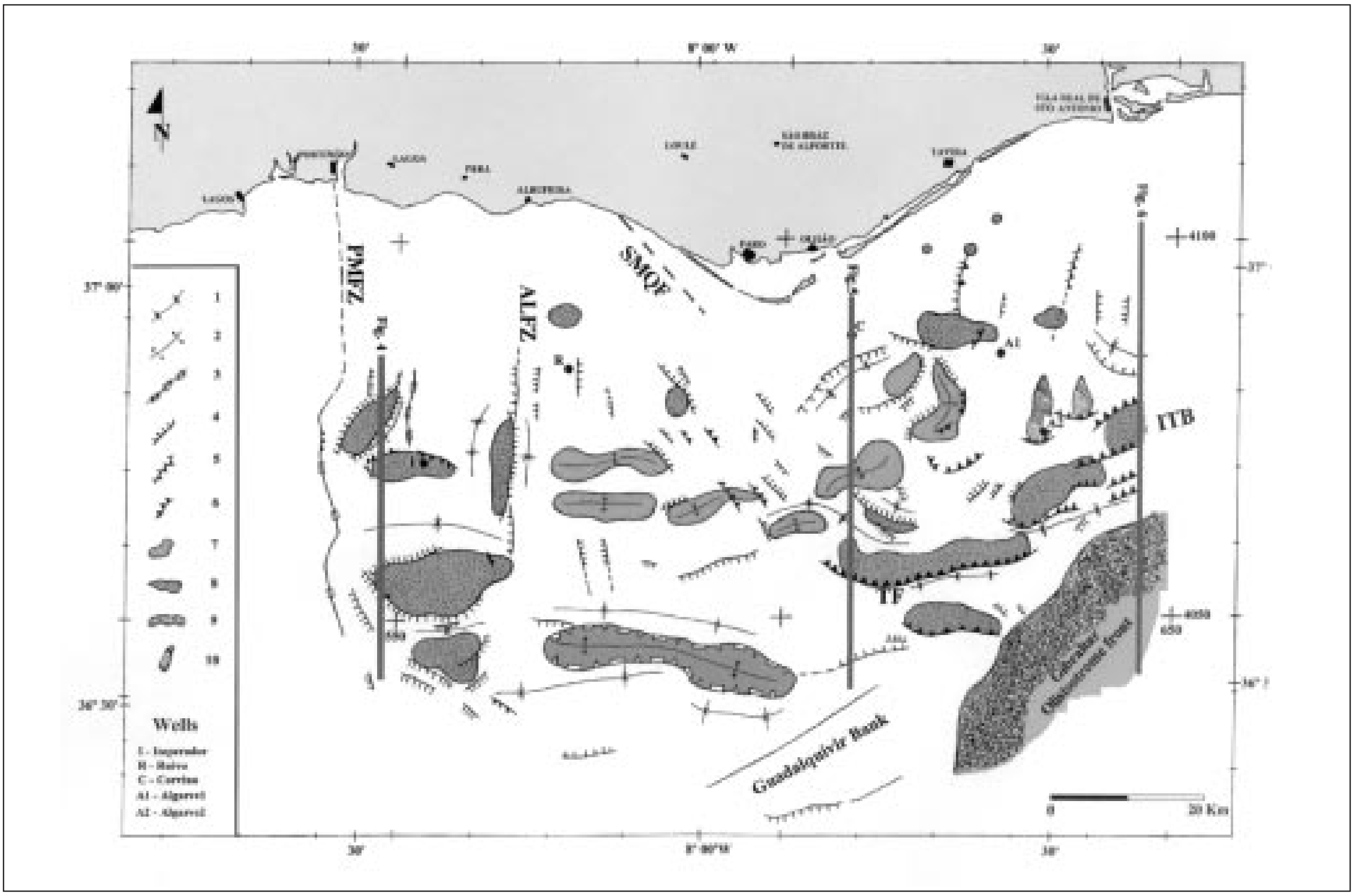

Fig. 3. Map of the main cenozoic structures. PMFZ: Portimão-Monchique Fault Zone; ALFZ: Albufeira Fault Zone; SMQF: São Marcos-Quarteira Fault Zone; TF: thrust front; ITB: imbricated thrust belt. 1: syncline axis; 2: anticline axis; 3: strike-slip fault; 4: normal fault; 5: reversal normal fault; 6: thrust fault; 7: structural high; 8: evaporitic structure; 9: reversal half-graben; 10: ramp anticline

Fig. 3. Mapa de las principales estructuras cenozoicas. PMFZ: Zona de Falla de Portimão-Monchique; ALFZ: Zona de Falla de Albufeira; SMQF: Zona de Falla de São Marcos-Quarteira; TF: frente de cabalgamiento; 7: alto estructural; 8: estructura evaporítica; 9: semi-fosa inversa; 10: rampa anticlinal

During the Cenozoic, the geodynamic evolution of the Algarve margin have been controlled by three major tectonic structures (Figs. 3 to 6) (e.g. Lopes, 2002): a) the Portimão-Monchique fault zone (PMFZ) (striking N-S); b) the Albufeira fault zone (ALFZ) (striking N-S); c) the São Marcos-Quarteira fault zone (SMQF) (striking N40ºW) that separates three tectonic domains: the Western domain, with N-S and E-W predominant structures and, secondarily, NW-SE and NE-SW; the Central domain, with E-W predominant antiforms; and the Eastern domain, dominated by WSW-ENE, NW-SE, NE-SW, NNE-SSW and NNW-SSE structures. Evaporitic structures occur mainly in the Western and Eastern domains, related with major lineaments. Thrust systems are concentrated in the Eastern domain, and they generally exhibit a southward and southeastward vergence. This tectonic signature has been attributed to the proximity of the Betic orogen and the Gibraltar Olistostrome front, and to the SMQF that acts as a buttress fault to the westward propagation of the compression of the Gibraltar Arc. The tectonic style is thin-skinned, with the Upper Triassic to Hettangian evaporites acting as a detachment layer during the extensional and compressional stages (Ribeiro *et al.*, 1990; Terrinha, 1998; Lopes, 2002). A persistent halokinetic activity occurred, with two major moments: a) syn-Unit C; b) syn- and post-Unit E. An increasing flexuration of the margin was identified, with spatial and temporal variation of the subsidence. The tectonic regime is considered as generally compressive, but some variations of the magnitude and of the orientation of the σ_1 were deduced. Two major compressive tectonic events have been recognised: i) immediately before the deposition of the Unit C (middle Eocene), causing uplift and a southward tilting of the margin, together with the development of folds and thrusts and is expressed by the H_5 intra-Eocene unconformity (see Fig. 2); ii) immediately before the deposition of the Unit E (middle Tortonian) and is expressed by the H_3 intra-Tortonian unconformity (see Fig. 2). The interpretation of the successive stress-fields is rendered difficult by the existence of tectonic sub-domains and the reactivation of evaporitic structures. As an exem-

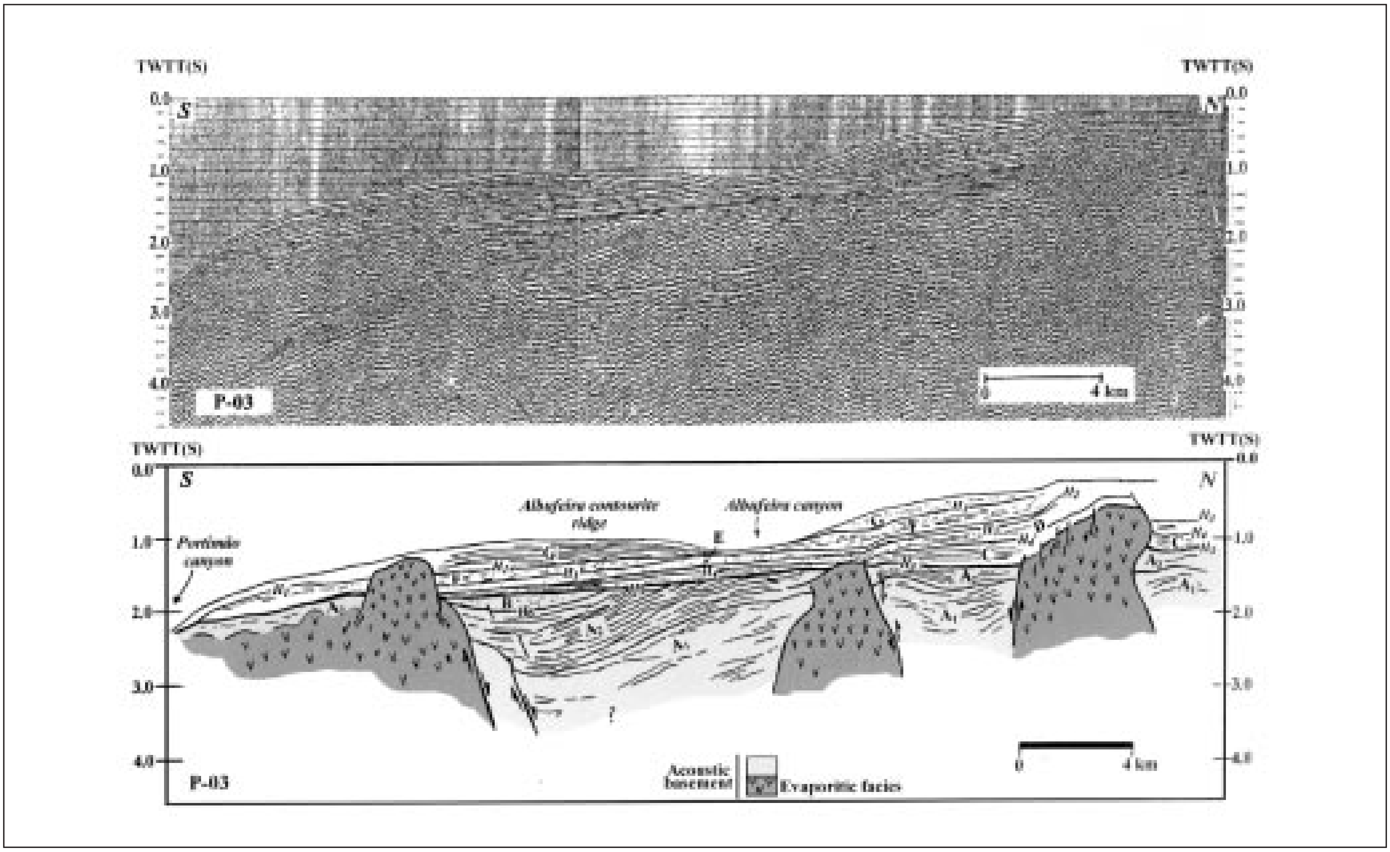

Fig. 4. P-03 seismic profile and interpretation (see Fig. 3 for location). Cenozoic halokinesis is reveled by the occurence of three evaporitic structures. The H5 reflector is an angular unconformity

Fig. 4. Perfil sísmico P-03 y su interpretación (ver Fig. 3 para localización). La halocinesis cenozoica se pone de manifiesto por la aparición de tres estructuras evaporíticas. El reflector H5 es una discordancia angular

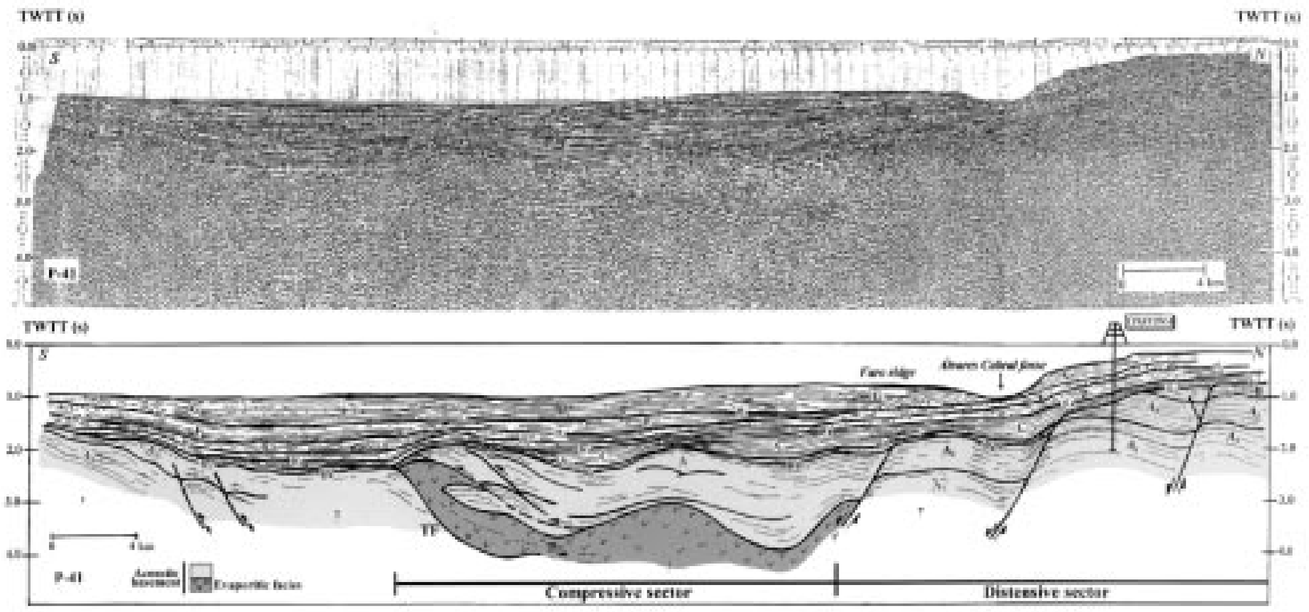

Fig. 5. P-41 seismic profile and interpretation (see Fig. 3 for location). A thin-skinned syn-Unit C raft tectonics is dominant. TF: thrust front
Fig. 5. Perfil sísmico P-41 y su interpretación (ver Fig. 3 para localización). Durante la sedimentación de la Unidad C domina la tectónica salina con despegues de tipo raft-tectonic. TF: frente de cabalgamiento

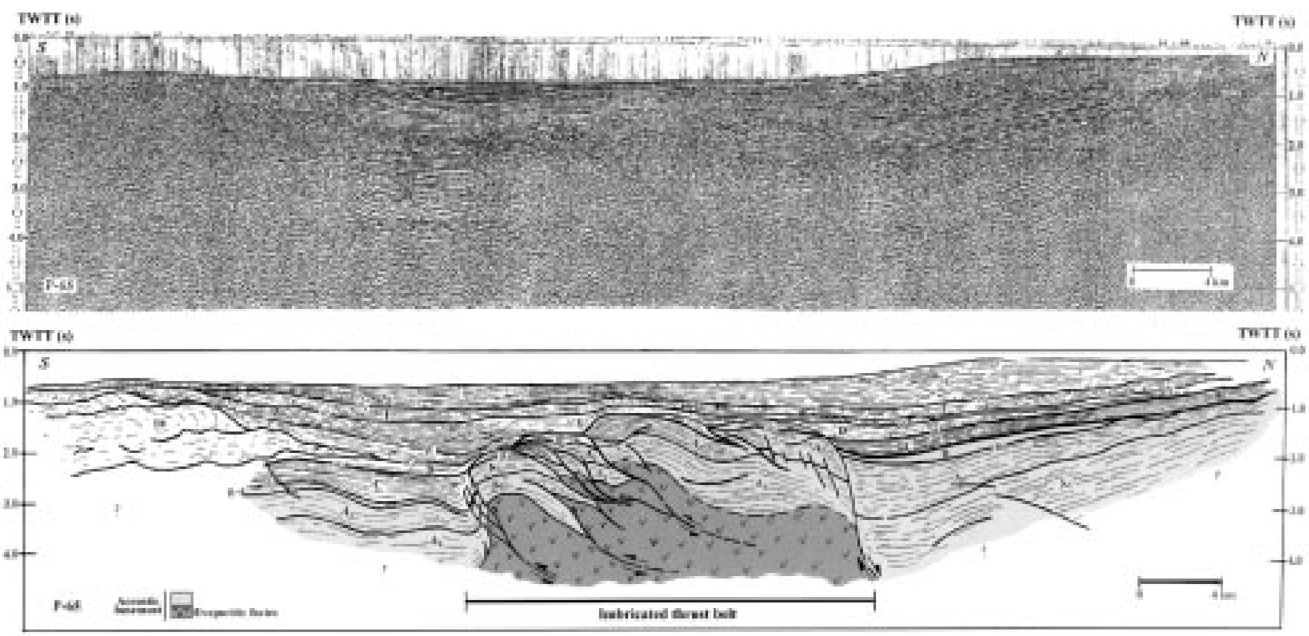

Fig. 6. P-65 seismic profile and interpretation (see Fig. 3 for location). The central section is dominated by a thin-skinned imbricated thrust belt. The southern section is dominated by the Gibraltar Olistostrome front
Fig. 6. Perfil sísmico P-65 y su interpretación (ver Fig. 3 para localización). En el sector central domina un sistema de cabalgamientos imbricados con despegues. En la sección meridional domina el frente olistostrómico de Gibraltar

ple, during the intense and widespread halokinetic activity that characterized the Unit C deposition, a raft-tectonic style of deformation was predominant in the Eastern domain of the margin, resulting in a distensive sector at the upper slope (Corvina area) and in a compressive sector at the base of the slope. These features provide an explanation for the existence of normal faults parallel to the axis of the folds and thrusts.

Correlation to the sedimentary record of near portuguese and spanish areas

The correlation between the onshore Cenozoic lithostratigraphic units (Pais *et al.*, 2000) and the offshore seismic units was proposed as Fig. 7. Subunit G3 corresponds to the "Faro-Quarteira Formation" (Uppermost Pleistocene to Holocene); subunit G2 corresponds to the "Morgadinho and Algoz deposits" (Lower Pleistocene); subunit G1 corresponds to the "Olhos de Água sands" (Piacenzian); Unit F corresponds to the "Galvana conglomerate" (Zanclean); Unit E corresponds to the "Cacela Formation" (Upper Tortonian to Messinian); uppermost of Unit D corresponds to the "Fine sands and sandstones with glauconite" (Lower Tortonian); lower and middle parts of Unit D corresponds to the "Lagos-Portimão Formation" (Lower Burdigalian to Upper Serravallian). Unit C do not has onshore equivalent; Unit B corresponds to the "Guia conglomerate" (possibly Upper Cretaceous to Lower Paleogene).

The seismic unconformities identified in the Algarve margin were also correlated with the main

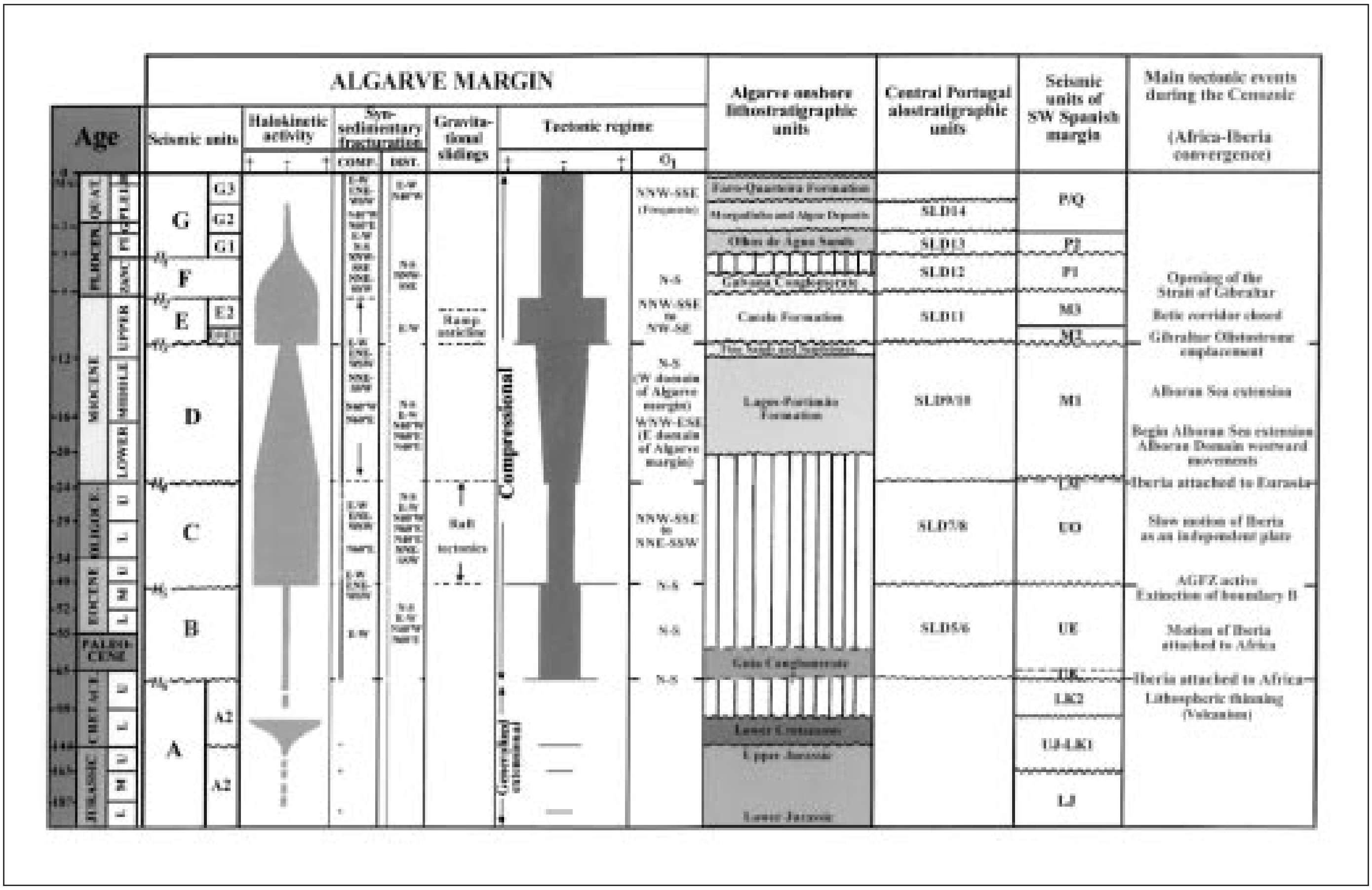

Fig. 7. Synthesis of the tectono-sedimentary features of the Algarve margin. Cenozoic seismic units and unconformities are correlated to the onshore lithostratigraphic units (Pais *et al.*, 2000), to the main sedimentary unconformities established in central Portugal (Cunha, 1992a,b) and to the Spanish seismic units (Maldonado *et al.*, 1999). Tectonic events and relative motion of Iberia and Africa are correlated with the development of the seismic units (modified from Lopes, 2002)

Fig. 7. Síntesis de los rasgos tecto-sedimentarios del margen del Algarve. Las unidades sísmicas y discordancias cenozoicas se correlacionan con las unidades litoestratigráficas de onshore (Pais et al.*, 2000), con las principales discordancias sedimentarias establecidas en Portugal central (Cunha, 1992a, b) y con las unidades sísmicas españolas (Maldonado* et al.*, 1999). Los eventos tectónicos y el movimiento relativo entre Iberia y África se correlacionan con el desarrollo de las unidades sísmicas (modificado de Lopes, 2002)*

sedimentary unconformities that bound the allostratigraphic Tertiary units (SLD's) established in central Portugal (Cunha, 1992a,b), namely (Fig. 7): H_1 correlates to the base of SLD13 (Piacenzian); H_2 correlates to the base of SLD12 (Late Massinian to Zanclean); H_3 correlates to the base of SLD11 (Upper Tortonian); H_4 correlates to the base of SLD9 (Aquitanian); H_5 correlates to the base of SLD7 (Middle Eocene); H_6 correlates to the base of SLD5 (Late Campanian).

Finally, the comparative study between the Algarve and Spanish continental margins of the Gulf of Cadiz, from the intersection between a Portuguese seismic reflection profile (P-65) and a Spanish seismic reflection profile (HE-91-3-Line 12), has enabled correlation between the Cenozoic seismic units identified in both margins (Spanish seismic units were proposed by Maldonado *et al.*, 1999) (Fig. 7): subunits G2 and G3 corresponds to the unit P/Q (Upper Pliocene-Quaternary); subunit G1 corresponds to the unit P2 (Upper Pliocene); Unit F corresponds to Unit P1 (Lower Pliocene); subunit E2 corresponds to the Unit M3 (Messinian); subunit E1 corresponds to the Unit M2 (Upper Tortonian); Unit D corresponds to the Unit M1 (Lower Langhian-Lower Tortonian); Unit C corresponds to the Unit UO-LM (Upper Eocene-Lower Miocene); Unit B corresponds to the Unit UK-UE (Upper Cretaceous-Middle Eocene). It was also possible to propose a Cenozoic structural map of the northern border of the Gulf of Cadiz, integrating the Algarve and the Spanish margins (Fig. 8).

Conclusions

The Cenozoic seismic units identified in the Algarve margin, deformed by active tectonic structures and bounded by unconformities related to the tectonic events that affected the southwestern border of Iberia, allowed the interpretation of the regional tectono-sedimentary context. These units can be correlated to the sedimentary records of the near areas and integrated in a more complete model for the evolution of the complex Azores-Gibraltar fracture zone. However, interpretation of the spatial and temporal variations of the stress-field is complicated by the existence of tectonic sub-domains (bounded by important fault zones), expressed by different compressive and distensive block interactions, and by the

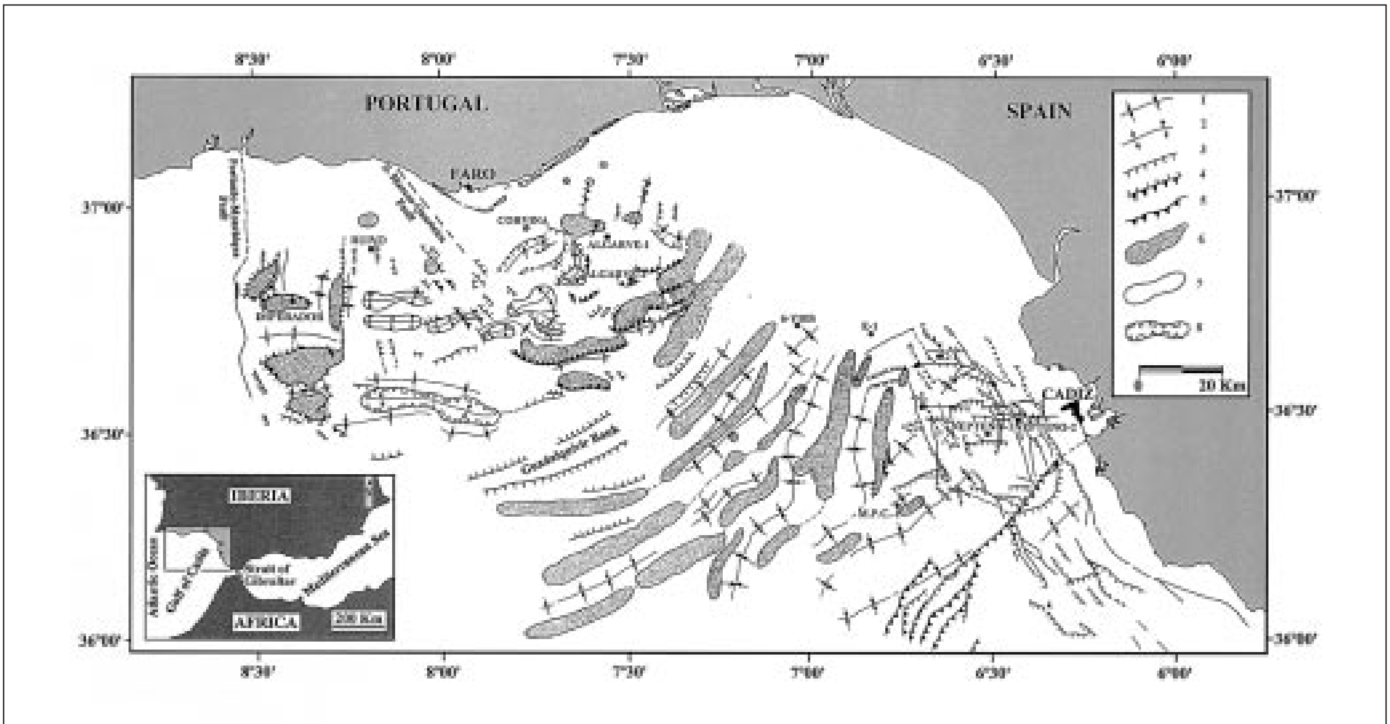

Fig. 8. Cenozoic structural map of the northern border of the Gulf of Cadiz, integrating the Algarve and the Spanish margins (modified from Lopes, 2002). 1: syncline axis; 2: anticline axis; 3: normal fault; 4: reverse normal fault; 5: thrust fault; 6: evaporitic structure; 7: structural high; 8: reversal half-graben

Fig. 8. Mapa estructural cenozoico del margen norte del Golfo de Cádiz, integrando los márgenes español y del Algarve (modificado de Lopes, 2002). 1: eje sinclinal; 2: eje anticlinal, 3: falla normal; 4: falla normal-inversa; 5: falla-cabalgamiento; 6: estructura evaporítica; 7: alto estructural; 8: semi-fosa inversa

reactivation of the evaporitic structures. This coexistence during the Cenozoic, but especially during the Miocene, also occurs in other regions of the Gulf of Cadiz. It is considered a consequence of: i) the horizontal migration of evaporites and implantation of a raft structural style; ii) the interaction between the convergence of Africa and Eurasia along the AGFZ (transpressive context) and the westward migration of the mountain front of the Gibraltar Arc, which causes a radial trajectory of σ_1 around the arc.

Acknowledgments

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