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THE PALEOGENE OF THE ALGARVE MARGIN: EVIDENCE FROM MULTICHANNEL SEISMIC DATA

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Key words: Paleogene, Algarve margin, tectono-sedimentary units, salt tectonics, multi-channel seismics.

ABSTRACT

The Paleogene of the Algarve Margin is documented, based on multichannel seismic (MCS) data interpretation. Two tectono-sedimentary phases, late Campanian to middle Eocene and middle Eocene to Oligocene in age, are reported, separated by main compressive tectonic events related to the Africa-Eurasia convergence. Triggered by regional compressive tectonics that affect the basement, the Upper Triassic-Hettangian evaporites played an important role in the tectono-sedimentary evolution of this margin by localizing both extensional and thrust detachments and generating both salt structures and salt-withdrawal sub-basins. During middle Eocene and Oligocene times, the 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.

INTRODUCTION

The Algarve margin, in the southwestern Iberia, is located on the northern border of the Gulf of Cadiz (Fig. 1), e.g. at the eastern end of the Azores-Gibraltar fracture zone (AGFZ) which forms a difuse transpressional plate boundary between the Iberian and African plates (Sartori *et al*., 1994). Its intricate geodynamic evolution, particularly during the latest Cretaceous and Cenozoic times, results from the convergence between Africa and Iberia along the eastern segment of the AGFZ (Dewey *et al*., 1989; Srivastava *et al*., 1990 a, b), together with the westward migration of the Gibraltar Arc front (e.g. Sanz de Galdeano, 1990; Ribeiro *et al*., 1990; Gràcia *et al*., 2003).

The seismic stratigraphy and some structural features of the Algarve margin were previously considered by Mougenot (1989) and Terrinha (1998a,b). Later, from a detailed interpretation of the available seismic, gravity and seismological dataset, the Cenozoic history of the Algarve margin was more precisely defined (e. g. Lopes, 2002; Lopes *et al*., 2006).

The main goal of the present paper is to summarize the late Cretaceous to Aquitanian tectono-stratigraphic features of the Algarve margin, as evidenced from oil-industry multichannel seismic (MCS) data.

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METODOLOGY

The dataset comprises a network of sixty four non-migrated MCS reflection profiles (100 x 80 km) located between Portimão and Vila Real de Santo António (36° 20'-37° 00' N, 7° 20'-8° 40' W), covering an area of 7700 km^2 in the central and eastern sectors of the margin (Fig. 2). Six main Cenozoic seismic units, with internal subunits, are recognized from seismic data interpretation, following the methodology of Mitchum and Vail (1977) and Mitchum *et al.* (1977). From the Upper Cretaceous to the Holocene, the seismic units are referred to as B to G and their corresponding boundaries are labelled as reflectors *H6* to *H1* (Fig. 3). Their ages are constrained by 1) accurate biostratigraphic data from five oil exploration wells, as deep as 3 km, drilled in the central and eastern sectors of the Algarve margin, and named as follows: *Imperador*-1, 1976; *Ruivo*-1, 1975; *Corvina*-1, 1976; *Algarve*-1, 1982; *Algarve*-2, 1982; 2) calibration with an adjacent Spanish MCS profile (Maldonado *et al.*, 1999) that intersects the Portuguese seismic grid under study; 3) lateral correlation with the Guadalquivir Allochthonous front, dated to the middle to late Tortonian in an adjacent area (e.g. Gràcia *et al.*, 2003); and 4) correlation with dated unconformities, related to the Iberia main tectonic events in adjacent Portuguese basins (Cunha, 1992a,b; Pais *et al.*, 2000; Alves *et al.*, 2003).

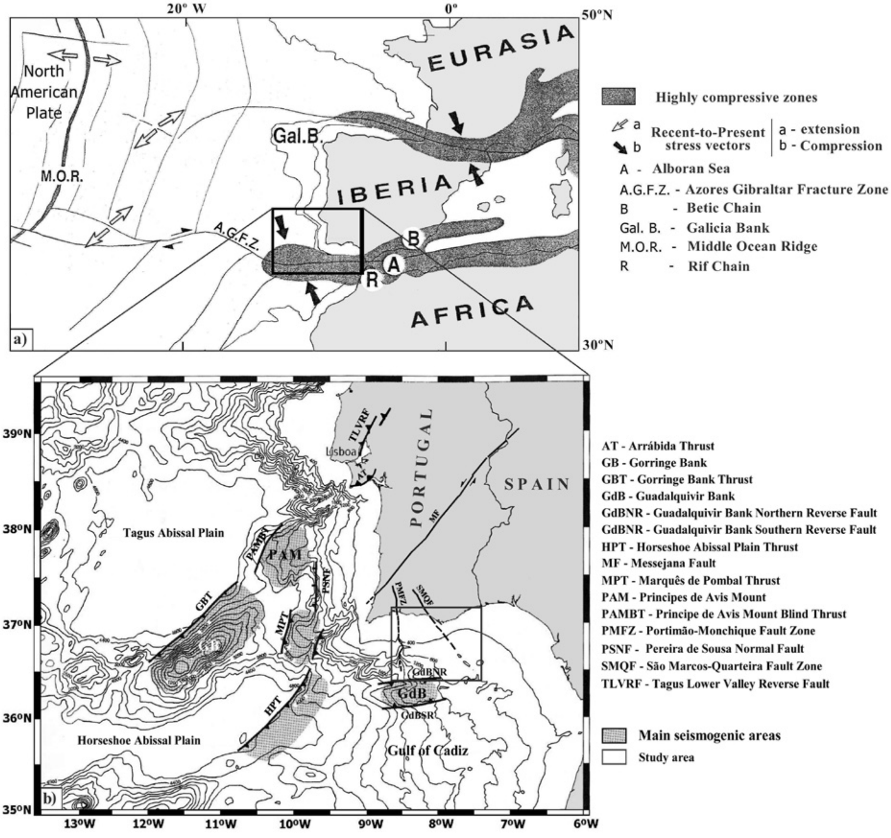

Figure 1: *a) Geological setting and present-day stress field at the periphery of the Iberian microplate (modifed from Olivet, 1996); b) Simplified bathymetric map of the SW Iberian margin, showing the main active faults and seismogenic areas (adapted from Ribeiro, 2005).*

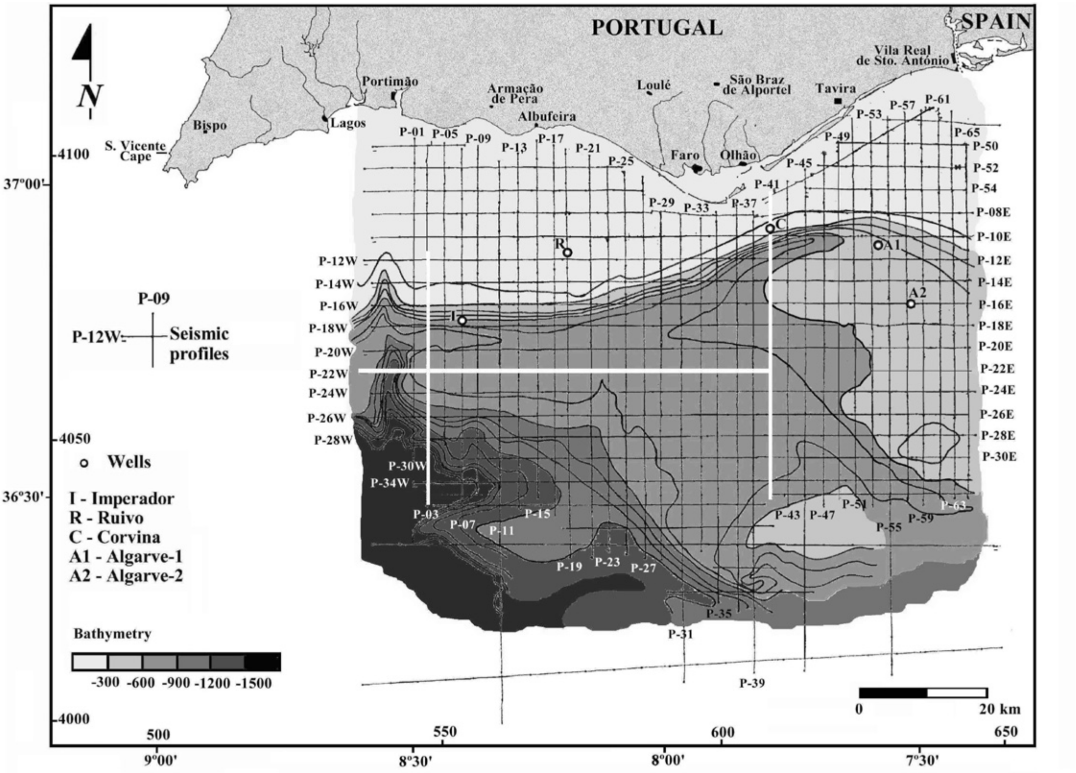

Figure 2.
Simplified bathymetric chart of the study area. The grid of the multichannel seismic (MCS) profiles and location of the five exploration wells are shown. The bold white lines indicate the location of the seismic profiles shown in Figure 5.

STRUCTURAL FRAMEWORK

The structural evolution of the central and eastern sectors of the Algarve offshore basin during Cenozoic times is controlled by major fault structures that determine three main tectonic domains, all bounded to the south by the N70°-trending Guadalquivir Bank (Figs. 1 and 4).

From W to E, this composite fault-controlled basinal area comprises the Western Central Domain, the Eastern Central Domain, and the Eastern Domain.

The narrow (25 km-wide) and N-S-trending Western Central Domain covers a nearly 1500 km^2 area limited to the west by the N-S striking Portimão-Monchique Fault Zone (PMFZ) and to the east by the N-S trending Albufeira anastomosing Fault Zone (ALFZ) (Figs. 4, 5a and 5b).

The Eastern Central Domain is a triangle-shaped area (1300 km^2) bounded to the west by the ALFZ and to the east by the N140°-striking São Marcos-Quarteira Fault Zone (SMQF) (Figs. 4 and 5b).

The Eastern Domain is more complex than the adjoining domains, and it forms an irregular structural depression (1800 km^2) dominated by compressive structures and the Guadalquivir Allocthonous front (Gràcia *et al*., 2003) (Figs. 4, 5b, 5c and 6).

UPPER CRETACEOUS TO AQUITANIAN TECTONO-SEDIMENTARY UNITS

The following sections characterise the main tectono-sedimentary units documented in the upper Campanian (?) to Aquitanian record of the Algarve margin (Figs. 3, 7 and 9).

4.1. Unit B (upper Campanian? - middle Eocene)

In the Algarve margin, the sedimentation started with the deposition of marls and sandstones, over a regional unconformity (H6 unconformity; Lopes *et al*., 2006) (Figs. 3, 5-7), followed by marine grey dolomites intercalated with marly limestones and micritic limestones, documented by wells data (Fig. 3) and corresponding to the seismic unit B. Seismic data show that this unit is better represented in the Eastern Domain where its thickness can be >0.4 sec TWTT. The unit is only recorded in some areas corresponding to E-W elongated synclines; some later erosion could have occurred, prior to the deposition of unit C (Fig. 7).

4.2. Unit C (midlle Eocene - Oligocene)

Seismic data show that an important regional unconformity (H5 unconformity; Lopes *et al*., 2006) (Fig. 3 and 8), related to a major tectonic event, marks the beginning of the middle Eocene to Oligocene phase. In the Western Central Domain of the Algarve margin, this is an important angular unconformity that truncates the pre-middle Eocene deposits (Figs. 3 and 5a). The middle Eocene to Oligocene phase was characterised by the extensive deposition of micritic

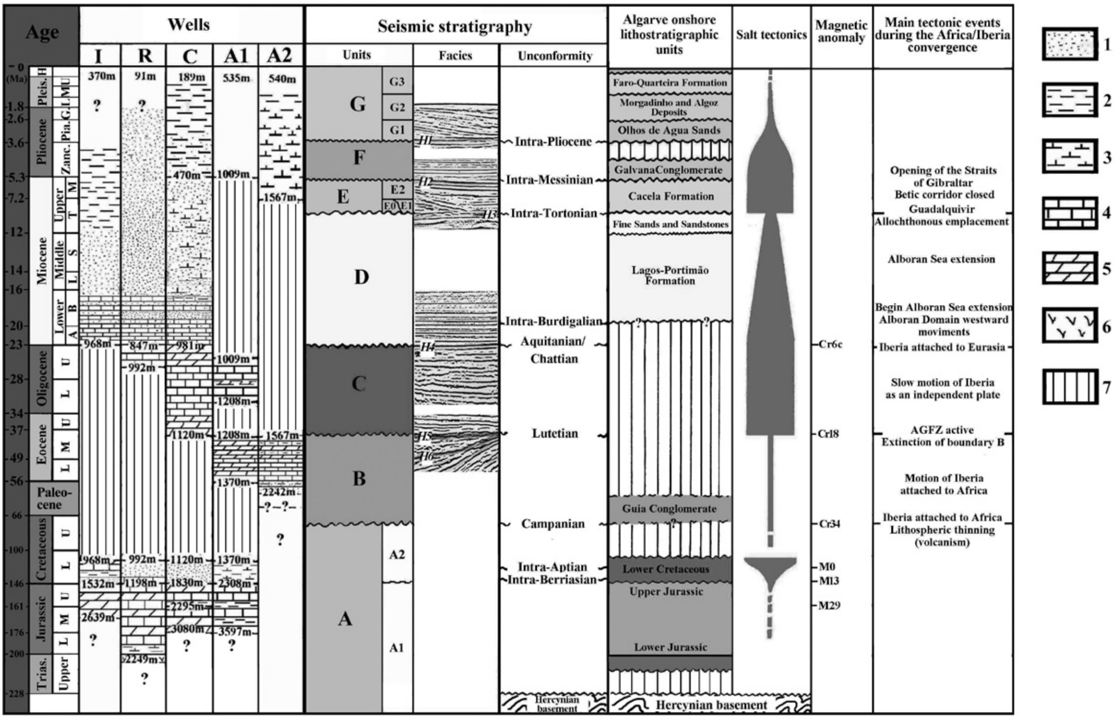

Figure 3. *Seismic stratigraphy, main unconformities and wells in the Algarve offshore margin.*
Wells: I - Imperador-1; R – Ruivo-1; C – Corvina-1; A1 – Algarve-1; A2 – Algarve-2. 1 – sands; 2 – clays; 3 – silts; 4 – limestones; 5 – dolomites; 6 – evaporites; 7 – hiatus.
Cenozoic seismic units and bounding unconformities are correlated with onshore lithostratigraphic units (Pais et al., 2000) and salt tectonics.
The tectonic events and relative motion of Iberia/Africa are correlated with the development of the seismic units. Numerical time scale from Gradstein et al. (2004).

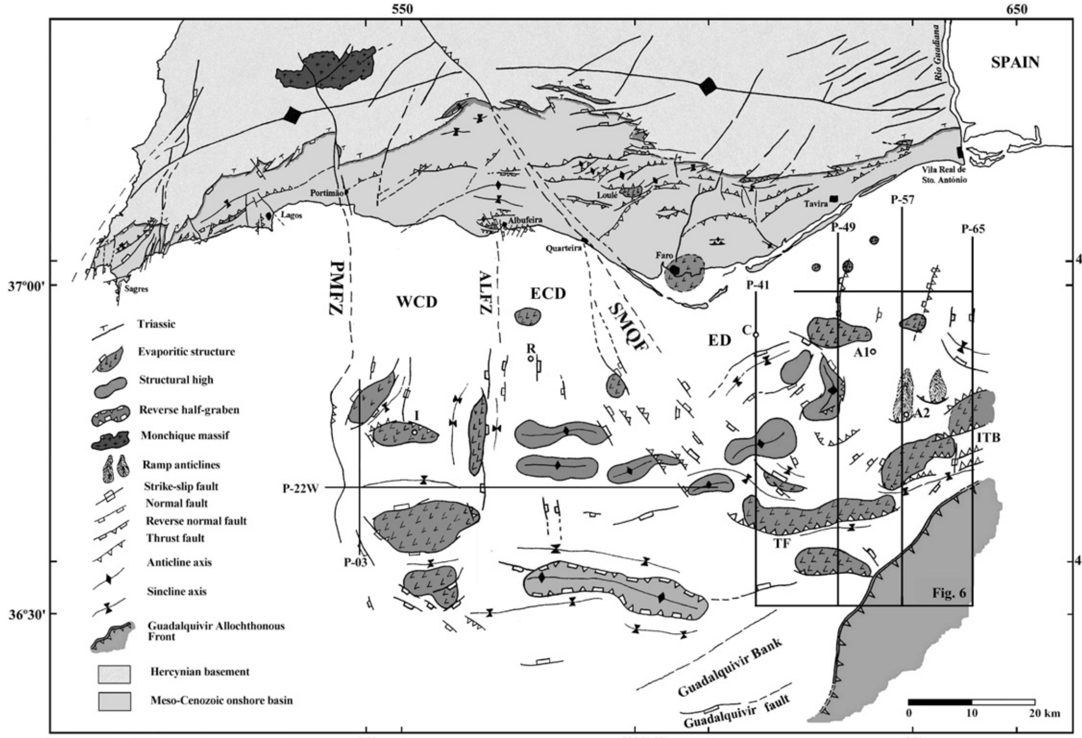

Figure 4.

Synthetic map of the main Cenozoic onshore and offshore structures. PMFZ – Portimão-Monchique Fault Zone; ALFZ – Albufeira Fault Zone; SMQF – São Marcos-Quarteira Fault Zone; TF – thrust front; ITB – imbricated thrust belt (modifed from Lopes et al, 2006). Solid lines: seismic profiles shown in this paper and location of Figure 9.

limestones (seismic unit C; Fig. 3), suggesting that a carbonate platform developed over the entire margin at that time. Although the thickness of Unit C is variable, it reaches more than 0.6 sec TWTT in half-grabens and foredeep basins mainly at the eastern Algarve margin (Figs. 5c, 6 and 9).

Seismic data show that the middle Eocene to Oligocene phase is expressed by intense and widespread halokinesis processes. 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 (Fig. 5b). In the northern sector of the Eastern Central Domain, a NE-SW flexural sub-basin was developed (Fig. 9). In the Eastern Domain gravity gliding of the cover was associated with uplift and tilting of the northern sector of the margin (Figs. 5c and 6). The glide tectonics resulted in stretched (upslope) domains and adjoining compressive (downslope) areas. The extensional sector was dominated by the development of a N60ºE-striking listric normal fault system, bounding northwesterly-tilted half-grabens. The contractional sector was characterised by the development of salt anticlines and turtle structures, in addition to an ENE-WSW 20 km-wide thin-skinned imbricate thrust front. A NNE-SSW steep westerly-dipping extensional fault system was also active (Fig. 9).

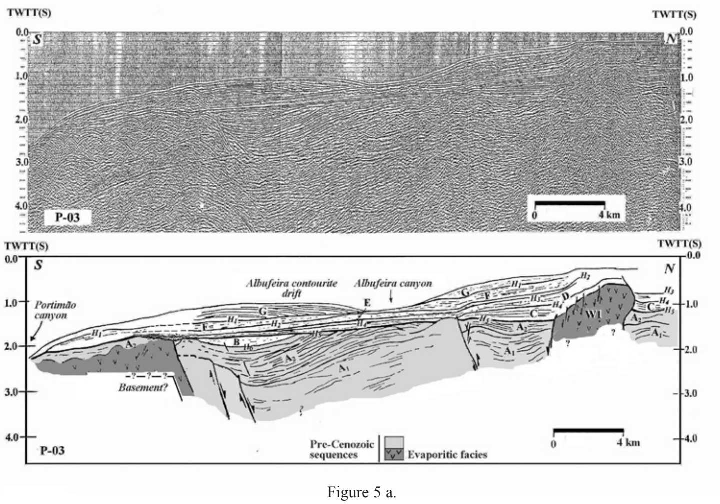

Figure 5 a.
P-03 seismic profile and interpretation (see Figure 2 for location) (from Lopes et al., 2006).

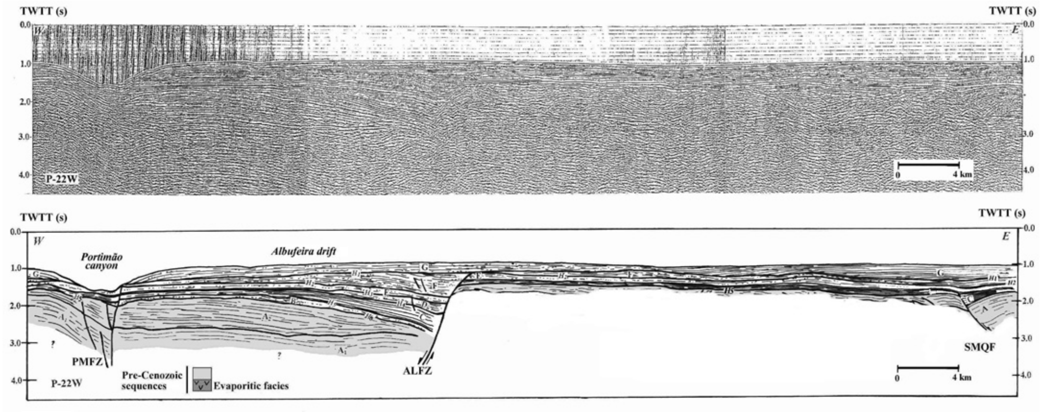

Figure 5 b.
P-22W seismic profile and interpretation (see Figure 2 for location). PMFZ – Portimão-Monchique Fault Zone; ALFZ – Albufeira Fault Zone; SMQF São Marcos-Quarteira Fault Zone (from Lopes et al., 2006).

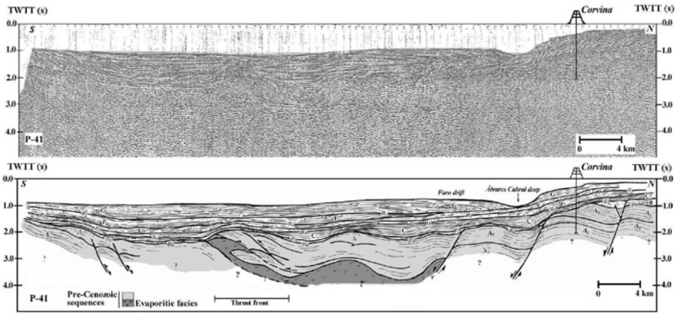

Figure 5 c.
P-41 seismic profile and interpretation (see Figure 2 for location) (from Lopes et al., 2006).

DISCUSSION

The geodynamic position of Iberia, at a critical point on active plate boundaries during late Cretaceous and Cenozoic times, provides a setting in which the type of relationships between the changing plate boundary conditions and the tectono-sedimentary processes can be addressed. Induced by the increasing African-Eurasian plate convergence, several tectonically-controlled breaks in deposition occurred during the regional differentiation in basin development and depositional setting in the Algarve margin, as documented on seismic data.

In the southwestern border of Iberia (Gulf of Cadiz), after a Campanian highly compressive episode (ca. 80 Ma; e.g. Mougenot, 1981; 1989), a upper Campanian to middle Eocene sequence was deposited irregularly, under a moderate phase of shortening, with significant facies variations, as documented by the Unit B in the Algarve margin and the unit UK-UE in the SW Spanish margin (Maldonado *et al*., 1999).

After this moderate phase of shortening, a more intense compressional strain, probably middle Lutetian in age, provoked strong positive inversion, with uplift, folding, thrusting and generation of the important unconformity that truncated pre-Unit C formations (H5 unconformity; Lopes *et al*., 2006) (Fig. 8).

During the Lutetian to Oligocene phase, a carbonate platform was developed over the northern margin of the Gulf of Cadiz, as documented by the Unit C in the Algarve margin and the unit UO-LM in the SW Spanish margin (Maldonado *et al*., 1999). Moreover, a significant structural rearrangement occurred over the studied area, synchronously with

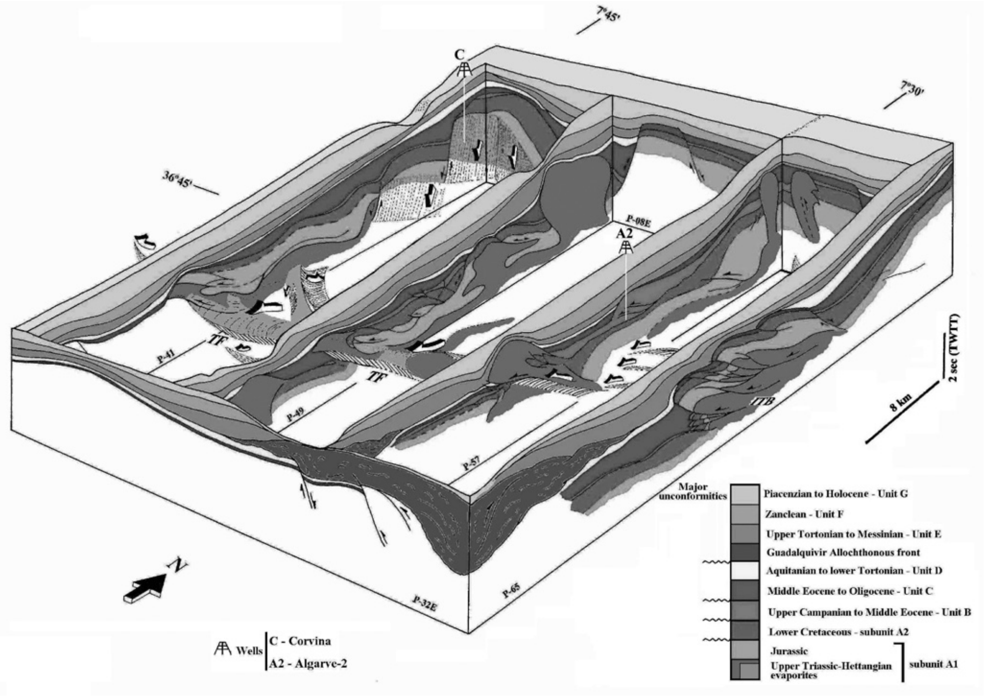

Figure 6.
3-D diagram of the eastern part of the Eastern Domain (ED), showing the seismic units and their geometrical relationship to tectonic structures.

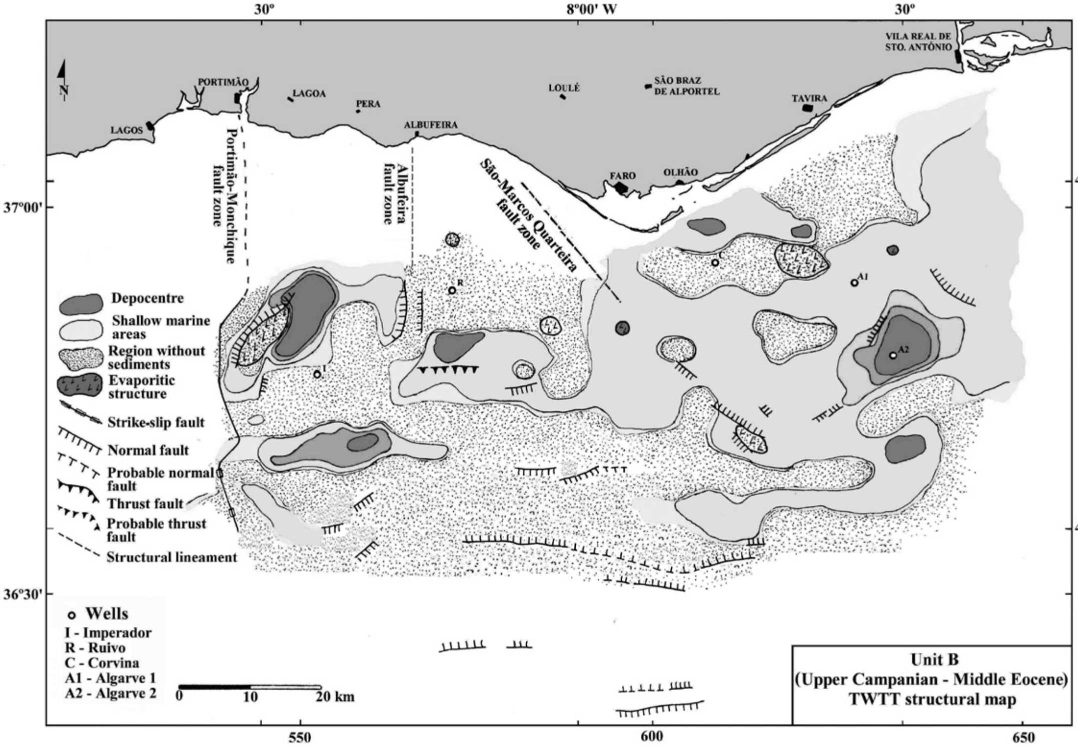

Figure 7.
Unit B (Upper Campanian to Middle Eocene) TWTT structural map (modified from Lopes et al., 2006).

halokinetic activity. In the Central Western Domain, salt bodies were intruded along N40º, N-S and E-W trending structures. Salt withdrawal from interdiapiric areas into these growing salt walls resulted in the formation of salt-withdrawal sub-basins with localised subsidence. The tectonic style in the Eastern Domain seems to result from both gravity gliding above a salt detachment layer and the inversion of a basement-rooted graben (Fig. 6). We propose that the gravity gliding of the sedimentary cover was associated with uplift and tilting of the northern sector of the margin, enhanced by the inversion of previous distensive structures (analogue of the Tertiary basin inversion and tilt of the Southern North Sea; Conward and Steward, 1995). Glide tectonics were responsible for the development of coeval and adjoining extensive (upslope) and compressive (downslope) domains (Fig. 10). The extensional area is characterised by thin-skinned tectonics marked by listric normal faults striking N60o and resulting in half-grabens. These fault-bounded depocentres are filled by the wedge-shaped Unit C that thickens towards the boundary faults. The contractional area is characterised by syn-sedimentary folds, showing anticlines and synclines, passing southwards into the thin-skinned E-W to ENE-WSW thrust front, with salt injection along the thrust plane, and associated frontal sub-basins. This type of folds and associated thrust front might have formed along salt pinch-out. In agreement with structural works elsewhere (Letouzey *et al*., 1996), emphasis is put here on the dominant role played by the basinward salt pinch-out in forming frontal contractional structures by increasing frictional resistance at the base of the sedimentary pile, thus preventing further basinward translation of the sediments.

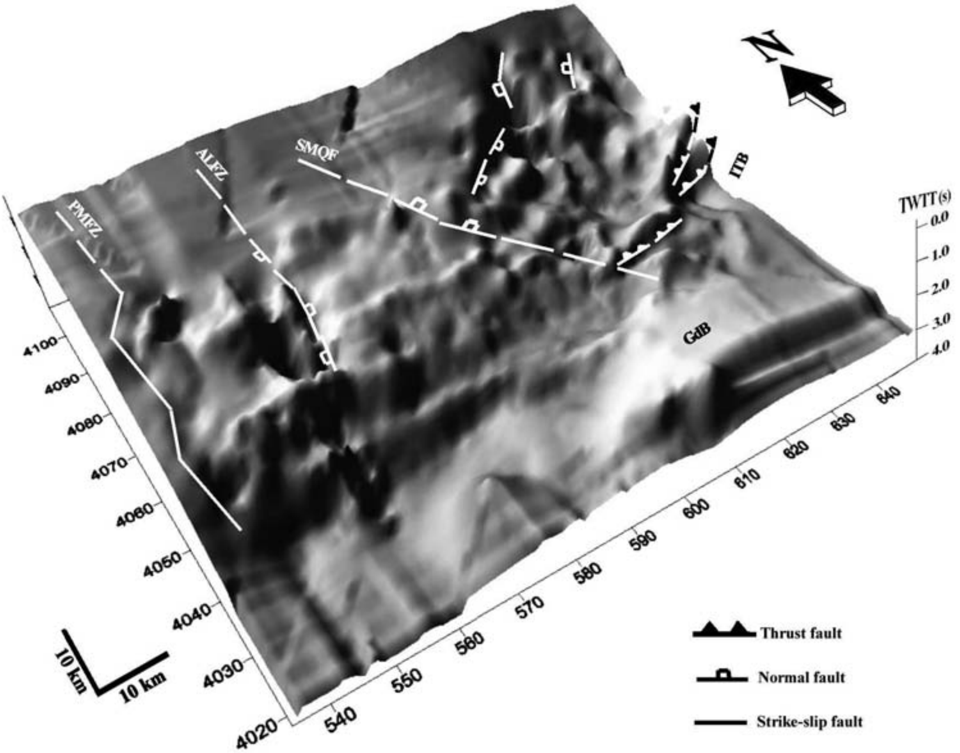

Figure 8.
3-D isobath map (TWTTs) of the H5 unconformity. GdB – Guadalquivir Bank. PMFZ – Portimão-Monchique Fault Zone; ALFZ – Albufeira Fault Zone; SMQF – São Marcos-Quarteira Fault Zone; TF – thrust front; ITB – imbricated thrust belt.

CONCLUSIONS

From the late Cretaceous to Aquitanian, two main tectono-sedimentary phases have been reported in the Algarve margin, based on MCS data, further calibrated by borehole stratigraphy: i) late Campanian to middle Eocene (Unit B), ii) middle Eocene to Oligocene (Unit C), bounded by main compressive tectonic events. These phases were characterized by the deposition of marine carbonates controlled by compressional deformation.

Triggered by the regional tectonics that probably also affected the basement, Upper Triassic-Hettangian evaporites played an important role in the tectono-sedimentary evolution by localizing both extensional and thrust detachments and generating salt structures and numerous and widespread fault/salt-withdrawal sub-basins.

During the Mesozoic, the Algarve margin was dominated by a distensive regime, recorded by graben-controlled sedimentation. However, in the middle Campanian, a significant shortening event started to develop thoughout these basins. From the late Campanian to middle Eocene, the tectonic signature is mainly represented by syn-sedimentary regional folding, the depocentres being restricted to E-W elongated synclines; this points to a N-S compressive regime along the Azores-Gibraltar fracture zone.

During middle Eocene and Oligocene, coeval development of compressive structures and normal fault systems, mainly in the Eastern domain, is interpreted as resulting from horizontal migration of evaporites and development of gravity glides controlled by the inversion of the basement

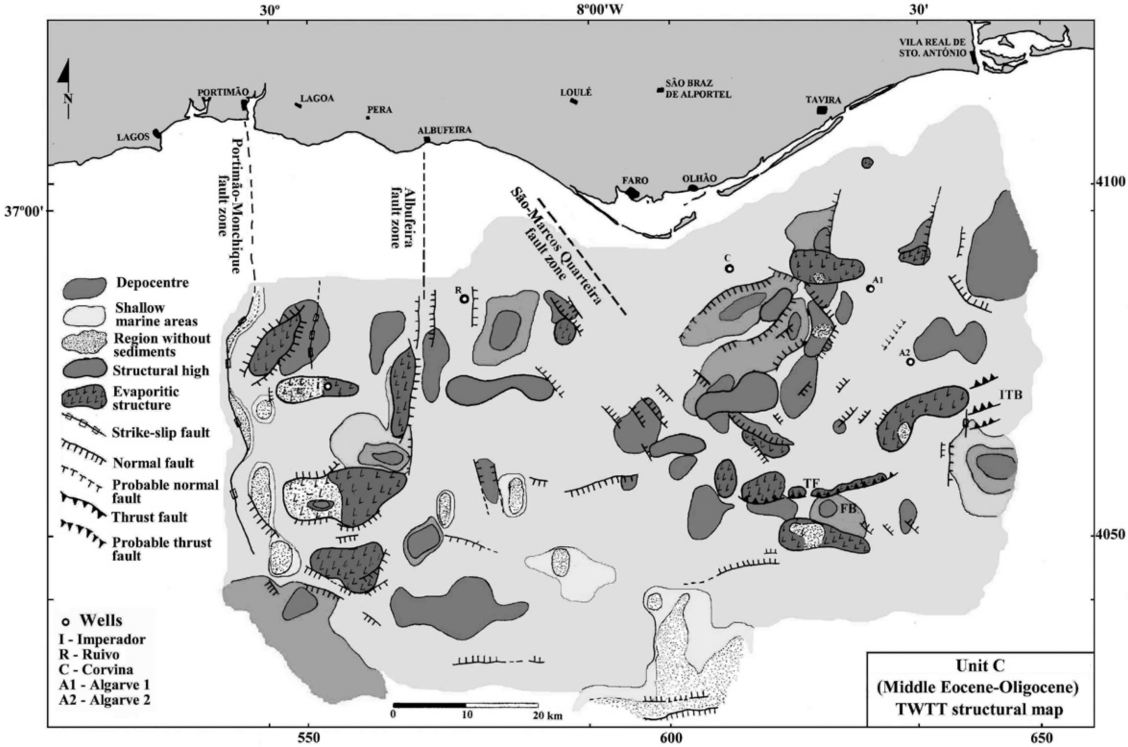

Figure 9.
Unit C (Middle Eocene to Oligocene) TWTT structural map. TF – thrust front; FB – foredeep basin; ITB – imbricated thrust belt (modified from Lopes et al., 2006).

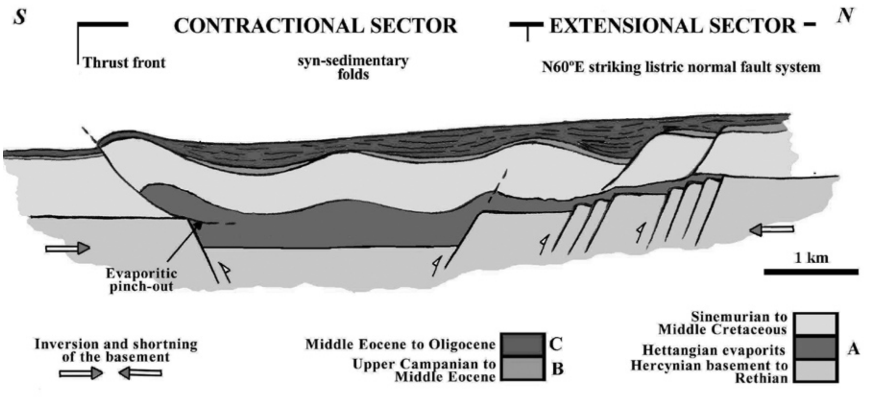

Figure 10.
Schematic tectonic reconstruction (North to South cross-section) of the Eastern Domain, based on the models of Conward and Steward (1995), and Letouzey et al. (1996) for the Southern North Sea.

structures, in relation with a transpressive regime along the Azores-Gibraltar fracture zone during the convergence of Africa and Eurasia.

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