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# Pliocene-Quaternary deformational structures in the eastern Algarve continental shelf, Gulf of Cadiz

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ABSTRACT

Evidences of tectonic deformation from the Pliocene to the Quaternary are evaluated on the northern Gulf Cadiz continental margin along the eastern Algarve continental shelf between the Guadiana River and Faro city, in a regional compressive context close to the Eurasia-Africa plate boundary. We studied an extensive set of 2D high-resolution seismic reflection profiles framed within previously published seismic-stratigraphic models. The seismic stratigraphic interpretation and regional correlation allow us to identify a major Middle Pleistocene (0.9–026 Ma) angular unconformity along the shelf, plus deformational structures affecting widespread depositional hiatuses in the Pliocene-Quaternary sedimentary units of the study area. Several deformation features indicate neotectonic activity: ENE-WSW to NE-SW thrusts moving pre-Middle Pleistocene shelf deposits and N-S to NW-SE folds and NNE-SSW to NNW-SSE high-angle normal faults affecting Middle to Upper Pleistocene shelf deposits. These structures are interpreted under the light of two major deformation phases that took place in the Algarve continental shelf. A first phase of Pre-Middle Pleistocene thrusting agrees with a dominant transpressive regime along the southwestern Iberian margin since the Tortonian, which is also recorded in the deep-water contouritic record of the southern Iberian margin, where compressional events caused intensification of the Mediterranean Outflow Water. A Middle to Upper Pleistocene tectonic phase is characterized by less intense deformation of the sedimentary cover involving individual structures (i.e., folds and faults), some of which remained active at least up to the Last Glacial Maximum. This more recent tectonic deformation is compatible with slowly uplifting trend recognized in the Portuguese mainland, and coetaneous diapiric reactivation that locally deformed Late Quaternary sediments along the southwestern Iberian margin. The study lends additional evidence of regional neotectonic activity producing Pliocene to Pleistocene deformation, and having ultimate implications for seismic hazard assessment, in offshore settings close to coastal population centers along the southern Portuguese coast.

## 1. Introduction

Convergent regimes along plate boundaries such as between the Eurasian and African plates result in diverse types of deformation. Strike-slip faulting with vertical movements, usually detected by lateral offsets of deposits, is quite common (e.g., Gràcia et al., 2012; Perea et al., 2012; Lafosse et al., 2017, 2020). These structures tend to exhibit along-axis structural variability, evidencing the occurrence of highly distributed active deformation (D'Acremont et al., 2014). Strike-slip faults may be associated with normal faults in transtensional settings (D'Acremont et al., 2014; Lafosse et al., 2017) or with thrusts, folds, pressure ridges, reverse faults and flower structures in transpressive settings (Gràcia et al., 2006; Perea et al., 2012; Moreno et al., 2016). The occurrence of both contractional (e.g. thrusts and folding) and extensional faults

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would suggest the influence of regional-scale tectonic processes (Barreca et al., 2018).

The inherited structures may be active in offshore areas, since they cut sedimentary units of Neogene to Late Quaternary ages (Gràcia et al., 2006; Maestro-González et al., 2008; Moreno et al., 2016). Some of these structures reach very recent stratigraphic intervals such as Late Quaternary lowstand surfaces (Perea et al., 2012), Holocene deposits (Ridente and Trincardi, 2006) or even the seafloor surface where they generate rectilinear seafloor scarps that point to present-day activity (Gràcia et al., 2012; Corradino et al., 2021) and could represent potential sources of large magnitude earthquakes (Gràcia et al., 2006).

The Gulf of Cadiz is crossed by the boundary between the Eurasian and African plates, or more precisely between the Iberia and Nubia subplates, where slow convergence has been underway since the Cenozoic (Sartori et al., 1994), causing the reactivation of previous extensional faults (Gràcia et al., 2003; Terrinha et al., 2009). The present-day regime along the plate boundary is characterized by compressional deformation (i.e. thrusts) passing laterally to the west to a narrow deformation band formed by strike-slip faults (Sartori et al., 1994; Terrinha et al., 2009; Zitellini et al., 2009; Bartolome et al., 2012), oblique to the direction of plate convergence.

The Algarve basin is located in the northwestern sector of the Gulf of Cadiz, north of the Africa-European plate boundary (Fig. 1a), where it is subjected to a present-day compressive regime (Zitellini et al., 2009). Regional-scale extensional to transtensional faults compartmentalized the Algarve Basin during the Mesozoic extension and induced salt tectonics (Terrinha, 1998; Matias et al., 2011; Ramos et al., 2017a), forming a variety of salt structures: diapirs, salt walls, domes and allochthonous salt bodies. The inshore Loulé and Faro diapirs (Davison et al., 2016) and the offshore Esperança Salt Nappe (Matias et al., 2011) are the most relevant salt structures (Fig. 1b). A Cenozoic tectonic inversion caused the reactivation of older inherited fault and fold systems due to plate convergence under compressional stress fields (Maestro-González et al., 2008; Ferranti et al., 2014; Lafosse et al., 2017) and the formation of synchronous extensional and thrust detachments along with abundant salt structures (Lopes et al., 2006; Ramos et al., 2017a).

Evidences of neotectonics activity have been reported from the emerged northern margin of the Algarve Basin to the deep realm of the Gulf of Cadiz. For example, diverse inshore features indicate the reactivation of pre-existing faults as strike-slip faults with a reverse component during the Pliocene to Quaternary (Terrinha, 1998; Ressurreição et al., 2011; Carvalho et al., 2012; Cabral et al., 2017). A long-term, slow tectonic uplift of the littoral zone (Cabral, 2012; Figueiredo et al., 2013) has been related with Quaternary movement of the faults (Figueiredo et al., 2019). Offshore, salt movements continued during the Pliocene-Quaternary, causing significant structural deformation of the overburdened sedimentary cover and locally affecting the present-day bathymetry (Matias et al., 2011). Finally, in the deep realm of the Gulf of Cadiz, active faulting is also inferred from diverse morphological (e.g. seafloor ruptures, scours, pockmarks and landslides) and tectonic indicators (e.g. en echelon and creep folds) (Gràcia et al., 2003; Terrinha et al., 2009).

The northern shelf of the Gulf of Cadiz represents a key area between

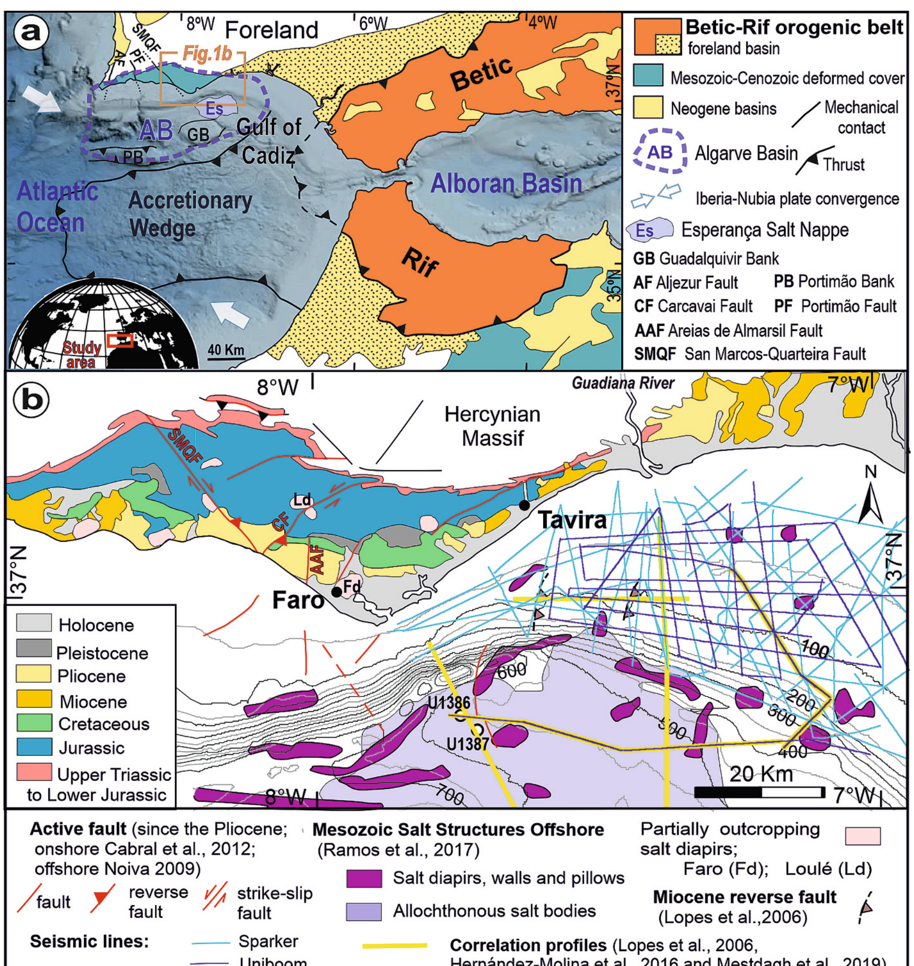


**Fig. 1.** a) Main tectonic domains of the Betic-Rif Orogen and associated Neogene basins. b) Geological map of the study area and location of seismic profiles (modified from Rodríguez-Fernández et al., 2015). IODP Exp. 339 sites shown as solid white circles.

the emerged inland and the deep water, harboring numerous evidences of neotectonics activity. However, there is a gap in our knowledge about the Algarve shelf, concerning the types of structures, occurrence of active faulting and timing of deformation during the Pliocene-Quaternary. Particularly, the offshore activity of inland faults has been deduced from Miocene-Lower Pliocene coastal deformation indicators (Noiva, 2009, Barreto et al., 2015), but fault activity has not been directly documented (Fig. 1b).

Based on the identification and age dating proposal of major unconformities, sedimentary units and tectonic structures are described in a proximal sector of the Algarve Basin, northern margin of the Gulf of Cadiz. The main objectives of this contribution are: (a) to characterize the styles of recent tectonic deformation in the shallow-water setting in close proximity to densely populated areas that could represent potential sources of large magnitude earthquakes.; and (b) to propose a model for the Pliocene-Quaternary geological evolution, considering the regional compressive regime and the influence of deep-rooted structures such as salt diapirs.

## 2. Regional setting

### 2.1. Geological framework and evolution of the Algarve Basin

The study area is located along the Algarve Basin in the western Gulf of Cadiz (Fig. 1a), close to the diffuse boundary between the Iberia and Nubia sub-plates (Sartori et al., 1994; Palano et al., 2015), southwest of the Iberian Peninsula. The Algarve Basin extends from the inshore to the offshore in the Gulf of Cadiz (Fig. 1a). In the foreland emerged area, the basement is composed by Palaeozoic rocks and a flysch sequence of slates and graywackes dating back to the Hercynian orogeny (Terrinha, 1998; Lopes, 2002; Terrinha et al., 2013). Offshore, the basin extends south of Portimão towards the Guadalquivir Bank, a basement high of Palaeozoic rocks (Fig. 1a). The Mesozoic sedimentary record includes continental siliciclastic and marine carbonate rocks deposited in a Late Triassic proto-basin (Terrinha, 1998). Evaporitic deposits (mainly halite) were deposited during the earliest Jurassic due to the occurrence of a marine incursion event (Matias et al., 2011; Davison et al., 2016). Cenozoic sedimentation comprises Miocene limestones and Pliocene to Pleistocene fluvial and marine detrital sediments (Terrinha, 1998; Lopes et al., 2006).

The evolution of the Algarve Basin comprises two major phases. The southwestern Iberian margin was formed during the Triassic to Jurassic extension and rifting that generated the Tethys Ocean due to the break-up of Pangea (Srivastava et al., 1990). As a consequence, NW-SE to N-S transfer regional faults —such as the Sao Marcos Quarteira Fault (SMQF), the Portimão Fault (PF) and Carcavai Fault (CF)— compartmentalized the Algarve Basin during the Mesozoic (Terrinha, 1998; Fig. 1). A later compressional phase from the Late Cretaceous to the present-day was due to N-S to NW-SE Iberia-Nubia convergence and development of the Betic-Rif orogenic arc from the Early Miocene onwards (Terrinha et al., 2009; Zitellini et al., 2009; Ramos et al., 2016; Fernàndez et al., 2019). The formation of the Betic-Rif mountain chains caused the development of Guadalquivir and Rharb Neogene foreland basins (Gràcia et al., 2003; Vergés and Fernàndez, 2012). The westward migration of the Betic-Rif orogenic system led to the formation of an accretionary wedge known as the "olistostrome unit" which deformed Late Mesozoic-Cenozoic strata around the Gulf of Cadiz ~8 Ma ago (Maldonado et al., 1999; Medialdea et al., 2004; Terrinha et al., 2009).

During the Cenozoic, the tilting of the Algarve Basin produced a regional inshore uplift and an unconformity between the Lower Cretaceous and the overlying Miocene strata, exposing the Mesozoic stratigraphic record (Terrinha, 1998; Maldonado et al., 1999; Lopes et al., 2006). Besides, Cenozoic shortening of the margin caused a local inversion of pre-existing Mesozoic faults and the reactivation of Mesozoic salt structures, along with squeezing, fluid flows and deformation of the Pliocene to present-day overburden (Terrinha, 1998; Matias et al., 2011; Ramos et al., 2016, 2017a). The most significant deformation associated with halokinetic movements is related to the reactivation of the Esperança Salt Nappe in the central and eastern Algarve Basin (Matias et al., 2011; Ramos et al., 2017a; Fig. 1).

More stable conditions dominated the Algarve Basin during the Late Miocene to the Quaternary (Lopes et al., 2006; Ramos et al., 2016). The contractive reorganization of the Betic-Rif region (Comas et al., 1999; Balanyá et al., 2007) caused land uplifting, the closing of the Betic and Riftian marine gateways at the end of the Late Miocene (Krijgsman et al., 2018; Martín et al., 2010) and the opening of the Strait of Gibraltar from the beginning of the Early Pliocene (Esteras et al., 2000; García-Castellanos et al., 2009; Luján et al., 2011). Different studies have documented neotectonic activity, deformation and significant seismicity, including historical and instrumental earthquakes, in the emerged Algarve Basin (Dias and Cabral, 2002a, 2002b; Cabral, 2012; Figueiredo et al., 2013; Custódio et al., 2015) and along the southwestern Iberian margin (e.g., Hernández-Molina et al., 2016; Mestdagh et al., 2019; Duarte et al., 2022) from the Late Pliocene to the present.

### 2.2. Physiography of the Algarve margin

The continental margin morphology of the Algarve Basin is characterized by three physiographic domains: i) the continental shelf, having an average seafloor gradient of 0.5° in the Portuguese shelf decreases to less than 0.3° in the Spanish shelf; ii) the continental slope is located between 130 and 4000 m water depths, exhibitings abundant erosive and depositional morphologies; and iii) the abyssal plain lies at water depths greater than 4300 m in the outer Gulf of Cadiz (Hernández-Molina et al., 2006).

This study of on the north-western Gulf of Cadiz continental margin, sourced by the Guadiana River in its central part, focuses on the continental shelf between the Guadiana River and the city of Faro. In this sector, the shelf width decreases from the east, where it is over 30 km wide, to the west, where it attains 6–7 km in width. In contrast, the shelf steepness increases from the east (0.2°) to the west (1.3°). The shelf break is located at approximately 140 m water depth (Fig. 1b).

### 2.3. Palaeoceanography

The opening of the Strait of Gibraltar during the Early Pliocene (Sandoval et al., 1995; Comas et al., 1999; Esteras et al., 2000; García-Castellanos et al., 2009) favored the Atlantic-Mediterranean reconnection and the subsequent exchange of water masses (Martín et al., 2010; Krijgsman et al., 2018). The newly formed westward bottom current is known as the Mediterranean Outflow Water (MOW), which gave rise to the build-up of an extensive contourite depositional system along the Gulf of Cadiz continental slope (Hernández-Molina et al., 2003, 2006; Llave et al., 2007, 2011; Roque et al., 2012). The circulation regime of the MOW underwent modifications in response to climatic and tectonic changes. The establishment of an enhanced MOW was coeval to shifting climatic conditions —from humid to cold and arid in the Late Pliocene at 3.4 Ma— and preceded the initial development of the contourite depositional system (Hernández-Molina et al., 2003, 2006, 2016; Lopes et al., 2006; Llave et al., 2007; Marchès et al., 2007; Roque et al., 2012; Duarte et al., 2022). The MOW became denser, deeper, and was intensified during the Late Pliocene to Lower Pleistocene, leading to widespread contourite deposition (Hernández-Molina et al., 2014a, 2016). A significant intensification of MOW current activity was coeval with a global cooling and sea-level fall from 3.2 to 2 Ma (Miller et al., 2011). From 2 Ma to the present day, hydrodynamic conditions have been characterized by a gradual strengthening of the MOW circulation and maximum sedimentation rates of slope contourites (Hernández-Molina et al., 2014a, 2016; Duarte et al., 2022). The climate deterioration during the Mid-Pleistocene Transition from 1.2 to 0.5 Ma (Voelker et al., 2014) was coeval with the shift to longer glacial/interglacial cycles (Lisiecki and Raymo, 2007). During these cool and arid periods, a faster MOW circulation prevailed (Hernández-Molina et al., 2014a).

### 2.4. Pliocene-Quaternary stratigraphy of the Algarve margin

Tectonic activity controlled the margin sedimentary stacking pattern while climate and relative sea-level changes impacted at shorter time-scales during the Quaternary (Hernández-Molina et al., 2016).

Two major Upper Pliocene unconformities have been discerned and dated by various authors in the Algarve margin (Fig. 2). A high-amplitude reflector designated as H1 by Lopes et al. (2006) corresponds to a regionally extensive erosional surface that preceded the initial development of the contourite depositional system (Hernández-Molina et al., 2003, 2006, 2016; Lopes et al., 2006; Llave et al., 2007; Marchès et al., 2007; Roque et al., 2012; Duarte et al., 2022). This erosional surface is correlated distally with an Intra-Pliocene Discontinuity (IPD) dated at 3.6–3.5 Ma (Hernández-Molina et al., 2016). Another angular erosional unconformity along the basin margin named the Late Pliocene Discontinuity or LPD (Fig. 2) has an estimated age of around 3.2–3 Ma. This unconformity has been related to a compressional event; it underlies the Pliocene-Quaternary sequence consisting of interbedded contourites and turbidites, with occasional debrites (Hernández-Molina et al., 2016).

An Early Quaternary Discontinuity-EQD is related with a marked change in sedimentation rates around 2.4–2 Ma and the onset of the present-day contourite drifts and erosional features (Hernández-Molina et al., 2016). Specifically, two Pleistocene unconformities, can be identified in the contourite depositional system on the Gulf of Cadiz middle slope. The Mid-Pleistocene Discontinuity–MPD (0.9–0.7 Ma) (Hernández-Molina et al., 2016; Lofi et al., 2016), associated to the mid-Pleistocene Revolution-MPR (Hernández-Molina et al., 2002, 2006; Llave et al., 2007, 2011), and the Late Quaternary Discontinuity–LQD, linked to a 0.6–0.3 Ma hiatus (Roque et al., 2012; Hernández-Molina et al., 2016). These discontinuities are marked in the major regional contourite features —such as the Faro contourite drift— as high-amplitude erosive surfaces and are related to periods of tectonic reactivation in the area (Roque et al., 2012; Hernández-Molina et al., 2016; Duarte et al., 2022).

On the shelf near the Guadiana River, the Late Quaternary record shows five major depositional sequences (Mestdagh et al., 2019; Fig. 2). These sequences exhibit strong progradational patterns and limited aggradation (Lobo and Ridente, 2014). Margin-wide surfaces (mws) 5 to 1 constitute Late Quaternary sequence boundaries related to periods of sea-level fall culminating in major glacial lowstands at Marine Isotopic Stages (MISs) 12, 10, 8, 6 and 2. Therefore, sequence development is inferred to have been driven by 100 kyr glacial-interglacial cycles (Mestdagh et al., 2019). The youngest boundary mws1 is associated with the Last Glacial Maximum–LGM at ~ 0.02 Ma (Lobo et al., 2018). The non-uniform stacking pattern of these shelf depositional sequences has been attributed to episodic tectonic uplift since the Middle Pleistocene, which has modulated glacio-eustatic sea-level fluctuations (Mestdagh et al., 2019).

## 3. Material & methods

### 3.1. Dataset

This study is based on the acquisition, processing and interpretation of different types of seismic reflection data. These datasets were collected on the continental shelf between Faro (Portugal) and east of the Guadiana River mouth during several oceanographic surveys: GOLCA 93, FADO 96, WADIANA 2000, COMIC 2013, and LASEA 2013. The seismic grid has a cumulative total length of more than 2200 km, with across- and along-shelf profiles between 20 and 300 m water depth (Fig. 1b). Two different types of 2D reflection seismic data were used: high to medium resolution Sparker seismic profiles and high-resolution vintage Uniboom profiles (Fig. 1b).

The seismic profiles acquired with a SIG Sparker source were collected during the LASEA 2013 and COMIC 2013 surveys. Acquisition involved a 300 J seismic source and a 75 m long SIG single-channel streamer; the shot interval was 2 s, the sampling frequency was 10 kHz and the trace length varied between 0.5 and 2 s. Post-processing included correction of navigation offset, gains, bandpass filtering, demultiple, tidal and swell static corrections, and top muting.

The aforementioned data were complemented with seismic data

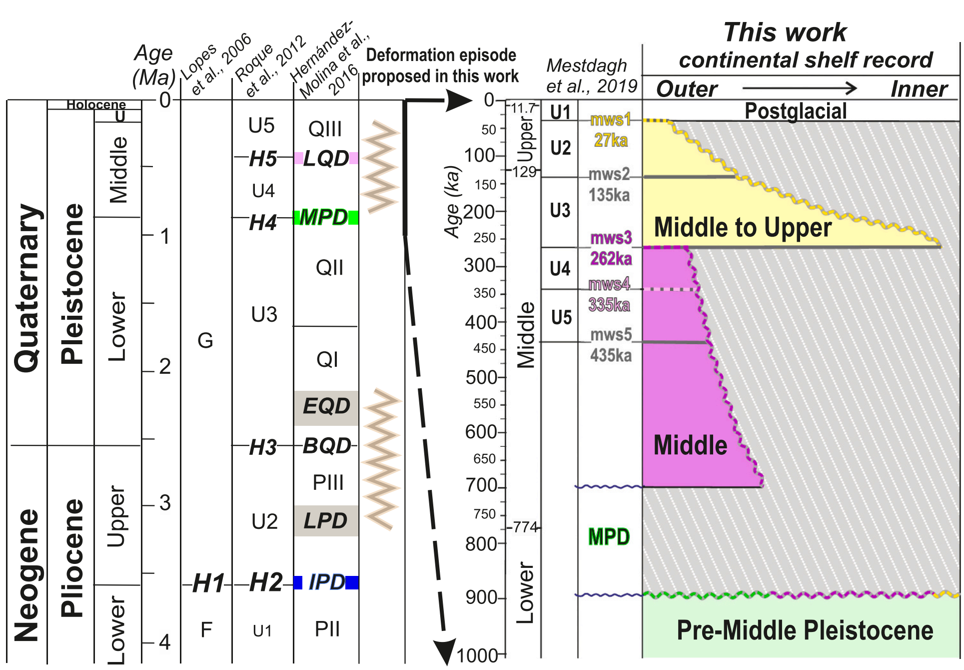


**Fig. 2.** Regional seismic stratigraphic correlations from previous authors, showing the main unconformities, seismic units and sub-units in the Algarve offshore area, as well as the lateral variability and continuity of the major Quaternary unconformities (or discontinuities) and hiatus along the shelf sectors in the study area. IPD: Intra Pliocene Discontinuity, LPD: Late Pliocene Discontinuity, BQD: Base Quaternary Discontinuity, EQD: Early Quaternary Discontinuity, MPD: Middle Pleistocene Discontinuity, LQD: Late Quaternary Discontinuity and major seismic surfaces (mws) identified on a margin-wide scale, mws5- mws1.

from previous surveys in the study area, such as GOLCA 93, FADO 96 and WADIANA 2000 surveys, which used a single-channel Uniboom source (Geopulse™). Basic post-processing included bandpass filtering, amplitude corrections (spherical divergence), 2D spike removal (burst noise removal), swell static corrections and top muting.

Assuming an average P-wave velocity of 1600–1650 m/s for the Pliocene-Quaternary sediments in the Gulf of Cadiz (e.g., Nelson et al., 1999), the maximum penetration is estimated to be 240–247.5 m (300 ms TWT) for the Sparker profiles and 160–165 m (200 ms TWT) for the Uniboom profiles respectively. The approximate vertical resolution of the profiles is 1–1.5 m.

### 3.2. Methodology

The seismic data pertaining to the study area were integrated in a seismic grid, interpreted using the S&P Global Software Kingdom Geoscience package. Depth and thickness from seismic profiles are expressed in milliseconds Two-Way Travel time (TWT). The interpretation procedure included entailed two main steps. First, picking seismic horizons constituting major unconformities or geological structures such as folds and faults within the study area. The seismic horizons and structures were laterally correlated using the entire seismic network (N-S to E-W sections), then gridded using the Flex Grid algorithm; they were represented using isochron contour maps in the Kingdom Geoscience package. Folds were detected on the E-W and ENE-WSW seismic sections and thrusts on the N-S, NE-SW and NW-SE seismic sections. Those neotectonics features were mapped in ArcGIS™. In addition, several bits of information were integrated in the GIS environment for regional correlation purposes: inshore data included in geological maps (Rodríguez-Fernández et al., 2015) and active faults in mainland Portugal (Dias and Cabral, 2002a; Cabral, 2012; Cabral et al., 2017); plus offshore data including salt structures (Ramos et al., 2017a,b,c), thrust and active faults (Lopes et al., 2006; Noiva, 2009; Cabral et al., 2019).

Age models are based on biostratigraphic and magnetostratigraphic date derived from IODP expedition 339 sites U1386 and U1387 in the Algarve middle slope, which enabled the generation of a chronostratigraphic framework (Stow et al., 2013; Hernández-Molina et al., 2014a, b; Voelker et al., 2014; Lofi et al., 2016). Seismic-to-well tie points were used to extend Late Quaternary ages from the IODP 339 sites from the slope to the shelf, by means several connecting seismic lines (Fig. 1b). An erosive surface in the upper slope between the Portimão Fault-PF and the Guadiana River mouth truncates the major slope seismic horizons, impeding a direct connection between the IODP sites and the nearby Algarve shelf. To avoid the upper slope erosion, the correlation profiles initially followed a W-E trend and turned to the northeast in the area where the upper slope became depositional (Fig. 1b). These major Late Quaternary seismic horizons were interpreted on the outer shelf east of the Guadiana River (Mestdagh et al., 2019). For the purposes of this study, we extended the age attribution of Late Quaternary seismic horizons to the eastern Algarve shelf, using the available seismic grid (Fig. 1b). Accordingly, we adopted the Quaternary stratigraphic framework for the northern Gulf of Cadiz continental margin off the Guadiana River proposed by Mestdagh et al. (2019) overlying the Middle Pleistocene Discontinuity (MPD) identified in the Algarve margin (Hernández-Molina et al., 2002, 2016).

Several pieces of information served for the correlation of pre-Quaternary seismic horizons: multichannel seismic reflection date (N-S, NW-SE and E-W correlation profiles, Fig. 1b) and isopach maps, used to identify the Pliocene seismic units and their boundaries in the eastern part of the Algarve continental margin and to correlate them with our seismic grid (Lopes et al., 2006; Hernández-Molina et al., 2016).

## 4. Results

### 4.1. Continental shelf seismic stratigraphy

Previous seismic stratigraphic analyses have provided a tentative slope to shelf correlation for the major Pliocene-Quaternary seismic surfaces and units of the northern Gulf of Cadiz continental margin (Lopes et al., 2006; Roque et al., 2012; Hernández-Molina et al., 2016; Mestdagh et al., 2019). Most Quaternary unconformities (or seismic discontinuities) tend to merge from the outer to the inner shelf, thus increasing the depositional hiatuses in a landward direction (Fig. 2). The steep and narrow morphology of the continental shelf west of the Guadiana River favors the overlap of these unconformities along the outer continental shelf (Fig. 3).

#### 4.1.1. Unconformities and depositional hiatuses

The oldest seismic horizon identified from the upper slope to the outer eastern shelf (>200 ms TWT; Figs. 3b and 4) is characterized by high amplitudes and mostly conformable contacts. This seismic horizon is correlated with the Mid Pleistocene Discontinuity-MPD dated at around 0.7–0.9 Ma (Hernández-Molina et al., 2016; Lofi et al., 2016). Mws5 to 1, identified on a margin-wide scale by Mestdagh et al. (2019), are also recognized on the outer shelf, where they exhibit widespread erosional truncations. There, mws4, 3 and 1 are the most extensive seismic horizons; on the outer shelf, they have high amplitudes and planar configurations, and truncate older seismic horizons (Figs. 3b and 4). Mws1 constitutes the most recent and prominent erosional truncation associated with the Last Glacial Maximum-LGM (~ 0.02 Ma, Lobo et al., 2018). This surface can be traced over the entire shelf where it exhibits a variable morphology, with planar and rugged erosional truncations (Figs. 3 and 4).

A continuous, high-amplitude seaward dipping reflection is found over the middle-outer continental shelf off the Guadiana River (>170 ms TWT; Fig. 3b). This major seismic horizon is generally concordant to slightly erosive (Fig. 4a, 5 and 6). This oldest surface is deformed and denoted as the IPD. The IPD is truncated by mws3, which is a high amplitude, continuous regional seismic horizon on the middle shelf at depths shallower than 190 ms TWT (Figs. 3b and 5b–c). Mws3 exhibits erosional truncation below and concordant to downlap patterns above (Figs. 3–8). Based on previous regional seismic stratigraphic analysis (Hernández-Molina et al., 2016; Mestdagh et al., 2019), this main surface represents a nearly 600 kyr (0.26–0.9 Ma) depositional hiatus (Fig. 2) that truncated IPD and MPD (Figs. 3–8). Mws1 is the youngest unconformity identified on the middle shelf, where it exhibits a planar pattern and erosional truncation of underlying reflections.

On the inner to middle shelf, mws1 truncates mws3 forming high paleo reliefs and representing a hiatus spanning from 0.9 to 0.02 Ma (Figs. 2, 3 and 4).

#### 4.1.2. Unconformity-bounded shelf units

The reported unconformities divide the sedimentary record into several wedge-shaped progradational seismic units. They mostly exhibit parallel-oblique configurations with erosional truncations to toplap upper terminations on the outer shelf. These seismic units exhibit seaward thickness increases towards the south-southeast (Figs. 3 and 4). Our seismostratigraphic interpretation divided the Quaternary sedimentary record of the Algarve continental shelf into four main intervals (Fig. 2).

1. Pre-Middle Pleistocene record

The older shelf deposits are pre-mid Pleistocene discontinuity (MPD) in age (i.e. before 0.9 Ma) and composed of Pliocene to Lower Pleistocene deposits; they are correlated with seismic units QII to PII (Hernández-Molina et al., 2016) (Fig. 2). These deposits are bounded at the top by three main seismic horizons, from MPD to mws3 and to mws1

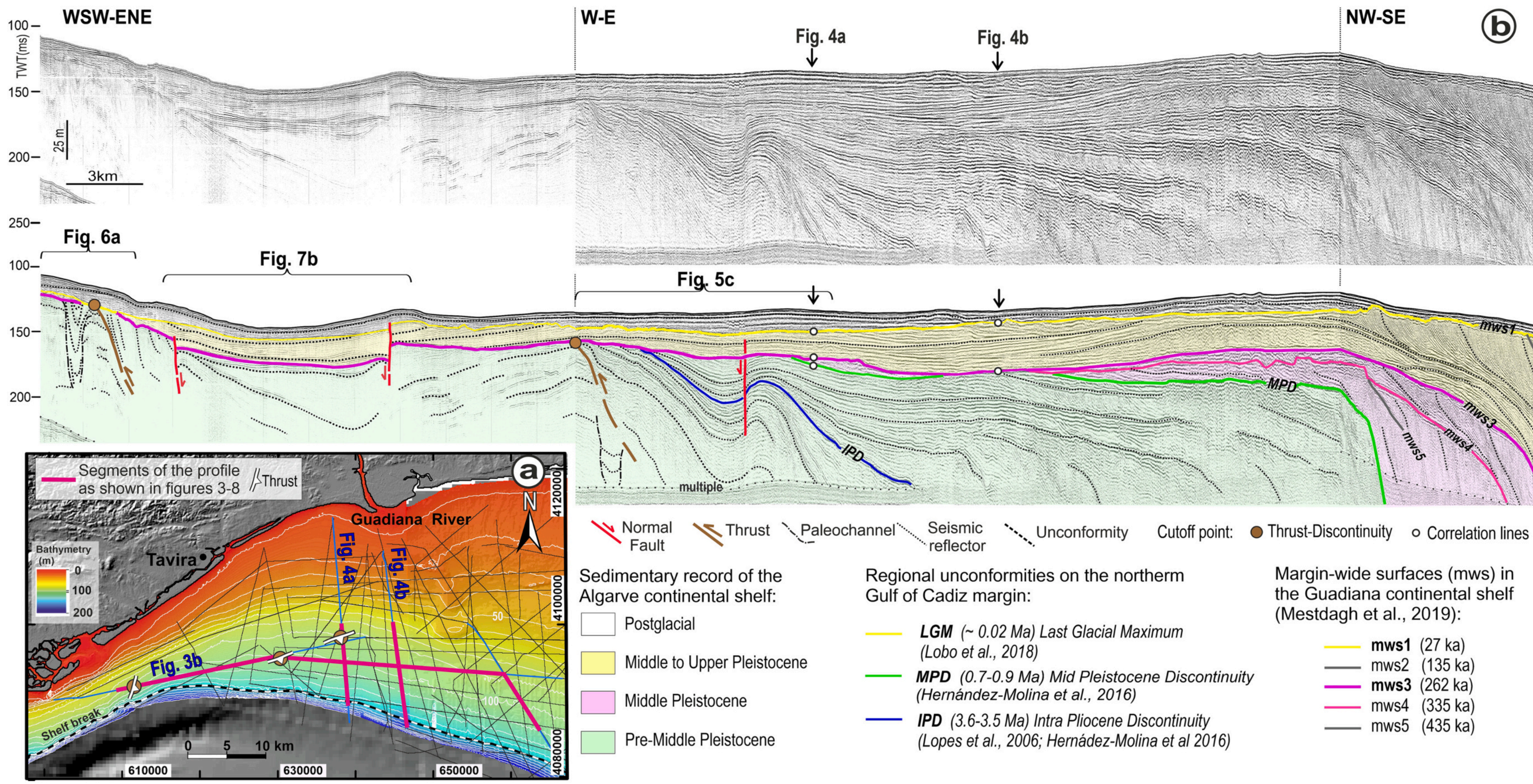


**Fig. 3.** a) Locations of Figs. 3b and 4 along the eastern Algarve continental shelf in the northern Gulf of Cadiz. b) WSW-ENE to NW-SE interpreted composite seismic profiles, as well as the main deformation structures. TWT- Two Way Travel time.

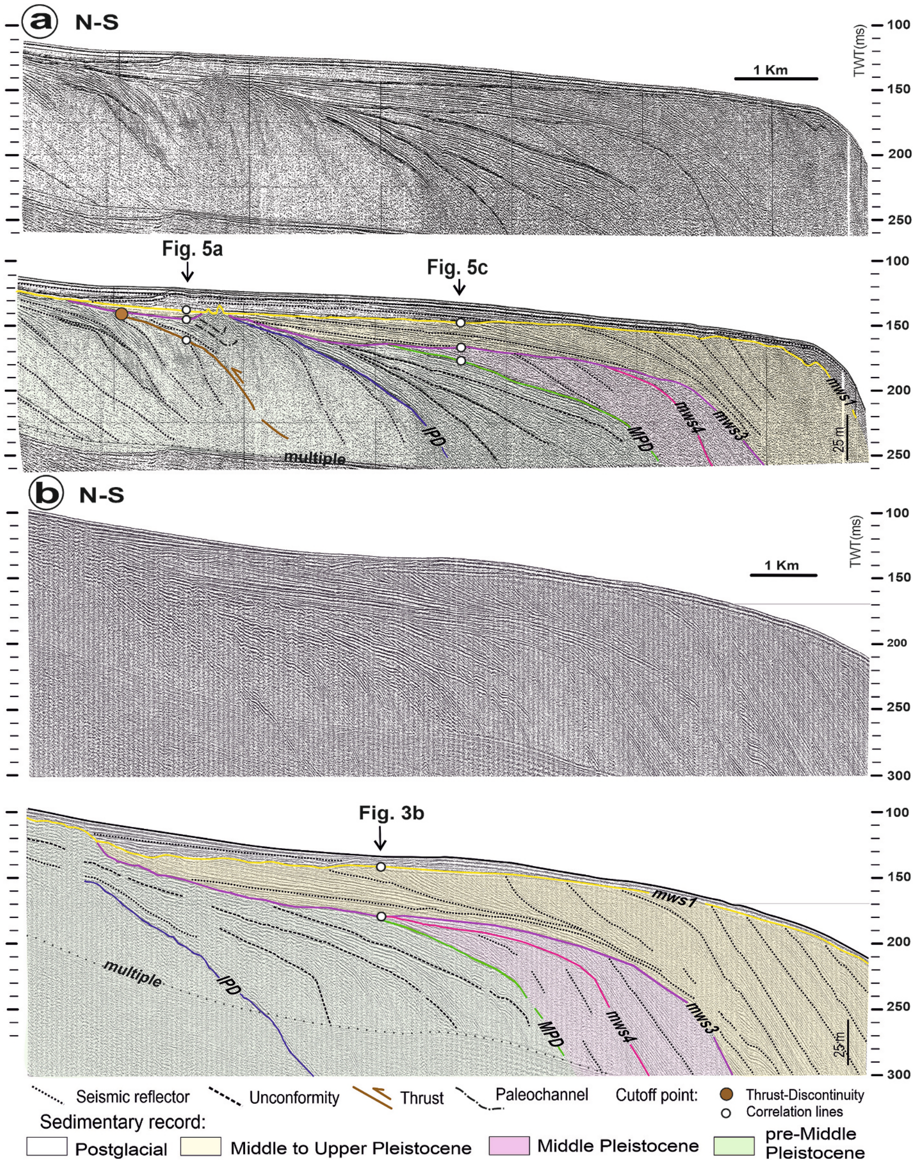


**Fig. 4.** N-S seismic profiles and their interpretation, located on the shelf offshore the Guadiana River mouth (see abbreviations in Fig. 3).

in a landward direction. The pre-Middle Pleistocene record exhibits top erosional truncations to toplap terminations against the MPD on the outer shelf off the Guadiana River and against mws3 on the middle shelf off the Guadiana River and on the western outer shelf off Tavira (Figs. 4 and 7). Internally, the sedimentary record displays a rather continuous, contorted parallel-oblique configuration dipping mostly towards the south to southeast (Fig. 3). One of the high-amplitude reflections was interpreted as the IPD (Figs. 3–5). Cut and fill geometries with onlapping patterns distinguished within the pre-Middle Pleistocene record (Figs. 5 and 6a) which exhibit a wedge-shaped geometry and thicken towards the outer shelf (Fig. 3).

2. Middle Pleistocene record

Middle Pleistocene deposits between MPD and mws3, having a tentative age from 0.7 to 0.26 Ma can be correlated with the lower part of seismic unit QIII of Hernández-Molina et al. (2016) and with seismic units U5 and U4 of Mestdagh et al. (2019) (Fig. 2). They are capped by mws3 on the outer to middle shelf (Figs. 3 and 4). This sedimentary record features discontinuous to locally continuous, medium-amplitude reflections (Figs. 4 and 5d). This record is mainly preserved on the outer shelf showing a marginal wedge geometry with lens-shaped sediment leftovers on the middle shelf off the Guadiana River (Figs. 3 and 5c–d).

3. Middle to Upper Pleistocene record

Middle to Upper Pleistocene deposits between mws3 and mws1 are 0.26–0.02 Ma in age and include the U3 to U2 seismic units from Mestdagh et al. (2019) (Fig. 2). The top reflection termination pattern shows toplap and erosional truncation on the middle and outer shelf below mws1, whereas bottom reflection terminations exhibit downlap on the outer shelf and onlap on the upper slope against mws3 (Figs. 3b and 4b). The internal architecture is characterized by subparallel and oblique continuous reflections with moderate to high amplitudes. They show a sheet-like external geometry on the inner to middle shelf, becoming wedge-shaped on the outer shelf, generating an overall progradational-aggradational configuration (Figs. 3 and 4).

4. Postglacial record

The most recent deposits are correlated with unit U1 (0.02 Ma-present) of Mestdagh et al. (2019). They overlie high paleoreliefs and

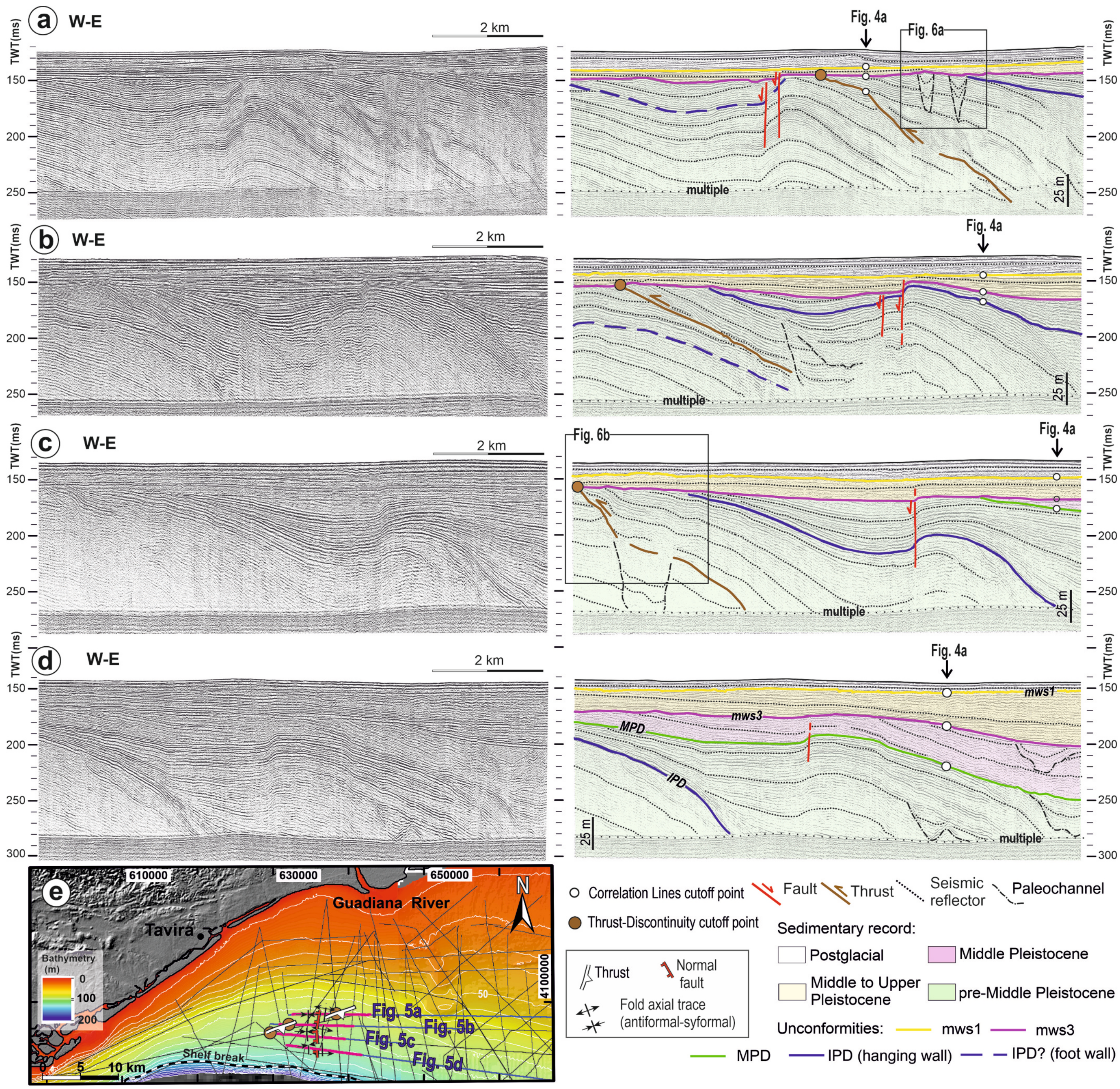


**Fig. 5.** W-E seismic profiles and their interpretation, located on the middle-out continental shelf of the Guadiana River mouth. The panels a), b), c) and d) are in panel e), including detailed paleostructural mapping (see abbreviations in Fig. 3).

erosional surfaces of mws1 and display continuous sub-parallel, high-amplitude reflections along the continental shelf (Figs. 3–8).

### 4.2. Deformational structures

Based on seismic interpretations, contour mapping of seismic horizons and geological contacts, three types of deformation structures could be distinguished in the study area. Our results evidence: thrusts, folds and high-angle faults.

#### 4.2.1. Thrusts

Thrusts are mapped, their fault surfaces being inferred from the shape of deformed reflections where footwall ramp geometries (Fig. 6b) are recognized on ESE-WNW, E-W, ENE-WSW and NE-SW seismic sections (Figs. 3b, 5a–c, 7 and 8a). These sections show basinward-dipping thrust faults with a landward (i.e. northwestward) transport direction, affecting the older shelf deposits (i.e., the pre-Middle Pleistocene record).

Footwall ramps of slices show that thrust surfaces cut up the stratigraphic section towards the N and W (Figs. 5a–c, 7 and 8a). A progressive shortening can be recognized by the formation of folds over footwall ramps (Fig. 5c) and the identification of narrow paleochannels crossing paleotopographic highs in the back limb of the hanging walls (Figs. 4a, 5a and 6a). These blind fault planes are truncated by mws3 (thrust-discontinuity cutoff point, Figs. 3–8). Three thrust traces can be mapped; two of these occur over the middle shelf off the Guadiana River in a ENE-WSW direction (Figs. 5e and 7d), while the other is identified in the westernmost part of the middle shelf, with NE-SW direction (Fig. 7d

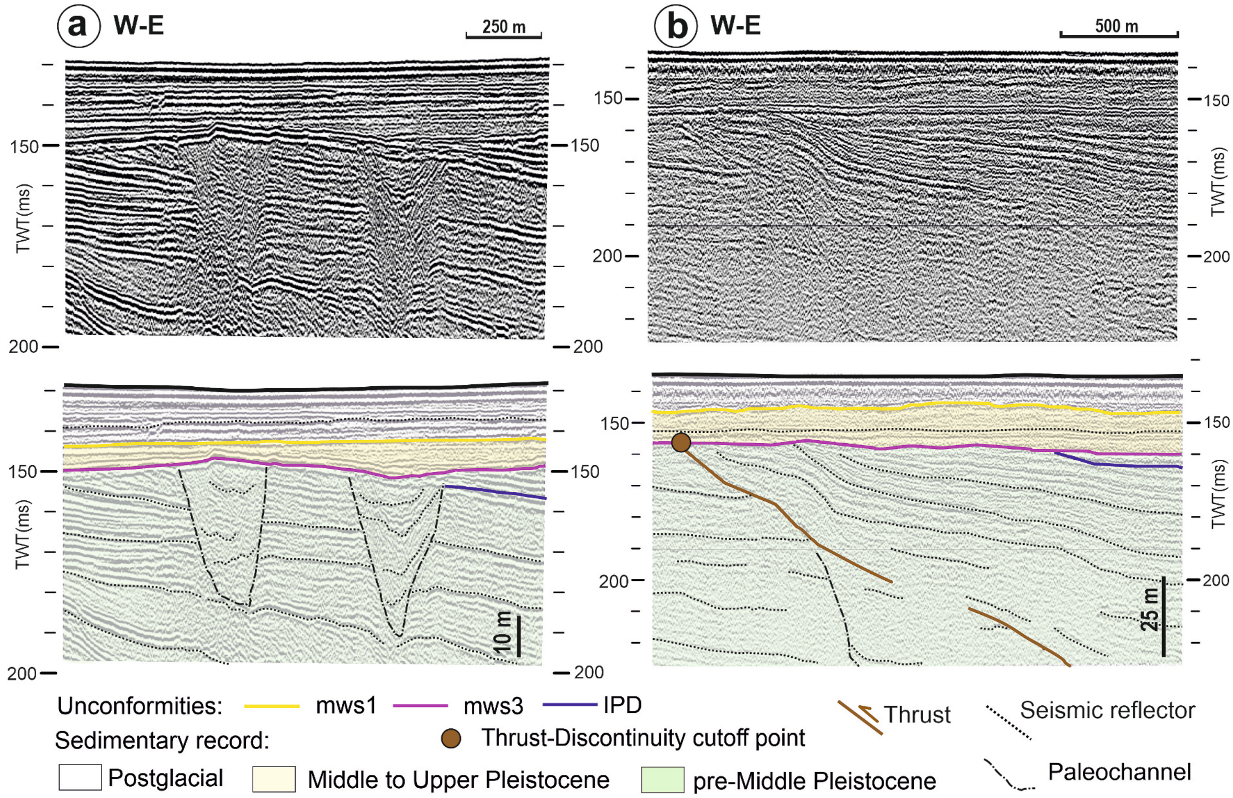


**Fig. 6.** Seismic zoom windows and corresponding interpretation of paleochannels (a) and thrust surface (b). See location in interpreted seismic lines of Fig. 5a and c, respectively and abbreviations in Fig. 3.

and 8c). The ENE-WSW striking thrusts extend laterally for 7 km, whereas the thrust slices are about 5 km wide in plain view (Fig. 9b).

#### 4.2.2. Folds

Kilometric-scale, N-S and NW-SE folds were identified (Figs. 5 and 7) mainly affecting the older shelf deposits predating the Middle Pleistocene. However, the Middle Pleistocene record preserved on the outer shelf off the Guadiana River is also deformed (Fig. 5d). The N-S folds are found on the shelf off the Guadiana River at depths of 150–200 ms TWT (ca. 122–162 m) (Fig. 5). They exhibit non-cylindrical and asymmetric geometries with acute anticlines. Anticline amplitudes decrease downsection and towards the north due to northward fold plunging. These folds deform the thrusts and paleochannels recognized in anticline (Fig. 5a) or syncline limbs (Fig. 5b). NW-SE folds occur on the continental shelf between Faro-Tavira at 100–160 ms TWT (ca. 81–130 m depth) with non-cylindrical and broad synclinal geometries. Folded reflections show a decrease in amplitude and increase in wavelength towards the outer shelf (Fig. 7). The sediment thickness along a WSW-ENE line (Fig. 7b) suggests a gradual westward migration of a synclinal depocenter.

#### 4.2.3. High-angle normal faults

Faults occur as discrete planar discontinuities across which stratal reflections are offset (Brown, 1996), identified in the study area as steeply dipping (60 to 80°) and kilometric-scale fault systems. On the shelf off the Guadiana River, an anticline limb is cut by N-S normal faults subparallel to the fold axial surface (Fig. 5e). They are high-angle normal faults (Fig. 5a and b) interpreted as crestal faults over diapirs (Matias et al., 2011). Towards the middle Guadiana shelf, these faults can cut and displace mws3 (Fig. 5b) but towards the outer shelf they displace the pre-Middle Pleistocene and the Middle Pleistocene records (Fig. 5d). In the western part of the study area, two planar fractures with NNE-SSW to NNW-SSE trends cut syncline limbs (Fig. 8c). These high-angle faults show a main normal movement in the sinking block (Fig. 8). However, they exhibit reverse drag folds (Grasemann et al., 2005) along an ENE-WSW distal seismic line, with a maximum vertical displacement of ca. 8 m (10 ms TWT), decreasing to zero at the top of the fault (Fig. 8b), which is typical for *syn*-sedimentary faulting (Childs et al., 2003). Mws3 shows a tightening of isochronous curves due to the offset generated by these faults; additionally, in the eastern part mws3 is locally curved due to the influence of underlying folds and faults (Fig. 9a). The high-angle faults were active throughout the Middle to Upper Pleistocene record with hanging walls exhibiting greater thickness than foot walls (see details in Figure b). Finally, the easternmost fault close to Tavira cuts mws1 and displaces the postglacial deposits.

## 5. Discussion

### 5.1. Shelf deformation episodes in the regional tectonic context

Since the Late Miocene, the counter-clockwise gradual rotation of the Iberia and Nubia sub-plates changed the convergence direction from NW-SE to WNW-ESE, which was accommodated by transpressive deformation along the southwestern Iberian margin (Dewey et al., 1989; Terrinha et al., 2009; Zitellini et al., 2009; Cunha et al., 2012). The oblique convergence has generated a new regional compressional regime, holding evidences indicate the reactivation of pre-existent faults during the Pliocene-Quaternary (Ressurreição et al., 2011; Cabral, 2012; Carvalho et al., 2012; Cabral et al., 2017). The interpretation and mapping of diverse deformational features with tentative ages based on their relationship to the major seismic unconformities reveal that the studied continental shelf was affected by at least two deformation episodes predating and postdating the mid-Pleistocene Discontinuity (MPD) around 0.7–0.9 Ma.

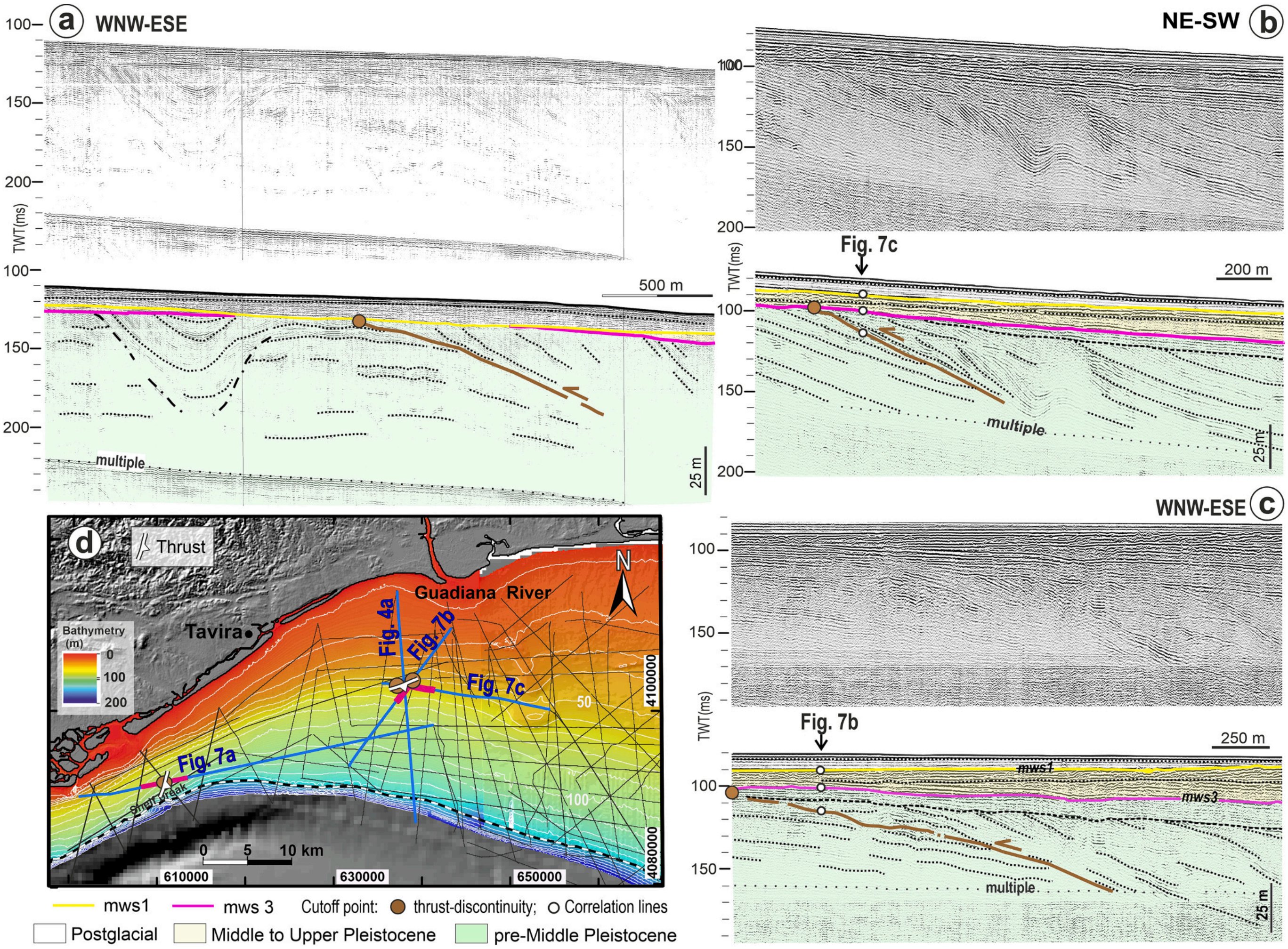


**Fig. 7.** Interpreted seismic profiles, a) Western segments of the composite seismic profile (Fig. 3b), b) NE-SW section line, c) WNW-ESE section line, d) location of the panels, including detailed paleostructural mapping (see abbreviations and legend in Fig. 3).

### 5.1.1. Deformation predating the MPD

A shift in the convergence between the Iberia and Nubia sub-plates from N-S to NW-SE took place during the Neogene (Mazzoli and Helman, 1994; Maldonado et al., 1999). The effects of the Neogene compressive phase are recorded by the inversion of previous distensive structures along the northern margin of the basin (Lopes et al., 2006; Duarte et al., 2011; Ramos et al., 2016) and by the opening of an important ocean gateway, the Strait of Gibraltar during the Early Pliocene (Esteras et al., 2000; García-Castellanos et al., 2009). As a consequence of the opening of the strait, a Pliocene-Quaternary contourite depositional system was generated along the northern Gulf of Cadiz margin. Within the contourite drifts, two regional erosional discontinuities have been documented: the LPD at around 3.2–3 Ma and the EQD at around 2.4–2 Ma (Fig. 2), marking an important change in the sedimentary stacking pattern of the deep basin. These unconformities have been linked to significant hydrodynamic changes brought on increased tectonic activity, with minor pulses of western compression recorded in the accretionary wedge of the Gulf of Cadiz (Hernández-Molina et al., 2016). In the study area, a first phase of deformation is inferred by ENE-WSW to NE-SW thrusts having a north-westward transport direction. These structures piled up the pre-Middle Pleistocene record and thrusted the sediments in the middle shelf (Fig. 9b). Given that these north- to northwest- vergent thrust faults cut the IPD and are truncated by mws3 at the middle shelf (Figs. 3–8), a main surface would indicate a depositional hiatus that began at 0.9 Ma. Our interpretation holds that these thrusts accommodated a shortening episode orthogonal to the margin during a time interval older than the MPD (Figs. 3 and 5).

A tentative chronology can be proposed based on the regional tectonic context. Considering that the most important compressional events affecting the southwest Iberian margin took place between the Late Pliocene and the Early Pleistocene (i.e., 3.2–2 Ma), we propose that the ENE-WSW to NE-SW thrusts that affected the continental shelf were coeval to those events, hence they predate 0.9 Ma (Fig. 2).

### 5.1.2. Deformation postdating the MPD

A regional tectonic reorganization occurred from 2 Ma onwards in relation to another WNW-ESE convergence change between the Iberia and Nubia sub-plates (Zitellini et al., 2009; Duarte et al., 2011). This recent activity is evidenced in diverse physiographic domains of the Algarve Basin, both inshore and offshore. Along the coasts of southern Portugal, a set of marine terraces can be found at variable altitudes —from near the present sea-level to a few hundreds of meters high. This geomorphological pattern has been attributed to ongoing tectonic uplift during the last 3 Ma (Cabral, 2012; Figueiredo et al., 2013). In addition, two major regional structures such as the SMQF and the CF show evidence of Quaternary activity inland (Ressurreição et al., 2011; Dias and Cabral, 2002a,b, Cabral et al., 2012; Cabral et al., 2019; Carvalho et al., 2012, see also Fig. 1b).

Offshore, two tectonic uplift pulses are recognized in the sedimentary stacking pattern of the shelf off the Guadiana River, before 0.3 Ma and during the last glacial cycle, i.e. before 0.1 Ma (Mestdagh et al., 2019). On the slope, salt movements occurred due to the reactivation of

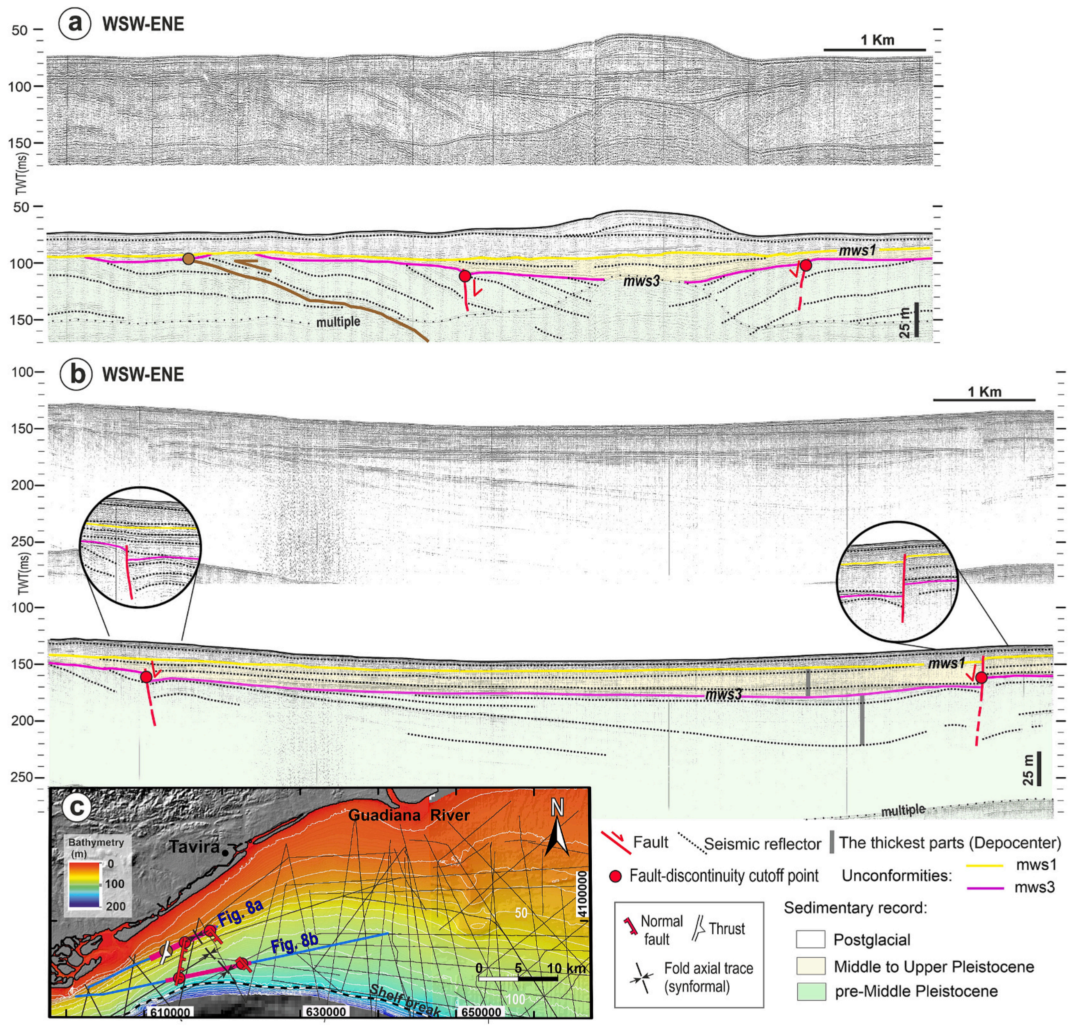


**Fig. 8.** Interpreted seismic profiles, located on the Tavira continental shelf, a) WSW-ENE section line, b) W-E section of the composite seismic profile (Fig. 3a), c) location of the panels, including detailed paleostructural mapping (see abbreviations and legend in Fig. 3).

Mesozoic allochthonous salt bodies (e.g., the Esperança Salt Nappe). They were accommodated through extensional and contractional structures (Ramos et al., 2017a), and locally deformed the Quaternary sedimentary cover in the Algarve Basin (Hernández-Molina et al., 2016). Finally, in the deep basin, two extensive erosional discontinuities (MPD and LQD, Fig. 2) attest to tectonic activity and uplift-induced erosion (Llave et al., 2007; Hernández-Molina et al., 2016) during the Middle Pleistocene.

NNW-SSE to N-S asymmetric folds and NNE-SSW to NNW-SSE and N-S normal faults identified in the middle to outer shelf of the study area (Fig. 9b), providing evidence of a second phase of deformation. Towards the east eastern part of the study area (i.e., the Guadiana shelf), the occurrence of deep salt domes could be inferred from local folded sediments that form an asymmetrical anticline (Figs. 5 and 9b). The high-angle normal faults a top of the anticline could be interpreted as crestal faults over halokinetic structures (Matias et al., 2011). According to our chronostratigraphic framework, those faults were mainly active until 0.26 Ma (mws3) (Fig. 5b). We relate the structures above the folds to the reactivation of Mesozoic allochthonous salt bodies.

In the western part of the study area, some NNE-SSW to NNW-SSE high-angle faults can be regarded as growth faults affecting mws3 (Fig. 8 and 9b). We infer that they were active until 0.26 Ma as well, their movement progressively decreasing upwards until the present. One NNW-SSE fault cuts mws1, causing the gradual westward migration of depocenters (Figs. 3 and 8b). This pattern may reflect strike-slip movements along the fault (e.g. Noda, 2013). We interpret this fault as indicative of recent tectonic activity in the margin during the last glacial cycle. Active faults with orientations parallel to those described here have been identified inshore (e.g. the Areias de Almarsil fault, Fig. 1b) and offshore close to Faro (Noiva, 2009; Cabral et al., 2012, Cabral et al., 2017; Terrinha et al., 2013).

Therefore, we propose that tectonic phases recognized regionally are also recorded in the study area by the second phase of deformation post-dating the MPD and extending at least to the Last Glacial Maximum at 0.02 Ma (Middle to Late Pleistocene in age, Fig. 2), with two distinct manifestations: (a) salt-related structural movements persisted until the Middle Pleistocene in the eastern part of the study area (Figs. 3 and 5); (b) recent faults activity with vertical and strike-slip movement components took place in the western part of the study area (Figs. 3 and 9), in agreement with regional neotectonic activity evidenced elsewhere.

### 5.2. Pliocene-Quaternary tectono-sedimentary evolution of the study area

Tectonic activity and relative sea-level changes interacted since the Early Pliocene as recorded by unconformities and deformation structures in the outer middle continental shelf off the Guadiana River (Fig. 9). During the Early Pliocene, the formation of prograding clinoforms in a submarine environment prevailed. The widespread submarine deposition was interrupted by a major sea-level fall that occurred after the Early Pliocene at around 3.6–3.5 Ma (Hernández-Molina et al.,

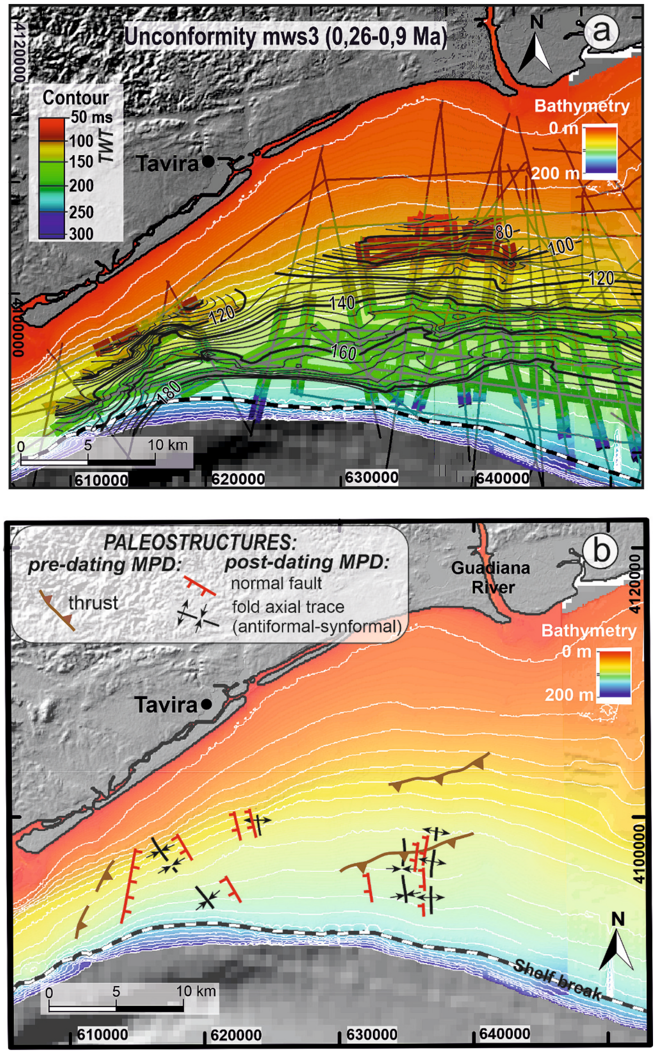


**Fig. 9.** a) Mws 3 isochron map (ms TWT), illustrating its spatial geometrical variation, b) interpreted paleostructural map of eastern Algarve continental shelf. The thrust was interpreted to be active before the Middle Pleistocene, whereas folds and faults have been active since the Middle Pleistocene.

2016). This sea-level fall was recorded by a regional erosional surface (IPD) and a network of incised valleys (Fig. 10a). Marine sedimentation conditions on the shelf continued from the Late Pliocene onwards. The shallow-water sediments were deformed by ENE-WSW thrusts (Fig. 10b). Syn-sedimentary deformation and thrusting could have occurred during the regional shortening phase affecting the Algarve Basin, estimated to have been triggered at around 3.2–3 Ma and showing continued activity until the Early Quaternary (2.4–2 Ma) (Hernández-Molina et al., 2016 see Fig. 2).

Important climatic and sea-level changes occurred from the Early to the Middle Pleistocene, with a significant sea-level fall at 0.9 Ma (Haq et al., 1987, Hernández-Molina et al., 2006), that led to the formation of MPD at 0.9–0.7 Ma (Brackenridge et al., 2013; Lofi et al., 2016; Hernández-Molina et al., 2016) (Fig. 10c). Conditions of relative steady subsidence were established in the distal shelf after 0.7 Ma, enabling the preferential deposition of shelf-margin wedges (i.e. the Middle Pleistocene record, Fig. 5d). These deposits would be coeval to the second phase of shelf deformation, which folded and faulted the Pliocene to Middle Pleistocene deposits (Figs. 2 and 10d). During the Middle Pleistocene, a relative sea-level fall during Marine Isotope Stage (MIS) 8 (Grant et al., 2014; Mestdagh et al., 2019) caused the cessation of sedimentation during the glacial lowstand on the shelf. Such conditions may have caused a poor preservation of Middle Pleistocene deposits, with a landward-increasing shelf hiatus from 0.9 to 0.26 Ma (Fig. 2), and the truncation of previous shortening structures (Fig. 10e). Since 0.26 Ma, increased sediment supplies were accompanied by relatively high subsidence rates on the continental margin (Mestdagh et al., 2019). Under such conditions, fold-related faults affected the sedimentary cover (Fig. 10f). During the Late Pleistocene the subsidence ceased and the last glacial cycle was terminated by the LGM during MIS 2, when the sea level fell between 120 m to 140 m below the present-day level (e.g. Clark et al., 2009; Lobo and Ridente, 2014). This event is recorded on the shelf by a strong erosional truncation (Figs. 2 and 10g). This subaerial surface merges towards the inner shelf with mws3 (Fig. 10g), the hiatus increasing landward from 0.9 to 0.02 Ma. Finally, postglacial sedimentation covered the entire shelf during sea-level rise to current highstand sea-level conditions (Fig. 10h).

## 6. Conclusions

The integration of a seismic stratigraphic interpretation with the analysis of tectonic structures on the eastern Algarve shelf improves our understanding of the Pliocene-Quaternary tectonic evolution of the northern Gulf of Cadiz continental margin in a regional compressive regime close to a diffuse plate boundary, closing the knowledge gap between the inshore and deep structures. Our study reveals that the Algarve continental shelf contains a major angular discontinuity recording the Early to Middle Pleistocene (0.26–0.9 Ma). This protracted shelf hiatus serves as a basis for limiting two major types of deformational features reflecting two major tectonic phases within a regional context of Cenozoic margin shortening. A transpressive phase prior to 0.9 Ma was characterized by shortening structures (ENE-WSW to NE-SW thrusts) that were partially truncated by the major shelf unconformity. The first thrusting deformation episode could accommodate the post Tortonian convergence between the Eurasia and Africa plates orthogonal to the margin. A second deformation phase postdating 0.9 Ma entailed minor deformations related to active faults with slow slip rates and non-cylindrical folds of NNW-SSE to NNE-SSW directions. The second episode is presumably linked to the Cenozoic reactivation of salt structures in the eastern Algarve basin; they locally deformed Late Quaternary sediments and active faults that also caused minor deformations. Those faults were active until the Last Glacial Maximum (0.02 Ma) and may be associated with vertical crustal movements previously recognized in the sedimentary stacking pattern of the shelf off the Guadiana River. The available evidence strongly suggests tectonic activity in the southwestern Iberian margin during the Middle to Late Pleistocene. Specifically, the results of this study demonstrate the occurrence of very recent neotectonic activity on the eastern Algarve shelf —which may pose a significant seismic threat— and the remarkable influence of structural features and tectonic events in controlling the morphology and the Plio-Quaternary evolution of the continental shelf under convergent regimes.

## CRediT authorship contribution statement

**María Luján:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco José Lobo:** Validation, Supervision, Software, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Thomas Mestdagh:** Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Álvaro Carrión-Torrente:** Validation, Methodology, Investigation, Conceptualization. **Juan Tomás Vázquez:** Validation, Resources. **Mª. Carmen Fernández-Puga:** Validation, Methodology. **David Van Rooij:** Validation, Supervision, Resources, Investigation, Conceptualization.

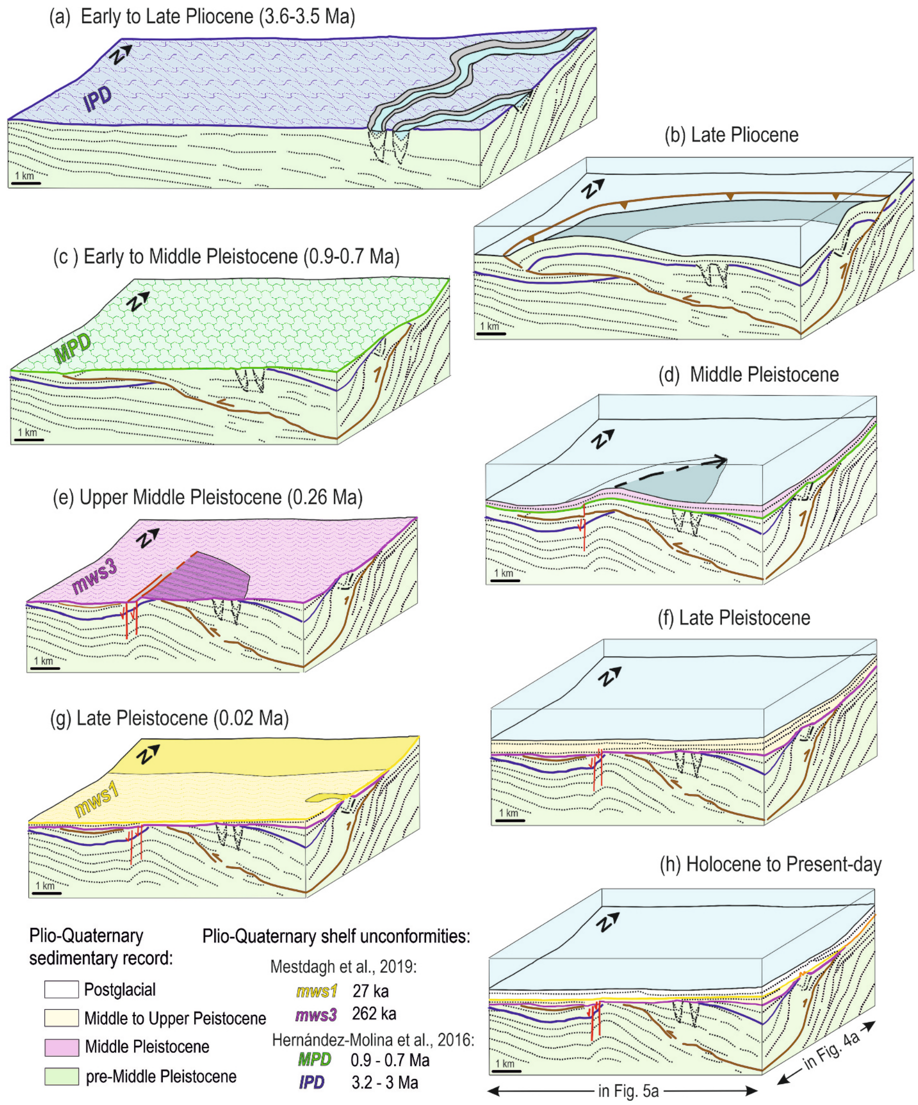


**Fig. 10.** Pliocene to present-day tectono-sedimentary evolution of the continental outer-middle shelf off the Guadiana River, reconstructed as a series of 3D block diagrams (a–h), based on interpretation of the 2D seismic data sets (Figs. 4a and 5a; see abbreviations in Fig. 3).

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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