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Understanding the complex geomorphology of a deep sea area affected by continental tectonic indentation: The case of the Gulf of Vera (Western Mediterranean)

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A R T I C L E I N F O

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A B S T R A C T

We present a multidisciplinary study of morphology, stratigraphy, sedimentology, tectonic structure, and physical oceanography to report that the complex geomorphology of the Palomares continental margin and adjacent Algerian abyssal plain (i.e., Gulf of Vera, Western Mediterranean), is the result of the sedimentary response to the Aguilas Arc continental tectonic indentation in the Eurasian–Africa plate collision. The indentation is imprinted on the basement of the margin with elongated metamorphic antiforms that are pierced by igneous bodies, and synforms that accommodate the deformation and create a complex physiography. The basement is partially covered by Upper Miocene deposits sealed by the regional Messinian Erosive Surface characterized by palaeocanyons that carve the modern margin. These deposits and outcropping basement highs are then covered and shaped by Plio-Quaternary contourites formed under the action of the Light Intermediate and Dense Deep Mediterranean bottom currents. Even though bottom currents are responsible for the primary sedimentation that shapes the margin, 97% of this region's seafloor is affected by mass-movements that modified contourite sediments by eroding, deforming, faulting, sliding, and depositing sediments. Mass-movement processes have resulted in the formation of recurrent mass-flow deposits, an enlargement of the submarine canyons and gully incisions, and basin-scale gravitational slides spreading above the Messinian Salinity Crisis salt layer. The Polopo, Aguilas and Gata slides are characterized by an extensional upslope domain that shapes the

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continental margin, and by a downslope contractional domain that shapes the abyssal plain with diapirs piercing (hemi)pelagites/sheet-like turbidites creating a seafloor dotted by numerous crests. The mass movements were mostly triggered by the interplay of the continental tectonic indentation of the Aguilas Arc with sedimentological factors over time. The indentation, which involves the progressively southeastward tectonic tilting of the whole land-sea region, likely generated a quasi-continuous oversteepening of the entire margin, thus reducing the stability of the contourites. In addition, tectonic tilting and subsidence of the abyssal plain favoured the flow of the underlying Messinian Salinity Crisis salt layer, contributing to the gravitational instability of the overlying sediments over large areas of the margin and abyssal plain.

1. Introduction

Our knowledge of the deep-sea submarine geomorphology has grown substantially in recent years, due to full-coverage multibeam bathymetric maps, their repetition, and the increasing accuracy (e.g., McAdoo et al., 2000; Smith et al., 2007; Chiocci and Ridente, 2011; Ercilla et al., 2011; Ceramicola et al., 2014; Mascle et al., 2014; Kelner et al., 2016). However, morphology alone does not enable us to accurately interpret geomorphic processes, especially along active tectonic continental margins. Geomorphological studies should also involve the analysis of seismic records and other geophysical data to decipher the deep structures that shape the continental margins and adjacent abyssal plains and their sedimentary architecture. Both physiographic domains can be affected by active structures that locally and regionally influence seafloor morphology (Bohoyo et al., 2019; Galindo-Zaldívar et al., 2019; Sakellariou et al., 2019; Lafosse et al., 2020; Tsampouraki-Kraounaki et al., 2021). Likewise, geomorphological studies should consider physical oceanographic analysis of the water masses impinging on the seafloor, in order to evaluate the potential role of bottom currents in shaping the margins and adjacent basins (Rebesco et al., 2014; Ercilla et al., 2016). In addition, when studying active geological margins, an integrated view that includes adjacent onshore structures can help us develop a better understanding of deep-sea geomorphic processes (Summerfield, 2005; Mosher et al., 2017). This approach is not a widespread practice amongst marine geologists and should become more frequent (Fig. 1A).

The main aim of this work is to understand the influence of the different processes that have generated the present-day geomorphology of the tectonically active Palomares continental margin and adjacent northwestern Algerian abyssal plain (i.e., the Gulf of Vera, SE Iberian margin, in the Western Mediterranean) (Fig. 1A and B). This gulf is developed in the framework of the collision between the Eurasian and African plates (DeMets et al., 2015), which generates the Aguilas Arc tectonic indentation structure on the continent (Coppier et al., 1989) (Fig. 1A and B). This is a very poorly studied area of the Mediterranean Iberian margin, although its interesting complex submarine structure is the result of a close interaction between tectonism and sedimentation (e.g., Comas and Ivanov, 2006; Acosta et al., 2013; Pérez Hernández et al., 2014; Giaconia et al., 2015). This study adopts for the first time an integrated approach combining morphology, stratigraphy, sedimentology, tectonic structure, and physical oceanography, in addition to a coupled offshore-onshore structural morphology perspective. Our results allow us to develop an updated geomorphological map and offer new insights and accurate interpretations of the sedimentary processes in the framework of the peculiar tectonic indentation setting. A new model of the geomorphic responses to tectonic indentation is presented, shedding light on the main sedimentary processes that have been governing the shaping of margin and adjacent abyssal plain.

2. Geological and oceanographic settings

2.1. Onshore-offshore geological setting

The Gulf of Vera has developed itself in the framework of the NNW-SSE collision between the Eurasian and African plates that has been uplifting both onshore and offshore reliefs since the late Tortonian (e.g., Comas et al., 1992; Braga et al., 2003; Stokes and Mather, 2003; Stokes, 2008; Acosta et al., 2013; Estrada et al., 2018) (Fig. 1A and B). The onshore relief is composed of folds with a general northward vergence, which form elongated mountain chains (Weijermars, 1985; Galindo-Zaldıvar et al., 2003). The E-W-elongated antiforms (Sierra de las Estancias, Sierra de Los Filabres, and Sierra Alhamilla-Sierra Cabrera) are separated by synformal depressions (Almanzora and Tabernas-Sorbas) filled by Neogene-Quaternary sediments. Northwards, the Aguilas Arc constitutes one of the most important recent tectonic indentation structures in the westernmost Mediterranean that has provoked coastal uplift of reliefs and tilting of the land-sea region (Coppier et al., 1989; Harvey et al., 2014) (Fig. 1B). This tectonic arc is also formed by elongated mountain chains (Sierra Almenara, Sierra Lomo de Bas and Sierra de Cabo de Gata) that determine the curved shape of folded structures, from the E-W-oriented northern branch (Sierra del Algarrobo), to the NNE-SSW southwestern branch (Sierra Almenara and Sierra de Gata). The folded structures are crossed by the Eastern Betic shear zone, which includes the Palomares and Serrata-Carboneras sinistral wrench faults (Fig. 1B) (Sanz de Galdeano, 1990).

The Palomares continental margin is located along the southwestern branch of the Aguilas Arc, a region of transition between the continental crust of the eastern internal zones of the Betic Cordillera and the oceanic crust of the Algerian Basin (Fig. 1B). The onshore-offshore geology of this zone can be correlated (Giaconia et al., 2012; Pedrera et al., 2012). This is evident by the metamorphic and volcanic nature of the basement and the active fault zones, such as the Mazarron, La Serrata-Carboneras and Palomares which have a land-sea continuation (e.g., Estrada et al., 1997; Fernández-Soler, 2001; Marro and Comas, 2005; Duggen et al., 2008; Pedrera et al., 2010; Giaconia et al., 2015) (Fig. 1B). Fault activity is evidenced by moderate to low-magnitude earthquakes, with epicentres located both offshore and onshore (www.ign.es). The adjacent Algerian Basin has been affected since the early Miocene by extreme crustal thinning (Medaouri et al., 2014) and oceanic crustal spreading (Aquitanian to Burdigalian), followed by thermal subsidence (Rehault et al., 1985; Gueguen et al., 1998).

Coastal uplift during the Plio-Quaternary has favoured the development of steep fluvial drainage systems that deeply incised (reaching 200 m) the eastern Betic Cordilleras, a region with an arid climate regime and little rain (Harvey and Wells, 1987; Stokes and Mather, 2003; Stokes, 2008). The seasonal Almanzora, Antas, Aguas, and Alias Rivers, from north to south, are the main rivers supplying sediment to the sea (Fig. 1C). Storm events contribute to remobilise sediment in the infralittoral and shelf domains, and to transport it offshore (Lobo et al., 2014).

2.2. Geomorphology and sedimentation history in the Gulf of Vera

The present-day physiography of the Palomares continental margin is defined by the shelf, slope, and rise provinces, which the literature shows as being bounded at different water depths (Acosta et al., 2013; Pérez Hernández et al., 2014; de la Peña et al., 2016). The physiography is dominated by the continental slope, where three outstanding elongated structural highs (the Maimonides, also known as the Banco de los Genoveses, Abubacer, and Aguilas) govern the location of two relatively

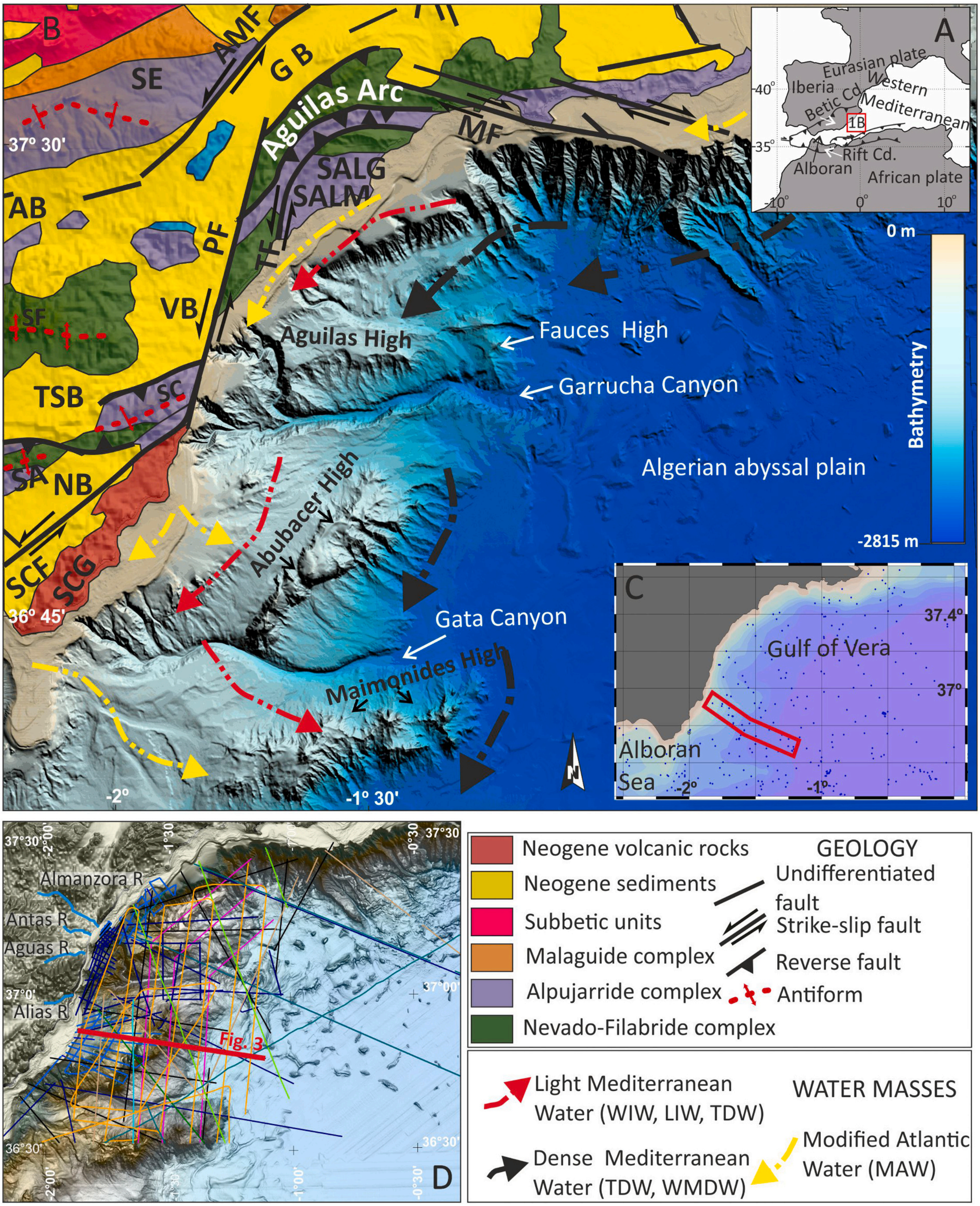

Fig. 1. Study area and datasets. A) Regional setting of the Gulf of Vera in the framework of the Eurasian–African plate boundary and the westernmost Mediterranean. Legend: Cd., cordillera; B) Geological sketch of the main onshore structural features defining the Aguilas Arc and nearby areas. The multibeam bathymetry of the Palomares continental margin with the most striking highs and canyons, and the Algerian abyssal plain are indicated. In addition, the oceanic circulation model of the main water masses comprising the water column is displayed. Geological legend: AB, Almanzora Basin; AMF, Alhama de Murcia Fault; GB, Guadalentín Basin; MF, Mazarron Fault; PF, Palomares Fault; SA, Sierra Alhamilla; SALG, Sierra del Algarrobo; SALM, Sierra Almenara; SC, Sierra Cabrera; SCG, Sierra del Cabo de Gata; SCF, Serrata-Carboneras Fault; SE, Sierra de las Estancias; TB, Tabernas Basin; TF, Terreros Fault; TSB, Tabernas-Sorbas Basin; VB, Vera Basin. Water mass legend: WIW, Western Intermediate Water; LIW, Levantine Intermediate Water; TDW, Tyrrhenian Deep Water; WMDW, Western Mediterranean Deep Water. C) Map showing the multichannel seismic lines used in this study. The colours refer to lines from different cruises. The thick red line indicates the location of the seismic line in Fig. 3. "R." refers to rivers. D) Map showing the distribution of the analysed Conductivity, Temperature and Depth (CTD) profiles from the Sea Data Net website (http://www.seadatanet.org). The red rectangle refers to CTD locations used for the hydrographic section displayed in Fig. 3.

long W-E-trending, shelf-indenting submarine canyons, namely, Gata and Almazora-Alias-Garrucha (hereafter referred to as Garrucha) (Fig. 1B). Erosive turbidity currents loaded with sediments from river floods and coastal erosion have contributed to their incision, shaping their floors and producing a great variety of bedforms (Pérez Hernández et al., 2014; Puig et al., 2017). The morphology of the continental slope and rise is also affected by sedimentary instability processes (Acosta et al., 2013; Pérez Hernández et al., 2009, 2014; de la Peña et al., 2016).

Seismic stratigraphic studies of the Palomares continental margin show the presence of an irregular basement covered by upper Miocene (Tortonian and Messinian) and Plio-Quaternary sediments (Giaconia et al., 2015; de la Peña et al., 2016). Three main events have affected the sedimentation in the region and near the Gulf of Vera. The oldest is the compressional tectonic inversion that affected the Alboran Domain and produced the uplift of the hinterland areas, conditioning the sediment sources (type and volume of sediment) (Stanley et al., 1975). The next is the Messinian Salinity Crisis (MSC) that isolated the Mediterranean Sea from the Atlantic Ocean and subaerially exposed the Iberian continental margins. This same event is represented in the stratigraphic record by a prominent irregular and erosive surface, named the Messinian Erosive Surface (MES) (Estrada et al., 2011). The latest event is related to the increasing frequency and greater amplitude of sea-level changes from the Pliocene to the Quaternary, and their influence on bottom current activity. This influence is reflected by higher acoustic amplitudes in the Quaternary seismic sedimentary stratigraphy (Alonso and Maldonado, 1992; Juan et al., 2016, 2020).

2.3. Physical oceanography

The western Mediterranean comprises five main water masses: one of Atlantic origin (Modified Atlantic Water, MAW) and four of Mediterranean origin (Western Intermediate Water, WIW; Levantine Intermediate Water, LIW; Tyrrhenian Deep Water, TDW; and Western Mediterranean Deep Water; WMDW) (e.g., Parrilla et al., 1986; Millot, 1987, 1999; Candela, 2001). Recent studies in the nearby Alboran Sea (Ercilla et al., 2016) have grouped these four Mediterranean water bodies into two main pockets: Light Mediterranean Water (LMW), formed by the WIW, LIW and upper TDW; and Dense Mediterranean Water (DMW), comprising the lower TDW plus the WMDW (Fig. 1B). The surface MAW reaches the Gulf of Vera, moving southwards and extending to a water depth of approximately 100/200 m, where its near-bottom layer affects the continental shelf/slope (Fig. 1B). The underlying LMW extends down to approximately 500/700 m and moves southward, following the contour of the continental slope (Fig. 1B). The lowest part of the water column is occupied by the DMW (Fig. 1B), which moves southward in the Gulf of Vera, also following the contour of the continental slope and rise and infilling the Algerian abyssal plain (Fig. 1B) (e.g., Parrilla et al., 1986; Millot, 1999; Ercilla et al., 2016).

3. Materials and methods

New and historical data used in this study comprise swath bathymetry, magnetic anomalies, seismic records and CTD (Conductivity-Temperature-Depth) data (Fig. 1C–D). The multibeam bathymetry was recorded using Simrad EM12 and Atlas HYDROSWEEP DS multibeam echosounders, during cruises from the Spanish Fishing General Secretary (2003 and 2004) and FAUCES (2018) Project. Multibeam datasets were merged and gridded at a 50 m resolution with CARIS software, prior to geormorphological map generation with Global Mapper software. Morphometric attributes such as slope gradients, profile curvatures, planar curvatures and roughness were obtained by ArcMap (GIS), and topographic profiles allowed us to obtain a better characterization of physiographic provinces and seafloor features. The continental topographic maps were downloaded from https://www.ngdc.noaa.gov/mgg/global/gridded and gridded at a 50 m resolution. The total field magnetic anomalies were based on the compilation by Galindo-Zaldívar et al. (1998) and the World Digital Magnetic Anomaly Map (Lesur et al., 2016; http://wdmam.org/). The magnetic anomaly map was incorporated into the global mapper to establish the relationship between the magnetic dipoles and the highs dotting the seafloor, as well as to define their nature. A collection of multichannel seismic records with different degrees of penetration (0.5 to 1.5 s) and resolution (from a few metres to decimetres) provided by different scientific projects were analysed (Fig. 1C). The seismic profiles were interpreted using the IHS KINGDOM software package. In addition, a conductivity, temperature and depth (CTD) dataset (Fig. 1D) was downloaded from the Sea Data Net website (http://www.seadatanet.org). Using the Ocean Data View (ODV) software (http://odv.awi.de) and considering the temperature, salinity and vertical and horizontal gradient data (Millot, 1987, 1999), the different water masses present in the water column were identified, as well as the water depth distribution of their respective bottom layers. They have were in a similar way and correlated with those established near the Alboran Sea (Ercilla et al., 2016).

In order to establish the Miocene, Pliocene and Quaternary seismic stratigraphic divisions, the updated regional stratigraphic boundaries were used, as defined in the nearby Alboran Sea by Estrada et al. (2011), Ercilla et al. (2016), and Juan et al. (2016, 2020). These stratigraphic boundaries were physically correlated through seismic profiles, as well as the mapped boundaries of the deposit types and physiographic provinces. In addition, contourites were characterized according to the criteria of Faugères et al. (1999), Stow and Faugères (2008), and Rebesco et al. (2014). Mass movement, the term for gravity-driven sediment movement, involves several types of instabilities, from slides to gravity flows (Hampton et al., 1996; Locat and Lee, 2002), therefore we applied the terminology and criteria for characterization of Shepard and Dill (1966), Gomberg et al. (1995), Harishidayat et al. (2018) and Tripsanas et al. (2004) to describe the erosive mass-movement features. Instead, to describe the depositional features we used the terminology of Masson et al. (1996), Laberg and Vorren (2000), Fort et al. (2004), and Rodriguez et al. (2012).

4. Results

4.1. Physiography

The datasets enables us to more clearly define the main physiographic provinces characterising the Gulf of Vera (Fig. 2). Table 1 shows the main morphometric characteristics. The edge of the *continental shelf* extends to shallower-water depths (<125 m water depth) than what is reported in previous studies (Acosta et al., 2013; de la Peña et al., 2016). The *continental slope* is the most striking domain; it displays an irregular topography and involves several subprovinces. These subprovinces include a relatively narrow and steep upper slope that borders a smooth and gentler slope platform. This passes seaward to the lower slope with highly irregular gradients. Locally, an intraslope basin (herein named Gata) has been identified southwards between the slope platform and the SW-NE Abubacer High (582 m water depth). This high, along with the other two main linear structural highs, the WSW-ENE-trending Aguilas (800 m water depth) and the WSW-ENE-trending Maimonides (784 m water depth), compartmentalise the lower slope. Other small-scale highs (Fauces, 1880 m water depth; others unnamed within 300–400 m water depth) dotting the slope platform and lower continental slope have also been mapped in the southern region. The gentler *continental rise* evolves into the flat-lying seafloor domain of the Algerian *abyssal plain*.

4.2. Water masses present in the water column

The three main groups of water masses (i.e., MAW, LMW, and DMW) defined in the literature are clearly characterized. In this study, they have been grouped in a similar way and correlated with those established near the Alboran Sea (Ercilla et al., 2016). Underlying the MAW is

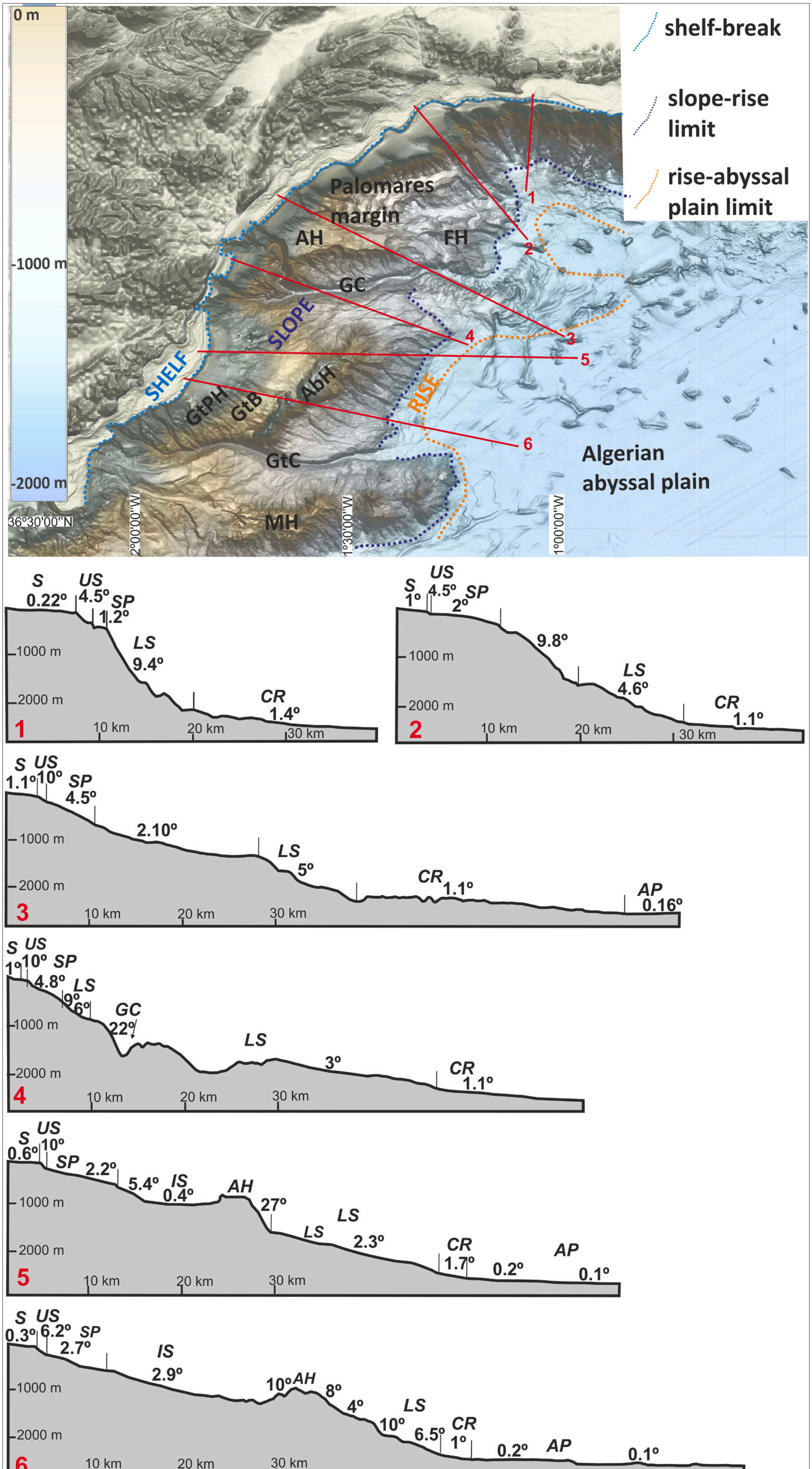

Fig. 2. Physiography of the Gulf of Vera. Topographic profiles crossing the Palomares continental margin and adjacent Algerian abyssal plain to illustrate the main physiographic domains and their average seafloor gradients. S, continental shelf; US, upper continental slope; SP, slope platform; IS, intraslope basin; LS, lower continental slope; CR, continental rise; AP, abyssal plain; AbH, Abubacer High; AH, Aguilas High; GtB, Gata Basin; GC, Garrucha Canyon; GtC, Gata Canyon; FH, Fauces High; GtPH, Gata palaeohigh.

Table 1
Physiographic provinces of the Gulf of Vera and their characteristics.

Province		Water depth (m)	Slope gradient (°)	Width (km)
Shelf		10 to 125	<1.1	<0.1 to <10
Slope	Upper slope	90/125 to 265	10°	0.24
	Slope platform	150 to 700	2 to 4.8	to 9
	Intraslope basin	700 to 1200	2 to >20	to 13.5
	Lower slope	to 2300/2400	2.3 to >20	10 to 45
Rise		2300 to 2600	≥1°	>2 to 20
Abyssal Plain		>2600	<1°	

the southward-moving LMW, and its interface extends down approximately 110–200 m. The LMW, combined with the WIW (38–38.4 psu and 12.85–13.25 °C), plus the LIW (38.5 psu, a temperature of 13.1–13.2 °C), and the upper TDW (38.4–38.5 psu and 13–13.4 °C) extend to variable water depths of 700 to 1100 m. Below these water depths the southward-moving DMW extends and comprises the lower TDW (38.4–38.5 psu and 12.85–13.05 °C) and most of the WMDW (38.4–38.5 s and 12.4–12.85 °C) (Fig. 3).

4.3. Seabed morphological features as revealed by multibeam bathymetry

The main elements shaping the seafloor of the Palomares continental slope and rise comprise mass-movement deposits and submarine canyons and gullies. Contourites were also mapped. The flat-lying seafloor of the Algerian abyssal plain is dotted by diapir crests (Fig. 4). Supplementary Table 1 summarizes their main morphologic characteristics.

Mass-movement deposits fall into two distinct groups: mass-flow deposits and large-scale slides (Fig. 4; Supplementary Table 1). *The mass-flow deposits* are characterized by two distinct features: scars and remobilized sediments. The scars (several km to 11 km wide) mainly occur where seafloor gradients are >5° on the lower open slope, the walls of the large canyons, and the highs (Fig. 4A and B; Supplementary Table 1). The scars are arcuate-elongated features that extend and narrow downslope, forming elongated negative reliefs. They are mostly irregular U-shaped bases, flanked by steep walls. They resemble gullies eroding the seafloor, but their roughness values are lower (<8), and the profile curvature is less variable (−1 to 3) (Fig. 4A, C and D). Locally, just upslope of the headscarps, upper cracks that run parallel to their curvature are mapped (Fig. 4A). Scars form clusters at different scales, suggesting a superimposition, coalescence and cannibalise each other. The area affected by the scar clusters, in general, evolves downslope to the area where the remobilized sediment deposits (areas from >100 to 300 km^2) (Fig. 4A; Supplementary Table 1). These areas are mapped where the seafloor has gradients of <5° in the open slope and rise, promoting an irregular seafloor that has lower roughness values (~0–4), and less spatial profile curvature variability than the scar areas (Fig. 4B–D).

The *slides*, herein named the Polopo, Aguilas, and Gata Slides, stand out due to their relatively large dimensions (areas up to 686 km^2; Supplementary Table 1; Fig. 4). They are characterized by the fact that their striking scars are attached to the sediment that slid. The Polopo slide affects the entire lower slope in front of the Aguilas Arc. It is defined by a WSW-ENE-oriented rectilinear headwall scar (~29 km long) eroded by gullies. The headwall connects to well-defined sidewall scars extending down into the continental rise boundary. In general, the seafloor of the slipped sediment shows an irregular staircase-like profile and depicts irregular downslope-concave scarps and depressions. Downslope of the Polopo Slide, the Aguilas Slide can be found (Fig. 4). Its scar (~46 km long) displays an open arc shape where it truncates/cannibalises the Polopo Slide sediment. The Gata Slide is located at the continental rise, and its irregular scar (~56 km long) runs along the slope-rise boundary. The Aguilas and Gata sediment that slid also displays rectilinear scarps facing downslope (Fig. 4A).

Two *large*, prominent shelf-indenting *canyons,* the Garrucha (~84 km long) and Gata (~62 km long), incise the entire margin and extend onto the abyssal plain (Fig. 4; Supplementary Table 1). The canyon heads comprise several sinuous (Garrucha) and rectilinear (Gata) V-shaped tributaries, which incise the entire continental shelf. The pathway of the Garrucha Canyon is rectilinear, except in the distal reach, where it becomes sinuous. The Gata Canyon, instead, is slightly sinuous. The main canyon courses are dominantly U-shaped (Garrucha) and V-shaped (Gata) and are flanked by the Aguilas and Maimonides Highs, respectively. The axial gradients are higher in the tributaries (5–7°) and decrease downslope along the main courses (4 to <1°) (Supplementary Table 1). The right leveed margin of the Garrucha Canyon mouth is affected by a field of asymmetric sediment waves whose crests are sinuous and roughly parallel to the seafloor slope (Fig. 4). *Shorter* and V-shaped slope-confined *canyons* and *gullies*, both with rectilinear pathways (up to 5 km long) and relatively high axial gradients (6 to 8°), incise the steeper lower slope northward off of the Aguilas Arc (Fig. 4; Supplementary Table 1). Gullies are also mapped on the proximal

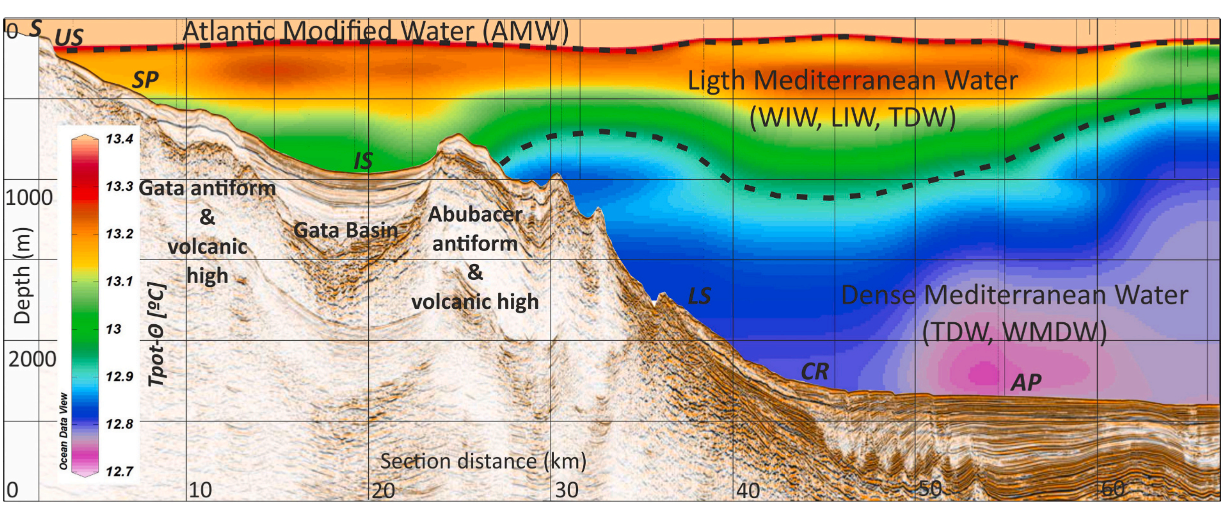

Fig. 3. Integrated seismic and hydrographic sections of the Palomares continental margin and adjacent Algerian abyssal plain, displaying the main water masses (Atlantic and Mediterranean) comprising the water column of the Gulf of Vera. The black vertical lines in the water column indicate the water depth to which the CTD was lowered. Colour-coding: temperature (°C). Legend: S, continental shelf; US, upper continental slope; SP, slope platform; IS, intraslope basin; LS, lower continental slope; CR, continental rise; AP, abyssal plain. For the water masses legend, see Fig. 1B. The location of the CTDs for seismic–hydrographic section is shown in Fig. 1B.

reaches of the Garrucha and Gata Canyon walls, and on the Polopo Slide scar (Fig. 4; Supplementary Table 1).

In contrast to the irregular seafloor configurations of the mass-movement deposits and canyons/gullies, the smooth seafloor of an alongslope *contourite* terrace stands out. This terrace, which defines the slope platform domain (Figs. 2–4A), presents gentler gradients (~2°) that are higher (4.8°) in front of the Aguilas Arc (Table 1 and Supplementary Table 1). A contourite marginal valley (a few km wide, tens of metres in relief) has also been identified locally at the foot of the Abubacer High (Fig. 4; Supplementary Table 1).

On the Algerian abyssal plain seafloor, the diapiric crests are the most striking morphological features, as they are mostly concentrated in front of the Aguilas Arc (Fig. 4; Supplementary Table 1). They create isolated pointy reliefs (few to several tens of metres of relief) displaying subcircular to elongated morphologies. These reliefs also form ridges that seem to be the result of several individual elements coalescing. The crests are arranged into two groups with different trend directions: SW-NE-trending lineations, which are laterally bounded by ESE-WNW lineations (Fig. 4A).

4.4. Basement structure and seismic stratigraphy

Seismic profiles reveal that the basement topography is covered and infilled by ~1000 ms thick sediments comprising undifferentiated upper Miocene deposits overlain by a Pliocene-Quaternary cover (Figs. 5–10).

4.4.1. Basement: nature and structure

The basement is characterized by a fairly irregular topography, with striking elongated (between 13 and 41 km crest long; 1 to 1.5 km high) highs (Maimonides, Gata, Abubacer, and Aguilas) and troughs (38 km long; up to 1 km of relief) that configure the Gata intraslope basin, the complex topography of the continental slope, and the slope-rise boundary (Figs. 2, 3, and 5–10). Seismically, the metamorphic basement is mostly characterized by discontinuous stratified facies with reflections of variable acoustic amplitude, as well as hyperbolic and hummocky reflections (Figs. 6, 9 and 10). The volcanic basement shows typical facies characterized by diffractive echoes (Figs. 6–9C and D). The magnetic anomalies are mainly related to volcanic rocks, as observed onshore where the Cape of Gata crops out, and display higher magnetic susceptibilities than the metamorphic host rocks (Fig. 5A) (Pedrera et al., 2006). The magnetic susceptibility contrast produces anomalous

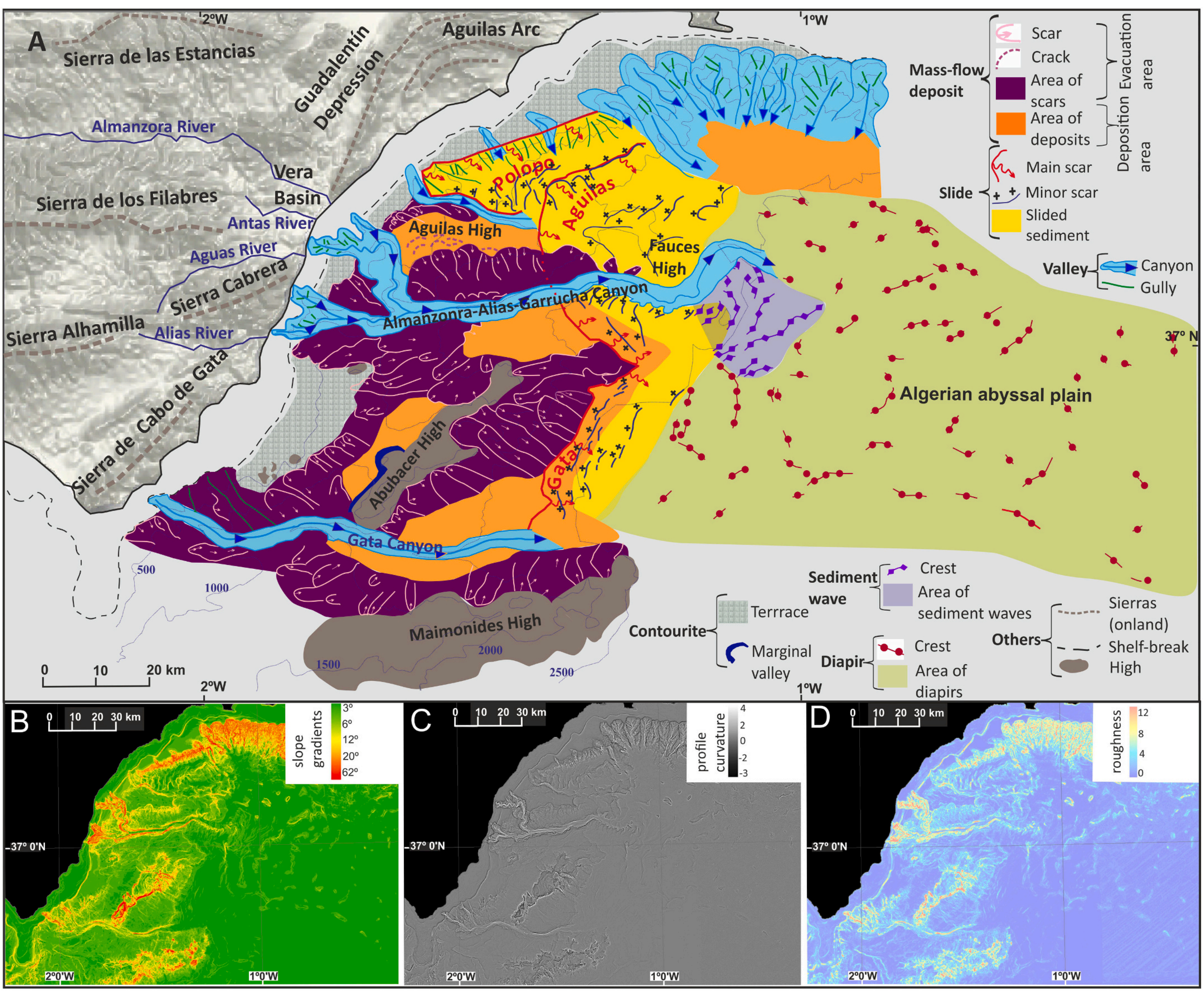

Fig. 4. Geomorphologic map and seafloor morphometric parameters of the Gulf of Vera. A) Map showing the main morphosedimentary features. Not all the gullies are mapped; they represent only a sample from the areas where they occur. B) Slope gradient map. C) Profile curvature map. D) Roughness map.

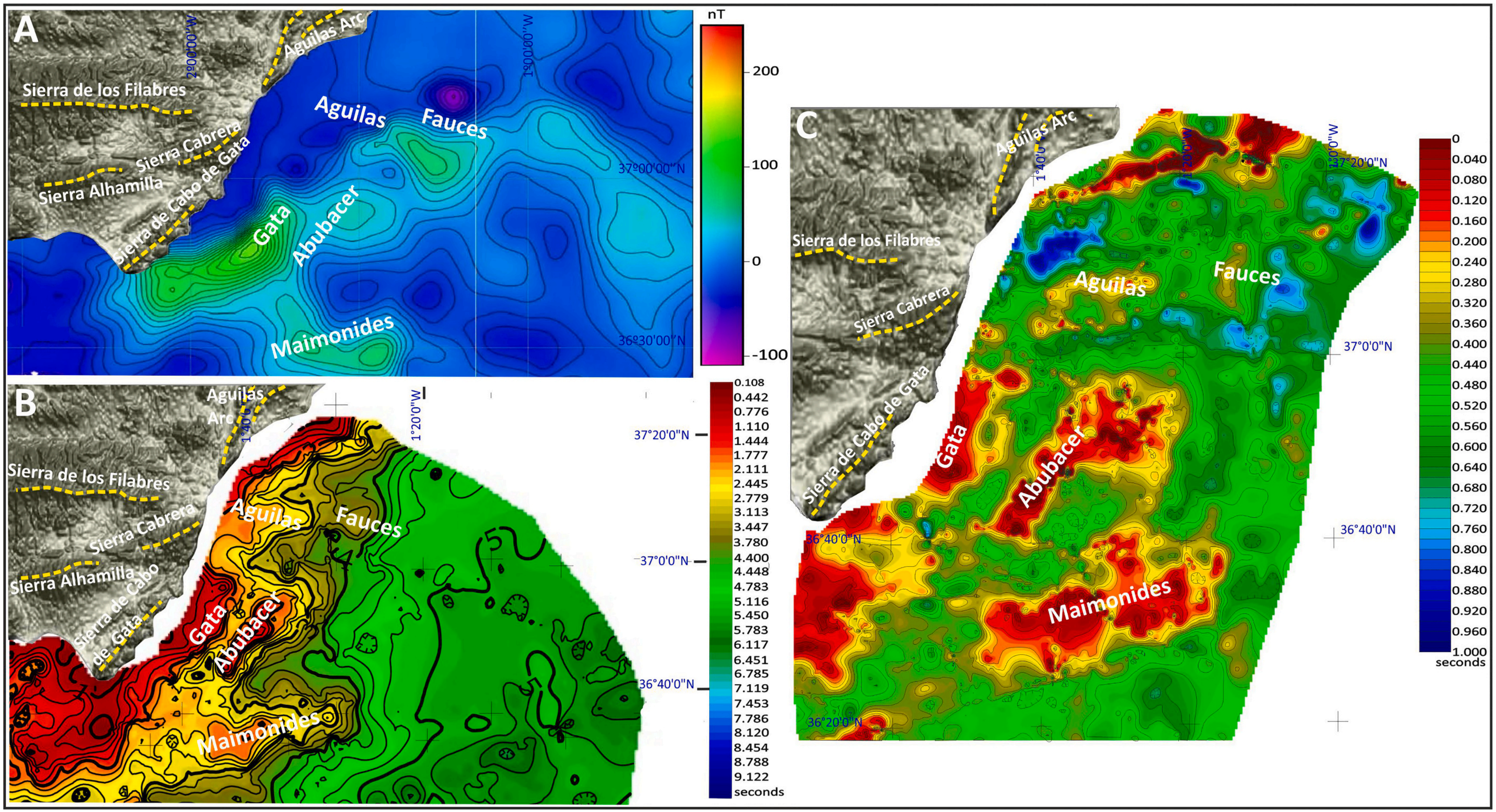

Fig. 5. Structure of the Gulf of Vera. A) Magnetic anomaly map (nT). Note the dipoles. B) Isobath map of the basement; C) Plio-Quaternary isochore map. Location of the Gata palaeohigh and the Maimonides, Abubacer, Aguilas and Fauces Highs are indicated in the maps.

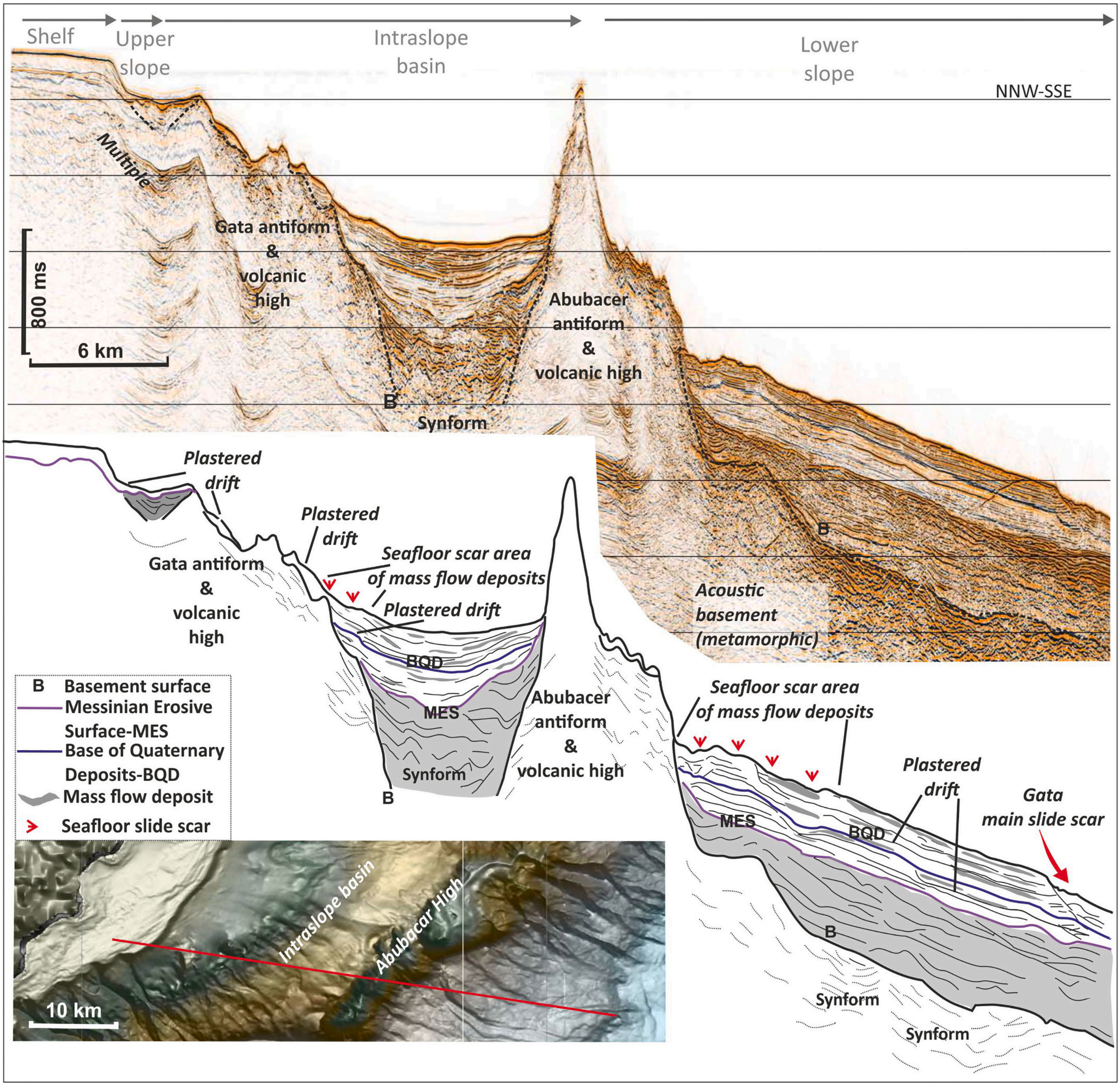

Fig. 6. Multichannel seismic profile and line drawing displaying the basement and the upper Miocene (grey area) to Quaternary seismic stratigraphy. The main Plio-Quaternary deposits and features and their seafloor fingerprints are indicated. The drawing of mass flow deposits and slide seafloor scars has been given by way of example of their abundance.

dipoles in the magnetic anomaly map, with maxima to the south and minima to the north that indicate the location of the main volcanic bodies (Fig. 5A). The map shows two principal regional dipoles: an E-W dipole related to the Maimonides High; and a NE-SW-elongated dipole that extends towards the central part of the Gulf of Vera and is associated with the Cape of Gata volcanic rocks. The latter dipole comprises a cluster of three minor dipoles. The southwesterly anomaly, near the Cape of Gata, is the most intense (maxima of >100 nT), and is related to the elongated igneous body that defines the Gata basement high, with a weak bathymetric expression. In the northern Abubacer High, an isometric dipole is located, although seismic facies indicate that the entire high is volcanic (Figs. 5A, 6 and 8). The third dipole is located in the easternmost zone of the Aguilas High, where a volcanic high (herein named Fauces) is identified, which is partially surrounded by the Garrucha Canyon (Fig. 5A). Beyond the areas affected by these magnetic anomalies, the basement of the continental margin corresponds to the host metamorphic rocks (Fig. 5A and B).

The multichannel seismic profiles also provide information on the deformation style. The profiles show that the discontinuous subparallel reflections contain traces of their original bedding, suggesting that they represent primary reflections (Figs. 6–9C and D). They indicate that the basement highs are broad antiforms, or domal structures, characterized by metamorphic rocks with volcanic intrusions, forming either NE-SW antiform-synform pairs (Abubacer and Gata) or ENE-WSW-trending antiformal structures (Maimonides and Aguilas). In fact, these structures represent the seaward continuation of the folds that affect the

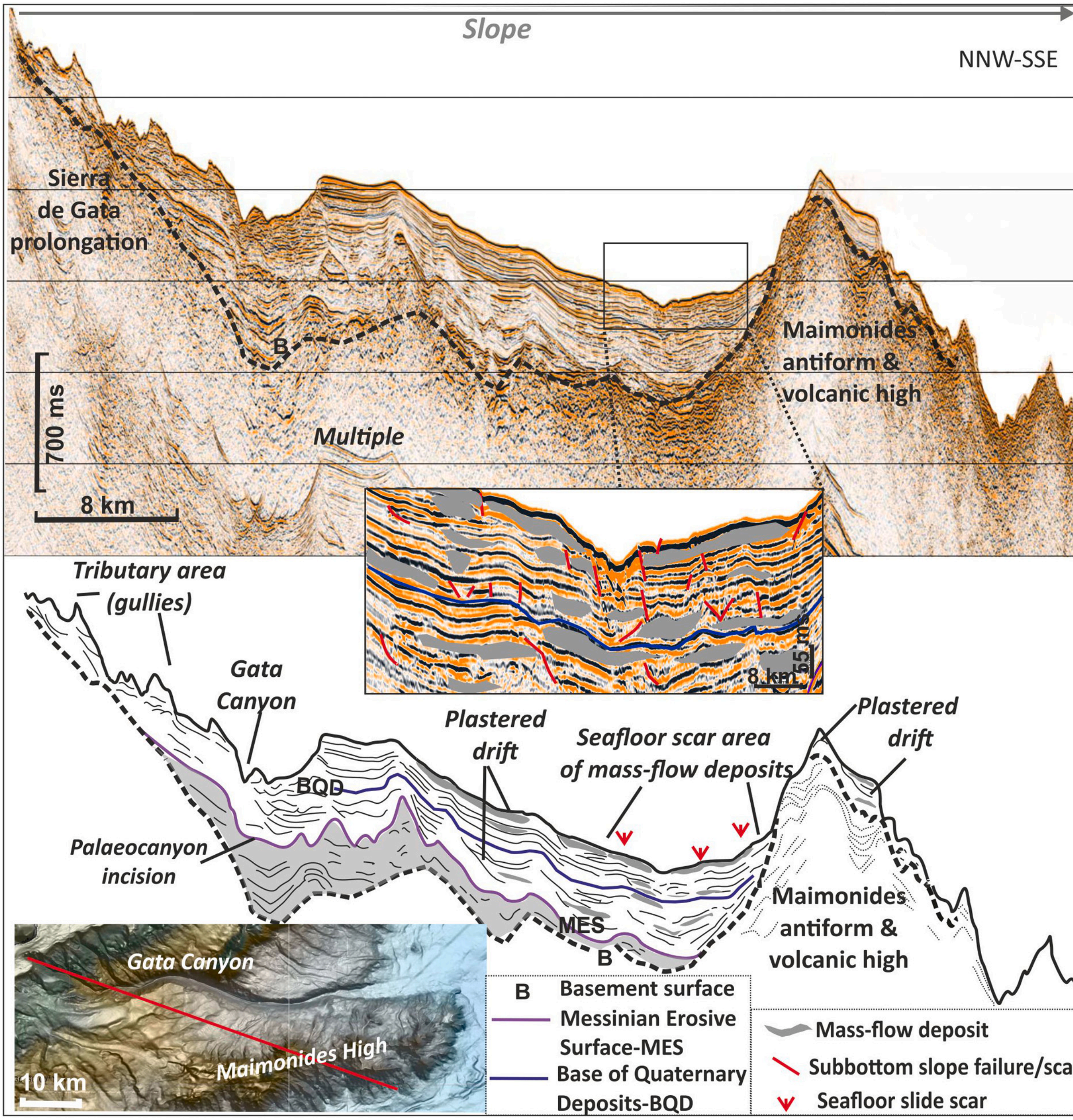

Fig. 7. Multichannel seismic profile and line drawing displaying the basement and the upper Miocene (grey area) to Quaternary seismic stratigraphy. The main Plio-Quaternary deposits and features and their seafloor fingerprints are indicated. The close-up image illustrates the abundant occurrence of mass-flow deposits. The drawing of mass flow deposits, subbottom slope failures/scars and seafloor slide scars has been given by way of example of their abundance.

adjacent hinterland (similar in style and trend) and uplift the elongated reliefs of the central–eastern Betic Cordillera (Weijermars, 1985; Galindo-Zaldıvar et al., 2003) (Figs. 1B and 5A and B).

4.4.2. Upper Miocene sequence and the Messinian Erosive Surface

The upper Miocene sequence (Tortonian to MSC deposits) contributes to the partial infilling of the basement synforms and corridors along the continental margin (grey sequence in Figs. 6 to 10). This sequence mostly comprises deformed stratified facies with reflections onlapping the basement highs showing a typical convergent configuration (more condensed) at the high sides, local chaotic facies along the continental slope, and well-layered reflections in the abyssal plain. The uppermost deposits of the sequence are deformed and broken by a transparent acoustic layer that can be correlated with the MSC salt layer (Lofi et al., 2011) (Fig. 9C and D). It is present over the entire abyssal plain up to the lower slope-rise boundary, except in front of the Aguilas Arc, where it broadens to reach the slope platform (Fig. 11, dashed dark blue line).

The upper boundary of the Miocene sequence is the MES unconformity (Figs. 6–10). This high acoustic amplitude and irregular surface erodes the underlying Miocene sediments and abuts the surface of the basement highs. The irregular MES shows U-shaped features resembling canyons that incise the upper Miocene deposits in the continental slope. The position of the palaeocanyons coincides with the present-day location of the large and small canyons (Fig. 7; Supplementary Table 1).

4.4.3. Plio-Quaternary sequence and deposit types

The Plio-Quaternary sediments of the Palomares margin and Algerian abyssal plain rest on the MES unconformity (Figs. 6–10). They have progressively draped broad areas of the basement, partially obliterating its morphology. The main Plio-Quaternary depocentres are located between the basement highs and along the areas incised by the Garrucha canyon (Figs. 5C–8 and 10). Other smaller-scale depocentres are present

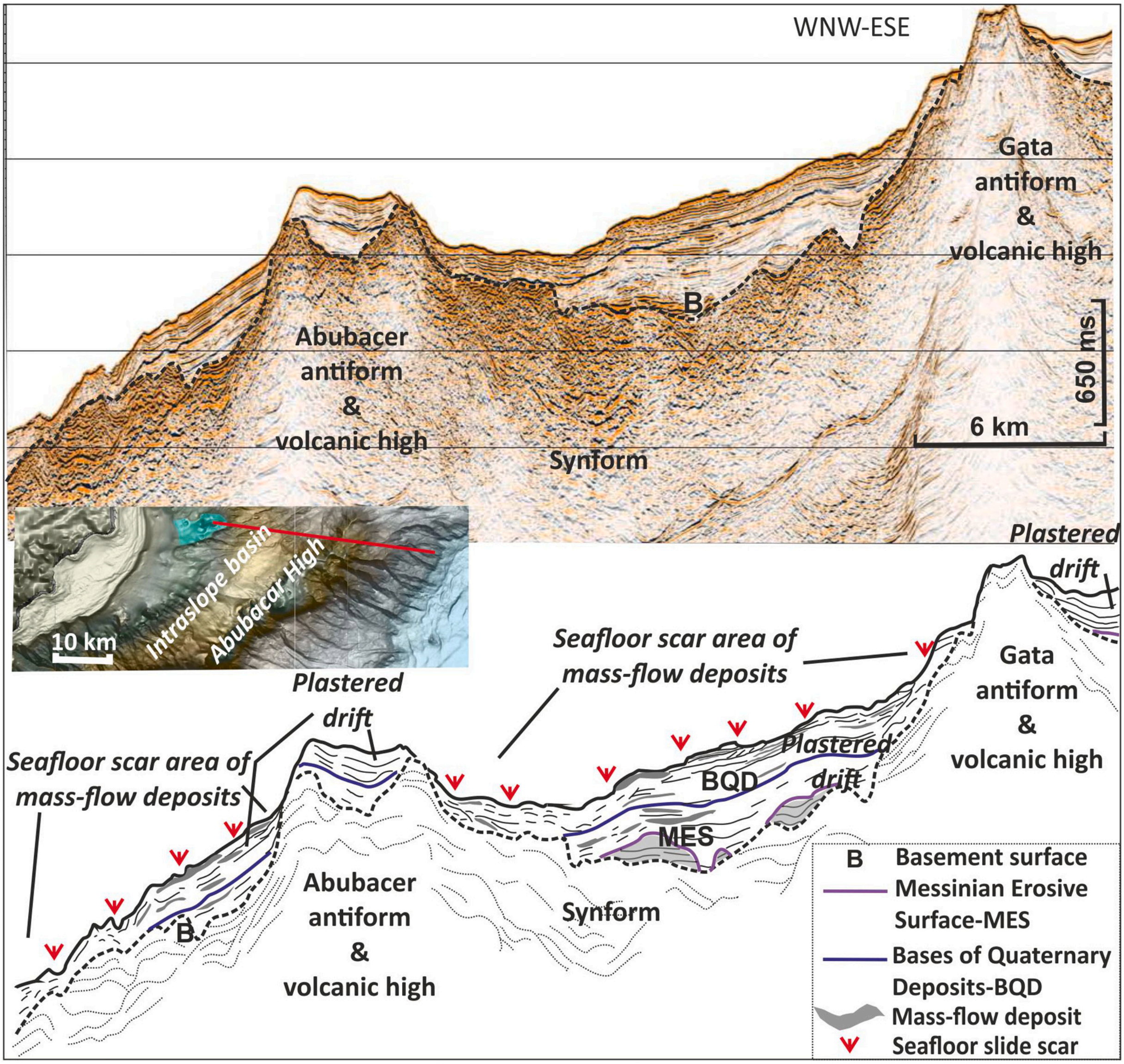

Fig. 8. Multichannel seismic profile and line drawing displaying the basement and the upper Miocene (grey area) to Quaternary seismic stratigraphy. The main Plio-Quaternary deposits and features and their seafloor fingerprints are indicated. The drawing of mass flow deposits and slide seafloor scars has been given by way of example of their abundance.

on the most distal slope platform, with an alongslope trend. The lower thicknesses of the Plio-Quaternary sequence are mostly located over the basement highs and, locally, on the proximal slope platform (Fig. 5C). The Pliocene and Quaternary sediments are separated by a regional paraconformity (Figs. 6–10) that is locally erosive and physically correlated with the Base of the Quaternary Deposits (BQD) stratigraphic boundary. Both units are characterized by continuous and discontinuous stratified and chaotic facies, although they show distinct acoustic amplitudes. The Pliocene deposits are semi-transparent facies due to the low amplitude of the reflections, which contrasts with the high acoustic amplitude that is typical of the Quaternary deposits in the nearby areas (Figs. 6–10). The interpretation of the Plio-Quaternary acoustic facies and sedimentary architecture has allowed us to characterize different types of deposits, namely, (i) contourites, (ii) mass-movement deposits and (iii) canyon- and gully-related deposits in the Palomares continental margin; and (iv) (hemi)pelagites/sheet-like turbidites in the Algerian abyssal plain (Figs. 6–10; Supplementary Table 1).

(i) The contourites comprise plastered drift deposits and an erosional terrace. The drift sediments are the main deposits that contribute to the outbuilding of the Palomares margin with an aggradational pattern, which is locally aggradational-progradational on the slope platform (Figs. 6–10; Supplementary Table 1). Their subparallel stratified reflections onlap the continental slope and the flanks of the basement highs. Overall, they are predominately low mounds, subtabular and wedge upslope (Figs. 6–8 and 10). The contouritic terrace occurs on the slope platform, where it truncates the stratified reflections of the plastered drift that shapes it (Fig. 9A, B; Supplementary Table 1). The plastered drift deposits and terrace correlate laterally with those defined along the Spanish margin of the nearby Alboran Sea (Juan et al., 2016, 2020).

(ii) The mass-movement deposits comprise mass-flow deposits and the Polopo, Aguilas and Gata Slides. They are deforming and eroding the plastered contourites and the walls of the Garrucha and Gata canyons (Figs. 6–10; Supplementary Table 1). The mass-flow deposits are acoustically characterized by abundant interbedded lenticular and irregular bodies (a few to tens of ms thick; hundreds to several km long) of chaotic, discontinuously stratified, and hyperbolic echoes that truncate contourites. Numerous isolated shallow-rooted (a few to tens of ms)

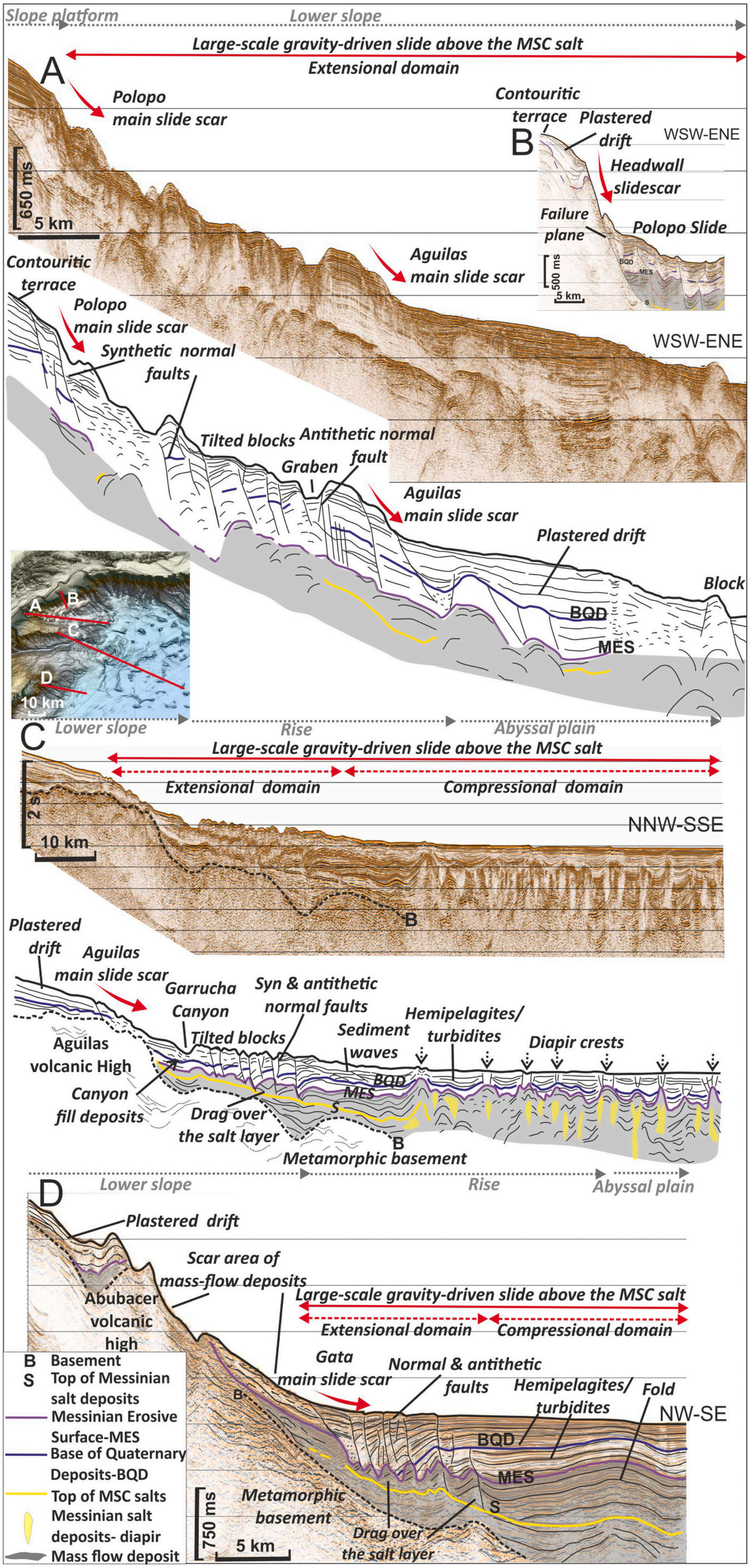

Fig. 9. Large-scale gravity-driven slides above the MSC salt layer and their seafloor fingerprints. A) Multichannel seismic profile and line drawing of the extensional domain comprising the Polopo and Aguilas Slides. Their seismic stratigraphy and extensional deformation pattern and features are shown. The drawing of mass flow deposits has been given by way of example of their abundance. B) Multichannel seismic profile showing detailed stratigraphic patterns and features of the main headscarp of the Polopo Slide, which affects the contourites. C) and D) Multichannel seismic profiles and line drawings of the extensional and compressional domains displaying the main deformational stratigraphic pattern and features. The extensional domain is mainly characterized by the Aguilas (C) and Gata (D) Slides in the margin, and by squeezed diapirs in the abyssal plain. The drawing of diapirs has been given by way of example of their abundance.

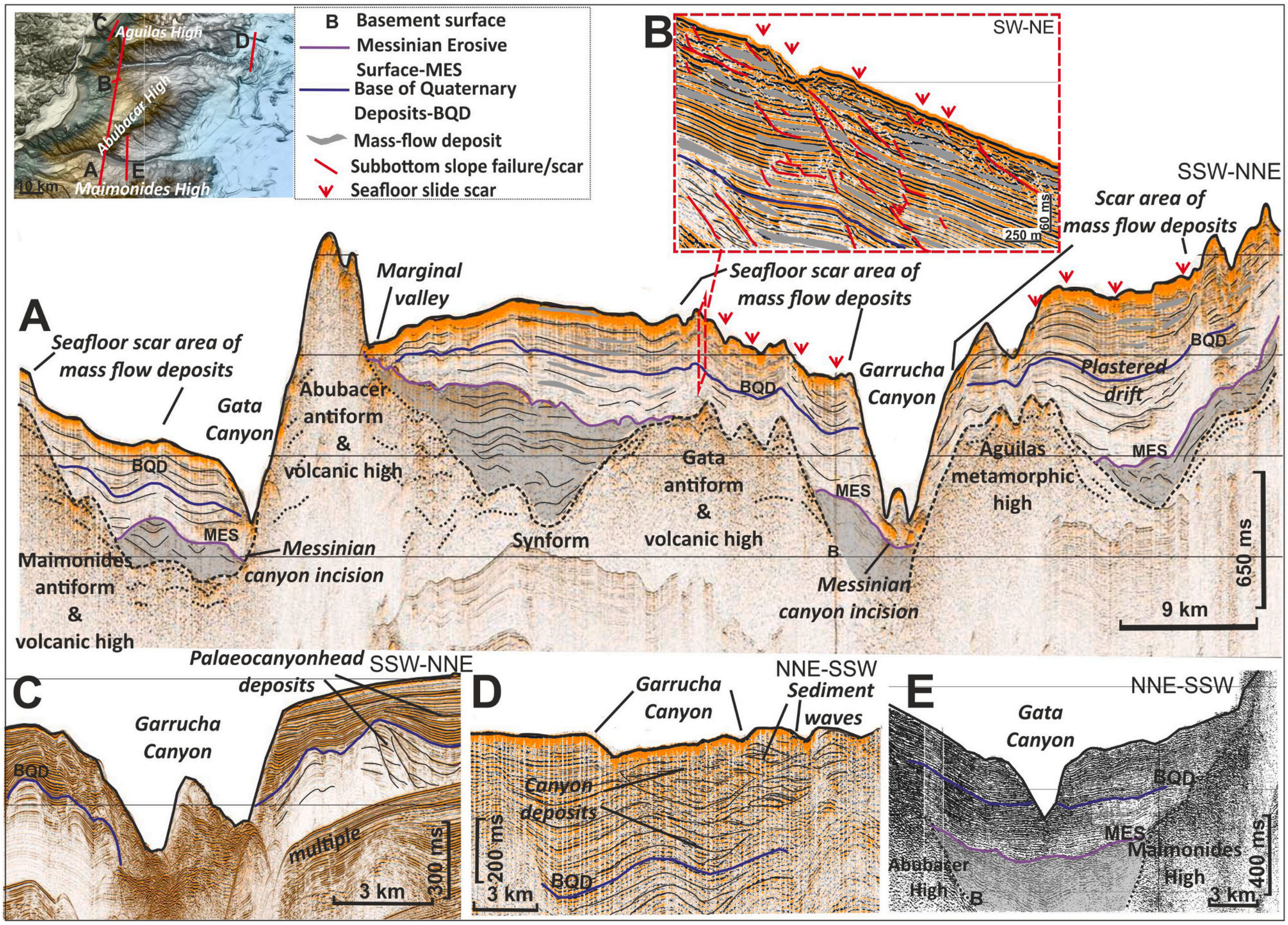

Fig. 10. The Gata and Garrucha Canyons in the seismic stratigraphic and structural contexts. A) Multichannel seismic profile crossing the Gata and Garrucha Canyons and adjacent continental slope areas, enhancing their deposits and features and their seafloor fingerprints. The drawing of mass flow deposits has been given by way of example of their abundance. B) Multichannel seismic profile detailing the abundant occurrence of mass-flow deposit features. C) Multichannel seismic profile crossing the tributaries feeding the Garrucha Canyon. Note the presence of ancient palaeocanyon deposits that correspond to ancient tributaries. D) Multichannel seismic profile crossing the mouth of the Garrucha Canyon showing the deposits and the sediment waves mapped on the right margin. E) Multichannel seismic profile crossing the Gata Canyon.

scars are also identified (Figs. 6–8). Mass flow deposits are in general more abundant in the Quaternary sequence (Figs. 6–8). On the other hand, the Polopo, Aguilas and Gata Slides have scars/surfaces of ruptures rooted to the MSC salt layer (Fig. 9). These slides are easily recognisable because they slightly to highly deform contourite deposits, indicating different degrees of remoulding. The affected deposits are faulted and back-rotated by several offshore- and onshore-dipping concave-upward surfaces, and their seafloor morphological expressions correspond to rectilinear and concave scarps and depressions imaged by bathymetry (Figs. 4 and 9).

(iii) The canyon- and gully-related deposits comprise fill deposits (a), levee deposits (b) and sediment waves (c). The fill deposits, better developed in the Garrucha Canyon, mostly comprise divergent stratified facies infilling ancient tributaries at the head area, while along the main course, they are mostly represented by cut-and-fill features made by chaotic facies and high-amplitude reflections of discontinuous stratified facies, affected by U-shaped erosive surfaces (Figs. 7, 9C and 10A, C and D; Supplementary Table 1). The depositional architecture of the Garrucha and Gata canyon-fill deposits shows that they are present throughout all the Pliocene and Quaternary units, except in their most distal reaches, where they seem to appear only in the Quaternary unit (Figs. 9C and 10C–E). The levee deposits (b) are identified bordering only the right margin of the Garrucha Canyon and in the Quaternary sequence, which are distinguished by the vertical migration and stacking of wavy stratified reflections (Fig. 10D; Supplementary Table 1).

On the abyssal plain, the Pliocene and Quaternary sediments are similar. The stratified reflections with high lateral continuity would be ascribed to (hemi)pelagites, as well as sheet-like turbidites (unconfined basinal turbidites), the latter occurring mostly off of canyon mouths. Sheeted contourites are disregarded, as the well-layered deposits have no apparent onlap and downlap reflection terminations. (Hemi)pelagites/sheet-like turbidites contribute to the infill, making the Algerian abyssal plain seafloor flat. They are faulted and folded in small antiforms and synforms by the underlying MSC salt deposits, which rise to different stratigraphic levels, forming diapiric structures (Fig. 9C; Supplementary Table 1). Locally, they extend upwards, piercing the sediments until they reach the seafloor. There, they coincide with the diapir crest features mapped on the seafloor (Figs. 4 and 9C; Supplementary Table 1).

5. Discussion

5.1. Geomorphic sedimentary processes in the Gulf of Vera after the MSC: linking seafloor and subbottom observations

The results from the interpretation of the seafloor multibeam bathymetry, water masses impinging on the seafloor and seismic records, provide new and complementary perspectives of the geomorphic sedimentary processes occurring in the Gulf of Vera. In particular, two main processes, bottom current activity (contouritic) and mass movements,

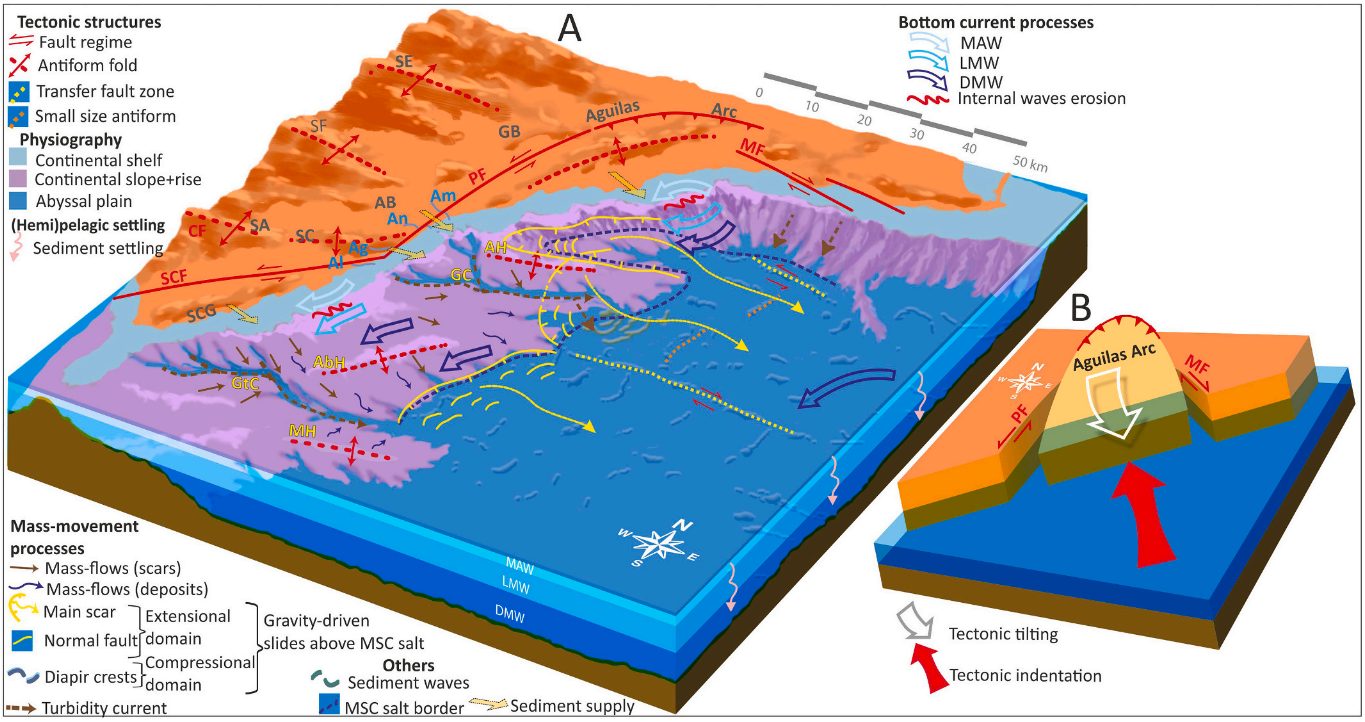

Fig. 11. Geomorphic responses to tectonic indentation in the Gulf of Vera. A) 3-D sketch of the present-day physiographic configuration and morphological features that can be explained after the integration of the Aguilas Arc tectonic indentation with the subsidence of the Algerian Basin, the halokinetic processes related to the Messinian salt layer, and the interaction of contourite and downslope gravitational sedimentary processes. More explanations are given in the text. River legend: Am, Almanzora River; An, Antas River; Ag, Aguas River; Al, Alias River. Submarine morphological legend: AbH, Abubacer High; AH, Aguilas High; GC, Garrucha Canyon; GtC, Gata Canyon; MH, Maimonides High. B) 3-D sketch to illustrate the regional tectonic tilting affecting the Gulf of Vera in response to tectonic indentation. Geological legend: AB, Almanzora Basin; GB, Guadalentín Basin; MF, Mazarron Fault; PF, Palomares Fault; SA, Sierra Alhamilla; SALG, Sierra del Algarrobo; SC, Sierra Cabrera; SCG, Sierra del Cabo de Gata; SCF, Serrata-Carboneras Fault; SE, Sierra de las Estancias; Water mass legend: MAW, Modified Atlantic Water; LMW, Light Mediterranean Water; DMW, Dense Mediterranean Water.

have been shaping the Palomares continental margin and adjacent Algerian abyssal plain. These processes have been active during the Plio-Quaternary, just after the Atlantic Zanclean flooding that marked the end of the MSC.

Analysis of the seismic data and physical oceanography allows us to determine the essential role that persistent bottom circulation has had in the Plio-Quaternary infilling, draping and shaping of the continental margin, with widespread accumulation of contourite sediments (Figs. 3 and 6–10). The LMW and DMW have been the main water masses controlling alongslope transport and primary deposition on the continental slope and rise (Figs. 1B and C and 3). The formation of contourites has been climatically controlled, with higher deposition rates during glacioeustatic sea-level falls, as interpreted through studies in the nearby Alboran Sea (Juan et al., 2016, 2020). In fact, the higher acoustic amplitude of the Quaternary contourite deposits reflects the modified character of the sea-level changes from the Pliocene to Quaternary, where the higher frequency and amplitude of these changes would also have influenced the bottom current activity, in combination with a higher terrigenous sediment discharge from inland (Figs. 6–8 and 10). The distribution of the near-bottom layers of the main water masses suggests that the plastered drifts on the slope platform and intraslope basin formed under the action of the LMW (100 to 1100 m water depth) (Figs. 1 and 4). The internal waves affecting the interface with the overlying MAW would have favoured the sculpting of the erosive contouritic terrace on the slope platform (e.g., McCave et al., 2001; Cacchione et al., 2002; Ercilla et al., 2016) (Figs. 3 and 9A, B; Supplementary Table 1). Where this interface touched the Palomares continental slope, the near-bottom burnishing processes of the internal waves would have resuspended and transported seafloor sediment longitudinally, as well as flattening the seafloor (Pomar et al., 2012; Shanmugam, 2013; Chen et al., 2014; Juan et al., 2020), which shapes the slope platform physiographic domain. In addition, the impingement of LMW against the Abubacer High would have built the marginal valley located at their foot (Figs. 3, 4 and 10; Supplementary Table 1). On the other hand, the underlying DMW bottom currents would have been responsible for the plastered drift deposits on the lower continental slope and rise (Figs. 3, 4 and 10).

Although alongslope bottom currents are the main processes responsible for primary sedimentation on the Palomares continental margin, morphobathymetric observations indicate that likely 97% of its seafloor is predominantly affected by downslope mass movements processes. These latter were responsible for the creation of an irregular and complex seafloor morphology that is the result of overall contourite dismantling (Fig. 4). The combination of these results with those of the seismic records highlights that mass movements have wide spatial and temporal recurrences and have reworked the contourites throughout the Plio-Quaternary (Figs. 6–10).

5.1.1. Geomorphological significance of a variety of mass-movement processes

5.1.1.1. Development of mass-flow deposits. The contourite sedimentary record reveals a high frequency of mass flows, which are evidenced by numerous intercalations of mass-flow deposits and scars that are more abundant in the Quaternary (Figs. 7 and 10). Contourite deposits are often affected by this type of process (Kvalstad et al., 2005; Baeten et al., 2014; Martorelli et al., 2016), as the alternation between fine and coarse textures and/or high accumulation rates increases the likelihood of sliding (Laberg and Camerlenghi, 2008; Somoza et al., 2012). Moreover, mass-flow features shaping the modern seafloor suggest they seem to have moved downslope along kilometres, although they tend to remain on the margin (Fig. 4A). The evacuation area of mass flows, where cohesive sediment flows erode the underlying sediments, occurs mostly where the seafloor gradients are relatively high (>5°), because acceleration of gravity flows is influenced by underlying seabed steepness. The depositional area occurs mostly on the open slope areas where the seafloor gradients are gentler to nearly flat, which would favour sluggish mass flows that promote deposition (Figs. 4, 6–8 and 10).

5.1.1.2. Development of large-scale gravity-driven slides above the MSC salt. The MSC and contourite sedimentary record also reveals that the Polopo, Aguilas and Gata Slides in the continental margin, plus the (hemi)pelagites/sheet-like turbidites affected by diapirs in the abyssal plain, form a continuous morphology at the basin scale. They are part of large-scale gravity-driven deformation above the MSC salt layer. This type of deformations commonly involves (Fort et al., 2004) i) a proximal domain affected by extensional deformational processes, which have formed the Polopo, Aguilas and Gata Slides in the margin; and ii) a distal domain affected by compressional deformational processes, which have formed the diapirs deforming and faulting the sliding abyssal sediments.

The Polopo, Aguilas and Gata (i) main slide scars are rooted to the MSC layer, and all of the sliding MSC and contourite sediments have extensional deformational structures, indicating relatively short transport distances (Fig. 9). This deformation is reflected in features such as synthetic normal faults limiting tilted blocks that display a staircase-like profile at the seafloor, and antithetic faults forming grabens (depressions on the seafloor) (Fig. 4; Supplementary Table 1). Differential drags over the salt layer would have caused block rotation (Davis and Engelder, 1985; Mauduit et al., 1997; Hudec and Jackson, 2007). Some of these extensional features are sealed, but most constitute growth faults that reach the seafloor (Fig. 9). This structural development suggests that sedimentary deformation remains active today; this is also shown by the different extensional structures in the MSC and contourite sediments. In fact, the uppermost Messinian and Pliocene strata pattern appears highly deformed, probably due to the long-term action of gravity-driven processes and the intrusion of salty material (Fig. 9). Small-scale models simulating gravity-driven processes (Fort et al., 2004) indicate that structures affecting the entire thickness of the sliding sedimentary column often occur in scenarios where both slope gradients (here, 1 to ~9°) and accumulation rates are high (common in contourites).

The diapir crests (ii) related to salty intrusions, deforming and faulting the (hemi)pelagites/turbidites abyssal sediments (Figs. 4 and 9A and C), have formed under contractional stress, which affects the distal zones of the sliding sediments (Sans and Koyi, 2001; Brun and Fort, 2004; Rowan and Vendeville, 2006) (Fig. 4 and 9A and C). We can, therefore, conclude that much of the Palomares margin and the adjacent abyssal plain are under the action of a large gravitational destabilization.

5.1.1.3. Development of submarine canyons. The newly obtained results allow us to establish that the present-day locations of the main courses of the large- and small-scale canyons roughly coincide with palaeocanyons incising the MES (Figs. 7 and 10A, C and E; Supplementary Table 1). The submarine canyons formed in subaerial conditions, during the MSC, and were submerged after the Zanclean Atlantic flooding, as suggested for other modern canyons in adjacent areas of the Mediterranean (Estrada et al., 2011; Ercilla et al., 2019; Juan et al., 2020). During the Plio-Quaternary, the Garrucha and Gata Canyons widened because the intense mass wasting of their walls from repeated near-surface sediment failures, which generated mass flows that form a continuum with the mass wasting of the bordering highs (Figs. 4, 7, 10A and 11). The downcutting of the small and large canyons also seems to be the result of the occurrence of long-lived powerful turbidity flows. The occurrence of these turbidity flows is suggested by their dominant erosive talwegs, as well as by the formation of levee deposits affected by sediment waves on the right margin of the Garrucha Canyon (Figs. 4, 9C and 10D; Supplementary Table 1). The sediment wave location and orientation, on the seabed and the internal strata, suggest that these strata developed via the overflow of thick turbidity flows (Wynn and Stow, 2002) (Fig. 11). Turbidity flows would have resulted from the downslope rheological and state transformations of the abundant mass flows (Shanmugam, 2019) affecting the canyon walls, as well as from the hyperpycnal flows sourced by the short and seasonal rivers draining the Betic Mountains. The alongshore drift to the Garrucha and Gata Canyons, which is favoured by the proximity of their heads to the coast (Pérez Hernández et al., 2014; Puig et al., 2017), was also a factor (Fig. 4A).

Furthermore, the depositional architecture of the Garrucha and Gata Canyons suggests that they have been getting longer due to the downslope cutting of their most distal course to the abyssal plain, during the Quaternary. The high amplitude and frequency of the Quaternary sea-level changes would have favoured a basinward increase in sediment and flow discharge, i.e., a major occurrence of high-power gravity flows leading to lengthening of the canyons (Chiocci et al., 1997; Ercilla et al., 2019).

5.2. Geomorphic responses to tectonic indentation: the Gulf of Vera scenario

We propose a new comprehensive model to explain the present-day geomorphology observed along the Gulf of Vera, linking the sedimentary response to the continental tectonic indentation.

The NW-SE Eurasian-African plate convergence has resulted in a tectonic indentation that leads to the formation of the adjacent Aguilas Arc on land (e.g., Harvey et al., 2014), and the uplift of onshore large folds with a succession of elongated antiformal reliefs separated by synformal basins (Pedrera et al., 2012) (Figs. 1 and 11). This indentation is also imprinted on the basement of the Palomares continental margin and has formed NE-SW antiforms (Abubacer and Gata Highs) separated by synforms (Gata Basin that defines the intraslope basin physiographic subprovince), and ENE-WSW antiformal structures (Maimonides and Aguilas Highs) that also accommodate most of the offshore deformation. These antiforms, which constitute main crustal heterogeneities, would have favoured the emplacement of igneous bodies (Figs. 6 and 10). These submarine antiformal and synformal structures are responsible for most of the present-day physiographic complexity imaged on the Palomares margin (Figs. 2, 3, 4 and 11), and also determines the location of the Garrucha and Gata Canyons during the MSC (Figs. 4, 10 and 11A).

The irregular basement was infilled and covered by late Miocene and Plio-Quaternary deposits, the latter being mainly responsible for shaping the margin (Figs. 6–10). During the Plio-Quaternary, contourite deposition by the alongslope action of the LMW and DMW, progressively occupied more space, contributing to the near obliteration of the palaeotopography created by the Gata antiform, the large infilling of the synform defining the intraslope basin, and the configuration of the slope platform with a contouritic terrace. In addition, coastal uplift of reliefs and southeastward tilting of the land-sea region (Coppier et al., 1989; Harvey et al., 2014) caused by tectonic indentation (Coppier et al., 1989) have interacted with sedimentation over time, provoking a general sedimentary destabilization of contourite deposits and an enlargement of the canyons (Fig. 11).

Counterpart contourite deposits are extensively present in the nearby Alboran Sea but are only affected by few sedimentary instabilities (Casas et al., 2011; Ercilla et al., 2011, 2016; Alonso et al., 2014); even in the Western Alboran Sea, mass movements are practically absent and contourites appear to be stable (Yenes et al., 2021). In contrast, across the entire Palomares margin, contourite deposits are affected by extensive mass-flow deposits, as well as their recurrence observed during the Plio-Quaternary, which seems to be higher during the last period probably because the increase in tectonic tilting affecting the margin over time (Figs. 4, 6–8, 10 and 11). This fact can be explained by the interplay of tectonic indentation and sedimentological factors. We tentatively suggest that the coastal uplift of reliefs and the progressively southeastward tectonic tilting of the whole land-sea region have generated a quasi-continuous overstepping readjustment of the entire margin and, subsequently, of the base level (Fig. 11B). Under the influence of tectonically produced seafloor slopes, the instability of sediments could increase (e.g., Leeder, 1993; Casas et al., 2003; Alonso et al., 2014). Despite the tectonic indentation of the Palomares margin, earthquakes have moderate to low magnitudes in the area (www.ign.es). Recurrent events of Mw > 4 for a return period of 1.6 years, a deduced PGA (Peak Ground Acceleration) of >0.17 g for a return period of 500 years in the offshore Garrucha area (Nespereira et al., 2019), and the sedimentary characteristics of the contourites (fine and coarse textures and/or high accumulation rates) would be enough to trigger sedimentary instabilities in the area.

Likewise, the interplay of tectonic and sedimentological factors would have conditioned the enlargement of the Garrucha and Gata Canyons, which are still far from mature (Pérez Hernández et al., 2014). The continuous tectonic activity has provoked constant adjustments of their equilibrium profiles triggering and reactivating erosive mass flows processes along their courses. Furthermore, uplifting coastal reliefs have produced new continental areas supplying substantial amounts of sediment to be funnelled by turbidity flows through the canyons (Braga et al., 2006).

The regional southeastward tectonic tilting also interacted with abyssal subsidence, favouring the MSC salt layer mobility/deformation that led also to a gravitational destabilization of overlying sediments at the margin-abyssal scale. In fact, basin salt is an unstable material that is able to flow under differential stresses, driven by sedimentary loading and due to margin tilting (Brun and Fort, 2011). The destabilized sediment is characterized by extensional deformation (Polopo, Aguilas and Gata Slides) in the margin, and compressional deformation (diapirs) in the abyssal plain (Figs. 4, 9 and 11). The Polopo Slide shows a relatively major deformation, and this is because it is in front of the Arc of Aguilas, where the land-sea tectonic tilting and related quasi-continuous readjustment of margin steepness would have been more important. Indeed, the slope gradients are higher in that sector of the margin (Fig. 2), where the extensional slide domain is larger than that of the Gata Slide and becomes cannibalised by the Aguilas Slide (Fig. 4, 9C and 11A). This relatively major deformation is also reflected by its distal compressional domain in the abyssal plain. There, major lineations of diapiric crests generally oriented SW-NE, orthogonal to the slope and transport direction of the gravitational destabilization, have been nucleated in small antiforms, locally associated with reverse faults. These folds and faults accommodated the shortening at the base of the gravity-driven slide (Figs. 4, 9C and 11A). Moreover, WNW-ESE lineations of diapiric crests parallel to the transport direction may represent transfer fault zones accommodating the different displacements of the slide sectors.

6. Concluding remarks

This work unveils the geomorphic processes that govern the morphological complexity of the Palomares continental margin and adjacent Algerian abyssal plain (Gulf of Vera, Western Mediterranean), affected by the Aguilas Arc continental tectonic indentation as a result of the Eurasian and African collision. The key to this objective has been a multidisciplinary analysis of the seafloor and subbottom that combined geomorphology, seismic stratigraphy, sedimentology, tectonic structure, and physical oceanography, alongside a coupled offshore-onshore morphology perspective. The seafloor and subbottom observations provided different, but complementary, perspectives that allowed us to establish the link between the sedimentary response to the indentation, and its seafloor fingerprints.

The tectonic indentation is imprinted in the metamorphic basement of the margin causing antiforms with emplaced igneous bodies, and synforms that accommodate the offshore deformation. The folds create a fairly irregular topography that currently imprints the complex physiography of the margin, mainly of the continental slope. Elongated highs, intraslope basins and corridors provoke lateral changes in the physiographic characteristics, and condition the location of two long canyons (Gata and Garrucha) formed in subaerial conditions during the MSC.

Two are the main geomorphic sedimentary processes occurring in the Gulf of Vera: the bottom currents and the mass movements. These processes have been active during the Plio-Quaternary, just after the Atlantic Zanclean flooding that marked the end of the MSC. The persistent action of the Light and Dense Mediterranean bottom currents has had an essential role in the general infilling, draping and obliteration of the basement irregularities with widespread stacked contourite deposits. These deposits occupied progressively more space over time, and have dictated the general shape of the modern continental margin. However, their morphology has been modified/re-shaped by the mass movement processes, such as mass- and turbidity flows, and large-scale gravity-driven slides that affect at about 97% of the margin seafloor, and also to the (hemi)pelagites/turbidites making the abyssal plain seafloor flat.

The triggering of the mass movements is mainly a sedimentary response to the Aguilas Arc continental tectonic indentation. We propose that this indentation has caused the coastal uplift of reliefs and the progressively southeastward tectonic tilting of the whole land-sea region. These processes would have generated a quasi-continuous oversteepening of the entire continental margin, thus reducing the stability of the contourite deposits. In addition, tectonic tilting and subsidence of the abyssal plain would have provoked the flow of the underlying Messinian salt deposits. Tectonic tilting and subsidence interplay would have favoured the gravity-driven deformation of the overlying sediments at the basin scale, which was more important in front of the Aguilas Arc, where the extensional (Polopo and Aguilas slides) and compressional (SW-NE and WNW-ESE diapir crest lineations) deformational features are better developed.

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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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Gamboa [Data set]. UTM-CSIC.doi: 10.20351/29SG20120517

References

Acosta, J., Fontán, A., Muñoz, A., Muñoz-Martín, A., Rivera, J., Uchupi, E., 2013. The morpho-tectonic setting of the Southeast margin of Iberia and the adjacent oceanic Algero-Balearic Basin. Mar. Pet. Geol. 45, 17–41. https://doi.org/10.1016/j.marpetgeo.2013.04.005.

Alonso, B., Maldonado, A., 1992. Plio-Quaternary margin growth patterns in a complex tectonic setting: northeastern Alboran Sea. Geo-Mar. Lett. 12, 137–143. https://doi.org/10.1007/bf02084924.

Alonso, B., Ercilla, G., Garcia, M., Vázquez, J.T., Juan, C., Casas, D., Estrada, F., Gorini, C., El Moumni, B., Farran, M., D'Acremont, E., 2014. Quaternary mass-transport deposits on the North-Eastern Alboran Seamounts (SW Mediterranean Sea). In: Krastel, S., Behrmann, J.H., Völker, D., Stipp, M., Berndt, C., Urgeles, R., Chaytor, J., Huhn, K., Strasser, M., Harbitz, C.B. (Eds.), Submarine Mass Movements and Their Consequences: 6th International Symposium. Springer International Publishing, Cham, pp. 561–570.

Baeten, N.J., Laberg, J.S., Vanneste, M., Forsberg, C.F., Kvalstad, T.J., Forwick, M., Vorren, T.O., Haflidason, H., 2014. Origin of shallow submarine mass movements and their glide planes-sedimentological and geotechnical analyses from the continental slope off northern Norway. J. Geophys. Res. Earth Surf. 119, 2335–2360. https://doi.org/10.1002/2013jf003068.

Bohoyo, F., Larter, R.D., Galindo-Zaldívar, J., Leat, P.T., Maldonado, A., Tate, A.J., Flexas, M.M., Gowland, E.J.M., Arndt, J.E., Dorschel, B., Kim, Y.D., Hong, J.K., López-Martínez, J., Maestro, A., Bermúdez, O., Nitsche, F.O., Livermore, R.A., Riley, T.R., 2019. Morphological and geological features of Drake Passage, Antarctica, from a new digital bathymetric model. J. Maps 15, 49–59. https://doi.org/10.1080/17445647.2018.1543618.

Braga, J.C., Martin, J.M., Quesada, C., 2003. Patterns and average rates of late Neogene–Recent uplift of the Betic Cordillera, SE Spain. Geomorphology 50, 3–26. https://doi.org/10.1016/s0169-555x(02)00205-2.

Braga, J.C., Martín, J.M., Betzler, C., Aguirre, J., 2006. Models of temperate carbonate deposition in Neogene basins in SE Spain: a synthesis. Geol. Soc. Lond. Spec. Publ. 255, 121–135. https://doi.org/10.1144/gsl.sp.2006.255.01.09.

Brun, J.P., Fort, X., 2004. Compressional salt tectonics (Angolan margin). Tectonophysics 382, 129–150. https://doi.org/10.1016/j.tecto.2003.11.014.

Brun, J.P., Fort, X., 2011. Salt tectonics at passive margins: geology versus models. Mar. Pet. Geol. 28 (6), 1123–1145. https://doi.org/10.1016/j.marpetgeo.2011.03.004.

Cacchione, D.A., Pratson, L.F., Ogston, A.S., 2002. The shaping of continental slopes by internal tides. Science 296, 724–727. https://doi.org/10.1126/science.1069803.

Candela, J., 2001. Mediterranean water and global circulation. In: Siedler, G., Church, J., Gould, J. (Eds.), Ocean Circulation and Climate Observing and Modelling the Global Ocean, International Geophysics, Book Series. Elsevier, pp. 419–429–XLVIII.

Casas, D., Ercilla, G., Baraza, J., Alonso, B., Maldonado, A., 2003. Recent mass-movement processes on the Ebro continental slope (NW Mediterranean). Mar. Pet. Geol. 20, 445–457. https://doi.org/10.1016/s0264-8172(03)00078-3.

Casas, D., Ercilla, G., Yenes, M., Estrada, F., Alonso, B., García, M., Somoza, L., 2011. The Baraza Slide: Model and dynamics. Mar. Geophys. Res. 32, 245–256. https://doi.org/10.1007/s11001-011-9132-2.

Ceramicola, S., Praeg, D., Coste, M., Forlin, E., Cova, A., Colizza, E., Critelli, S., 2014a. Submarine mass-movements along the slopes of the active ionian continental margins and their consequences for marine geohazards (Mediterranean Sea). In: Krastel, S., Behrmann, J.H., Völker, D., Stipp, M., Berndt, C., Urgeles, R., Chaytor, J., Huhn, K., Strasser, M., Harbitz, C.B. (Eds.), Submarine Mass Movements and their Consequences: 6th International Symposium. Springer International Publishing, Cham, pp. 295–306.

Chen, G.Y., Wu, C.L., Wang, Y.H., 2014. Interface depth used in a two-layer model of nonlinear internal waves. J. Oceanogr. 70, 329–342. https://doi.org/10.1007/s10872-014-0233-9.

Chiocci, F.L., Ercilla, G., Torre, J., 1997. Stratal architecture of Western Mediterranean margins as the result of the stacking of Quaternary lowstand deposits below 'glacio-eustatic fluctuation base-level'. Sediment. Geol. 112, 195–217. https://doi.org/10.1016/s0037-0738(97)00035-3.

Chiocci, F.L., Ridente, D., 2011. Regional-scale seafloor mapping and geohazard assessment. The experience from the italian project MaGIC (Marine Geohazards along the Italian Coasts). Mar. Geophys. Res. 32, 13–23. https://doi.org/10.1007/s11001-011-9120-6.

Comas, M.C., García-Dueñas, V., Jurado, M.J., 1992. Neogene tectonic evolution of the Alboran Sea from MCS data. Geo-Mar. Lett. 12, 157–164. https://doi.org/10.1007/bf02084927.

Comas, M.C., Ivanov, M., 2006. Southeastern Iberian Margins: the Alboran Basin and the Palomares and Cartagena Margins: preliminary results of geological and geophysical investigations during the TTR-14 leg 2 cruise of R/V Professor Logachev. In: IOC Technical Series. UNESCO, pp. 44–61.

Coppier, G., Griveaud, P., de Larouziere, F.-D., Montenat, C., Ott d'Estevou, P., 1989. Example of Neogene tectonic indentation in the Eastern Betic Cordilleras: the Arc of Aguilas (Southeastern Spain). Geodin. Acta 3, 37–51. https://doi.org/10.1080/09853111.1989.11105173.

Davis, D.M., Engelder, T., 1985. The role of salt in fold-and-thrust belts. Tectonophysics 119, 67–88. https://doi.org/10.1016/0040-1951(85)90033-2.

de la Peña, L.G., Gràcia, E., Muñoz, A., Acosta, J., Gómez-Ballesteros, M., Ranero, C.R., Uchupi, E., 2016. Geomorphology and Neogene tectonic evolution of the Palomares continental margin (Western Mediterranean). Tectonophysics 689, 25–39. https://doi.org/10.1016/j.tecto.2016.03.009.

DeMets, C., Iaffaldano, G., Merkouriev, S., 2015. High-resolution Neogene and Quaternary estimates of Nubia-Eurasia-North America Plate motion. Geophys. J. Int. 203, 416–427. https://doi.org/10.1093/gji/ggv277.

Duggen, S., Hoernle, K., Klügel, A., Geldmacher, J., Thirlwall, M., Hauff, F., Lowry, D., Oates, N., 2008. Geochemical zonation of the Miocene Alborán Basin volcanism (westernmost Mediterranean): geodynamic implications. Contrib. Mineral. Petrol. 156, 577–593. https://doi.org/10.1007/s00410-008-0302-4.

Ercilla, G., Casas, D., Vázquez, J.T., Iglesias, J., Somoza, L., Juan, C., Medialdea, T., León, R., Estrada, F., García-Gil, S., Farran, M., Bohoyo, F., García, M., Maestro, A., 2011. Imaging the recent sediment dynamics of the Galicia Bank region (Atlantic, NW Iberian Peninsula). Mar. Geophys. Res. 32, 99–126. https://doi.org/10.1007/s11001-011-9129-x.

Ercilla, G., Juan, C., Hernández-Molina, F.J., Bruno, M., Estrada, F., Alonso, B., Casas, D., Farran, M., Llave, E., García, M., Vázquez, J.T., D'Acremont, E., Gorini, C., Palomino, D., Valencia, J., El Moumni, B., Ammar, A., 2016. Significance of bottom currents in deep-sea morphodynamics: an example from the Alboran Sea. Mar. Geol. 378, 157–170. https://doi.org/10.1016/j.margeo.2015.09.007.

Ercilla, G., Juan, C., Periáñez, R., Alonso, B., Abril, J.M., Estrada, F., Casas, D., Vázquez, J.T., d'Acremont, E., Gorini, C., El Moumni, B., Do Couto, D., Valencia, J., 2019. Influence of alongslope processes on modern turbidite systems and canyons in the Alboran Sea (southwestern Mediterranean). Deep Sea ResI Oceanogr. Res. Pap. 144, 1–16. https://doi.org/10.1016/j.dsr.2018.12.002.

Estrada, F., Ercilla, G., Alonso, B., 1997. Pliocene-Quaternary tectonic-sedimentary evolution of the NE Alboran Sea (SW Mediterranean Sea). Tectonophysics 282, 423–442. https://doi.org/10.1016/s0040-1951(97)00227-8.

Estrada, F., Ercilla, G., Gorini, C., Alonso, B., Vázquez, J.T., García-Castellanos, D., Juan, C., Maldonado, A., Ammar, A., Elabbassi, M., 2011. Impact of pulsed Atlantic water inflow into the Alboran Basin at the time of the Zanclean flooding. Geo-Mar. Lett. 31, 361–376. https://doi.org/10.1007/s00367-011-0249-8.

Estrada, F., Galindo-Zaldívar, J., Vázquez, J.T., Ercilla, G., D'Acremont, E., Alonso, B., Gorini, C., 2018. Tectonic indentation in the central Alboran Sea (westernmost Mediterranean). Terra Nova 30, 24–33. https://doi.org/10.1111/ter.12304.

Faugères, J.-C., Stow, D.A.V., Imbert, P., Viana, A., 1999. Seismic features diagnostic of contourite drifts. Mar. Geol. 162, 1–38. https://doi.org/10.1016/s0025-3227(99)00068-7.

Fernández-Soler, J.M., 2001. Volcanics of the Almería Province. In: Mather, A.E., Harvey, A.M., Braga, J.C., Martín, J.M. (Eds.), A Field Guide to the Geology and Geomorphology of the Neogene Sedimentary Basins of the Almería Province, SE Spain. Blackwell, Oxford, pp. 58–88.

Fort, X., Brun, J.-P., Chauvel, F., 2004. Salt tectonics on the angolan margin, synsedimentary deformation processes. AAPG Bull. 88, 1523–1544. https://doi.org/10.1306/06010403012.

Galindo-Zaldívar, J., González-Lodeiro, F., Jabaloy, A., Maldonado, A., Schreider, A.A., 1998. Models of magnetic and Bouguer gravity anomalies for the deep structure of the central Alboran Sea basin. Geo-Mar. Lett. 18, 10–18. https://doi.org/10.1007/s003670050046.

Galindo-Zaldıvar, J., Gil, A.J., Borque, M.J., González-Lodeiro, F., Jabaloy, A., Marın-Lechado, C., Ruano, P., Sanz de Galdeano, C., 2003. Active faulting in the internal zones of the central Betic Cordilleras (SE, Spain). J. Geodyn. 36, 239–250. https://doi.org/10.1016/S0264-3707(03)00049-8.

Galindo-Zaldívar, J., Braga, J.C., Marín-Lechado, C., Ercilla, G., Martín, J.M., Pedrera, A., Casas, D., Aguirre, J., Ruiz-Constán, A., Estrada, F., Puga-Bernabéu, Á., Sanz de Galdeano, C., Juan, C., García-Alix, A., Vázquez, J.T., Alonso, B., 2019. Extension in the Western Mediterranean. In: Quesada, C., Oliveira, J.T. (Eds.), The Geology of Iberia: A Geodynamic Approach: Volume 4: Cenozoic Basins. Springer International Publishing, Cham, pp. 61–103.

Gomberg, J., Bodin, P., Savage, W., Jackson, M.E., 1995. Landslide faults and tectonic faults, analogs?: the Slumgullion earthflowColorado. Geology 23 (1), 41–44. https://doi.org/10.1130/0091-7613(1995)023<0041:LFATFA>2.3.CO;2.

Giaconia, F., Booth-Rea, G., Martínez-Martínez, J.M., Azañón, J.M., Pérez-Peña, J.V., 2012. Geomorphic analysis of the Sierra Cabrera, an active pop-up in the constrictional domain of conjugate strike-slip faults: the Palomares and Polopos fault zones (eastern Betics, SE Spain). Tectonophysics 580, 27–42. https://doi.org/10.1016/j.tecto.2012.08.028.

Giaconia, F., Booth-Rea, G., Ranero, C.R., Gràcia, E., Bartolome, R., Calahorrano, A., Lo Iacono, C., Vendrell, M.G., Cameselle, A.L., Costa, S., Gómez de la Peña, L., Martínez-Loriente, S., Perea, H., Viñas, M., 2015. Compressional tectonic inversion of the Algero-Balearic basin: latemost Miocene to present oblique convergence at the Palomares margin (Western Mediterranean). Tectonics 34, 1516–1543. https://doi.org/10.1002/2015tc003861.

Gueguen, E., Doglioni, C., Fernandez, M., 1998. On the post-25 Ma geodynamic evolution of the western Mediterranean. Tectonophysics 298, 259–269. https://doi.org/10.1016/s0040-1951(98)00189-9.

Hampton, M.A., Lee, H.J., Locat, J., 1996. Submarine landslides. Rev. Geophys. 34, 33–59. https://doi.org/10.1029/95rg03287.

Harishidayat, D., Omosanya, K.O., Johansen, S.E., Eruteya, O.E., Niyazi, Y., 2018. Morphometric analysis of sediment conduits on a bathymetric high: implications for palaeoenvironment and hydrocarbon prospectivity. Basin Res. 30, 1015–1041. https://doi.org/10.1111/bre.12291.

Harvey, A.M., Wells, S.G., 1987. Response of Quaternary fluvial systems to differential epeirogenic uplift: Aguas and Feos river systems, Southeast Spain. Geology 15, 689–693. https://doi.org/10.1130/0091-7613(1987)15<689:roqfst>2.0.co;2.

Harvey, A.M., Whitfield, E., Stokes, M., Mather, A., 2014. The late Neogene to Quaternary drainage evolution of the uplifted neogene sedimentary basins of Almería, Betic Chain. In: Gutiérrez, F., Gutiérrez, M. (Eds.), Landscapes and Landforms of Spain. Springer, Netherlands, Dordrecht, pp. 37–61.

Hudec, M.R., Jackson, M.P.A., 2007. Terra infirma: understanding salt tectonics. Earth Sci. Rev. 82, 1–28. https://doi.org/10.1016/j.earscirev.2007.01.001.

Juan, C., Ercilla, G., Hernández-Molina, F.J., Estrada, F., Alonso, B., Casas, D., García, M., Farran, M., Llave, E., Palomino, D., Vázquez, J.-T., Medialdea, T., Gorini, C., D'Acremont, E., El Moumni, B., Ammar, A., 2016. Seismic evidence of current-controlled sedimentation in the Alboran Sea during the Pliocene and Quaternary: palaeoceanographic implications. Mar. Geol. 378, 292–311. https://doi.org/10.1016/j.margeo.2016.01.006.

Juan, C., Ercilla, G., Estrada, F., Alonso, B., Casas, D., Vázquez, J.T., d'Acremont, E., Medialdea, T., Hernández-Molina, F.J., Gorini, C., El Moumni, B., Valencia, J., 2020. Multiple factors controlling the deep marine sedimentation of the Alboran Sea (SW Mediterranean) after the Zanclean Atlantic Mega-flood. Mar. Geol. 423, 106138 https://doi.org/10.1016/j.margeo.2020.106138.

Kelner, M., Migeon, S., Tric, E., Couboulex, F., Dano, A., Lebourg, T., Taboada, A., 2016. Frequency and triggering of small-scale submarine landslides on decadal timescales: analysis of 4D bathymetric data from the continental slope offshore Nice (France). Mar. Geol. 379, 281–297. https://doi.org/10.1016/j.margeo.2016.06.009.

Kvalstad, T.J., Andresen, L., Forsberg, C.F., Berg, K., Bryn, P., Wangen, M., 2005. The Storegga slide: evaluation of triggering sources and slide mechanics. Mar. Pet. Geol. 22, 245–256. https://doi.org/10.1016/j.marpetgeo.2004.10.019.

Laberg, J.S., Vorren, T.O., 2000. The Trænadjupet Slide, offshore Norway — morphology, evacuation and triggering mechanisms. Mar. Geol. 171, 95–114. https://doi.org/10.1016/s0025-3227(00)00112-2.

Laberg, J.S., Camerlenghi, A., 2008. The significance of contourites for submarine slope stability. In: Rebesco, M., Camerlenghi, A. (Eds.), Developments in Sedimentology. Elsevier, Amsterdam, pp. 537–556.

Lafosse, M., d'Acremont, E., Rabaute, A., Estrada, F., Jollivet-Castelot, M., Vazquez, J.T., Galindo-Zaldivar, J., Ercilla, G., Alonso, B., Smit, J., Ammar, A., Gorini, C., 2020. Plio-Quaternary tectonic evolution of the southern margin of the Alboran Basin (Western Mediterranean). Solid Earth 11, 741–765. https://doi.org/10.5194/se-11-741-2020.

Leeder, M.R., 1993. Tectonic controls upon drainage basin development, river channel migration and alluvial architecture: implications for hydrocarbon reservoir development and characterization. Geol. Soc. Lond. Spec. Publ. 73, 7–22. https://doi.org/10.1144/gsl.sp.1993.073.01.02.

Lesur, V., Hamoudi, M., Choi, Y., Dyment, J., Thébault, E., 2016. Building the second version of the World Digital magnetic Anomaly Map (WDMAM). Earth Planets Space 68, 27. https://doi.org/10.1186/s40623-016-0404-6.

Lobo, F.J., Ercilla, G., Fernández-Salas, L.M., Gámez, D., 2014. The Iberian Mediterranean shelves. Geol. Soc. Lond. Mem. 41, 147–170. https://doi.org/10.1144/m41.11.

Locat, J., Lee, H., 2002. Submarine landslides: advances and challenges. Can. Geotech. J. 39 (1), 193–212.

Lofi, J., Déverchère, J., Gaullier, V., Gillet, H., Gorini, C., Guennoc, P., Loncke, L., Maillard, A., Sage, F., Thinon, I., 2011. Atlas of the "Messinian salinity crisis" seismic markers in the Mediterranean and Black seas. Comm. Geol. Map World (CGGMW)/ Mém. Soc. Géol. Fr. 179, 72.

Marro, G., Comas, M.C., 2005. Morphology and shallow structure of two se iberian margin segments (Palomares and Cartagena margins, Western Mediterranean). In: Hamoumi, N., Henriet, J.P., Kenyon, N., Suzyumov, A.E. (Eds.), Geosphere-biosphere Coupling Processes: The TTR Interdisciplinary Approach Towards Studies of the European and North African Margins.IOC Workshop Report N° 197. UNESCO, Paris, pp. 36–37.

Martorelli, E., Bosman, A., Casalbore, D., Falcini, F., 2016. Interaction of down-slope and along-slope processes off Capo Vaticano (southern Tyrrhenian Sea, Italy), with particular reference to contourite-related landslides. Mar. Geol. 378, 43–55. https://doi.org/10.1016/j.margeo.2016.01.005.

Mascle, J., Mary, F., Praeg, D., Brosolo, L., Camera, L., Ceramicola, S., Dupré, S., 2014. Distribution and geological control of mud volcanoes and other fluid/free gas seepage features in the Mediterranean Sea and nearby Gulf of Cadiz. Geo-Mar. Lett. 34, 89–110. https://doi.org/10.1007/s00367-014-0356-4.

Masson, D.G., Kenyon, N.H., Weaver, P.P.E., 1996. Slides, debris flows, and turbidity currents. In: Thorpe, S.A. (Ed.), Oceanography: An Illustrated Guide. CRC Press, London, UK, pp. 138–153.

Mauduit, T., Guerin, G., Brun, J.P., Lecanu, H., 1997. Raft tectonics: the effects of basal slope angle and sedimentation rate on progressive extension. J. Struct. Geol. 19, 1219–1230. https://doi.org/10.1016/s0191-8141(97)00037-0.

McAdoo, B.G., Pratson, L.F., Orange, D.L., 2000. Submarine landslide geomorphology, US continental slope. Mar. Geol. 169, 103–136. https://doi.org/10.1016/s0025-3227(00)00050-5.

McCave, I.N., Hall, I.R., Antia, A.N., Chou, L., Dehairs, F., Lampitt, R.S., Thomsen, L., van Weering, T.C.E., Wollast, R., 2001. Distribution, composition and flux of particulate material over the european margin at 47°–50°N. Deep Sea ResII Top. Stud. Oceanogr. 48, 3107–3139. https://doi.org/10.1016/s0967-0645(01)00034-0.

Medaouri, M., Déverchère, J., Graindorge, D., Bracene, R., Badji, R., Ouabadi, A., Yelles-Chaouche, K., Bendiab, F., 2014. The transition from Alboran to Algerian basins (Western Mediterranean Sea): chronostratigraphy, deep crustal structure and tectonic evolution at the rear of a narrow slab rollback system. J. Geodyn. 77, 186–205. https://doi.org/10.1016/j.jog.2014.01.003.

Millot, C., 1987. Circulation in the western Mediterranean Sea. Oceanol. Acta 10, 143–149.

Millot, C., 1999. Circulation in the Western Mediterranean Sea. J. Mar. Syst. 20, 423–442. https://doi.org/10.1016/s0924-7963(98)00078-5.

Mosher, D.C., Campbell, D.C., Gardner, J.V., Piper, D.J.W., Chaytor, J.D., Rebesco, M., 2017. The role of deep-water sedimentary processes in shaping a continental margin: the Northwest Atlantic. Mar. Geol. 393, 245–259. https://doi.org/10.1016/j.margeo.2017.08.018.

Nespereira, J., Casas, D., Yenes, M., Monterrubio, S., López-González, N., Ercilla, G., Mata, P., Vázquez, J.T., Bárcenas, P., Palomino, D., Casalbore, D., Martínez-Díaz, P., Pérez, N., Alonso, B., Pato, N., Team, Fauces, 2019. Preliminar stability assessment of the submarine slopes surrounding the garrucha harbour area (Sw Mediterrarean). In: 34 IAS. Meeting of Sedimentology, 10-13 September, Rome.

Parrilla, G., Kinder, T.H., Preller, R.H., 1986. Deep and intermediate mediterranean water in the western Alboran Sea. Deep Sea ResA Oceanogr. Res. Pap. 33, 55–88. https://doi.org/10.1016/0198-0149(86)90108-1.

Pedrera, A., Marín-Lechado, C., Galindo-Zaldívar, J., Rodríguez-Fernández, L.R., Ruiz-Constán, A., 2006. Fault and fold interaction during the development of the Neogene-Quaternary Almería-Níjar basin (SE Betic Cordilleras). Geol. Soc. Lond. Spec. Publ. 262, 217–230. https://doi.org/10.1144/gsl.sp.2006.262.01.13.

Pedrera, A., Galindo-Zaldívar, J., Tello, A., Marín-Lechado, C., 2010. Intramontane basin development related to contractional and extensional structure interaction at the termination of a major sinistral fault: the Huércal-Overa Basin (Eastern Betic Cordillera). J. Geodyn. 49, 271–286. https://doi.org/10.1016/j.jog.2010.01.008.

Pedrera, A., Galindo-Zaldívar, J., Marín-Lechado, C., García-Tortosa, F.J., Ruano, P., López Garrido, A.C., Azañón, J.M., Peláez, J.A., Giaconia, F., 2012. Recent and active faults and folds in the central-eastern Internal zones of the Betic Cordillera. J. Iber. Geol. 38, 191–208. https://doi.org/10.5209/rev_jige.2012.v38.n1.39213.

Pérez Hernández, S., Comas, M., Escutia, C., Martínez García, P., 2009. Los deslizamientos submarinos de Águilas (Margen de Palomares, Mediterráneo Occidental). Geogaceta 47, 93–97.

Pérez Hernández, S., Comas, M.C., Escutia, C., 2014. Morphology of turbidite systems within an active continental margin (the Palomares margin, western Mediterranean). Geomorphology 219, 10–26. https://doi.org/10.1016/j.geomorph.2014.04.014.

Pomar, L., Morsilli, M., Hallock, P., Bádenas, B., 2012. Internal waves, an under-explored source of turbulence events in the sedimentary record. Earth Sci. Rev. 111, 56–81. https://doi.org/10.1016/j.earscirev.2011.12.005.

Puig, P., Durán, R., Muñoz, A., Elvira, E., Guillén, J., 2017. Submarine canyon-head morphologies and inferred sediment transport processes in the Alías-Almanzora canyon system (SW Mediterranean): on the role of the sediment supply. Mar. Geol. 393, 21–34. https://doi.org/10.1016/j.margeo.2017.02.009.

Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., Wåhlin, A., 2014. Contourites and associated sediments controlled by deep-water circulation processes: state-of-the-art and future considerations. Mar. Geol. 352, 111–154. https://doi.org/10.1016/j.margeo.2014.03.011.

Rehault, J.P., Boillot, G., Mauffret, A., 1985. The Western Mediterranean Basin. In: Stanley, D.J., Wezel, F.-C. (Eds.), Geological Evolution of the Mediterranean Basin: Raimondo Selli Commemorative Volume. Springer New York, New York, NY, pp. 101–129.

Rodriguez, M., Fournier, M., Chamot-Rooke, N., Huchon, P., Zaragosi, S., Rabaute, A., 2012. Mass wasting processes along the Owen Ridge (Northwest Indian Ocean). Mar. Geol. 326–328, 80–100. https://doi.org/10.1016/j.margeo.2012.08.008.

Rowan, M.G., Vendeville, B.C., 2006. Foldbelts with early salt withdrawal and diapirism: physical model and examples from the northern Gulf of Mexico and the Flinders RangesAustralia. Mar. Pet. Geol. 23, 871–891. https://doi.org/10.1016/j.marpetgeo.2006.08.003.

Sakellariou, D., Rousakis, G., Panagiotopoulos, I., Morfis, I., Bailey, G.N., 2019. Geological structure and Late Quaternary geomorphological evolution of the Farasan islands continental shelf, south Red sea, SW Saudi Arabia. In: Rasul, N.M.A., Stewart, I.C.F. (Eds.), Geological Setting, Palaeoenvironment and Archaeology of the Red Sea. Springer, Cham., pp. 629–652

Sans, M., Koyi, H.A., 2001. Modeling the role of erosion in diapir development in contractional settings. In: Koyi, H.A., Mancktelow, N. (Eds.), Tectonic Modeling: A, Honor of Hans Ramberg, Volume in. Geological Society of America, Boulder, pp. 111–122.

Sanz de Galdeano, C., 1990. Geologic evolution of the Betic Cordilleras in the Western Mediterranean, Miocene to the present. Tectonophysics 172, 107–119. https://doi.org/10.1016/0040-1951(90)90062-d.

Shanmugam, G., 2013. Modern internal waves and internal tides along oceanic pycnoclines: challenges and implications for ancient deep-marine baroclinic sands. AAPG Bull. 97, 799–843. https://doi.org/10.1306/10171212101.

Shanmugam, G., 2019. Slides, slumps, debris flows, turbidity currents, hyperpycnal flows, and bottom currents☆. In: Cochran, J.K., Bokuniewicz, H.J., Yager, P.L. (Eds.), Encyclopedia of Ocean Sciences, Third edition. Academic Press, Oxford, pp. 228–257.

Shepard, F.P., Dill, R.F., 1966. Submarine Canyons and Other Sea Valleys. Rand McNally, Chicago, Ill.

Smith, D.P., Kvitek, R., Iampietro, P.J., Wong, K., 2007. Twenty-nine months of geomorphic change in upper Monterey Canyon (2002–2005). Mar. Geol. 236, 79–94. https://doi.org/10.1016/j.margeo.2006.09.024.

Somoza, L., Medialdea, T., León, R., Ercilla, G., Vázquez, J.T., Farran, M., Hernández-Molina, J., González, J., Juan, C., Fernández-Puga, M.C., 2012. Structure of mud volcano systems and pockmarks in the region of the Ceuta Contourite Depositional

System (Western Alborán Sea). Mar. Geol. 332–334, 4–26. https://doi.org/10.1016/j.margeo.2012.06.002.
Stanley, D.J., Kelling, G., Vera, J.A., Sheng, H., 1975. Sands in the Alboran Sea: a model of input in a deep marine basin. Smithson. Contrib. Earth Sci. 1–51 https://doi.org/10.5479/si.00810274.15.1.
Stokes, M., Mather, A.E., 2003. Tectonic origin and evolution of a transverse drainage: the Río Almanzora, Betic Cordillera, Southeast Spain. Geomorphology 50, 59–81. https://doi.org/10.1016/s0169-555x(02)00208-8.
Stokes, M., 2008. Plio-Pleistocene drainage development in an inverted sedimentary basin: Vera basin, Betic Cordillera, SE Spain. Geomorphology 100, 193–211. https://doi.org/10.1016/j.geomorph.2007.10.026.
Stow, D.A.V., Faugères, J.C., 2008. Contourite facies and the facies model. In: Rebesco, M., Camerlenghi, A. (Eds.), Developments in Sedimentology. Elsevier, Amsterdam, pp. 223–256.
Summerfield, M.A., 2005. A tale of two scales, or the two geomorphologies. Trans. Inst. Br. Geogr. 30, 402–415. https://doi.org/10.1111/j.1475-5661.2005.00182.x.
Tsampouraki-Kraounaki, K., Sakellariou, D., Rousakis, G., Morfis, I., Panagiotopoulos, I., Livanos, I., Manta, K., Paraschos, F., Papatheodorou, G., 2021. The Santorini-Amorgos Shear Zone: evidence for Dextral Transtension in the South Aegean Back-Arc RegionGreece. Geosciences 11 (5), 216. https://doi.org/10.3390/geosciences11050216.
Tripsanas, E.K., Bryant, W.R., Phaneuf, B.A., 2004. Slope-instability processes caused by salt movements in a complex deep-water environment, Bryant Canyon area, Northwest Gulf of Mexico. AAPG Bull. 88, 801–823. https://doi.org/10.1306/01260403106.
Weijermars, R., 1985. Uplift and subsidence history of the Alboran Basin and a profile of the Alboran Diapir (W-Mediterranean). Geol. Mijnb. 64, 349–356.
Wynn, R.B., Stow, D.A.V., 2002. Classification and characterisation of deep-water sediment waves. Mar. Geol. 192, 7–22. https://doi.org/10.1016/s0025-3227(02)00547-9.
Yenes, M., Casas, D., Nespereira, J., López-González, N., Casalbore, D., Monterrubio, S., Alonso, B., Ercilla, G., Juan, C., Bárcenas, P., Palomino, D., Mata, P., Martínez-Díaz, P., Pérez, N., Vázquez, J.T., Estrada, F., Azpiroz-Zabala, M., Teixeira, M., 2021. The Guadiaro-Baños contourite drifts (SW Mediterranean). A geotechnical approach to stability analysis. Mar. Geol. 437 https://doi.org/10.1016/j.margeo.2021.106505.