# Tectono-sedimentary phases of the latest Cretaceous and Cenozoic compressive evolution of the Algarve margin (southern Portugal)

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**ABSTRACT**

The latest Cretaceous and Cenozoic tectono-sedimentary evolution of the central and eastern Algarve margin (southwestern Iberia) is reconstructed as a series of structural maps and three-dimensional diagrams based on multichannel seismic reflection data. Six seismic stratigraphic units, bounded by unconformities related to tectonic events during the African–Eurasian convergence, have been identified. Several episodes of major regional change in palaeogeography and tectonic setting are distinguished: they occurred in the Campanian, Lutetian, Oligocene–Aquitanian transition, middle Tortonian, Messinian–Zanclean transition and Zanclean–Piacenzian transition. These changes were induced by geodynamic events primarily related to the relative motions of the African and Eurasian plates. The Late Cretaceous and Cenozoic in the Algarve margin were dominated by compressional deformation. Triggered by the regional tectonics that affected the basement, Upper Triassic–Hettangian evaporites played an important role in tectono-sedimentary evolution by localizing both extensional and thrust detachments and generating both salt structures and salt-withdrawal sub-basins. During middle Eocene and Oligocene times, coeval development of compressive structures and normal fault systems in the eastern Algarve domain is interpreted as resulting from gravity gliding due to a general tilt of the margin. The increasing effects of the African–Eurasian convergent plate boundary zone resulted in the uplift of some areas, overprinted by an increasingly general subsidence of the domains studied.

**Keywords** Cenozoic, Algarve margin, Gulf of Cadiz, Iberia, Europe, tectonics.

## INTRODUCTION

Differential motions between tectonic plates create intense deformation along their boundaries. Interaction between the African/Arabian and Eurasian plates has generated a broad collision zone comprising the Himalayan–Alpine chains, running from southeast Asia to southwest Europe. In the case of Iberia, located at the western end of this zone of convergence, the progressive opening of the North Atlantic Ocean has been the most important control in the complex pattern of differential motion between Iberia, Eurasia and Africa (e.g. Ziegler, 1988). After a long period in the Mesozoic, during which extension was the dominant mode of deformation, the Late Cretaceous to present-day has been a period of compression in the Iberian peninsula. The major compressive tectonic intervals can be related to the Pyrenean collision, opening of the western part of the Mediterranean basin, and collision in the Betics. According to Andeweg & Cloetingh (2001), Iberia has been dominated by compressive regimes with the maximum horizontal compressive stress ($Sh_{max}$) ranging between northeast and northwest; the dominant stress regimes range from uniaxial compression to transpression.

The main aim of this paper is to characterize the latest Cretaceous and Cenozoic tectono-sedimentary

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phases of the Algarve margin, a region in a critical location for the study of evolving plate boundaries, showing sedimentary evolution and salt tectonics in a compressional setting. A secondary aim is to discuss the tectono-stratigraphic interrelationships between the coeval development of the study area and the adjacent domains, which is important in understanding the large-scale tectonic processes that caused the plate deformation and in placing its evolution in a broader tectonic context. This integration of data improves the interpretation of the regional geodynamic evolution (Gulf of Cadiz), which is relevant to the understanding of the Azores–Gibraltar plate boundary.

## GEOLOGICAL SETTING

The Algarve margin, in southwestern Iberia, is situated on the northern border of the Gulf of Cadiz (Fig. 1) at the eastern end of the Azores–Gibraltar fracture zone (AGFZ), a diffuse transpressional plate boundary between the Iberian and African plates (Sartori *et al.*, 1994). Its complex geodynamic evolution, particularly during the latest Cretaceous and Cenozoic, has resulted from the convergence between Africa and Iberia along the eastern segment of the AGFZ (Dewey *et al.*, 1989; Srivastava *et al.*, 1990a, b) and the westward migration of the front of the Gibraltar Arc (e.g. Ribeiro *et al.*, 1990; Sanz de Galdeano, 1990; Gràcia *et al.*, 2003). During Neogene compressional phases, concentric wedges of fold and thrust belts and large allochthonous masses were emplaced in the Gulf of Cadiz (Campo de Gibraltar, External Betics and Guadalquivir Allochthon; e.g. Flinch *et al.*, 1996; Gràcia *et al.*, 2003), from the southeast (pre-early Langhian) towards the northwest (late Tortonian). Large gravitational accumulations and submarine landslides formed the 'Giant Chaotic Body' identified in the outer part of the Gulf of Cadiz (e.g. Bonnin *et al.*, 1975; Lajat *et al.*, 1975; Auzende *et al.*, 1981; Malod, 1982; Flinch *et al.*, 1996; Maestro *et al.*, 2003). The present-day geodynamics in the region of the Gulf of Cadiz, Gibraltar Arc and westernmost Alboran Sea, where the relative convergence between Iberia and Africa is only 4 mm $yr^{-1}$, are compatible with an active east-dipping subduction zone beneath the Gibraltar Arc (Gutscher *et al.*, 2002).

The stratigraphic record of the Algarve basin, both onshore and offshore, spans from Upper Triassic to Quaternary times, with several unconformity-bounded sequences (Terrinha, 1998; Lopes & Cunha, 2000; Lopes, 2002). This record can be briefly summarized as follows. Triassic to Lower Jurassic units are 500 m thick onshore. The Triassic red fluvial siliciclastics are capped by Hettangian evaporites and volcanics, followed by Sinemurian to Toarcian dolomites and marly limestones. The Middle Jurassic succession is 960 m thick and comprises bioclastic limestones that change upwards to marls and limestones, whereas the Upper Jurassic consists of 1000 m of dolomites and limestones. Lower Cretaceous strata are 900 m thick, comprising limestones, dolomites, sandstones and clays, but Upper Cretaceous to Paleocene sediments are not widely developed. Paleogene sediments have been reported from offshore wells but are not known onshore. The 675-m-thick upper Campanian(?) to middle Eocene succession comprises dolomites and some limestones. The middle Eocene to Oligocene succession is 200 m thick, comprising micritic limestones and minor dolomites. Probable Aquitanian to lower Tortonian deposits could be 100 m thick and are mainly limestones that are overlain by fine sandstones. The 1000-m-thick upper Tortonian to Quaternary succession comprises siltstones and sandstones.

The basement consists of metasediments and some igneous rocks, belonging to the South Portuguese Zone of the Variscan External Belt. Basement-related movements may have controlled a significant part of the structural deformation of the Algarve basin, under the changing stress field; pre-Tertiary structures played a major role in the later deformation (Ribeiro *et al.*, 1979). The Cenozoic tectonic style was thin-skinned, both onshore and offshore; Hettangian evaporites acted as a detachment layer during the extensional and compressional stages (Ribeiro *et al.*, 1990; Terrinha, 1998; Lopes, 2002).

## METHODS

The present study is based on the interpretation of a 1974 Chevron and Challenger multichannel seismic reflection (MCS) survey, consisting of a grid of seismic profiles covering an area of about 125 × 100 km,

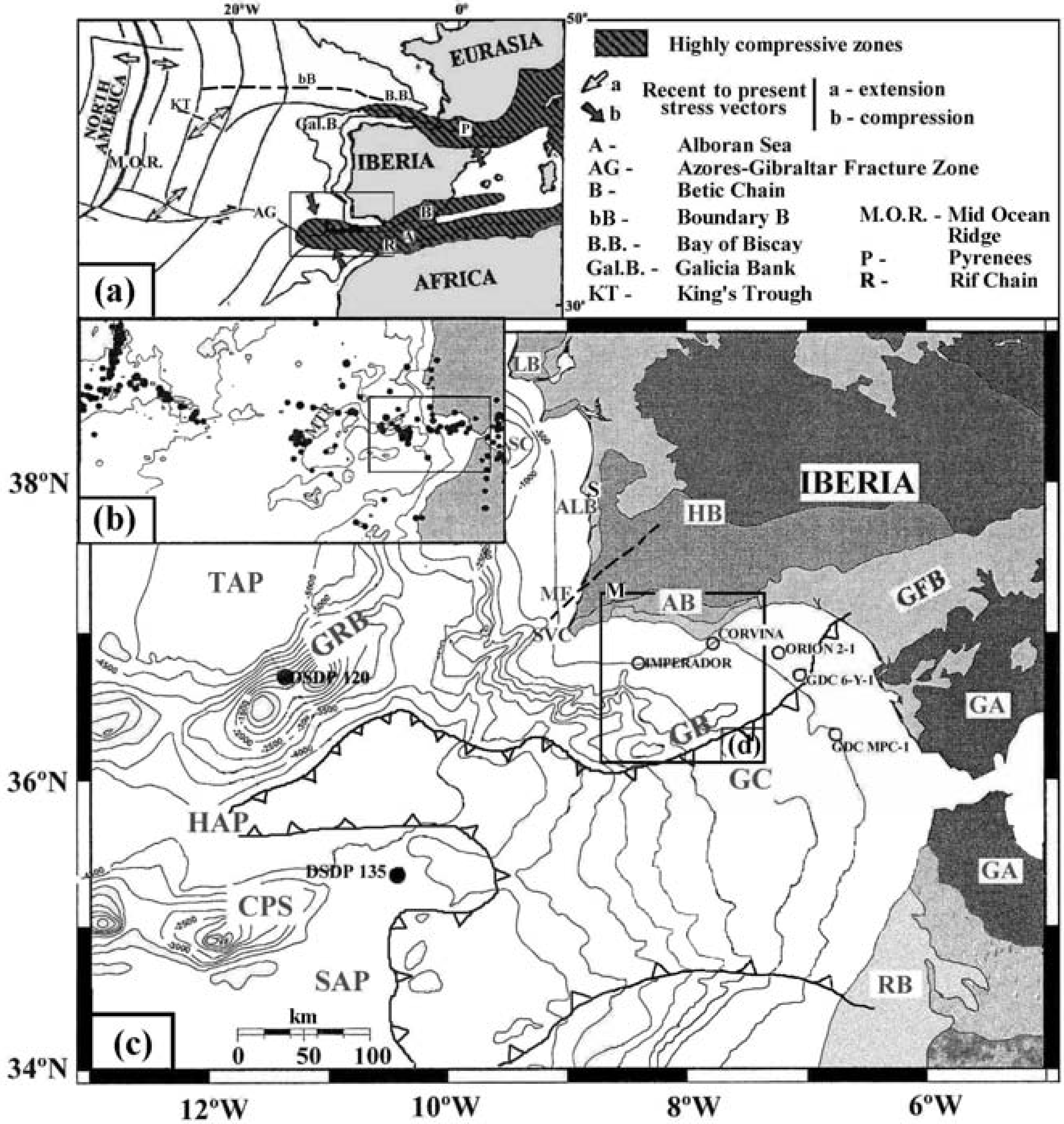


**Fig. 1** (a) Present-day stress field at the periphery of the Iberian microplate (adapted from Olivet, 1996). (b) Location of the earthquakes with M > 3 in the Azores–Alboran region; MTR: Madeira-Tore Ridge (adapted from Buforn *et al.*, 1988). (c) Geological setting and simplified bathymetry of the Gulf of Cadiz and surrounding areas (adapted from Le Gall *et al.*, 1997; Tortella *et al.*, 1997). AB, Algarve basin; ALB, Alentejo basin; CPS, Coral Patch Seamont; GA, Gibraltar Arc; GB, Guadalquivir Bank; GC, Gulf of Cadiz; GFB, Guadalquivir foreland basin; GRB, Gorringe Bank; HAP, Horseshoe Abyssal Plain; HB, Variscan Basement; LB, Lusitanian basin; M, Monchique; MF, Messejana fault; RB, Raarb basin; SAP, Seine Abyssal Plain; S, Sines; SC, Setúbal canyon; SVC, São Vicente canyon; TAP, Tagus Abyssal Plain; filled circles, DSDP sites; open circles, exploration wells; line with open triangles, 'Giant body' boundary. (d) Study area.

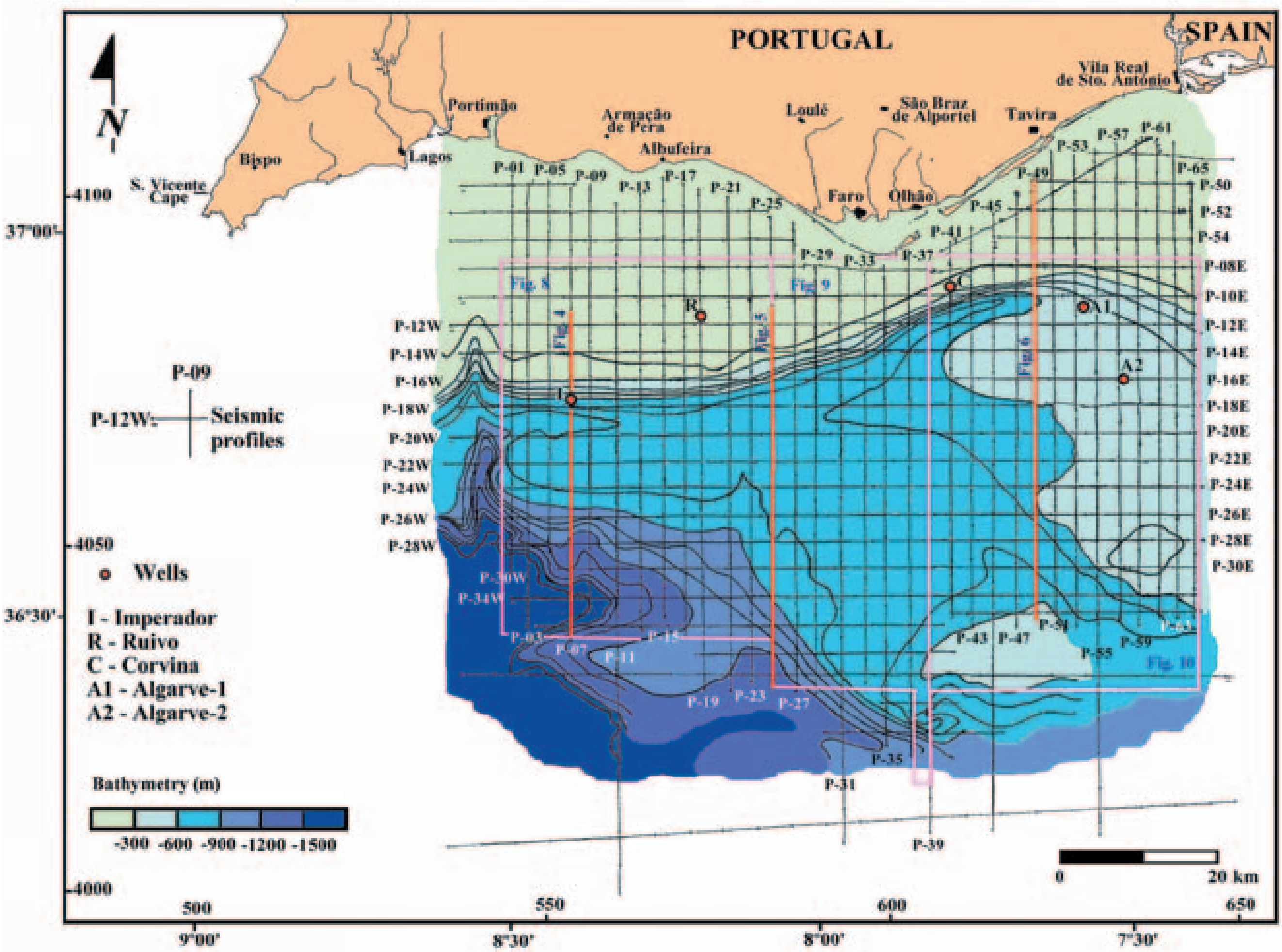


**Fig. 2** Simplified bathymetric chart of the study area. The grid of the multichannel seismic (MCS) profiles and location of the five exploration wells are shown. The bold red lines indicate the location of the seismic profiles shown in Figs 4–6. The pink boxes represent the areas displayed in Figs 8, 9 & 10.

in the central and the eastern sectors of the Algarve margin (longitudes 8°30′W and 7°30′W; latitudes 36°10′N and 37°00′N). The seismic profiles are tied to five oil exploration wells (Imperador-1, 1976; Ruivo-1, 1975; Corvina-1, 1976; Algarve-1, 1982; Algarve-2, 1982) drilled as deep as 3 km, in this part of the Algarve margin (Figs 2 & 3).

The offshore uppermost Cretaceous to recent seismic units (labelled B–G), bounded by unconformities (labelled as reflectors *H6–H1*), previously identified and characterized by Lopes & Cunha (2000) and Lopes (2002), support the establishment of tectono-sedimentary phases presented here (Fig. 3). It is not possible to show all the seismic data used for this study, so only three representative lines and interpretations are presented (Figs 4–6) in order to validate the interpretation of the seismic data.

The ages of the seismic units have been interpreted on the basis of:

**1** biostratigraphic data from the oil exploration well reports;
**2** the intersection between the Portuguese seismic grid and an adjacent Spanish MCS profile interpreted by Maldonado *et al.* (1999), allowing the correlation of the Cenozoic seismic units recognized in both margins;
**3** the presence of the Guadalquivir Allochthonous front, dated as middle to late Tortonian in the adjacent area (e.g. Gràcia *et al.*, 2003);
**4** correlation with unconformities dated in adjacent Portuguese basins (Cunha, 1992a, b; Pais *et al.*, 2000;

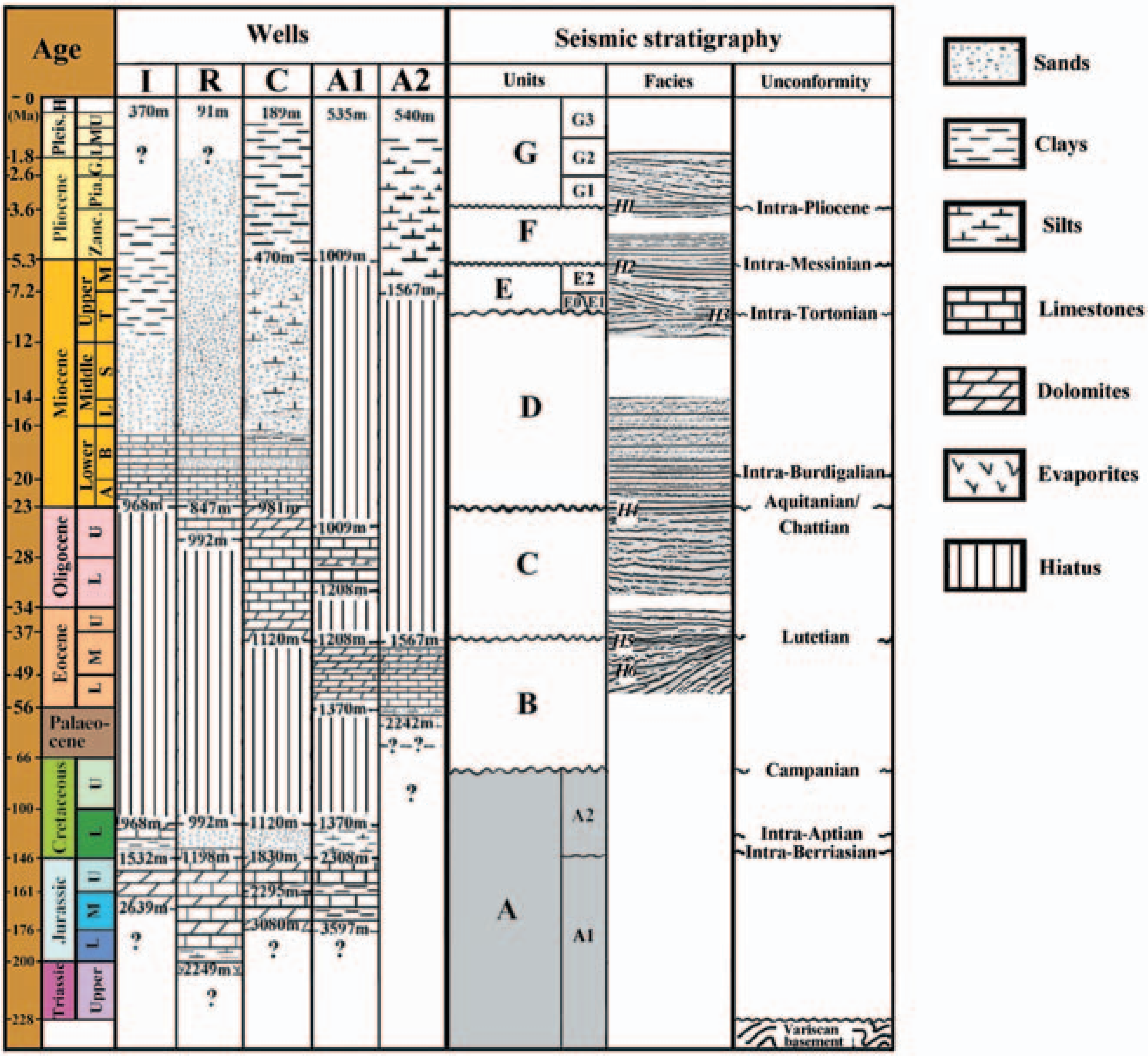


**Fig. 3** Seismic stratigraphy, main unconformities and wells in the Algarve offshore. Wells: I, Imperador-1; R, Ruivo-1; C, Corvina-1; A1, Algarve-1; A2, Algarve-2. Chronological time-scale from Gradstein *et al.* (2004).

Alves *et al.*, 2003) and related to the tectonic events that affected Iberia.

## STRUCTURAL FRAMEWORK

Four major fault zones, roughly transverse to the Azores–Gibraltar Fracture Zone, segment the Algarve margin.

**1** The Messejana fault zone, striking N60°E, crops out onshore and offshore. Its recent activity is indicated by the São Vicente submarine canyon (Fig. 1) and seismic activity.

**2** The Portimão–Monchique fault zone (PMFZ), striking N–S and also identified onshore, is about 70 km long offshore (Fig. 7). It is well documented in the E–W seismic reflection profiles, the westernmost ends of which intersect this fault. Its recent activity

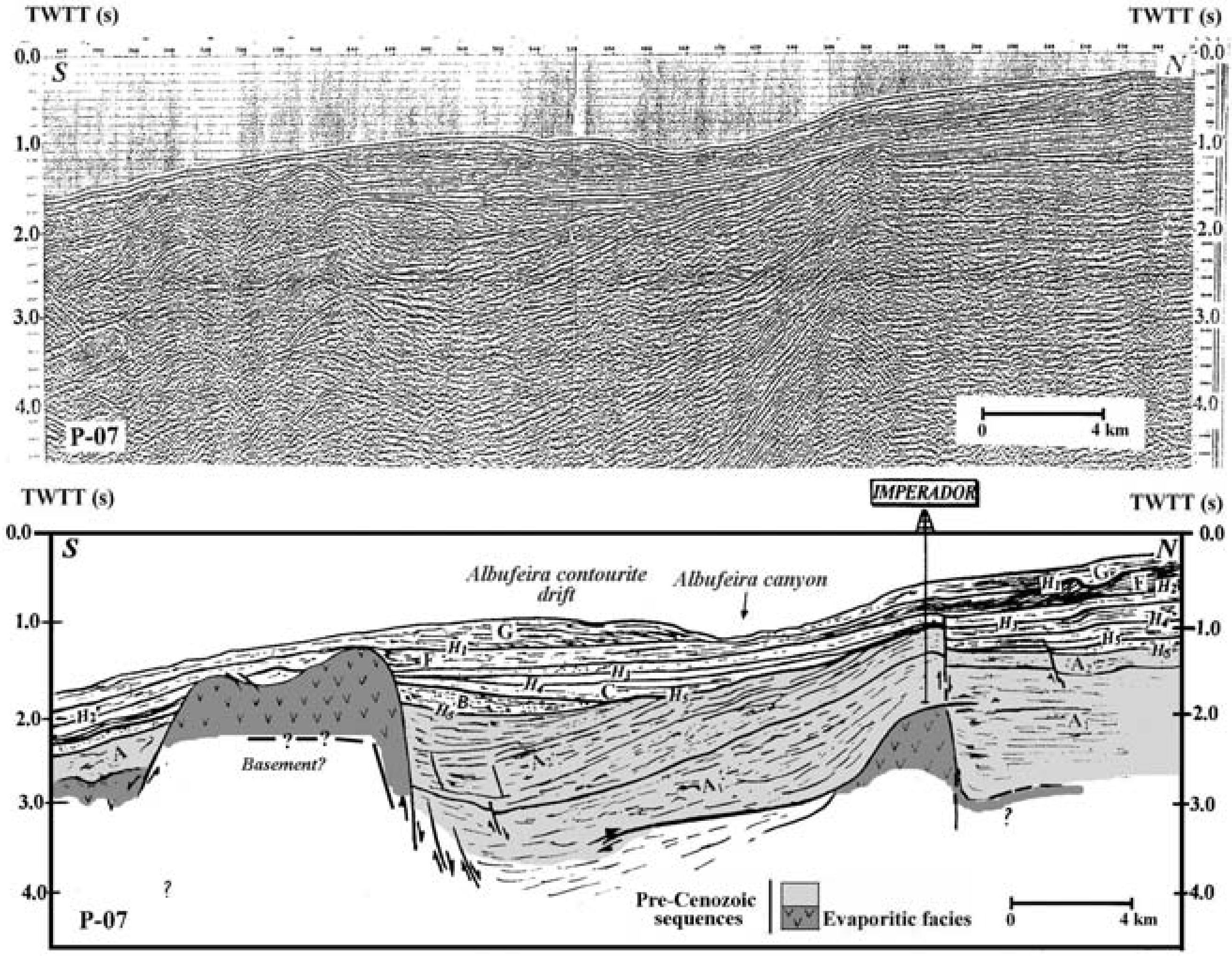


**Fig. 4** P-07 seismic profile and interpretation (see Fig. 2 for location).

is indicated by the Portimão submarine canyon and seismic activity. According to Terrinha (1998) and Terrinha *et al.* (1999), this structure is a segment of an intermittent late Variscan dextral vertical fault that was reactivated as a main transfer fault during tectonic extension and tectonic inversion of the Algarve Basin and as a dextral strike-slip fault during the Late Cretaceous rotation of Iberia. As a consequence of the NW–SE middle Tortonian compressive event, PMFZ became a sinistral strike-slip fault.

**3** The Albufeira fault zone (ALFZ) strikes approximately N–S and appears to be a segmented listric extensional fault involving three main fault segments with opposite polarities. Its activity was diachronous along-strike, with younger fault displacements in its southernmost segment. Here, there is evidence for important extensional displacements along the eastern margin of an easterly facing half-graben filled with syntectonic sequences ranging from unit C up to unit F (Fig. 8). The central segment is marked by a 2–3-km-thick elongate salt-body intrusion.

**4** The São Marcos–Quarteira fault (SMQF) zone strikes N40°W and also crops out onshore; it is 70 km long offshore and coincides with the Diogo Cão deep. According to Terrinha (1998), this is an inherited Variscan thrust reactivated as a major dextral transtensional fault during Mesozoic extension. In the eastern area of the basin, the downthrow of the eastern block allowed deposition of sediments more than twice as thick as the western equivalent. During tectonic inversion, the São Marcos–Quarteira fault zone was reactivated mainly as a dextral strike-slip fault. The SMQF zone is thought to be a transfer fault of the offshore southward verging E–W to ENE–WSW thrust front.

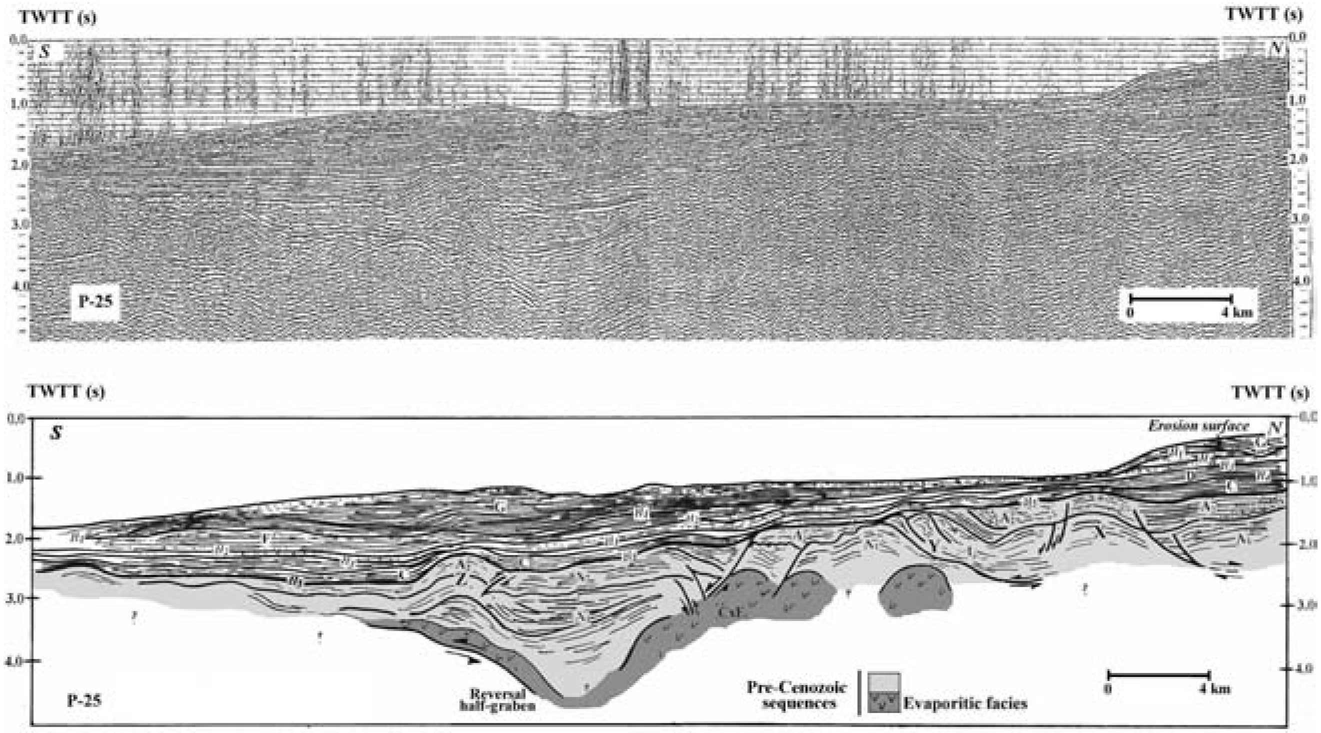


**Fig. 5** P-25 seismic profile and interpretation (see Fig. 2 for location).

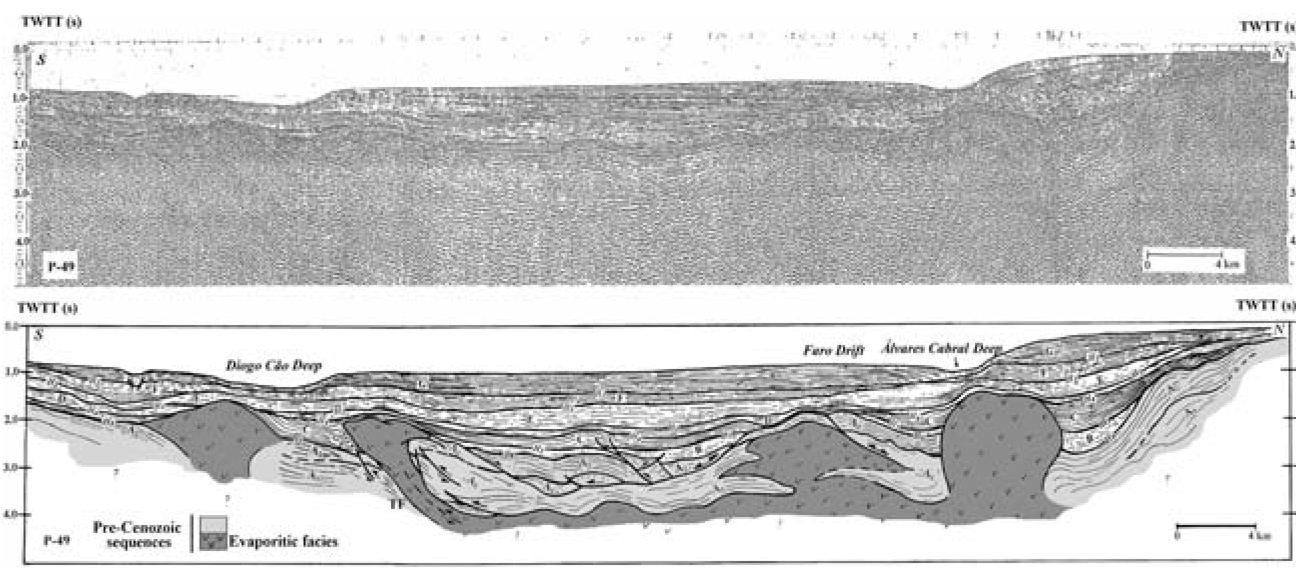


**Fig. 6** P-49 seismic profile and interpretation (see Fig. 2 for location). A thin-skinned syn-unit C gravitational gliding and the later inversion of the structures are dominant.

The latter three fault zones (b–d, above) define the three tectonic domains of the study area (Fig. 7), all bounded to the south by the N70°E-trending Guadalquivir Bank, a morphotectonic high located on the middle continental slope of the Atlantic Southern Iberian margin, 100 km south of Faro (Portugal). The Guadalquivir Bank is the offshore continuation of the Iberian Variscan Massif

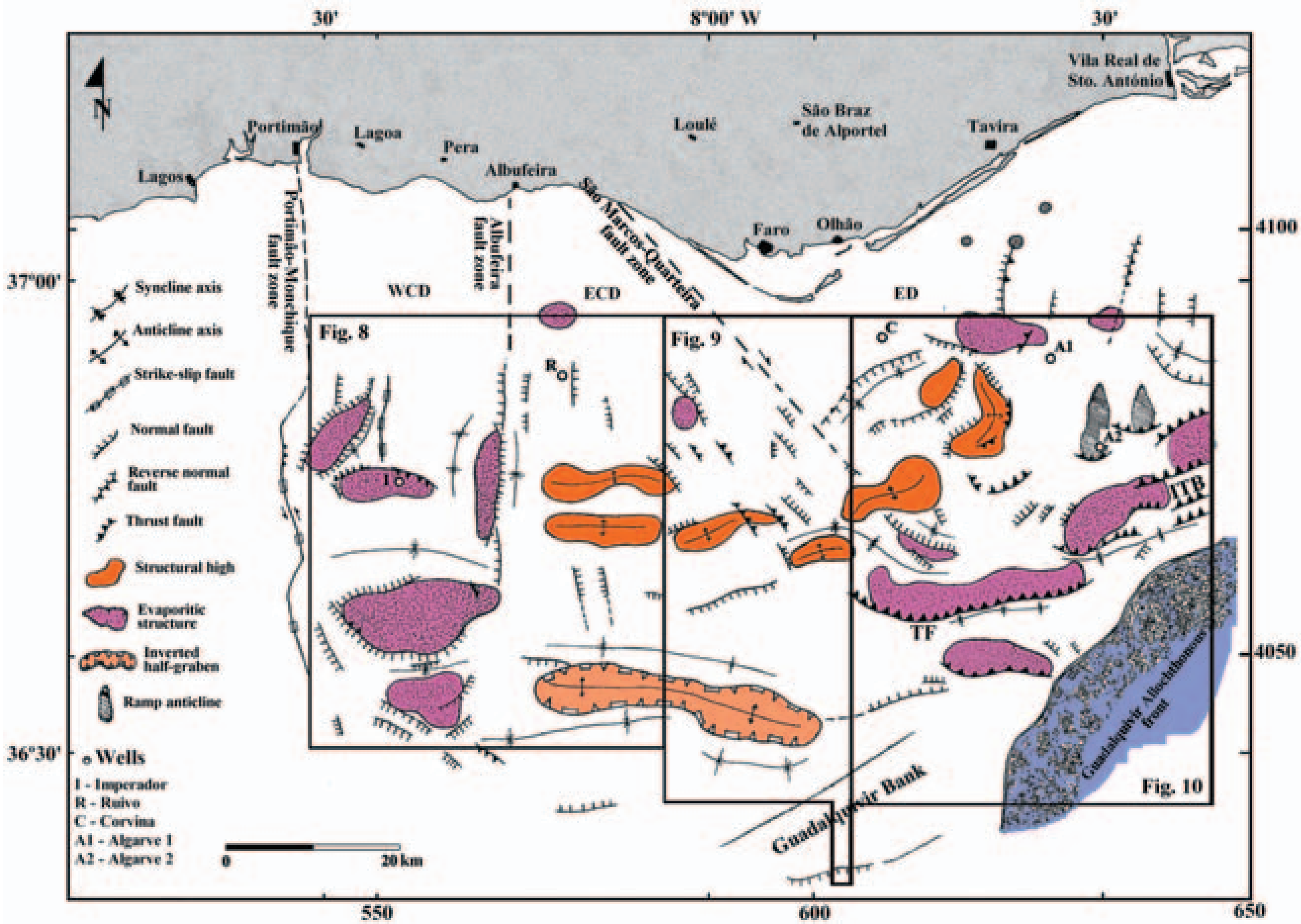


**Fig. 7** Summary map of the main Cenozoic tectonic structures. Boxes show the areas covered by Figs 8–10: WCD, Western Central Domain; ECD, Eastern Central Domain; ED, Eastern Domain; TF, thrust front; ITB, imbricated thrust belt.

(Dañobeitia *et al.*, 1999; Gràcia *et al.*, 2003; Vegas *et al.*, 2004).

The Western Central Domain (WCD) is a narrow (25 km wide) N–S-trending domain, about 1500 km$^2$ in area, limited to the west by the Portimão–Monchique fault zone and to the east by the Albufeira fault zone. It includes predominant N–S- and E–W-trending structures and, secondarily, NW–SE and N40°E structures. The main morphotectonic features are four evaporitic walls associated with N–S (central segment of the ALFZ), E–W and N40°E lineaments respectively (Figs 4, 7 & 8).

The Eastern Central Domain (ECD) is a triangular area (1300 km$^2$) bounded to the west by the Albufeira fault zone and to the east by the São Marcos–Quarteira fault zone. The main morphotectonic features of this domain are three parallel antiforms with E–W- to ENE–WSW-trending axes (Figs 5 & 7–9).

The Eastern Domain (ED) is an irregular-shaped area (1800 km$^2$), tectonically more complex than the others, that corresponds to a structural depression dominated by three main lineaments (Figs 7 & 10): a WSW–ENE 20-km-long thrust front, verging to the south, located north of the Guadalquivir Bank (near latitude 36°38′N), which involves salt slices at depth (Fig. 6); N60°E, southeasterly dipping listric normal faults, located close to the upper slope, and a 20-km-wide zone of imbricate thrust faults verging to the south, located at the southeast margin of the domain; NNE–SSW reverse faults,

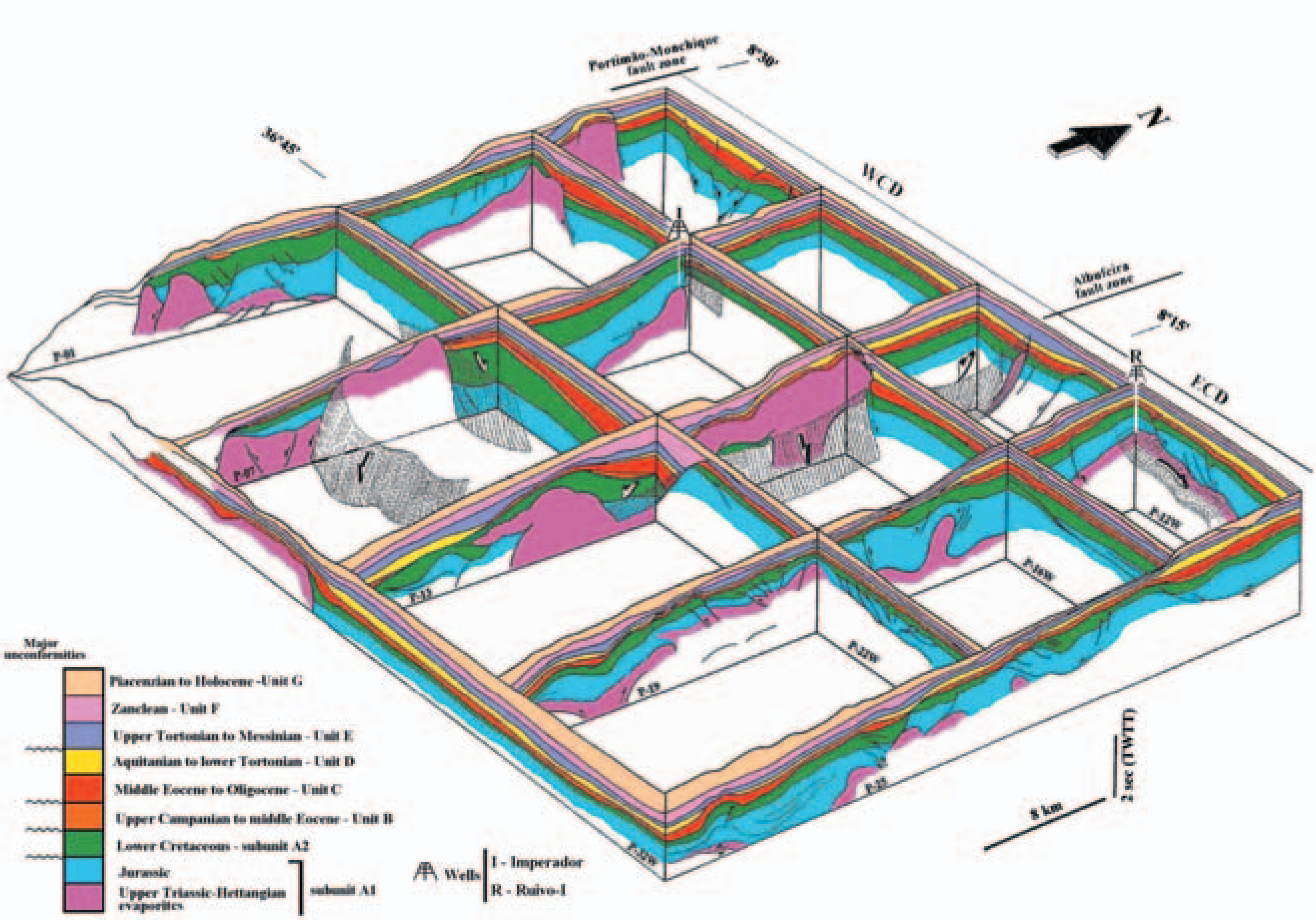


**Fig. 8** Three-dimensional diagram of the Western Central Domain (WCD) and part of the Eastern Central Domain (ECD), showing the seismic units and their geometrical relationship to tectonic structures.

verging to the west, located southeast of Tavira. These reverse faults resulted from the inversion of previous extensional structures. The Eastern Domain is also dominated by the Guadalquivir Allochthonous front, located in the southeastern extremity of the study area. This 50-km-wide front has a wedge-shaped geometry, with decreasing thickness northwards and westwards (Figs 7 & 10).

## TECTONO-SEDIMENTARY PHASES OF THE ALGARVE MARGIN

Evaluation of the tectono-stratigraphic interrelations makes it possible to infer episodes of major change that simultaneously affected the adjacent parts of the convergent plate boundary zone in the past 80 Myr. The following sections characterize the six tectono-sedimentary phases documented in the Algarve margin (Fig. 11).

### Late Campanian to middle Eocene tectono-sedimentary phase

In the Algarve margin, the late Campanian to middle Eocene phase started with the deposition of marls and sandstones, followed by marine grey dolomites intercalated with marly limestones and micritic limestones. This is documented by well data (Fig. 3) and corresponds to seismic unit B. This unit is better represented in the Eastern Domain where it can reach more than 0.4 s TWTT equivalent thickness (Figs 6, 10 & 12). In some areas unit B is only preserved in E–W-trending synclines; some later erosion, prior to deposition of unit C, may have occurred.

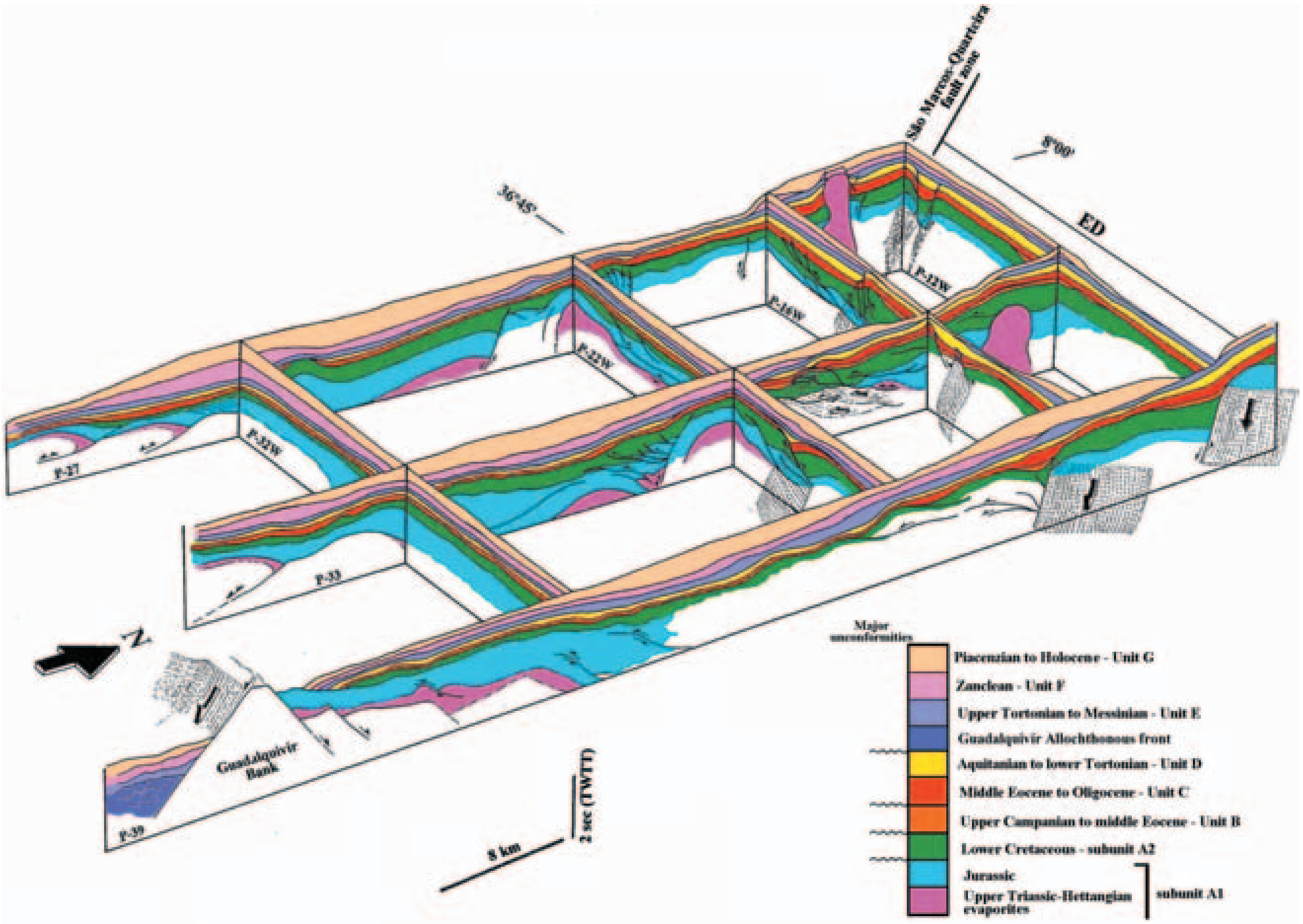


**Fig. 9** Three-dimensional diagram of the eastern part of the Central Domain and the boundary with the Eastern Domain (ED), showing the seismic units and their geometrical relationship to tectonic structures.

#### Middle Eocene to Oligocene tectono-sedimentary phase

In the Western Central Domain of the Algarve margin, an important angular unconformity truncates the folded pre-unit-C deposits, testifying to a major tectonic event (Fig. 4). The middle Eocene to Oligocene phase was characterized by the deposition of micritic limestones (seismic unit C; Fig. 3), suggesting that a carbonate platform developed over the entire margin. Although the thickness of unit C is variable, values of more than 0.6 s TWTT are found in half-grabens and foredeep basins mainly at the eastern Algarve margin (Fig. 6).

Seismic data show that the middle Eocene to Oligocene evolution of the Algarve margin was marked by intense and widespread halokinesis (Figs 6, 8–10 & 13). Salt withdrawal from interdiapiric areas and transfer into growing salt pillows or salt walls resulted in the formation of salt-withdrawal sub-basins. A salt-/fault-controlled (thin-skinned) subsidence influenced the thickness and the lateral distribution of unit C. In the Western Central Domain, the southern part of the Albufeira fault zone was active during this phase. In the northern sector of the Eastern Central Domain, a NE–SW flexural sub-basin was active (Figs 8 & 13). In the Eastern Domain gravity gliding of the cover was associated with uplift and tilting of the northern sector of the margin, enhanced by tectonic inversion of the basement. The resultant glide tectonics formed an area under tension upslope and an area under compression downslope. The extensional sector was characterized by the development of a N60°E-striking listric normal fault system. Half-grabens were developed in the

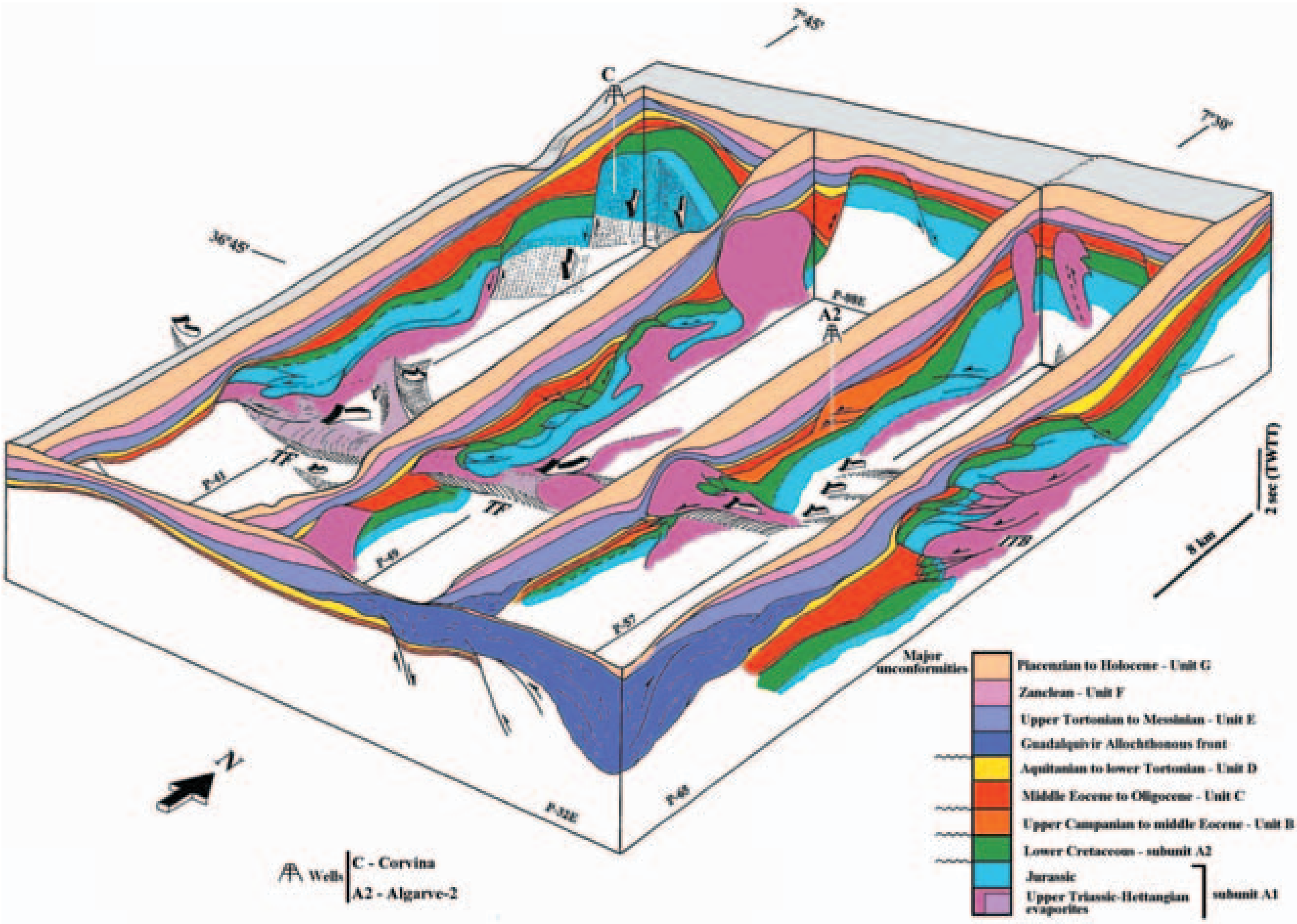


**Fig. 10** Three-dimensional diagram of the eastern part of the Eastern Domain (ED), showing the seismic units and their geometrical relationship to tectonic structures: TF, thrust front; ITB, imbricated thrust belt.

northwestward tilted hanging-wall blocks. The contractional sector was characterized by the development of salt anticlines and turtle structures and the ENE–WSW 20-km-wide thin-skinned imbricate thrust front. The frontal contractional structures were controlled by basinward salt pinch-out (Letouzey *et al.*, 1996). During this time, the NNE–SSW lineament was a steep westerly-dipping extensional fault system.

#### Aquitanian to early Tortonian tectono-sedimentary phase

The Aquitanian(?) to lower Tortonian sequence (seismic unit D) comprises marine carbonates and later siliciclastics. Unit D is widespread and exhibits variable seismic facies across the study area, reaching more than 0.25 s TWTT in thickness (Figs 4–6 & 14). The first deposits of unit D, mainly corresponding to marine platform carbonates, reached the modern onshore (Lagos–Portimão Formation). The upper part of unit D, represented in the onshore by the Tortonian 'Fine Sands and Sandstones' (Pais *et al.*, 2000; Fig. 11), indicates that marine environments were replaced by transitional ones and the deposits became carbonate–siliciclastic.

During this phase, regional halokinesis decreased. In the Eastern Central Domain new N–S normal faults and E–W antiforms were developed (Fig. 14). Two W–E- to ENE–WSW-trending subbasins appeared north and south of the meridional antiform. At the end of this stage, the northeastern sector of the Eastern Domain was subjected to major uplift and southward tilting; the inversion of the NNE–SSW-striking fault set, the attenuation

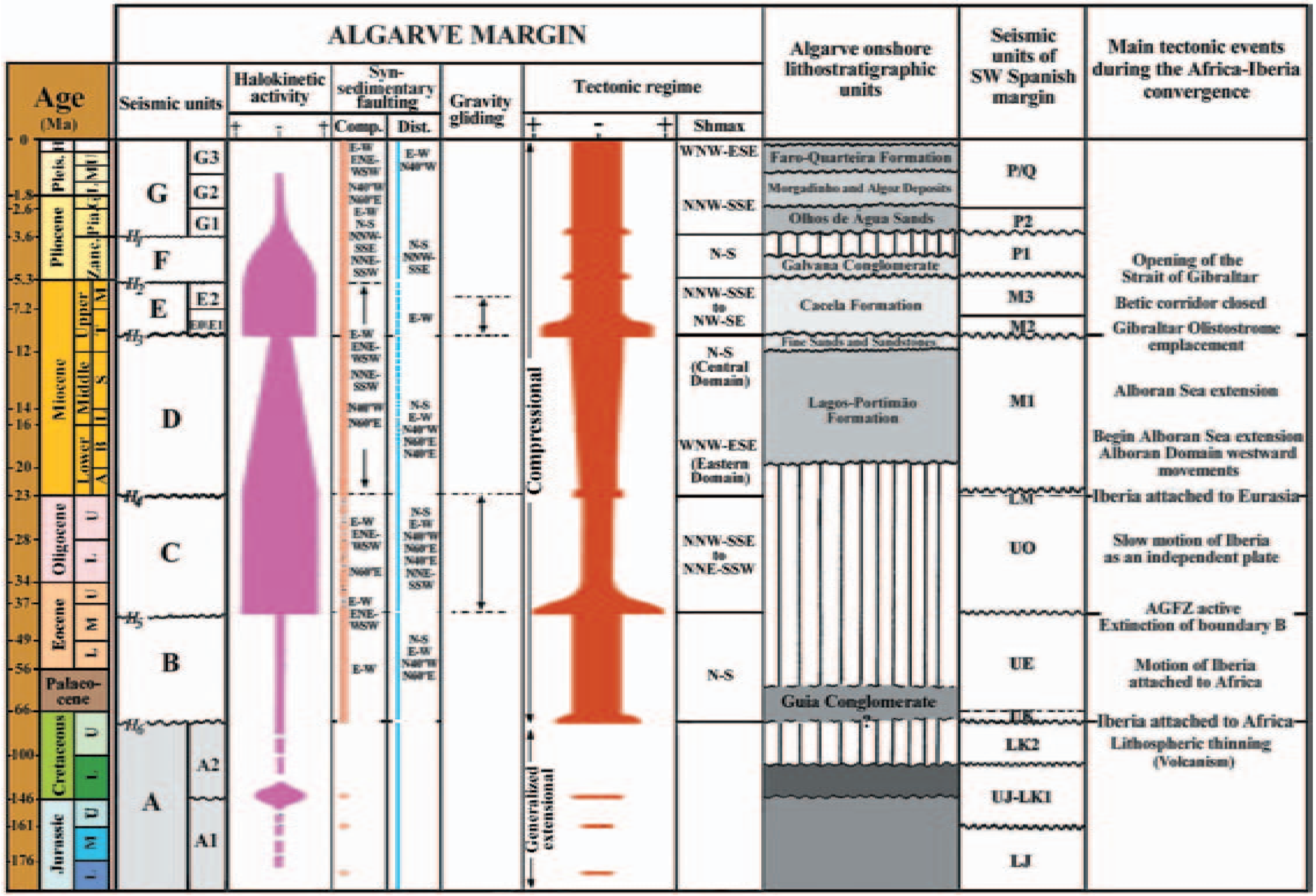


**Fig. 11** Synthesis of the tectono-sedimentary stages of the Algarve margin. Cenozoic seismic units and bounding unconformities are correlated to the onshore lithostratigraphic units (Pais *et al.*, 2000) and to the seismic units of southwest Spanish margin (Maldonado *et al.*, 1999). The tectonic events and relative motion of Iberia and Africa are correlated with the development of the seismic units. Chronological time-scale from Gradstein *et al.* (2004).

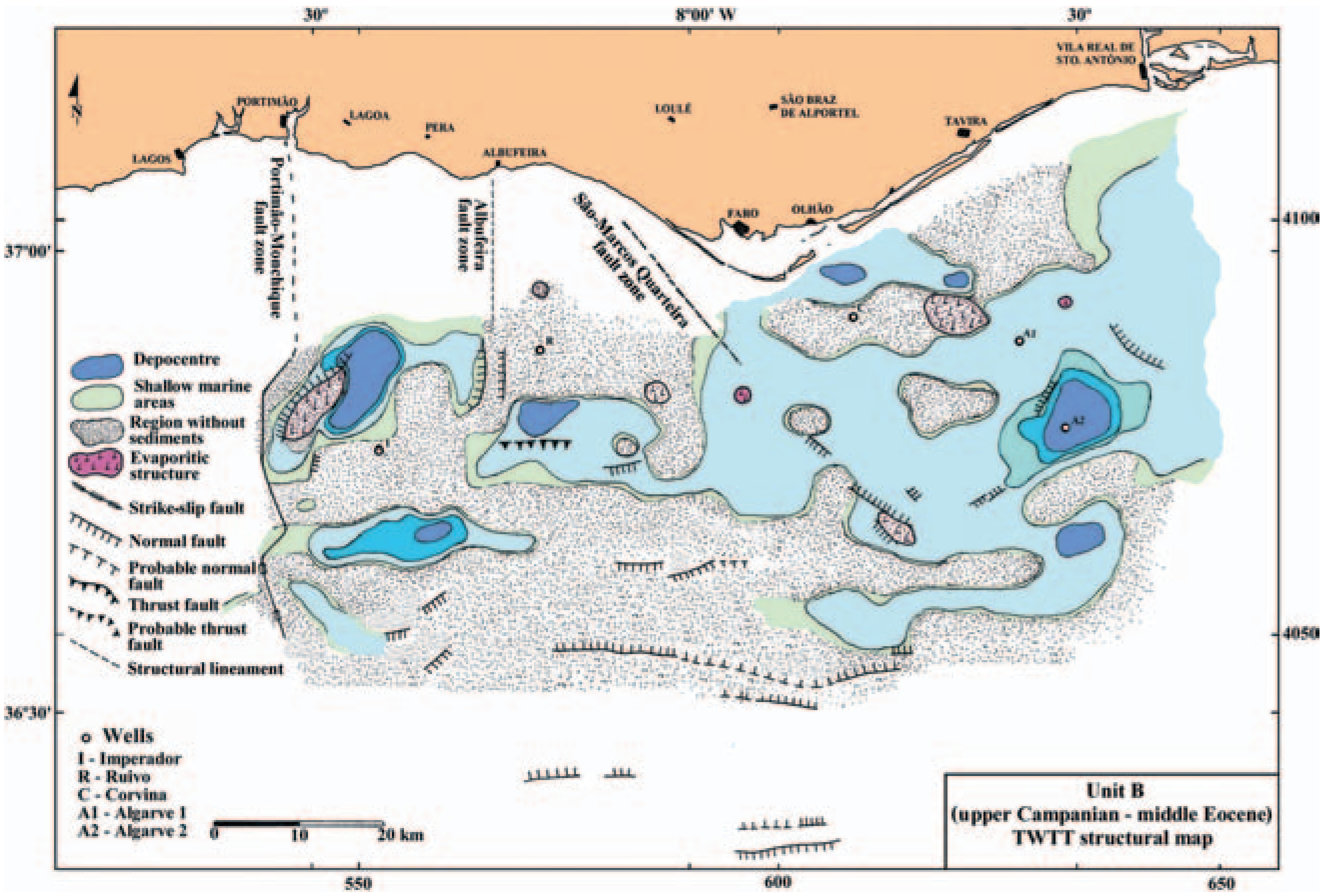


**Fig. 12** Unit B (upper Campanian to middle Eocene) TWTT structural map. Areas with no data are represented in white.

of syn-sedimentary folding and the activity in the E–W to ENE–WSW thrust front all occurred.

#### Late Tortonian to Messinian tectono-sedimentary phase

This phase was marked by significant uplift and southward tilting of the northeastern sector of the Eastern Domain (Figs 14 & 15), leading to the erosion of unit D over a 15-km-wide N–S-trending zone located between Tavira and Vila Real de Santo António and extending southwards to the Algarve-1 and Algarve-2 well sites. In this region, southward gravitational sliding occurred, leading to the formation of ramp anticlines downslope (Figs 10 & 15). A subsiding N60°E-trending central sub-basin was developed, with northeastward migration. General siliciclastic sedimentation (seismic unit E) began with the arrival of the Guadalquivir Allochthonous front in the southeastern Algarve margin during the late Tortonian. Close to the Guadalquivir Allochthonous front and in some small depressions on the top of this chaotic body, detrital deposits accumulated, grading northwards into pelagic deposits.

During this phase, a generalized NNW–SSE compressional regime induced the tectonic inversion of most previous structures and reactivation of the ENE–WSW thin-skinned thrust faults (Figs 6, 10 & 15). Widespread halokinesis also occurred, with reactivation of the previous salt structures that pierced their cover. In the Western Central Domain, the southern part of the Albufeira fault zone was characterized by quiescence during the deposition of unit E, which has the same thickness on both sides of the fault (Fig. 15). Uplift is documented in some sections of the Portimão–Monchique fault zone and at the

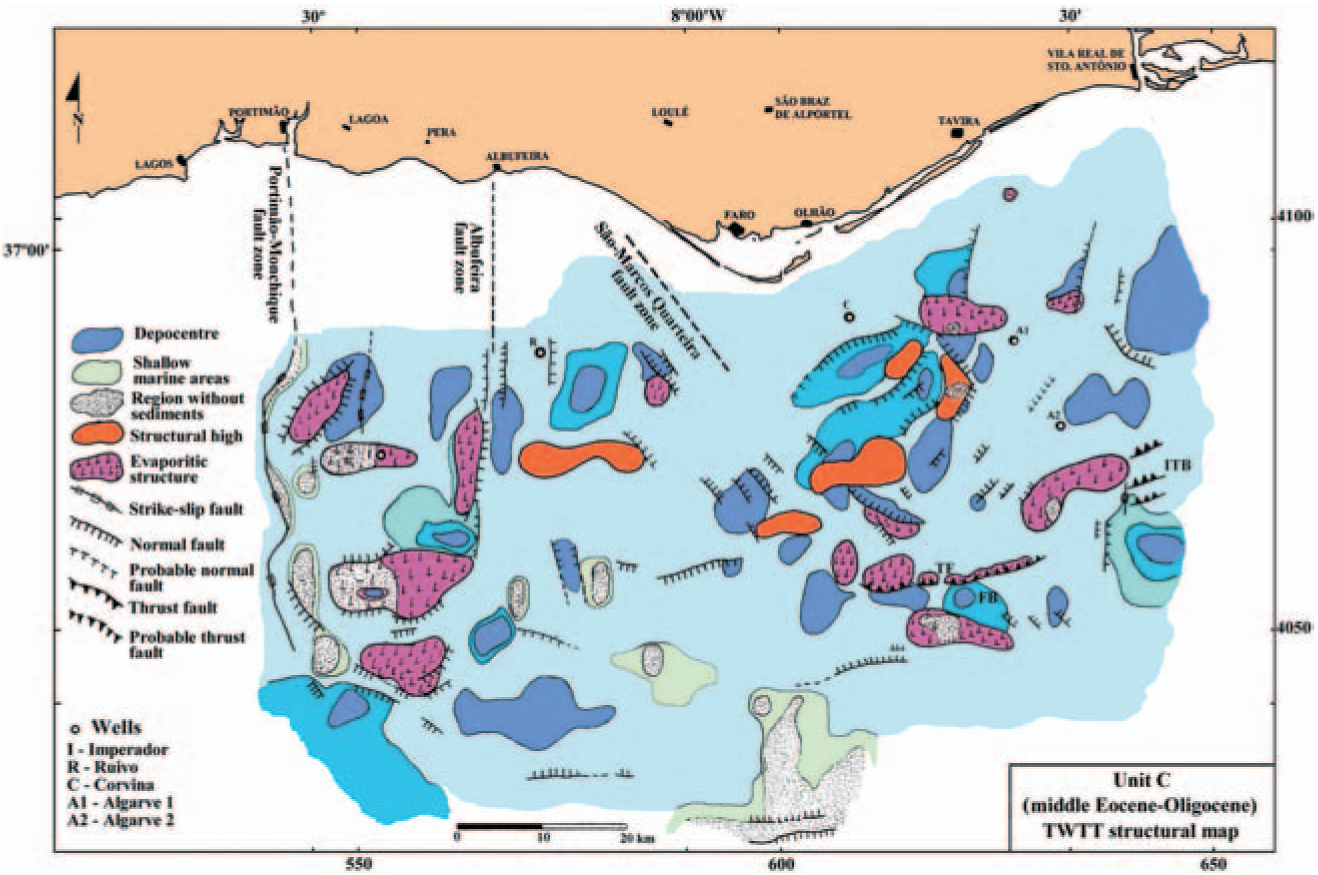


**Fig. 13** Unit C (middle Eocene to Oligocene) TWTT structural map. TF, thrust front; FB, foredeep basin; ITB, imbricated thrust belt. Areas with no data are represented in white.

northeastern end of the Eastern Domain (Figs 4, 8 & 15). In the Eastern Central Domain the anticlines were active.

#### Zanclean tectono-sedimentary phase

Data from the wells (Imperador, Ruivo and Corvina) indicate that the lithologies corresponding to seismic unit F consist of upper to lower bathyal mudstones and sandstones with interbedded sandy mudstones (Fig. 3). The thickness of these deposits is variable and was controlled by the underlying fault/salt structures (Figs 4–6, 8–10 & 16). Values of more than 0.6 s TWTT are documented in half-grabens, particularly in the western Algarve margin.

During the Zanclean, in all the study area, the depressions underlying unit F were filled. In the Western Central Domain, the southern part of the Albufeira fault zone was reactivated. In the Central Eastern Domain, the southern anticline became inactive and its northern and southern boundary sub-basins became a single, rapidly subsiding N60°E-trending depocentre. In the Eastern Domain, strong subsidence occurred in a N60°E-trending depocentre located northwestwards of the Guadalquivir Bank. Decreasing halokinesis is documented, with a more localized diapirism, forming small rim synclines.

#### Piacenzian to Holocene tectono-sedimentary phase

Seismic unit G comprises hemipelagic silts and sands, turbiditic sands and current-drift sands. Basinwards, this phase was characterized by rapid subsidence along a roughly N60°E-trending axis, where a considerable thickness was accumulated (more than 0.7 s TWTT) (Figs 4–6, 8–10 & 17).

During the Piacenzian to Holocene phase the present-day Gulf of Cadiz marine current regime

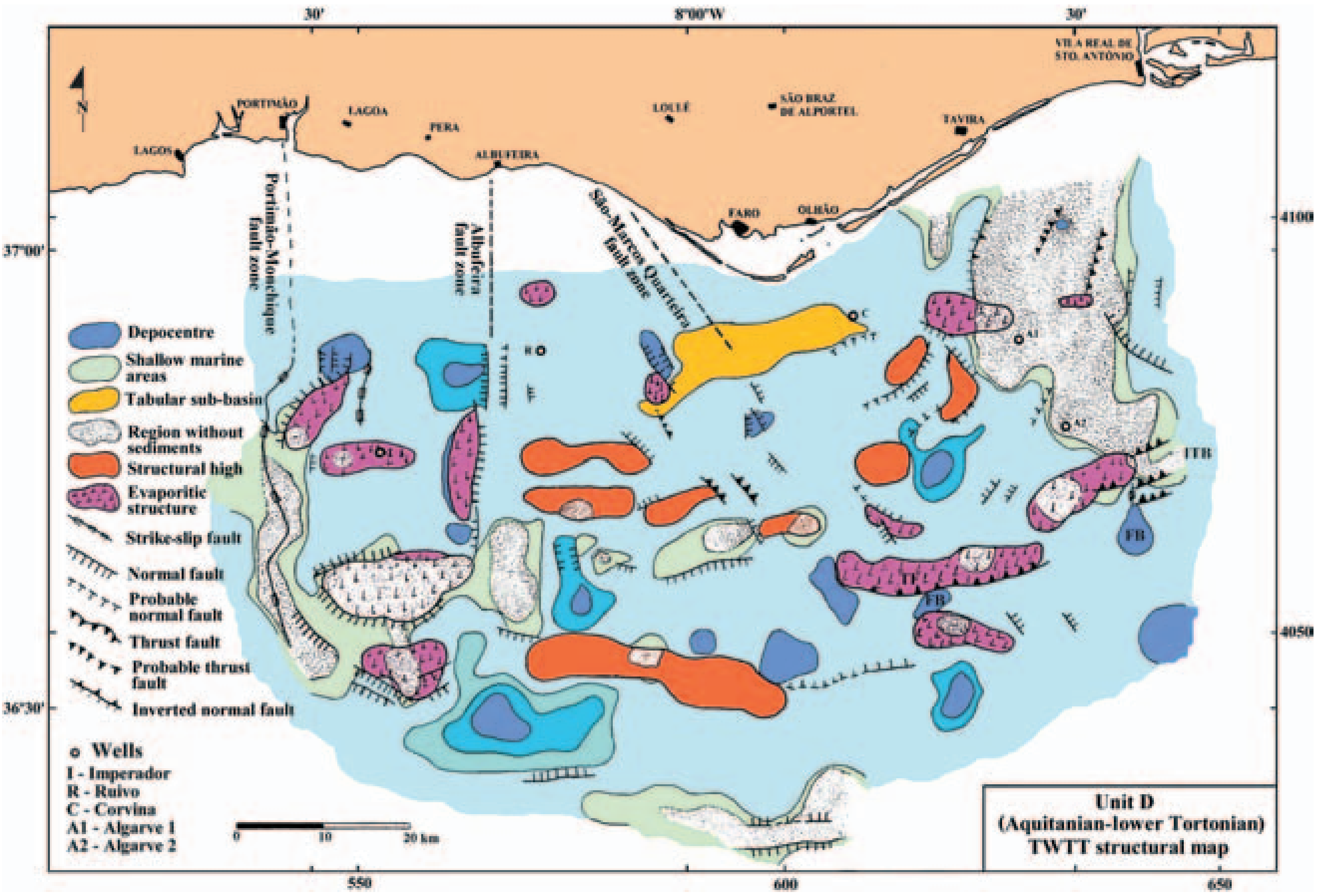


**Fig. 14** Unit D (Aquitanian to lower Tortonian) TWTT structural map. TF, thrust front; FB, foredeep basin; ITB, imbricated thrust belt. Areas with no data are represented in white.

became established (e.g. Mougenot & Vanney, 1982). The Portimão and Albufeira canyons and the Álvares Cabral and Diogo Cão deeps were developed and the north-northwestwards progradational contourite drifts of Albufeira and Faro established their present-day positions (e.g. Nelson *et al.*, 1999) (Figs 4, 6 & 17). The halokinesis seems to decrease (onshore, some salt structures such as the Loulé Diapir were still active in the Quaternary; Terrinha *et al.*, 1990) and the previous depressions were progressively filled. The orientation and type of the syn-sedimentary faults suggest the development of a stress field with $Sh_{max}$ oriented NNW–SSE, but also WNW–ESE. Significant present-day seismicity is dominantly offshore (Cabral, 1995), mainly related to the Portimão–Monchique and São Marcos–Quarteira fault zones, the ENE–WSW thrust front, NNE–SSW reverse faults and the Guadalquivir Bank (Lopes, 2002).

## SYNTHESIS OF THE REGIONAL GEODYNAMIC EVOLUTION

### Late Cretaceous to Lutetian

At Chron 34 (Santonian, 84 Ma), Iberia was attached to the African plate and the plate boundary with Eurasia was then located in the Bay of Biscay (boundary B; Srivastava *et al.*, 1990a, b). The new geodynamic setting caused north–south convergence ( Dewey *et al.*, 1973, 1989; Argus *et al.*, 1989). This resulted in inversion of the northern margin of Iberia, developing into northward subduction/underthrusting of the plate (starting in the Campanian; Puigdefàbregas & Souquet, 1986) and creating the Pyrenees. In mainland Portugal, a compressive episode occurred in the middle Campanian (around 80 Ma; e.g. Mougenot, 1981, 1989), with $Sh_{max}$ oriented north–south, leading to

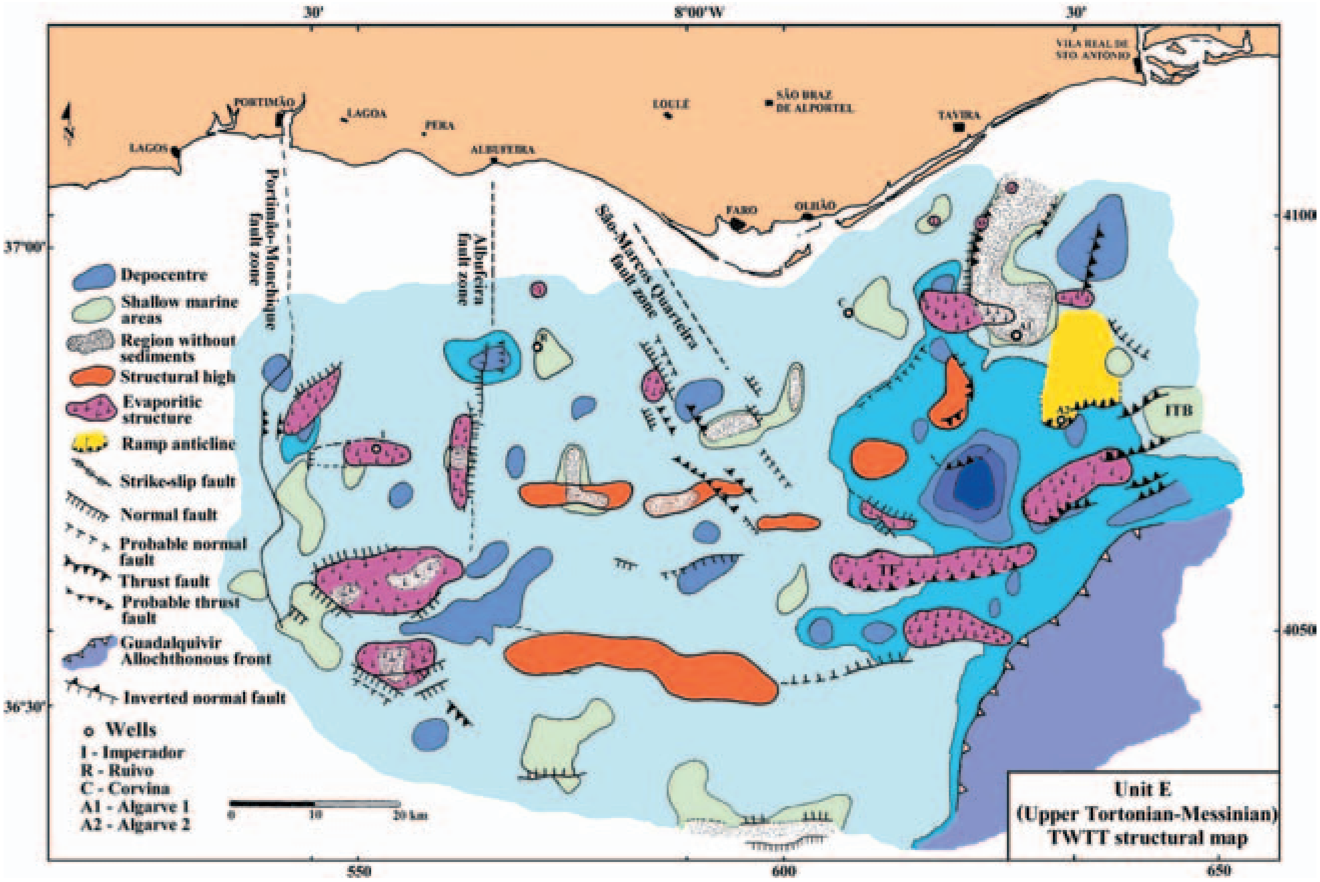


**Fig. 15** Unit E (upper Tortonian to Messinian) TWTT structural map. TF, thrust front; ITB, imbricated thrust belt. Areas with no data are represented in white.

the intrusion of the Sintra, Sines and Monchique alkaline plutons, probably along a deep-seated dextral strike-slip fault (e.g. Ribeiro *et al.*, 1979; Abranches & Canilho, 1981; Terrinha, 1998; Gomes & Pereira, 2004). Significant volcanic activity, diapirism and faulting also occurred in central Portugal (Cunha & Pena dos Reis, 1995; Pinheiro *et al.*, 1996). In the Algarve margin, this event is recorded by unconformity H6 (Figs 3 & 11). The upper Campanian to middle Eocene sequence was deposited irregularly, with significant facies variations, as documented by unit B in the Algarve margin (Lopes, 2002) and the unit UK-UE in the southwest Spanish margin (Maldonado *et al.*, 1999).

#### Lutetian to Chattian

At the start of the Lutetian an important event occurred – the inception of rifting in western Europe, initiating basins of the European Cenozoic Rift System (Sissingh, 2001). Compression related to the Pyrenean collision was transmitted into the central part of the Iberian mainland: NNE–SSW compression and perpendicular extension generated the Portuguese Tertiary basins (Mondego, Lower Tejo and Sado basins) and a large number of basins in Spain were created (Lutetian compressive phase), filled by arkose sediments resulting from the erosion of the Hesperic Massif (Variscan basement). Despite the belief that deformation decreased southward, away from the active boundary, the southwestern border of Iberia (Gulf of Cadiz) was affected by a compressive event (Fig. 11) that resulted in:

**1** The cessation of movement along boundary B, and the jumping of the plate boundary to the region of King's Trough, extending eastward along the

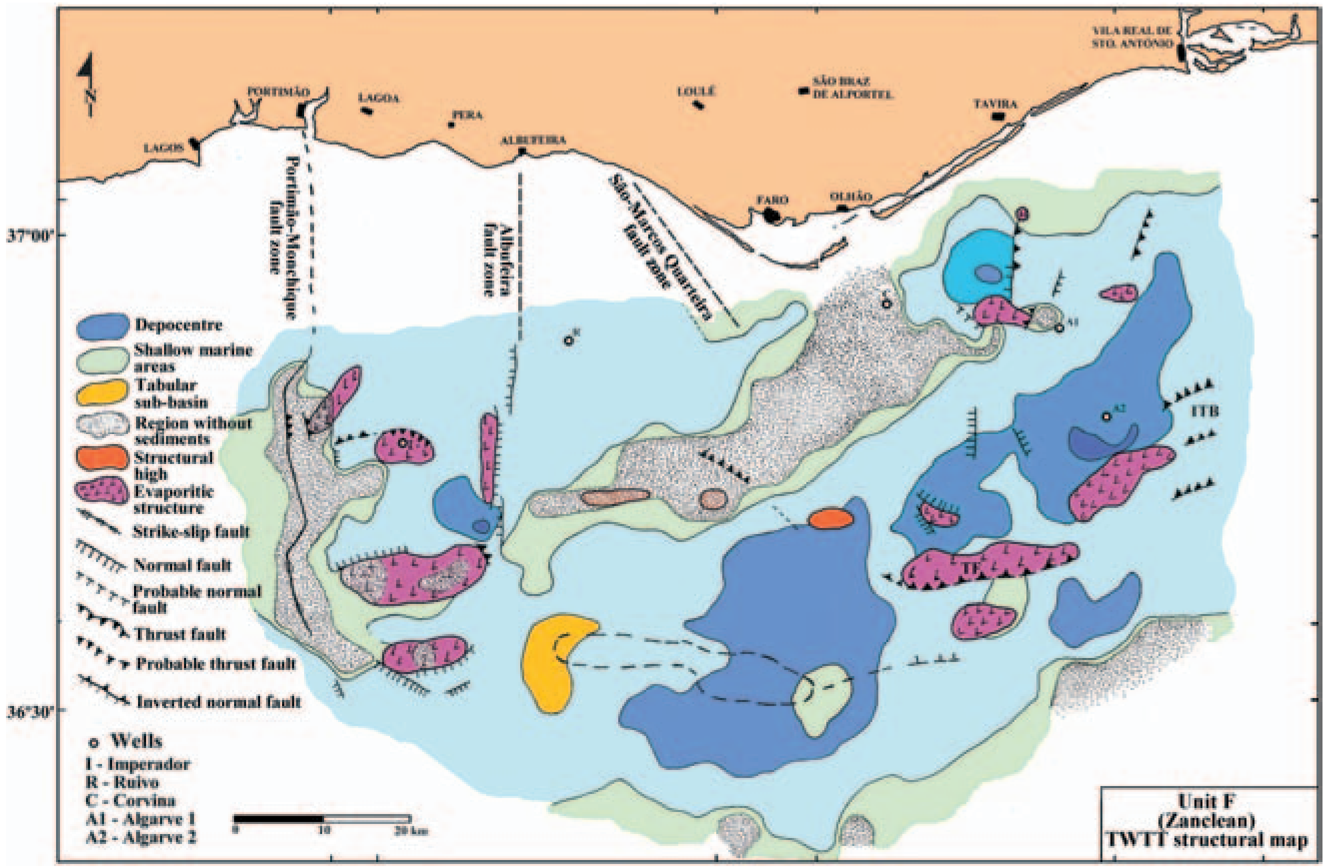


**Fig. 16** Unit F (Zanclean) TWTT structural map. TF, thrust front; ITB, imbricated thrust belt. Areas with no data are represented in white.

Azores–Biscay to the North Spanish Trough and Pyrenees (Srivastava *et al.*, 1990a, b; Roest & Srivastava, 1991); the movement was extensional in the King's Trough and compressive along the Pyrenees (Fig. 1a).

**2** The reactivation of the Azores–Gibraltar fracture zone, constituting again a plate boundary between Africa and Iberia (Chron 18, 42 Ma; Srivastava *et al.*, 1990a, b). Until the amalgamation of Iberia with Eurasia along the Pyrenean suture, Iberia moved as an independent plate from 42 to 24 Ma (Roest & Srivastava, 1991).

According to Maldonado *et al.* (1999) the transpressive movement between Iberia and Africa along the Gulf of Cadiz started at this time, with probable subduction of thinned Tethyan crust towards the south.

In the Algarve margin, this major compressive episode provoked strong tectonic inversion (uplift, folding, thrusting) and the generation of the important H5 unconformity (Fig. 11). The northern sector and the Guadalquivir Bank emerged. Westward, this intense instability was recorded by a very thin or absent sedimentary record (Hayes *et al.*, 1972) and by important uplift and amplification of the Gorringe Bank (Le Gall *et al.*, 1997).

After this intense compressive episode, the structures identified as active suggest that the tectonic regime became NNW–SSE to NNE–SSW moderately compressive, until the end of the Oligocene. In the southern border of Iberia, along a corridor that linked the central Atlantic and Mediterranean basins, a vast carbonate platform developed, with deposition of unit E1 in the Alentejo margin (Alves *et al.*, 2003), unit C in the Algarve margin (Lopes, 2002) and of unit UO-LM in the southwest Spanish margin (Maldonado *et al.*, 1999). In the Algarve margin, intense halokinesis occurred; in the Eastern Domain, gravitational

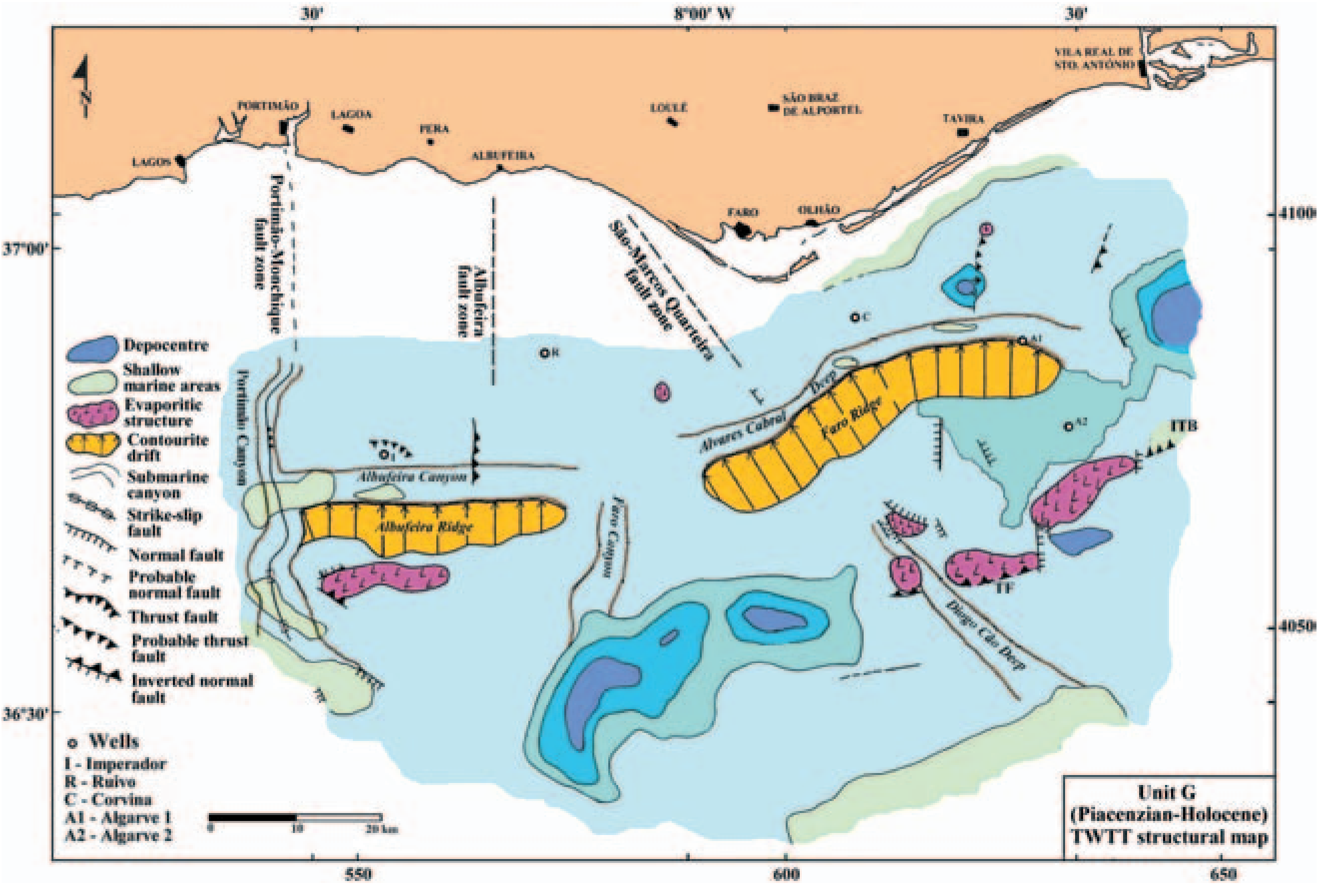


**Fig. 17** Unit G (Piacenzian to Holocene) TWTT structural map. TF, thrust front; ITB, imbricated thrust belt. Areas with no data are represented in white.

extension and concomitant compression in the distal and deeper parts of the basin were due to a general tilt of the margin.

During the Chattian to Aquitanian, in the Mediterranean area, the Algerian–Provençal Basin was developed (Sanz de Galdeano, 1990), acting as a back-arc basin relative to the subduction of Africa under the South Sardinian Domain or Alkapeca (Bouillin *et al.*, 1986), located between Africa and Eurasia (Fig. 18a).

#### Aquitanian to middle Tortonian

At the Chattian–Aquitanian transition (anomaly 6c; around 23 Ma), the plate boundary along the King's Trough–Azores–Bay of Biscay–Pyrenees became extinct and Iberia was integrated with the Eurasian plate. The plate boundary became located along the Azores–Gibraltar fracture zone (Srivastava *et al.*, 1990a, b; Roest & Srivastava, 1991; Fig. 11).

At this time, a widespread change to marine conditions in the western domains of the Peri-Tethyan platforms was probably related to the counterclockwise rotation of the Corsica–Sardinia block (Meulenkamp & Sissingh, 2003). A major sedimentary break at the Chattian–Miocene boundary is recognized in the Iberian Tertiary basins (Cunha, 1992a, b; Calvo *et al.*, 1993; Alves *et al.*, 2003). In the Gulf of Cadiz, the Chattian–Aquitanian boundary was also marked by an important regional unconformity (H4 in the Algarve margin; Lopes, 2002), followed by the deposition, respectively, of unit D (Algarve margin) and unit M1 (southwest Spanish margin; Fig. 11). By this time, the opening of the Algerian–Provençal Basin became accentuated, provoking the fragmentation of the South Sardinian Domain (Fig. 18a; Sanz de

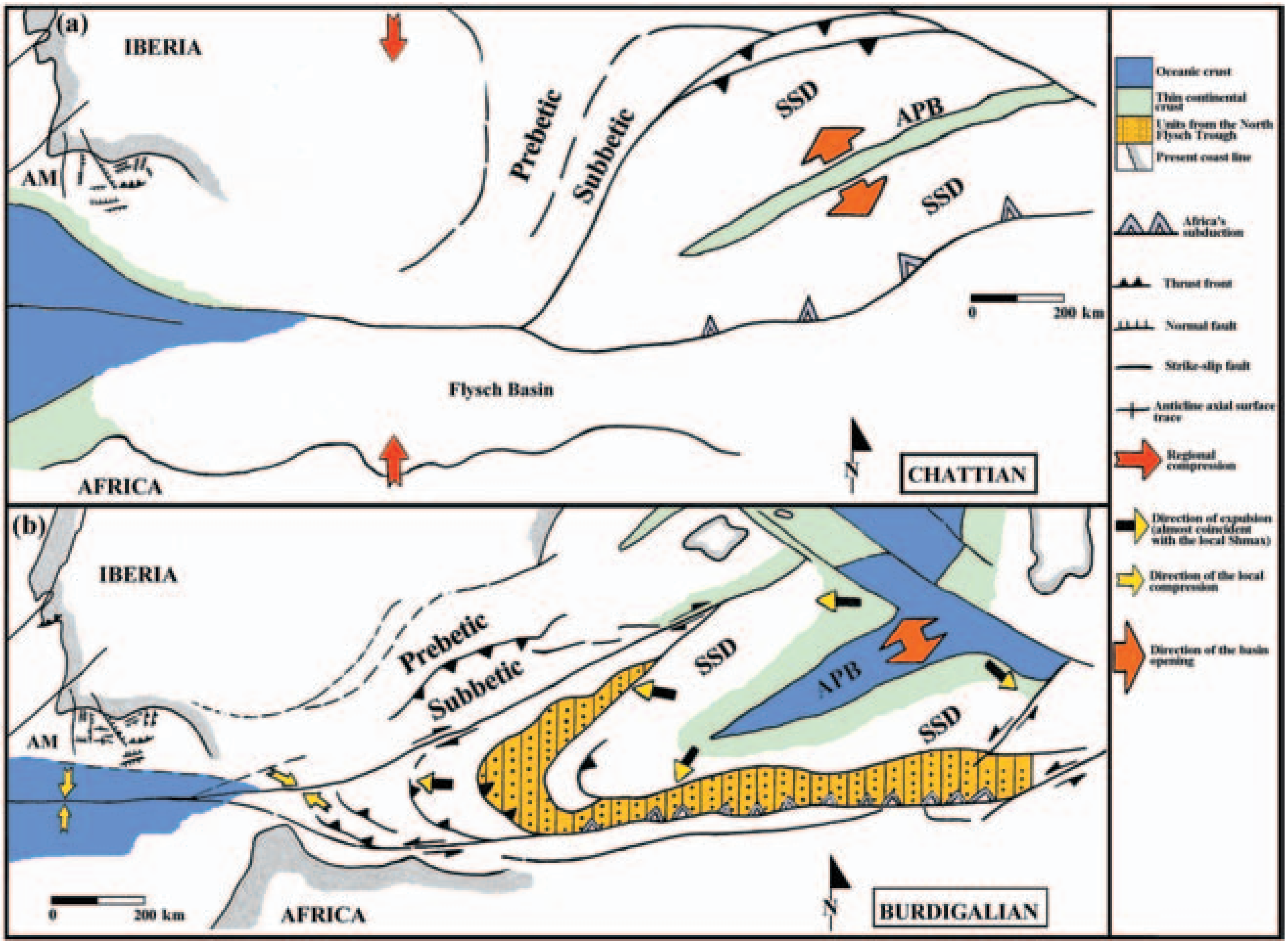


**Fig. 18** Synthetic reconstruction of the geodynamic evolution of the westernmost alpine Mediterranean area, during the (a) Chattian and (b) Burdigalian (modified from Sanz de Galdeano, 1990, 2000; Sanz de Galdeano & Vera, 1991; Sanz de Galdeano & Rodríguez-Fernández, 1996). AM, Algarve margin; APB, Algerian-Provençal basin; SSD, South Sardinian Domain.

Galdeano, 1990; Sanz de Galdeano & Vera, 1991) and the expulsion towards the west-southwest of one of its constituents, the Alboran Domain (Andrieux *et al.*, 1971; Durand-Delga & Fontboté, 1980).

The South Sardinian Domain expulsion reached its climax during the Burdigalian (Hermes, 1985), reflected by significant compressive effects in the sedimentary cover of the South Iberian and North African continental margins, leading to the formation of the Rift and Betic External Zones (Fig. 18b). The Sub-Betic Zone was compressed by the western movement of the Internal Zones and the North Betic Strait appeared, linking the Atlantic to the Mediterranean Sea (Sanz de Galdeano & Vera, 1991). In the most active sector of this chain-front basin (Betic trough), with migration towards the north-northwest, large volumes of allochthonous masses were deposited. According to Sanz de Galdeano & Rodríguez-Fernández (1996), the main displacement of the Internal Zones ended in the early Langhian. In consequence of the Internal Zones' emplacement, progressive lithospheric delamination of the African plate provoked the extensional collapse of the Alboran Sea (Platt & Vissiers, 1989; Maldonado *et al.*, 1999).

### Late Tortonian to Holocene

A fourth episode of major regional change in palaeogeography and tectonic setting occurred in

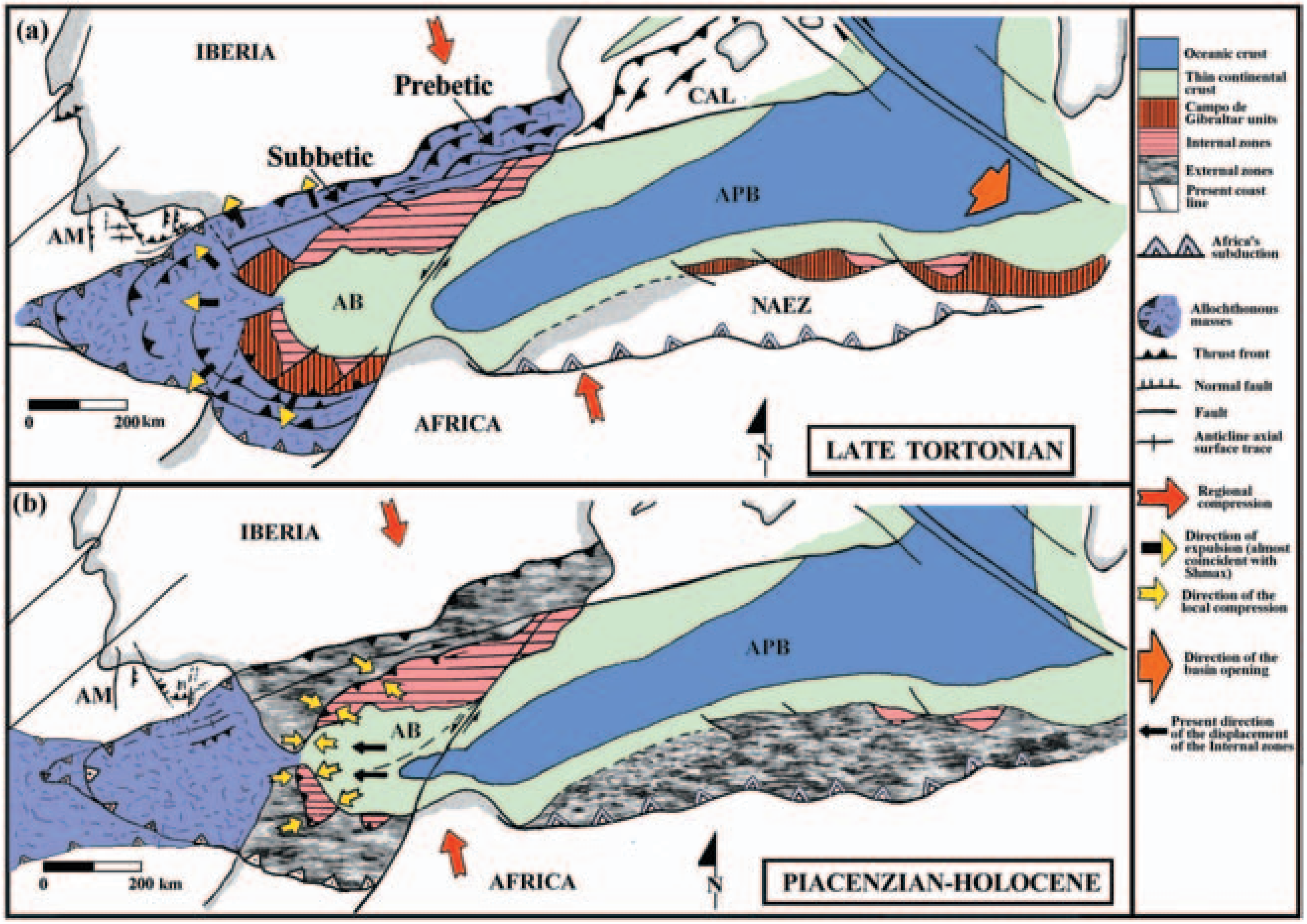


**Fig. 19** Synthetic reconstruction of the geodynamic evolution of the westernmost alpine Mediterranean area, during the (a) late Tortonian and (b) Piacenzian to Holocene (modified from Sanz de Galdeano, 1990, 2000; Sanz de Galdeano & Vera, 1991; Sanz de Galdeano & Rodríguez-Fernández, 1996). AB, Alboran basin; AM, Algarve margin; APB, Algerian–Provençal basin; CAL, Cadiz–Alicante line; NAEZ, North African External Zones.

the Tortonian, around 9–8 Ma, affecting the majority of the domains of the African–Eurasian convergent plate boundary zone. The resultant modifications included enhanced uplift and emergence of large parts of western and central Europe in association with the end of sedimentation in the northern Alpine foreland (Meulenkamp & Sissingh, 2003). It coincided with a change in the direction of convergence from north-northwest to northwest between Africa and Eurasia and led to the development of the Gibraltar Arc. Inversion tectonics became active in the interior of the Iberian plate in the Spanish Central System (Vicente *et al.*, 1996) and in the Portuguese Central Range (Ribeiro *et al.*, 1990).

The middle Tortonian highy compressive event, with $Sh_{max}$ oriented NNW–SSE, affected the whole Gulf of Cadiz and Betic areas (Sanz de Galdeano, 1990; Sanz de Galdeano & Vera, 1991; Sanz de Galdeano & Rodríguez-Fernández, 1996; Maldonado *et al.*, 1999) and is recognized by an important unconformity (H3 reflector, in the Algarve margin; unconformity BFU, in the southwest Spanish margin).

This event coincided with the last major radial expulsion of the External Zones (Prebetics and Flysch Basin, coeval with the stretching of the Internal Zones); the North Betic Strait became restricted to the western sector of the Betic trough (Sanz de Galdeano & Vera, 1991; Fig. 19a) and most of the Betic Neogene basins were developed (Sanz de Galdeano & Vera, 1992). It led to the emplacement, in the Southern Iberian margin and in the central Gulf of Cadiz, of an accretionary prism (Guadalquivir Allochthonous; Gràcia *et al.*, 2003)

(Figs 10 & 19a) where, because of imbricating thrusts with low-angle detachments, Mesozoic and Cenozoic fragments of the Betic margin were included (Bonnin *et al.*, 1975; Lajat *et al.*, 1975; Malod, 1982; Sanz de Galdeano, 1990; Flinch *et al.*, 1996; Maldonado *et al.*, 1999; Maestro *et al.*, 2003). Large masses of Triassic–Hettangian evaporites, tectonically incorporated, were responsible for the halokinesis in the central part of the gulf since the Messinian (Flinch *et al.*, 1996). Gravity processes were largely responsible for the migration of the allochthonous mass towards the Horseshoe and Seine abyssal plains (Gràcia *et al.*, 2003; Fig. 1).

The Tortonian event was also marked by the arrival of the Guadalquivir Allochthonous front to the southeast Algarve margin; its progression towards the interior may have been inhibited by the Guadalquivir Bank. Intense halokinesis and inversion tectonics were also recorded. In the southwest Iberian margin, this phase of intense instability was responsible for some vertical development of the Gorringe Bank (Le Gall *et al.*, 1997).

During the late Tortonian and Messinian, the widespread compressive regime led to the emergence of a great part of the Betic Range, coeval with an important sea-level fall (Haq *et al.*, 1987). The straits between the Betics and Rif were closed (Sanz de Galdeano, 1990), which led to the 'Mediterranean salinity crisis' (e.g. Maldonado & Nelson, 1999). In the west sector of the Betic trough, clockwise rotation of the depocentres was coeval with the development of the Guadalquivir Basin (Sierro *et al.*, 1996; Fig. 1). In the far eastern Algarve basin, onshore (Cachão, 1995) and offshore, an increase in subsidence and a migration towards the northeast of the depocentre were recorded. The sedimentary units that can be related to this tectonic phase are units B, C and D in the Guadalquivir Basin (Sierro *et al.*, 1992a, b, 1996), units M2–M3 in the southwest Spanish margin (Maldonado *et al.*, 1999) and unit E in the Algarve margin. According to Alves *et al.* (2003), the third Cenozoic deformation event affecting the Alentejo margin relates to late Tortonian–Zanclean tectonics and is responsible for the initiation of the modern Setúbal and São Vicente submarine canyons (Fig. 1).

#### Zanclean

By the late Messinian, $Sh_{max}$ became oriented roughly N–S (Phillip, 1987, in Maldonado & Nelson, 1999), a transtensional regime became dominant in the Betic range and a connection between the Atlantic and Mediterranean through the Gibraltar Strait was opened. This opening, coeval with a significant increase in subsidence (Maldonado & Nelson, 1999; Maldonado *et al.*, 1999), allowed the establishment in the Zanclean of the marine hydrodynamic setting that has continued to the present (Malod, 1982). North of the Gibraltar axis, sedimentation was controlled by halokinesis coeval with high subsidence; south of the Gibraltar axis, sedimentation continued in the same style as in the latest Miocene.

During the Zanclean, coeval with a eustatic sea-level high (Haq *et al.*, 1987), the Gulf of Cadiz was dominated by the incursion of saline Mediterranean water and the sedimentary regime was characterized by the formation of deposits of deep-currents and contourites (Nelson *et al.*, 1993; Maldonado & Nelson, 1999). Ongoing compressive strike-slip activity of N20−40°E-trending faults is documented in the eastern Betics (Andeweg & Cloetingh, 2001). In the southwestern Iberian border, the southwest Spanish margin unit P1 (Maldonado *et al.*, 1999) and the Algarve margin unit F were deposited (Fig. 11). In the Algarve margin, the old depocentres underwent progressive infill. A N–S to NNW–SSE oriented $Sh_{max}$ is suggested by the strike and type of syn-sedimentary faults.

In mainland Portugal, during the late Tortonian to Zanclean, endorheic alluvial fans developed along active NNE–SSW indent-linked strike-slip faults and NE–SW reverse faults (Cunha, 1992a, b; Cunha *et al.*, 2000), controlled by intense NNW–SSE crustal shortening (Ribeiro *et al.*, 1990); exorheic drainage systems were developed only at the transition to the more humid conditions of the Piacenzian.

#### Piacenzian to Holocene

The Piacenzian, Gelasian and the Quaternary (Fig. 19b) are represented by units P2 and Q/P in the southwest Spanish margin and by unit G in the Algarve margin. The spatial distribution of these deposits was controlled by a complex interplay between sea-level changes, sediment supply and variation in the speed of marine currents (Nelson *et al.*, 1993, 1999; Rodero *et al.*, 1999).

Present-day seismicity indicates that the majority of the tectonic structures are still active (Cabral, 1995), controlled by complex dextral slip along the crustal segment between the Gorringe Bank and the Gualdalquivir basin (Maestro *et al.*, 1998). A high $Sh_{max}$, acting obliquely to the western Portuguese continental margin, is interpreted by Ribeiro *et al.* (1996) as reactivating this passive margin, with the nucleation of a subduction zone in the Gorringe Bank (Fig. 1), propagating northward along the base of the continental slope.

## CONCLUSIONS

The position of Iberia, located at a critical point on active plate boundaries throughout the Late Cretaceous and Cenozoic, provides a setting in which the relationship between the changing plate boundary conditions and the tectono-sedimentary processes is relatively direct. Several tectonically controlled breaks in deposition, induced by the increasing effects of African–Eurasian convergence, occurred during the regional differentiation in basin development and depositional setting in the Algarve margin; their timing is similar to those identified in adjacent areas.

Six tectono-sedimentary phases have been reported: (i) late Campanian to middle Eocene, (ii) middle Eocene to Oligocene, (iii) Aquitanian to early Tortonian, (iv) late Tortonian to Messinian, (v) Zanclean and (vi) Piacenzian to Holocene. Their sedimentary character changed through time, from carbonate to siliciclastic, and they are widely involved in the polyphase structures of the different tectonic domains. The increase in the siliciclastic content may be related to the concomitant growth of the land mass, reflecting the impact of a large-scale, tectonically induced inversion process.

Evaporitic structures occur mainly in the Western Central and Eastern Domains of the Algarve margin, related to major structural lineaments. Thin and thick-skinned thrusts, orientated E–W to ENE–WSW, and N60°E imbricate thrusts are concentrated in the Eastern Domain and they generally exhibit a southward or southeastward vergence. This tectonic signature is attributed to the proximity of the Betic Orogen and the Guadalquivir Allochthonous front, and to the São Marcos–Quarteira fault zone that acts as a buttress fault to the westward propagation of the compression of the Gibraltar Arc.

An important role in the tectono-sedimentary evolution was played by Triassic–Hettangian evaporites, which acted as a major detachment during the extensional and compressional stages and generated both salt structures and salt-withdrawal sub-basins. From the wedge-shaped geometry of the sedimentary packages in the salt-withdrawal sub-basins between the salt structures, major halokinetic activity is likely to have occurred during the middle Eocene to Oligocene and the late Tortonian to Messinian; halokinesis was limited during the Aquitanian to earlier Tortonian and later decreased. During the middle Eocene to Oligocene phase, widespread halokinesis was generated by a moderate compressional reactivation of basement-related structures. The progressive basement graben inversion in the Eastern Domain, with uplift and tilting of the northern sector of the margin, led to the gravity gliding of the sedimentary cover above a salt detachment layer. Folds and the thrust front were generated downslope coeval with extension upslope. Southeastward, N60°E-trending imbricated thrust faults were induced by the basement contraction.

A generalized subsidence increased during the Cenozoic. The Paleogene was characterized by fault/salt control and flexure, leading to the formation of numerous and widespread depocentres. Since the middle Tortonian, the structural control exerted by the northern border of the basin and by the Guadalquivir Bank (in the south) was probably caused by the NW–SE to NNW–SSE compressive regime. This allowed the development of a strongly subsiding N60°E-trending basin, with increasing flexure of the margin; large subsidence in the Guadalquivir Basin, located northeastward along this axis, was coeval.

In summary, the main compressive structures were: the E–W to ENE–WSW thrust front; N60°E imbricate thrusts; E–W anticlines; NNE–SSW reverse faults; N40°W thrusts. Normal fault systems were also identified, with development of half-grabens oriented N–S to NNE–SSW; N40°E; N60°E; E–W; N40°W. The coeval development of compressive structures and normal fault systems is considered a consequence of:

**1** Paleogene horizontal migration of evaporites and the development of a gravity gliding structural style controlled by the inversion of the basement structures related to the convergence of Africa and Eurasia along the Azores–Gibraltar fracture zone (transpressive regime);

**2** Neogene horizontal migration of evaporites into the rising salt structures, convergence of Africa and Eurasia along the AGFZ (transpressive regime), and the westward migration of the Gibraltar Arc, causing a radial trajectory of $Sh_{max}$ around it.

The interpretation of the tectono-sedimentary features of the Algarve margin contributes to the understanding of the geodynamic evolution of the Gulf of Cadiz, primarily controlled by the enhanced coupling of the African and Iberian plates. A generalized compressive tectonic regime can be recognized, with two highly compressional phases that occurred in the Lutetian and in the Tortonian.

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