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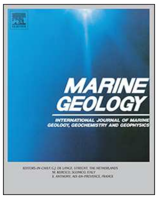

Multiple factors controlling the deep marine sedimentation of the Alboran Sea (SW Mediterranean) after the Zanclean Atlantic Mega-flood

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ABSTRACT

A new basin-scale comprehensive view of contourite features, turbidite systems, and mass-wasting deposits comprising the Spanish and Moroccan margins and basins of the Alboran Sea has been achieved after a new detailed seismic stratigraphic analysis and the construction of sedimentary maps for the Pliocene and Quaternary sedimentary units. Multiple contourite systems were defined in this sea: i) the Intermediate Mediterranean contourite system (IMCS), formed under the action of the LMW on the Spanish continental margin; ii) the Deep Mediterranean contourite system (DMCS), formed under the action of the DMW and made up of contourites mostly found on the Moroccan margin and annex sub-basins; and iii) the Atlantic contourite system (ACS), shaped by the AW and its interfaces with the LMW and DMW on the uppermost continental slopes of both margins. The contourite features (drifts, moats, channels and terraces) coexist during the various stages of the Plio-Quaternary with turbidite systems showing different onsets and cessations in activity, and with mass-wasting deposits. In this work, the temporal and spatial distributions of contourite and turbidite systems can be considered as proxies to deduct the long-term impacts of bottom-current circulations and related processes, and ultimately allowed to decipher past bottom-current dynamics and the multiple factors controlling Plio-Quaternary sedimentation in the Alboran Sea.

1. Introduction

Deep marine sedimentary systems are archives of local, regional and global palaeoenvironmental, palaeooceanographic and palaeoclimatic changes occurring off- and on-shore (Miall, 2010). The deep marine sedimentary systems located beyond the shelf break mostly comprise turbidites and hemipelagites/pelagites (Miall, 2010). Additionally, over the past 40 years, contourites have been characterised in many seas and oceans (Stow and Lovell, 1979; Viana et al., 1998; Faugères et al., 1999; Ito, 2002; Hernández-Molina et al., 2008; Van Rooij et al., 2010; Preu et al., 2012; Chen et al., 2014; Sun et al., 2017; Juan et al., 2018). These publications highlight the significant role of the contourites in continental margin building and marine basin infilling, generating debate over the multiple factors controlling deep marine sedimentation. The best approach to analyse the complex interactions of the various sedimentary systems is to consider the entire basin and to analyse their temporal and spatial interactions with simultaneous, alternating, or interacting growth. Despite the literature includes studies that analyse these interactions (Pudsey, 2002; Mulder et al., 2006; Marchès et al., 2007; Mulder et al., 2008; Biscara et al., 2010; Dall'Olio et al., 2010; Brackenridge et al., 2013; Ercilla et al., 2019a), most do not reach basin scale.

The Alboran Sea is a relatively small (150 km wide and 350 km long, with about 1800 m maximum water depth -wd-) tectonically active and complex, siliciclastic marine basin (Ercilla and Alonso, 1996) located in the SW Mediterranean Sea, where the Atlantic and

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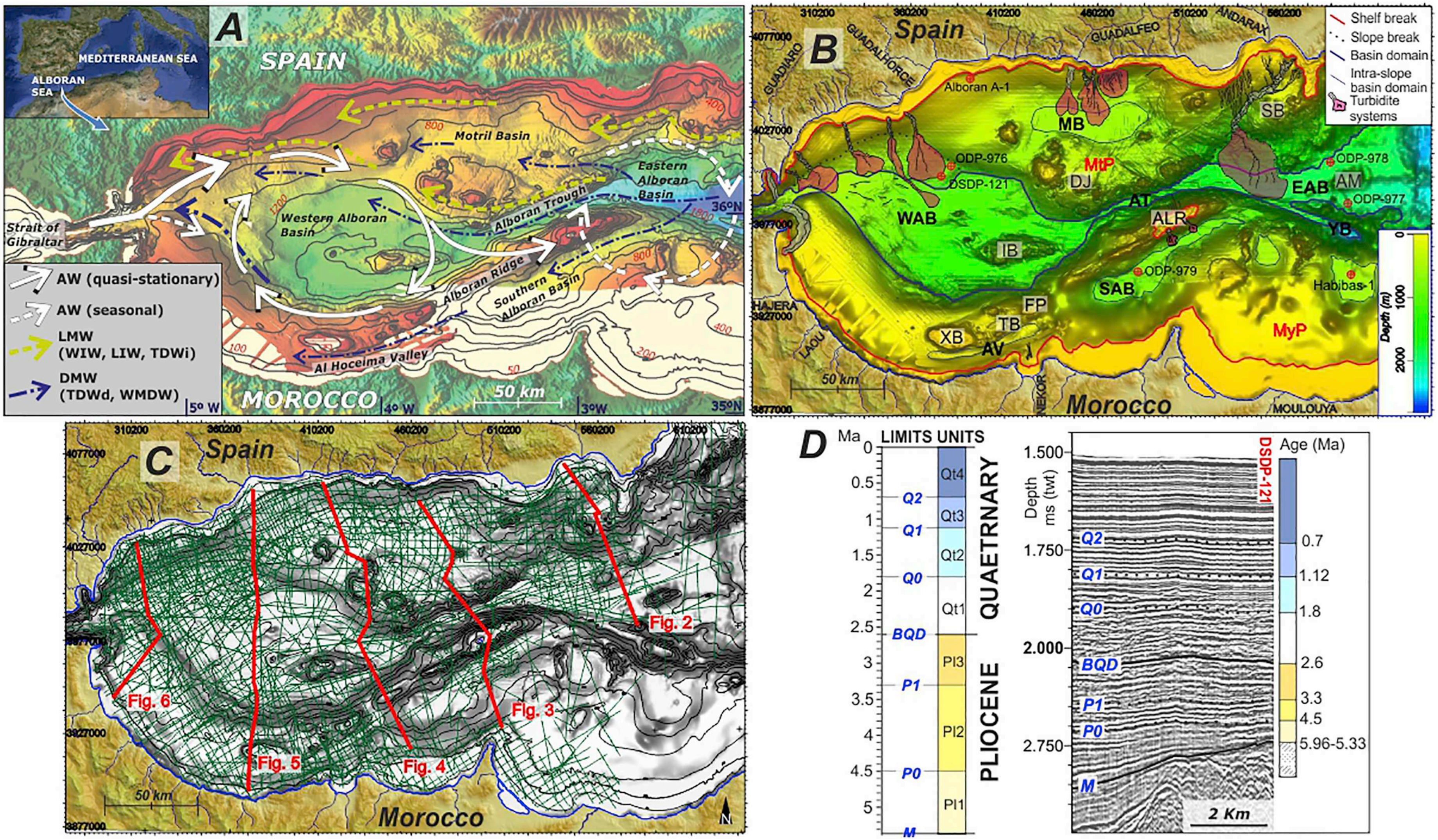

Fig. 1. Study area and dataset. A) Present-day regional circulation model of the Alboran Sea, located in the westernmost Mediterranean Sea. Legend: AW, Atlantic Water; WIW, Western Intermediate Water; LIW, Levantine Intermediate Water; LMW, Light Mediterranean Water; TDW, Tyrrhenian Dense Water (i – intermediate, d – deep); WMDW, Western Mediterranean Deep Water; and DMW, Dense Mediterranean Water. Modified from Ercilla et al. (2016). B) Bathymetric map showing the boundaries between the physiographic provinces. Legend: i) Basins and intra-slope basins: AT-Alboran Through; AV-Al Hoceima Valley; EAB-Eastern Alboran Basin; MB-Motril Basin; SAB-Southern Alboran Basin; WAB-Western Alboran Basin; YB-Yusuf Basin. ii) Selected seamounts: ALR-Alboran Ridge; AM-Al Mansour; DJ-Djibouti Ville Bank; FP-Francesc Pages Bank; IB-Ibn Batouta Seamount; SB-Sabinar Bank; TB-Tofiño Bank; XB-Xauen Bank. iii) Plateaus: MtP-Motril Plateau; MyP-Moulouya Plateau. C) Database of single and multi-channel seismic profiles used in this work, available at the ICM-CSIC website (*http://www.icm.csic.es/geo/gma/SurveyMaps/*). D) Seismic line crossing the location of the DSDP 121, showing the vertical stacking of the Pliocene (in yellow) and Quaternary units (in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mediterranean waters meet (Fig. 1A). During the Messinian Salinity Crisis (MSC) that affected the Mediterranean Basin, the Alboran Basin dried out and was subject to subaerial erosion (Estrada et al., 2011). The MSC (starting at 5.96 Ma, Ryan et al., 1973) and the Zanclean Atlantic mega-flood (circa 5.46 Ma, Bache et al., 2012) generated a prominent erosive and polygenetic unconformity that marks one of the most important changes in the sedimentary infill history of the Alboran Sea. The interest in this basin derives from the fact that it offers a basin-scale perspective of the onset and building of marine sedimentary systems after the Atlantic mega-flood, being a unique and valuable palaeoclimatic and palaeoceanographic sedimentary register. This study presents an updated seismic stratigraphic framework and analysis of the sedimentary systems that sheds light on the multiple factors driving deep marine sedimentation during the Plio-Quaternary.

The aim of this paper is to attain a better understanding of basin-scale sedimentation by developing a detailed sedimentary model of the complex superposition of sedimentary systems, even where well or core data are not available. Additionally, this geological approach enables to define multiple factors controlling the sedimentation, among which the major palaeoceanographic processes stand out, and to determine their occurrences, relative energies, and timings.

2. Regional setting

2.1. Geological framework

The Alboran Sea is an extensional basin that evolved in the Euroasia-Africa convergent tectonic setting during the Upper Oligocene-Miocene rifting (Dillon et al., 1980; Dewey et al., 1989; Comas et al., 1999; Jolivet and Faccenna, 2000; Vázquez et al., 2015a). From the Tortonian to the present, the basement of the Alboran Domain has been deformed by the tilting and the uplift of the Spanish and Moroccan continental margins and the simultaneous shortening and deepening of the Tortonian basin (Martínez-García et al., 2013; Vázquez et al., 2015a). Tectonic activity continued throughout the Plio-Quaternary and was marked by the interaction of the extensional and compressional regimes after the Early Pliocene that promoted changes in the palaeoceanographic configuration of the sea floor encompassed with sub-basins and passage formation, uplifting of seamounts, and sub-basin subsidence (Maldonado et al., 1992; Rodriguez-Fernandez and Martin-Penela, 1993; Estrada et al., 1997; Galindo-Zaldívar et al., 2009; Martínez-García et al., 2013; d'Acremont et al., 2014; Do Couto et al., 2016).

Two important events affected the Cenozoic sedimentary history of the Alboran Basin: the Messinian Salinity Crisis (MSC), which began at 5.96 Ma (Ryan et al., 1973), and the subsequent opening of the Gibraltar Strait at approximately 5.46 (Bache et al., 2012) - 5.33 Ma (Ryan, 1973). The mega-flood subsequent to the opening of the Gibraltar Strait caused extensive erosion of the sea floor, excavating prominent features, such as the Atlantic Flooding Channel that crosses the entire Alboran Sea as well as various terraces and escarpments in the Western Alboran Basin (WAB) (Estrada et al., 2011). The resulting polygenetic surface developed after the MSC and the subsequent reflooding, seismically identified as M reflector (5.96 to 5.46 Ma; Bache et al., 2012), marks a change in the sedimentation influenced by the acceleration of the Mediterranean waters flowing towards the Strait of Gibraltar (Juan et al., 2016). The update of the existing stratigraphies already defined in the literature (Juan et al., 2016) allowed to confirm, relocate and define the following boundaries: the *M* boundary at 4.96 to 5.46 Ma; the intra-Lower Pliocene *P0* boundary at ca. 4.5 Ma; the top of the Zanclean *P1* boundary at ca. 3.3 Ma; the base of the Quaternary *BQD* boundary at ca. 2.6 Ma; the top of the Gelasian *Q0* boundary at ca. 1.8 Ma; the intra-lower Quaternary *Q1* boundary at ca. 1.12 Ma; and the top of the Calabrian *Q2* boundary at ca. 0.7 Ma (Fig. 1D).

The physiography of the Alboran Sea is controlled by its general margin-basin geometry which was produced by the structural changes in the Miocene (Comas et al., 1992), and by the long-term action of the bottom-current processes during the Plio-Quaternary which have shaped the limits between the physiographic provinces (Ercilla et al., 2016). The present physiography (Fig. 1B) is defined by the Spanish and Moroccan continental margins with shelf breaks at approximately 90–115 m and 100–150 m, respectively, and irregular continental slopes extending down to 575–945 m wd. These margins are separated by two main basins, the Western Alboran Basin (WAB, 1510 m wd) and the Eastern Alboran Basin (EAB, 1980 m wd), which are separated by the NE-SW oriented Alboran Trough (1800 m wd) and Ridge that emerges on the Alboran Island. Additionally, two main intra-slope sub-basins, which are named the Motril Basin (MB, 920 m wd) and the Southern Alboran Basin (SAB, 1180 m wd) have been mapped on the Spanish and Moroccan continental margins, respectively. The margins and basins also show scattered seamounts (400 to 1000 m high). Last, a few seamounts aligned along the Moroccan margin form a structural passage named the Al Hoceima Valley (maximum depth circa 700 m).

2.2. Oceanographic setting

The oceanographic setting is defined by the eastward-flowing Atlantic Water (AW), which circulates in two anticyclonic gyres down to 150–250 m (Parrilla et al., 1986; Millot, 1999), and the westward-flowing Mediterranean waters (Fig. 1A). Five water masses have been defined within the Alboran Sea (Millot, 2009, 2014; Ercilla et al., 2016): one of Atlantic origin (Atlantic Water - AW) and four of Mediterranean origin. These last water masses comprise the Western Intermediate Water (WIW) (Flexas et al., 2006; Millot, 2009, 2014), the Levantine Intermediate Water (LIW) (Gascard and Richez, 1985; Parrilla et al., 1986; Parrilla and Kinder, 1987; Millot, 1999), the Western Mediterranean Deep Water (WMDW) (Gascard and Richez, 1985; Pistek et al., 1985; Parrilla and Kinder, 1987; Millot, 1999), and the Tyrrhenian Dense Waters (TDW) which depending on the year behaves as LIW or WMDW (Millot, 2009, 2014), and for simplicity will be considered as part of these water masses (Ercilla et al., 2016). The WIW and LIW constitute the light, intermediate Mediterranean waters (hereafter, the LMW) which flow as ain and circulate westward adjacent to the Spanish margin according to Coriolis (Millot, 2009), and the WMDW constitutes the dense Mediterranean waters (hereafter, the DMW) (Millot, 2009; Ercilla et al., 2016) (Fig. 1A), which is trapped by a) topography and b) the northern LMW circulation (Millot, 2009) and flows over the basins and adjacent to the Morocco margin (Pistek et al., 1985) forced by the clockwise western Alboran gyre and accelerated by the Bernoulli effect at the Gibraltar Strait (Naranjo et al., 2012). These two main groups of water masses are characterised by vertical density gradients at their interfaces (Ercilla et al., 2016).

3. Data and methods

This study is based on the review of a database comprising > 1500 single and multichannel seismic records with diverse resolutions, already analysed in several local and regional studies on the Plio-Quaternary sedimentation of the Alboran Sea (Campillo et al., 1992; Ercilla et al., 1992; Jurado and Comas, 1992; Estrada et al., 1997; Pérez-Belzuz et al., 1997; Alonso et al., 1999; Pérez-Belzuz, 1999; Ercilla et al., 2002; Hernández-Molina et al., 2002; Estrada et al., 2011). This database is the result of Spanish geophysical surveys, as well as datasets obtained through the collaboration with French and Moroccan academic institutions and commercial entities. The individual datasets are available online at the ICM-CSIC (*http://gma.icm.csic.es/sites/default/files/geowebs/surveymaps/index.htm*) and SIGEOF (*http://info.igme.es/catalogo/*) databases (Fig. 1C).

These seismic records were integrated into a Kingdom Suite project (IHS Kingdom) for correlation and interpretation. The previously mentioned regional seismic boundaries that were recently updated by Juan et al. (2016) supported by commercial and scientific wells were used for our seismic stratigraphic analysis (Fig. 1D). These boundaries have been correlated throughout the entire seismic database, allowing the creation of isochore and palaeorelief maps for each seismic unit at basin scale. Additionally, the acoustic facies making up the different units and their vertical and spatial distributions, configurations, geometries and thicknesses were also analysed. Due to the changes in the acoustic characteristics from survey to survey and due to different seismic sources or different processing algorithms, we have taken a flexible approach that pays special attention to the general acoustic features, patterns and geometric relationships, allowing us to obtain consistent results (Veeken, 2007). As a result, this detailed analysis allowed the characterization and mapping of morpho-sedimentary features and deposits, and allowed the comparison of their characteristics throughout the Pliocene and Quaternary sequences.

We applied the terminology of Faugères et al. (1999) and Rebesco et al. (2014) to describe and classify the contourite drifts; that of García et al. (2009) and Hernández-Molina et al. (2014) for the contourite erosional features, and applied the terminology described by Normark et al. (1993), Richards et al. (1998) and Richards and Bowman (1998) to the turbidite systems.

4. Results and interpretation

4.1. Revised Plio-Quaternary seismic stratigraphic framework

A detailed, basin-wide analysis of the seismic units after the Zanclean Atlantic mega-flood is here offered, based on acoustic facies, types of boundaries, isochore maps and geometry (Figs. 2 to 6).

4.1.1. Pliocene seismic units

Three seismic units have been identified in the Pliocene sequence of Juan et al. (2016) (Fig. 1D), which, from base to top, are *Pl1 (early Lower Pliocene)*, *Pl2 (late Lower Pliocene)* and *Pl3 (Upper Pliocene)* (Figs. 2 to 6). The boundaries of these seismic units (M, P0, P1 and BQD, form the oldest to the more recent one) are similar in character, being defined by onlapping (Figs. 2; 3A, B, C; 4; 5; and 6B) and local downlapping surfaces (Figs. 2A; 3B, D; 4A; 5A, D; and 6C). These units extend from the uppermost continental slope to the basins, and their distributions are irregular, as they were mostly developed within the basins and are relatively reduced or locally absent in the margins (Figs. 3, 5 and 6). Units *Pl1* and *Pl2* have similar acoustic facies and geometries, which contrast with those of *Pl3*.

Units *Pl1* and *Pl2* (Tables S1 and S2) are mainly characterised by tilted stratified subparallel facies with reflections of relatively low acoustic amplitudes (Figs. 2A; 3; 4B, C; 5C, D; 6B, C) and with a local slightly terraced shape in the uppermost continental slope of the western margins (Figs. 4C and 5). The dominant stratified facies is interrupted by laterally confined depositional bodies. These bodies present discontinuous and continuous stratified and chaotic facies of higher acoustic amplitudes with fan and lobate shapes. These facies are mostly located on the distal Spanish margin and its adjacent basins, and are less common on the Moroccan Mediterranean margin (Figs. 3D, 5 and 6). The *Pl1* and *Pl2* deposits also form irregular and mounded sedimentary patches draping and infilling the irregular ancient MSC palaeoreliefs (e.g., the channel sculpted after the Zanclean mega-flood). Their isochore maps (Fig. 7) show that the sediment distribution is interrupted by highs and Messinian relict reliefs (Estrada et al., 2011). In fact, the depocentres show general parallel, oblique and even perpendicular trends with respect to the margin, mainly due to the irregular palaeotopography of the MSC surface and the local presence of highs (Fig. 7A).

Unit *Pl3* (Table S3) is defined by a higher spatial variability of acoustic facies and geometries. *Pl3* deposits generally display terraced, subtabular to wedged geometries (~5 km long) on the margins and are mostly characterised by subparallel stratified facies with low to middle amplitude at their base that increase upwards (Figs. 3, 4A and 5C), and by high amplitude oblique facies on the western Mediterranean Moroccan margin (Fig. 6A). Discontinuous stratified and chaotic facies with fan and lobate geometry are less frequent. The *Pl3* isochore map shows that this unit is the thinnest (up to 320 ms) Pliocene unit (Fig. 7) and marks the end of the influence of much of the MSC palaeotopography on the sediment distribution.

4.1.2. Quaternary seismic units

Four seismic units have been identified within the Quaternary sequence of Juan et al. (2016) (Fig. 1D), which are (from base to top): *Qt1* (*Early Lower Pleistocene*; Gelasian), *Qt2 (Middle Lower Pleistocene;* early Calabrian), *Qt3 (Late Lower Pleistocene;* late Calabrian), and *Qt4* (*Middle and Upper Pleistocene* -Ionian and Tarantian– and *Holocene*) (Figs. 2 to 6). The boundaries of these units (BQD, Q0, Q1, Q2 and the sea floor, form the oldest to the more recent one) have similar characters, being defined by onlap and local downlap surfaces (Figs. 2C; 3A, B; 4; 5A, B, C; 6B, C), erosive truncations (Fig. 6A, C) and their correlative conformity surfaces (Figs. 2A, 3C and 5D). Units *Qt2* and *Qt3* show similar acoustic facies, geometries and thicknesses, which contrast with those of *Qt1* and of *Qt4* (Tables S4 to S7).

Unit *Qt1* (Table S4) is mostly defined by stratified oblique facies (Figs. 2C, 4 to 6) displaying i) a sloping terraced wedge geometry pinching out landwards at the Spanish and Moroccan margins (Figs. 2C; 3 to 6); ii) stratified subparallel aggrading facies with subtabular geometries on the distal margins and basins (Figs. 2A, B; 3C; 4B); and iii) stratified mounded facies with prograding configurations and mounded geometries at the feet of structural highs (Fig. 3). The stratified facies are laterally interrupted by deposits with discontinuous stratified and chaotic facies with fan and lobate geometries (Figs. 3D, 5D and 6B), mostly in the WAB, MB and EAB. The sediment distribution also reveals that *Qt1* deposits begin to drape but do not obliterate the remnants of the Messinian reliefs (Fig. 8A).

Units *Qt2* and *Qt3* (Tables S5 and S6) are characterised by relatively major progradation of the sloping wedge deposits on the margins (Figs. 4 to 6). As a result, the aggradational tabular deposits characterised by stratified subparallel facies are progressively confined to basins (Figs. 2A, 3C, 4B and 5C). Mounded stratified deposits at the feet of the structural highs and escarpments become more frequent and are better developed (Figs. 3 and 5B). From *Qt2* onwards, the seismic facies are highly cyclic in nature, with alternating high and low amplitude reflections (Figs. 2A, 4A and 6A). The areas with discontinuous stratified and chaotic facies with fan and lobate geometries decrease in size, mainly during *Qt3* (Fig. 5D). The thickness distributions of *Qt2* and *Qt3* show depocentres located along the continental margins that increase in thickness and size (Fig. 8).

The most striking difference of *Qt4* (Table S7) when compared to the previous Quaternary units is the enhancement of the acoustic rhythmic reflection pattern of its deposits (Figs. 4 and 6A) and the decrease in the size of the discontinuous stratified and chaotic deposits with fan and lobate geometries (Figs. 5D and 6B). *Qt4* is the thickest Quaternary unit (0 to 407 ms).

4.1.3. Growth patterns

A change in the growth pattern of the Alboran Sea occurs from the Pliocene to Quaternary units, being more remarkable at the western Spanish and Moroccan margins. The Pliocene units tend to infill palaeoreliefs, and are aggradational when there is no confinement. This stacking pattern mainly results in the onlapping of units onto the margin and the infilling of the basins (Figs. 3 to 5). Despite the Quaternary units continued the basin infilling with a mostly aggradational growth pattern, they show a progradational character in the margins where units progressively onlap upslope (Figs. 3 to 5).

4.2. Plio-Quaternary sedimentary features

The detailed analyses of the acoustic facies, their vertical and lateral

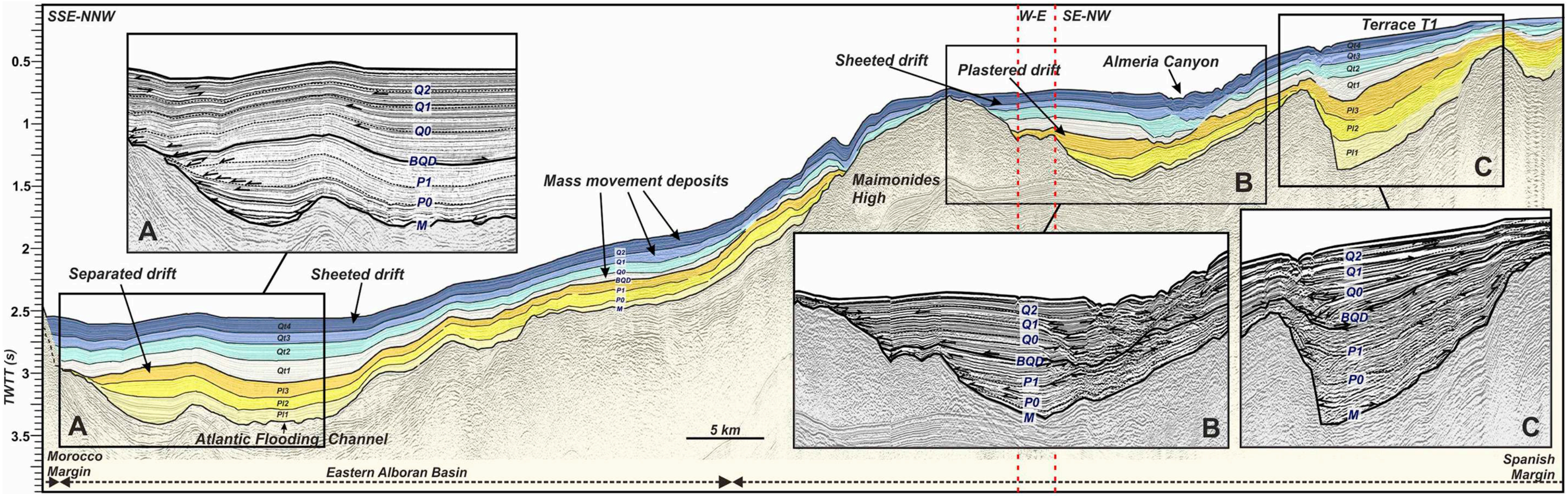

Fig. 2. Seismic profile located in the eastern EAB. See Fig. 1C for location. The Pliocene units are represented in yellow, and the Quaternary units are represented in blue. Unit names are shown in black, and boundary names are shown in blue. Inset A - Buried mounded elongated-separated drift. Inset B - Almeria canyon. Inset C - Terrace cut by a major fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

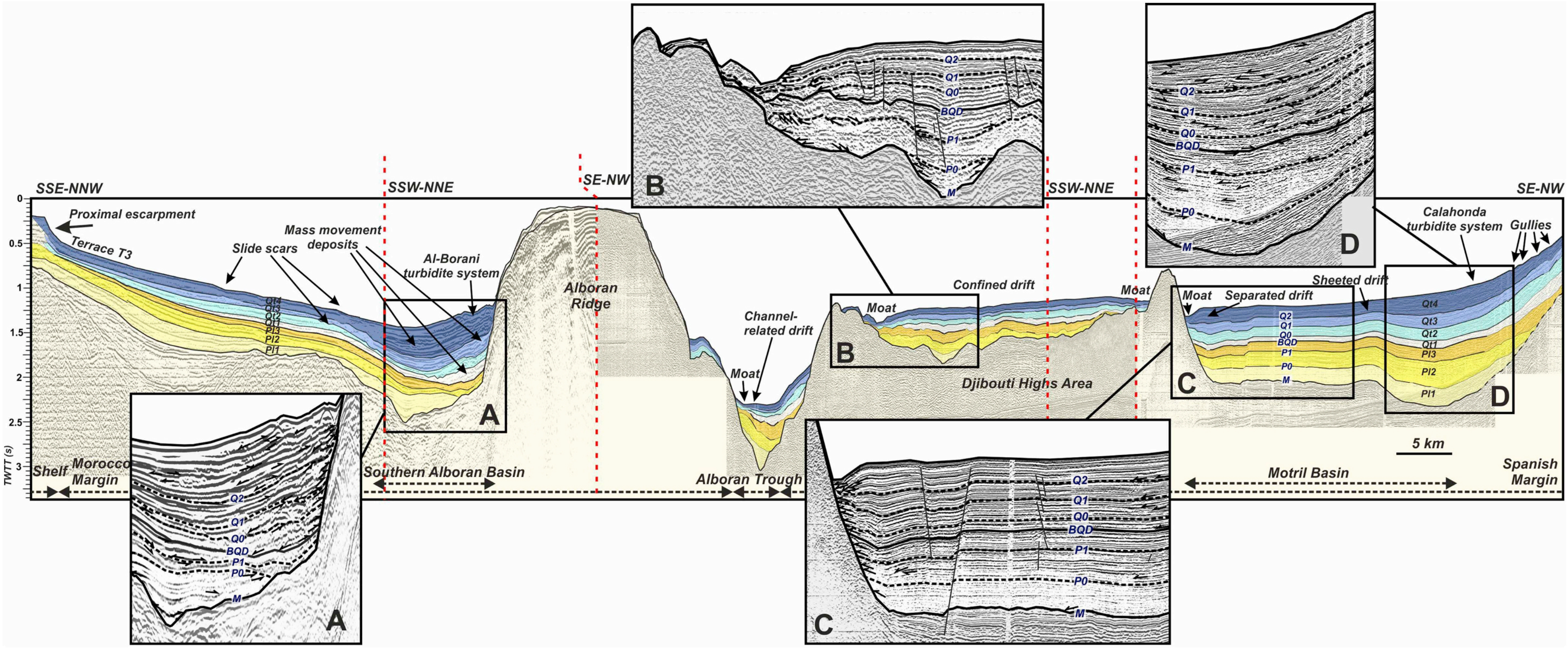

Fig. 3. Seismic profile in the central Alboran Sea. See Fig. 1C for location; the details are as described in Fig. 2. Inset A - Terraced plastered drift. Inset B - Southern end of a confined drift with moat. Inset C - Mounded confined drift. Inset D - Sheeted drift.

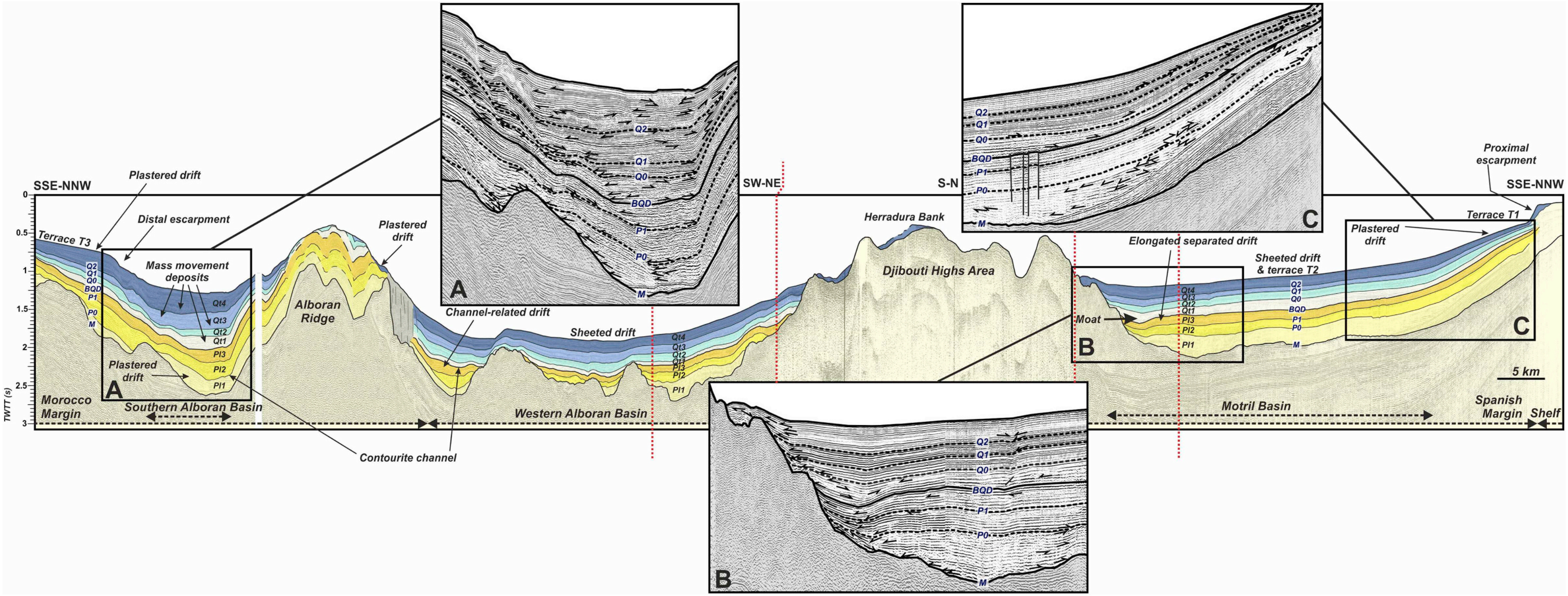

Fig. 4. Seismic profile of the central Alboran Sea. See Fig. 1C for location; the details are as described in Fig. 2. Inset A - Plastered drift in the Lower Pliocene as well as escarpment and mass-wasting deposits in the Quaternary. Inset B - Elongated-separated drift in the Pliocene. Inset C - Plastered drift and terrace.

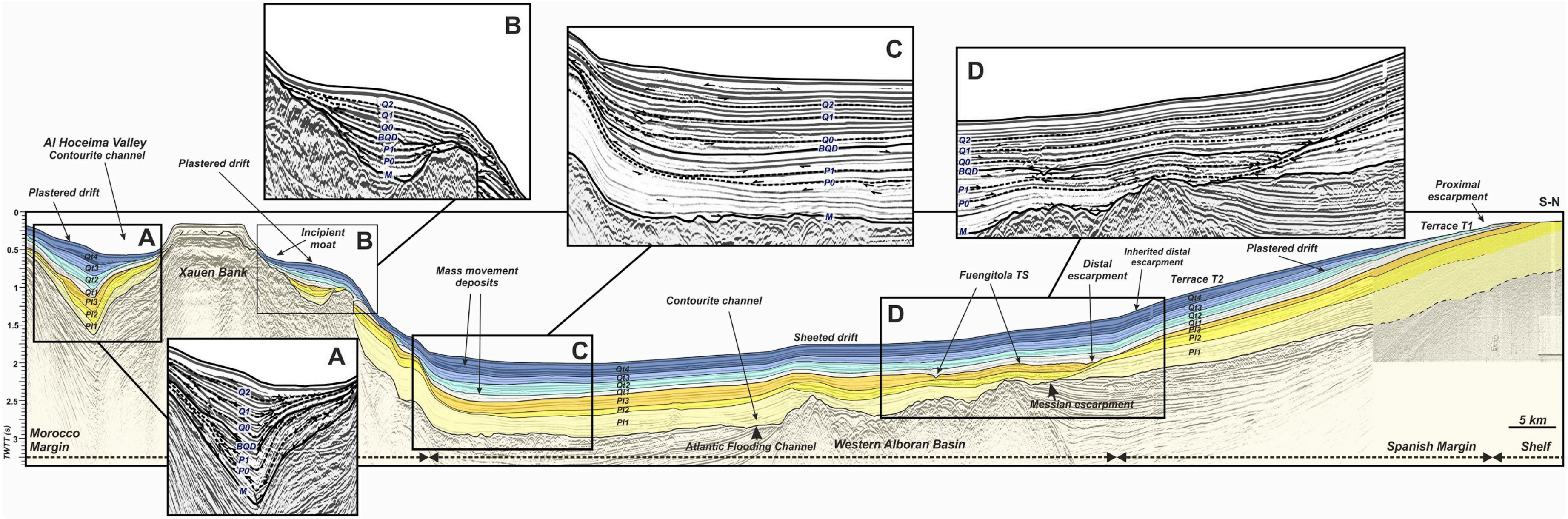

Fig. 5. Seismic profile in the western Alboran Sea. See Fig. 1C for location; the details are as described in Fig. 2. Inset A - Tilted sediments, plastered drift and the Al Hoceima contourite channel. Inset B - Terraced plastered drift. Inset C - Contourite channel in the Upper Pliocene and mass-wasting deposits in the Quaternary. Inset D - Erosive escarpment and turbidite deposits in the Pliocene and Lower Quaternary as well as a sheeted drift in the Upper Quaternary.

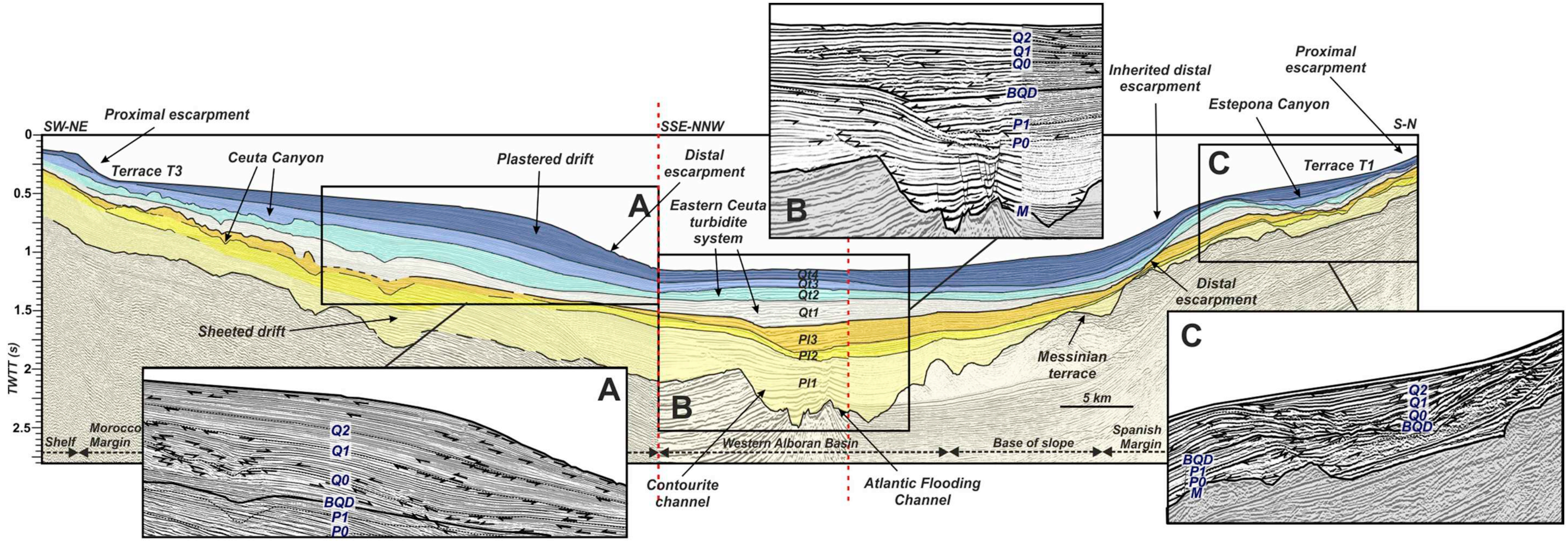

Fig. 6. Seismic profile of the western Alboran Sea. See Fig. 1C for location; the details are as described in Fig. 2. Inset A - Plastered drifts and erosive escarpment. Inset B - Zanclean Channel, Early Pliocene plastered drifts and erosive escarpment, and the Late Pliocene and Quaternary turbidite deposits. Inset C - Estepona buried canyon deposits and terrace.

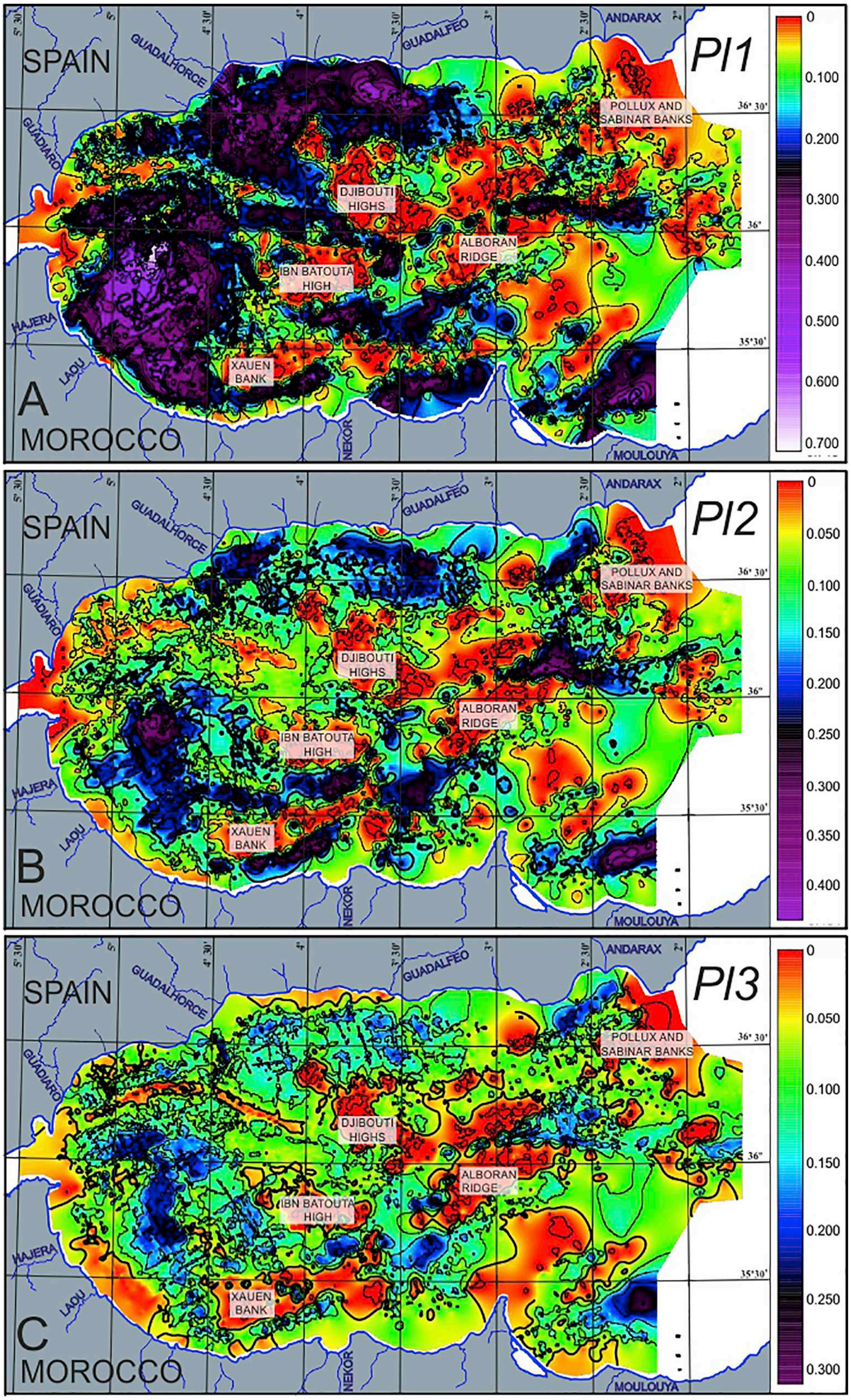

Fig. 7. Isochore maps (in milliseconds) of the Pliocene units showing the locations of the main depocentres. The colour scales are equivalent to those of Fig. 8. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

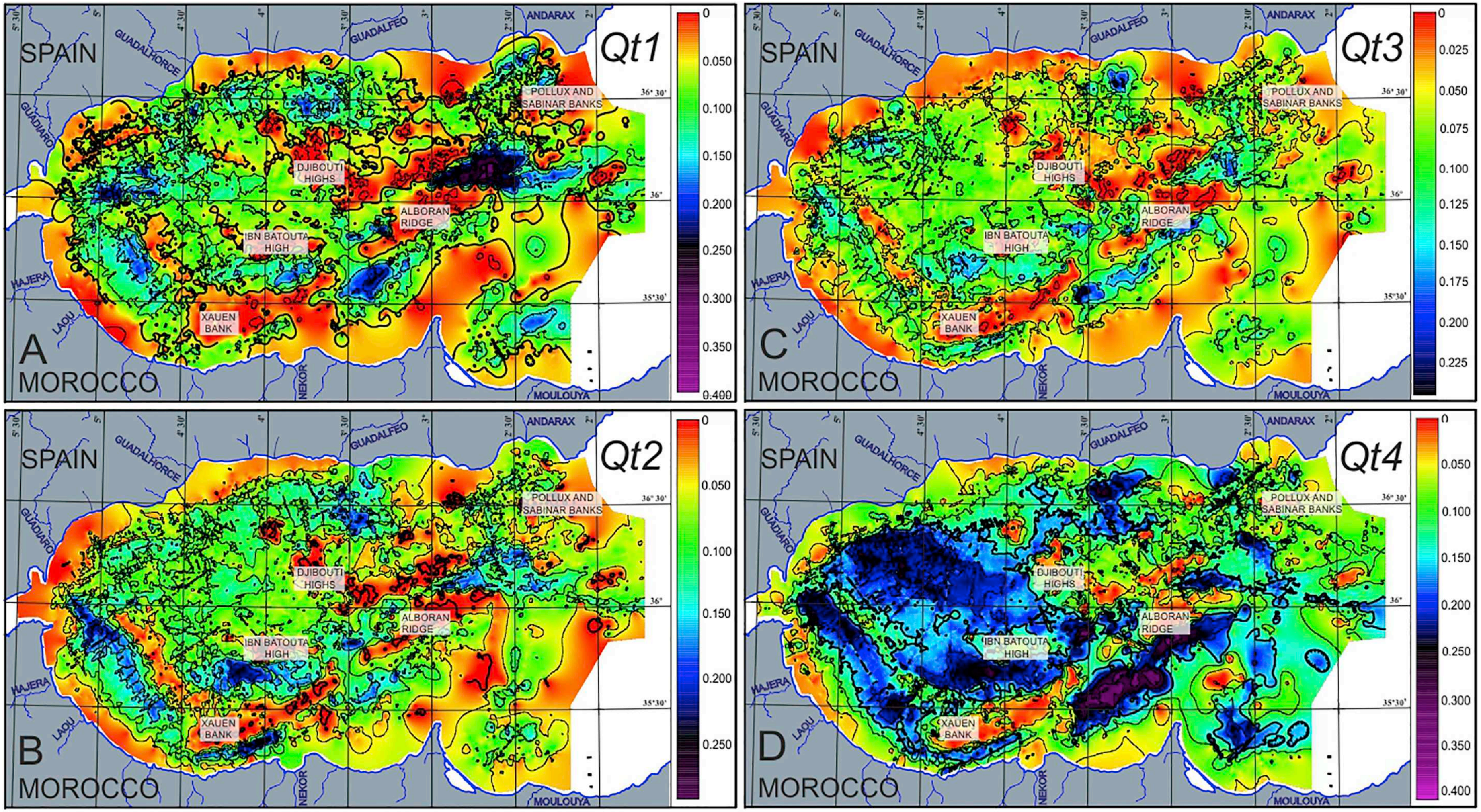

Fig. 8. Isochore maps (in milliseconds) of the Quaternary units showing the location of the main depocentres. The colour scales are equivalent to those of Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

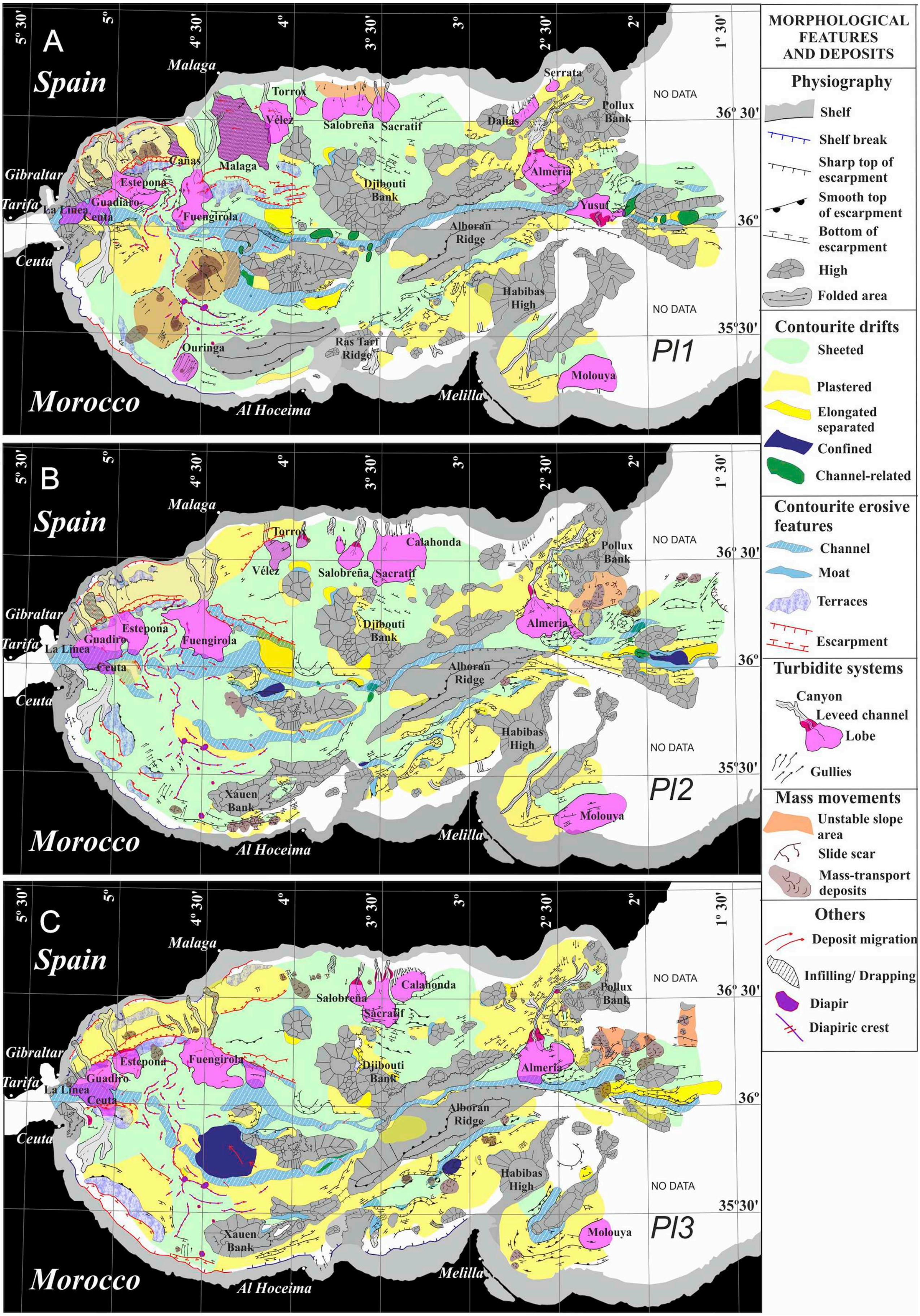

Fig. 9. Maps showing the distributions of the main morphosedimentary features of each Pliocene unit based on the seismic dataset.

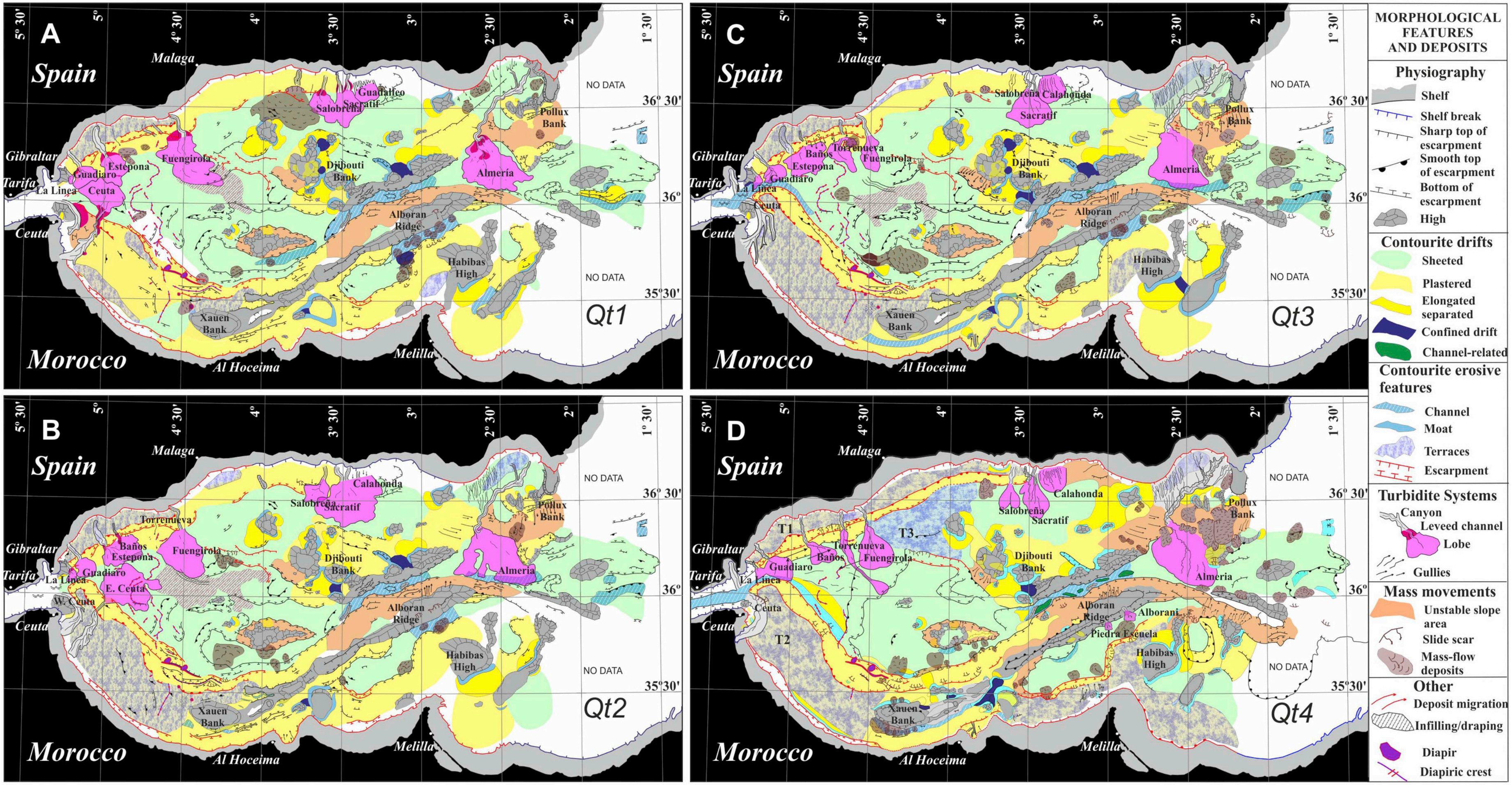

Fig. 10. Maps showing the distributions of the main sedimentary features of each Quaternary unit based on the seismic dataset.

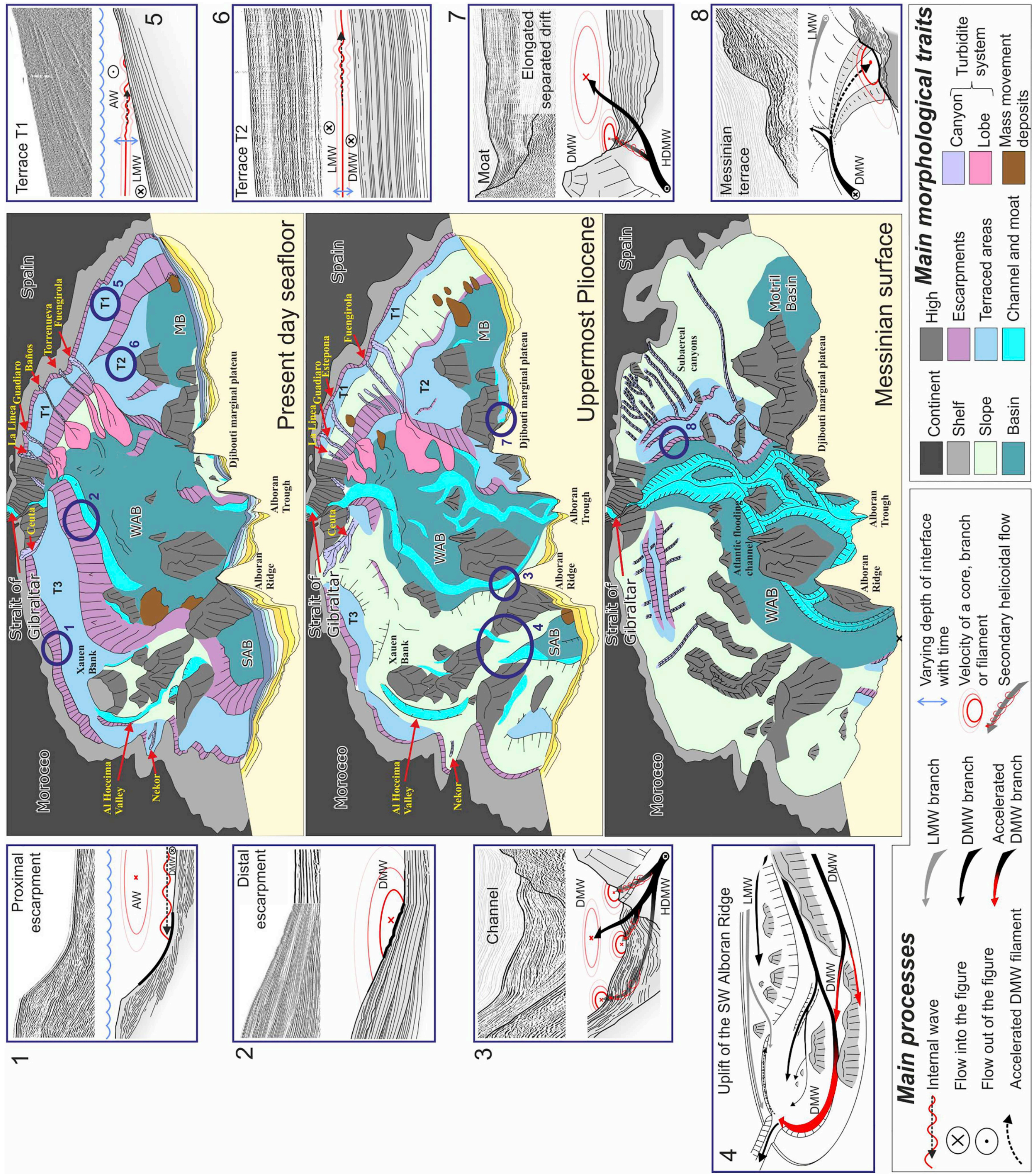

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Fig. 11. 3D sketches with stratigraphic cross-sections summarizing the generalised sedimentary features of the present-day sea floor, uppermost Pliocene sea floor, and Messinian surface. These sketches illustrate the changes in the distributions and of the terraced areas, main channels and moats, turbidite systems and mass-wasting features since the beginning of the Atlantic flooding at the end of Messinian (Bache et al., 2012), during the Pliocene and up until the modern sea floor. The paleogeographic reconstruction is based on this study, as well as Aguirre (2000), Estrada et al. (2011), and Martínez-García et al. (2013). Schematic models summarizing the main oceanographic processes (1 to 8) have been placed around the 3D sketches. These conceptual models show the relationship between the along-slope bottom currents and contourite features.

distributions and the relationships between them have allowed a great variety of sedimentary features to be identified in the Plio-Quaternary units. These features can be categorised into three groups, based on their geneses: a) contourites, including depositional (drifts) and erosional features; b) turbidite systems; and c) mass-wasting deposits (Tables S1 to S7).

4.2.1. *Contourite systems*

Contourite drifts are the most prominent features of the Plio-Quaternary units in the Alboran Sea (Ercilla et al., 2016; Juan et al., 2016) (Figs. 2 to 6). The dominant drifts are the large-scale sheeted (Fig. 11, inset 6) and plastered drifts (Fig. 11, insets 2, and 5). Smaller confined, elongated-separated and channel-related drifts have been locally defined, being scattered throughout the Alboran Sea (Figs. 9, 10 and 11, insets 3 and 7).

Sheeted drifts are characterised by subtabular geometries with relatively flat surfaces that mimic the morphology of the basins and the longitudinal trend of the margins. These drifts make up a practically flat and smooth (palaeo)sea floor and cover broad areas of up to 50–100 km length and width, being thicker during the Pliocene (about 100–200 ms and up to 280 ms thick) than during the Quaternary units (about 60–100 ms and up to 265 ms thick) (Tables S1 to S7). These drifts are defined by (sub)parallel stratified deposits with no remarkable internal discordances and locally layered wavy facies, with sediments that usually end up in onlap terminations at high walls and escarpments. Sheeted drifts are found in all Plio- Quaternary units, carpeting the Spanish and Moroccan continental margins, infilling the basins and draping morphological irregularities (Figs. 2 to 6; Tables S1 to S7). These deposits generally have broader extension in the Pliocene units (*Pl1* to *Pl3*);in the Quaternary units (*Qt1* to *Qt4*) these deposits are mostly restricted to the basins but show higher lateral continuities (Figs. 9, 10 and 11, inset 6).

Plastered drifts are low to high mound features with elongated and wedged to terraced geometries (Figs. 4–6), always located attached to or plastered against a slope (continental slope and high walls) (Figs. 4 to 6, 10 and 11, insets 2 and 5). These drifts are highly variable in size (tens to hundreds of kilometres long/wide and tens to a few hundred metres in relief). These drifts are internally defined by oblique stratified deposits with onlap terminations upslope, downlap terminations downslope, and occasional internal erosions (Figs. 4C, 5 and 6). Plastered drifts appear scattered within the Early Pliocene units (*Pl1* and *Pl2*) and get wider and longer (up to 300 km long and 6 to 40 km wide) in the Quaternary units (*Qt1* to *Qt4*) (Tables S4 to S7), eventually covering most of the Spanish and Moroccan margins. These drifts are better developed near the Strait of Gibraltar in both the Pliocene and the Quaternary units (Figs. 5, 6 and 11).

Elongated-separated drifts show asymmetric mounded geometries (Figs. 3B, C; 4B) with variable dimensions (< 42 km long and 8 km wide, 75–240 ms thick), and appear at the feet of relatively steep sea floor slopes associated with moats (Tables S1 to S7). These drifts are defined by stratified deposits with convergent configuration towards the mound end that downlap on the internal erosive reflections of the adjacent moat (Fig. 4B). These drifts are identified in the Plio-Quaternary units, although they are more numerous in the Quaternary (Figs. 9, 10 and 11, inset 7). Their distributions also show temporal and spatial changes: in the Pliocene units (*Pl1* to *Pl3*), the largest elongated-separated deposits are located in the deep basins, whereas in the Quaternary units (*Qt1* to *Qt4*), the largest drifts are found on the continental slopes and highs, with smaller ones in the basins.

Confined drifts show low- to high-mounded geometries with variable dimensions (typically 8 km and up to 20 km long; 5–6 km wide; 100 to 300 m thick) (Tables S1 to S7). The deposits are well stratified, with facies converging towards topographic confinements where moats develop (Fig. 3). The acoustic amplitudes of these deposits are usually higher near the borders of the topographic confinements, where they also show downlap and onlap terminations. Confined drifts have been identified over most of the Pliocene (*Pl2* and *Pl3*) basins and Quaternary seismic units (*Qt1* to *Qt4*) but are more frequent in those Quaternary units on the continental slope associated with some structural highs (Figs. 9, 10 and 11).

The lateral and axial *channel-related patched drifts* usually show mounded (Fig. 3) and occasionally wedged geometries (3 to 11 km long, < 5 km wide, and up to 220 ms thick) (Tables S1 to S7). These drifts mostly consist of stratified mounded and (sub)parallel deposits with locally oblique configurations (Fig. 3). The strata pattern includes the downlap terminations into the channel itself and the frequent onlap terminations at the channel sidewalls or structural highs. These drifts are mapped in the Lower Pliocene seismic units (*Pl1* and *Pl2*) on the EAB and WAB and in the Upper Quaternary seismic units (*Qt4*) on the margins and basins (Figs. 9, 10 and 11, inset 3).

The erosive contourite features identified in the Plio-Quaternary units can be grouped into two types: a) channels and moats with linear trend, and b) terraces, with planar morphology. *Contourite channels* are U-shaped features with low (tens of ms) to high reliefs (hundreds of ms), relatively wide (typically ~1.5 km, and up to 6.5 km) and long (up to 50–70 km) (Figs. 3; 4; 5A). Their deposits are mostly characterised by discontinuous and continuous stratified facies with highly reflective chaotic facies (Tables S1 to S7). The channel deposits are affected by slightly erosive surfaces as well as by low-angle onlaps and downlaps over internal discontinuities. Locally, they can also contain allochthonous deposits (e.g., mass-wasting deposits). The presence of contourite channels in the Alboran Sea is conditioned by pre-existing morphosedimentary and structural features. The Pliocene contourite channels are mostly constrained to basins and occur in relation to narrow structural palaeocorridors (i.e., the proto-Alboran Trough and SAB) and to the relict Atlantic Flooding Channel (Figs. 4, 5, 6A, 9, 10 and 11, inset 4). The Quaternary contourite channels are represented by the narrow structural passages of the Alboran Trough (Figs. 3 and 11) and the Al Hoceima Valley (Fig. 5A).*Contourite moats* are also narrow U-shaped concave features, but smaller in size and in association with mounded drifts (Figs. 3 and 4). These moats are typically incised tens of metres deep and < 6 km wide at the feet of structural highs (Tables S1 to S7). Moat deposits comprise the stacking of obliquely stratified, discontinuously stratified and chaotic facies separated by stacked internal erosive surfaces (Figs. 3 and 4). Locally, these facies can also contain allochthonous deposits (e.g., mass-wasting deposits). Moat deposits have been identified in the Plio-Quaternary units, and are more frequent in the Quaternary units (Figs. 9, 10 and 11).

Terraces represent an alongslope subhorizontal surface shaping the contourite drifts, with a narrow erosive area truncating the drift deposits, that evolves seaward to a depositional conformity surface (Figs. 4 to 6; 10D; Tables S1 to S7), and bounded upslope or down-slope by escarpments (Figs. 9, 10 and 11, insets 1 and 2). Terraces are up to 100 km in length, 30 km in width and dip seaward (from 0.5 to 1°). Four terraces have been mapped, one relict of Messinian age (Fig. 11, inset 8), and three modern (T1 to T3, Fig. 11). The relict terrace was excavated during the Zanclean mega-flood (Estrada et al., 2011) and outcrops in the northern WAB within the Pliocene seismic units (*Pl1* to *Pl3*) as a relict feature swept by a countercurrent before being mostly obliterated by the Quaternary units (*Qt1* to *Qt3*) (Figs.6 and 11, inset 8). The three modern terraces (T1 to T3) (Ercilla et al., 2016) have been identified through the Plio-Quaternary units at different water depths. The T1 and T3 terraces are shallower and currently located at 160–400 m wd for T1 and 180–600 m wd for T3. They occur on the Spanish (T1, Figs. 4C; 5; 6C; 10D, 11, inset 5) and Moroccan upper margins (T3, Figs. 6, 10D and 11, inset 1) (Ercilla et al., 2016; Juan et al., 2016), displaying an abrupt enlargement after *Pl3*. T2 occurs in the MB and affects the sheeted drift infilling this basin (Figs. 4 and 5); its onset occurred in the late Upper Pliocene (top of *Pl3*), outbuilding mostly in the Quaternary units. This terrace is easily identified on the present-day sea floor between 1000 and 1300 m wd (Figs. 5 and 11, inset 6) (Ercilla et al., 2016) on the central Spanish margin.

4.2.2. *Turbidite systems*

Turbidite systems interrupt the nearly-ubiquitous contourites that make up the Alboran margins and basins (Figs. 2B; 3A, D; 5D; 6B, C; 9; 10; 11). The internal seismic character of the turbidite systems can be clearly observed due to their sharp lateral contact with the surrounding dominant contourite deposits (Tables S1 to S7). Their seismic facies comprise i) chaotic facies that onlap and infill U-shape cut and fill features, defining canyon-fill, gully-fill, channel-fill deposits (Figs. 2B and 6C); ii) discontinuous and continuous stratified facies with a wedge and lenticular shape, that respectively define levee deposits and channelised lobes (Figs. 3A, D; 6B). All these deposits show a well-defined 3D geometry, quasi-perpendicular to the continental margin protruding with respect to the adjacent contourites. The turbidite system development is mostly related to point sources represented by submarine canyons (Figs. 2B; 6C), or multiple gullies (Fig. 3).

A total of 22 turbidite systems have been mapped in the Plio-Quaternary units (Figs. 9 and 10) in the margins and basins. Of these, 13 are already present in *Pl1* on the Spanish margin, which are (from west to east): La Linea, Guadiaro, Estepona, Cañas, Fuengirola, Málaga, Velez, Torrox, Salobreña, Sacratif, Dalias, Serrata and Almeria. A few disappear during the Pliocene (Cañas, Malaga, and Serrata in *Pl1 unit*; Velez and Torrox in *Pl2 unit*; Dalias merges with the Almeria after *Pl1unit*) and Quaternary (Estepona disappears in or immediately after *Qt3*). Additionally, new ones appear in the Pliocene (Calahonda, in *Pl2*) and Quaternary units (Torre Nueva in *Qt2*, Baños in *Qt3*) (Figs. 9 and 10), reaching up to 16 turbidite systems developed in the Spanish margin along the Plio-Quaternary seismic units. The sizes of most of the turbidite systems generally decrease in the Quaternary units (Fig. 10).

On the Morocco margin, only 3 full turbidite systems (Moulouya, Ouringa and Ceuta) have been mapped, and none of these systems have remained active, except the Ceuta feeder canyon that enters the Strait of Gibraltar. In addition, the Nekor canyon never developed a turbidite fan. The Ouringa fan was buried immediately after *Pl1*; the Moulouya system became inactive after the*Pl3 unit*, and the Ceuta lobe deposits disappeared during the *Qt3* unit after a change in the course of its feeder canyon (Fig. 10B, C, D).

Within the deep basins, 3 turbidite systems have been characterised: the Yusuf turbidite system developed at the foot of the Habibas escarpment during the early Lower Pliocene (*Pl1 unit*) and was buried immediately after this unit; the Piedra Escuela and Al Borani turbidite systems were mapped at the southern Alboran Ridge during the late Quaternary (*Qt1*) (Vázquez et al., 2010) (Fig. 3A).

4.2.3. *Mass-wasting deposits*

Mass-wasting deposits differ from contourite and turbidite systems in their geometry and seismic facies (Figs. 2; 3A; 4A; 5C, Tables S1 to S7). These deposits generally occur as slides associated with major tectonic features, such as the Alboran Ridge and other seamounts (Alonso et al., 2014). They are characterised as wedge and lenticular bodies internally defined by semitransparent and chaotic facies. They range from a few to tens of milliseconds in thickness and surfaces of hundreds meters to a few km^2 (Tables S1 to S7). These features have been identified in all the seismic units and physiographic environments (Figs. 9 and 10), being more frequent: a) at the western Moroccan continental margin and adjacent WAB in the Lower Pliocene unit; b) at the MB and SAB in the Upper Pliocene unit; c) at the north (from *Qt2*) and south (from *Qt4*) of the Xauen Bank and other nearby seamounts (e.g., Xauen, Petit Xauen, Tofiño, Eurofleet, Ramon Margalef, Francesc Pagès, Pollux, Sabinar Bank); and d) along the northern Alboran Ridge and Habibas High in all Plio-Quaternary units (Figs. 9 and 10).

5. Discussion

The results reveal that the Plio-Quaternary depositional architecture of the Alboran Sea beyond the shelf break is more complex than previously realised (Alonso and Maldonado, 1992; Ercilla et al., 1992, 1994; Juan et al., 2016). The depositional architecture results from the interplay of the three main sedimentary systems (contourites, turbidites, and mass-wasting deposits), which present spatial and temporal variations. Contourite and turbidite systems coexist on the Spanish margin; on the opposite, contourites dominate the Moroccan continental margin; last, contourite, turbidite, and mass-wasting systems are found in the intra-slope basins and deep basins. All these deposits developed in distinct tectonic contexts and under different oceanographic conditions. The detailed sedimentary model shed light on their spatial and temporal distributions through the different units making up the Pliocene and Quaternary sequences, and has allowed identifying the multiple factors controlling the Plio-Quaternary sedimentation in the Alboran Sea.

5.1. *Deciphering past bottom-current dynamics based on contourite features*

The ubiquitous distribution of contourites through the Plio-Quaternary units suggest that bottom currents were one of the main factors controlling transport and sedimentation in the Alboran Sea (Figs. 9 and 10). The depositional architecture and growth pattern of the large-scale drifts indicate that their sedimentation occurs uninterruptedly. Then, we can assume that the contourites were formed and shaped by the three major present-day water masses (AW, LMW, and DMW) and their past equivalents (Ercilla et al., 2016; Juan et al., 2016). For this reason, we can define multiple CDSs in this sea: i) the Intermediate Mediterranean contourite system (IMCS), comprising contourites formed under the action of the LMW on the Spanish continental margin; ii) the Deep Mediterranean contourite system (DMCS), made up of contourites mostly found on the Moroccan margin and annex sub-basins, which have formed under the action of the DMW; and iii) the Atlantic contourite system (ACS) comprising terraces T1 and T3, shaped by the AW and its interfaces with the LMW and DMW on the uppermost continental slopes of both margins (Fig. 11, insets 1 and 5).

5.1.1. *Temporal variations in the characteristics of the water masses*

The detailed stratigraphic and sedimentary analysis of the Plio-Quaternary contourites has allowed inferring variations in the characteristics (e.g., relative velocity and location of current branches and filaments) of the Atlantic and Mediterranean water masses over time, as well as changes in their circulation pattern. These variations have been decoded in particular from changes displayed by the controurite drift geometry and their acoustic facies (i), and the development of contourite terraces (ii).

Contourite drift geometry (i) results from fundamental differences in the strength of bottom flows: muddy sheeted drifts generally form under a regionally stable tabular water mass that flows with lower velocities operating over relatively large and flat seabeds; on the opposite, mounded drifts form under a more intense flow, mostly over steep or irregular sea floors (Faugères et al., 1999; Hernández-Molina et al., 2008; Stow et al., 2008; Ercilla et al., 2016; Juan et al., 2016). The evolution of the large-scale drifts on the Spanish and Moroccan continental slope also hints at variations in the bottom flow over time (Figs. 2 to 6; 9; 10; 11 inset 4; Tables S1 to S7). Those drifts located on the slopes have evolved from sheeted to mound plastered type, from the Late Pliocene onwards. This change suggests that from the opening of the Strait of Gibraltar to the Late Pliocene, the MWs operated with relatively lower energy; whereas from the Late Pliocene onwards their overall strength increased. This strengthening is in agreement with the enhanced thermohaline circulation and Mediterranean water ventilation related to the Quaternary sharp climatic periods (Rogerson et al., 2012). The increased energy of the bottom currents would be also reflected by the increased acoustic reflectivity displayed by the Quaternary drift deposits (Hernández-Molina et al., 2002), although the influence of other factors, such as sediment supply or sea-level changes, cannot be ruled out. These variations in the geometries and facies of the Alboran contourite drifts are similar to those of the well-known Cadiz and Le Danois CDSs on the neighbouring Atlantic Iberian margin (Van Rooij et al., 2010; Llave et al., 2011; Roque et al., 2012).

The *development of contourite terraces (ii)* shaping the Spanish and Moroccan margins from the Late Pliocene onwards seems to be related to the progressive strengthening of the density contrast between water masses, as hinted by Juan et al. (2016). The cause-effect link between interfaces with high density contrast and the formation of contourite terraces was first suggested by Hernández-Molina et al. (2008) for the Brazilian Margin, by Preu et al. (2012) and Preu et al. (2013) for the Argentine continental margin, and later proved by Hernández-Molina et al., (2017) and Ercilla et al. (2019b) for other margins. Turbulent processes (e.g., internal waves-induced) travelling along the interfaces rework, resuspend and transport sediment, flattening the sea floor of the continental slope (Sarnthein et al., 1982; Puig et al., 2004; Pomar et al., 2012; Shanmugam, 2013a, 2013b; Chen et al., 2014) and forming contourite terraces. Based on modern hydrographic analyses, Puig et al. (2004) and Ercilla et al. (2016) demonstrated the occurrence of internal waves travelling along the present-day interfaces in the Alboran Sea, sweeping the Spanish and Moroccan continental slopes. The wider terraces that have been identified and mapped since the Late Pliocene prove that the proto-AW and –MWs had a higher density contrast than in the early Pliocene, allowing internal waves and associated turbulent processes to sculpt the margin.

5.1.2. Factors influencing bottom current sedimentation

Bottom currents interact with other factors, including: i) tectonics and the sub-basin configuration; ii) topography; and iii) climate and sea-level changes. The specific combinations of these factors with bottom currents predominantly condition the spatial and temporal variability of contourites.

(i) *Tectonics and sub-basin configuration.* The Alboran Basin achieved its present-day configuration as a result of the compressional tectonics of the Tortonian inversion (Weijermars et al., 1985; Comas et al., 1992). Later on, tectonics continued shaping the sea floor morphology (causing local subsidence and uplift) during the Plio-Quaternary (Martínez-García et al., 2013). The most striking palaeogeographic consequence was the progressive uplift of the Alboran Ridge and other aligned seamounts during the Pliocene (e.g., Xauen, Petit Xauen, Tofiño, Eurofleet, Ramon Margalef, and Francesc Pagès highs), which lead to the formation of the large, longitudinal ridge that divides the Alboran Sea into the present-day sub-basins at the end of the Pliocene (Martínez-García et al., 2013) (Fig. 11). As a result, the WAB became deeper and semi-confined during the Pliocene, and the SAB became an independent sub-basin during the Quaternary (Docherty and Banda, 1992; Estrada et al., 1997; Rodríguez-Fernández et al., 1999; Martínez-García et al., 2013). These changes promoted the recirculation of the proto-DMW in the WAB during the Pliocene (Alhammoud et al., 2010; Juan, 2016; Juan et al., 2016), as well as enhanced proto-DMW circulation in the SAB during the Quaternary. This helps explain the presence of thicker Pliocene sheeted contourites in the WAB (about 350–450 ms) (Fig. 7) and thicker Quaternary sheeted contourites in the SAB (up to 400 ms) (Fig. 8). Additionally, tectonics have contributed to the formation of two large structural passages, the Alboran Trough and the Al Hoceima Valley (Martínez-García et al., 2013), which act as contourite channels during the Quaternary (Figs. 10 and 11). These structural passages favoured the separation of the proto-DMW flow into accelerated branches (Figs. 1 and 11, inset 4) under which erosion, non-deposition and channel-related drifts were common (Fig. 11, inset 3).

(ii) *Topography.* The inherited Atlantic mega-flood topography and the seamounts are the two main topographic features that have interacted with the bottom currents during the Plio-Quaternary. The Atlantic mega-flood, which put an end to the MSC, eroded a striking, longitudinal, deeply-incised channel crossing the entire Alboran Sea as well as longitudinal escarpments (Estrada et al., 2011). Later on, the confining morphology of the flooding channel influenced the pathway of the proto-DMW bottom currents, resulting in the formation of a locally accelerated flow. This accelerated flow along the narrow conduit (now acting as a contourite channel) (Fig. 5) favoured the formation of various channel-related drifts in the WAB and EAB (Figs. 2 and 4). In turn, these drifts contributed to the progressive infilling and obliteration of the flood channel topography by the end of the Pliocene. Additionally, the proto-DMW flow was forced against the lower MSC escarpment in the Spanish margin and locally accelerated, (Alhammoud et al., 2010; Mulder et al., 2011) keeping it mostly free of sediment throughout the Pliocene and being precursory of the escarpment that still shapes this area in the present.

The seamounts dotting the Alboran Sea have volcanic and structural origins, and formed at different times (Comas et al., 1992; Palomino et al., 2015). Seamount topography locally affected the velocity of the water masses, leading to the formation of faster, turbulent current filaments that formed moats at their foot (Hernández-Molina et al., 2006). The eroded sediments deposited close to the moats, building elongated separated and mounded drifts (e.g., Rebesco and Camerlenghi, 2008), which are more frequent in the Quaternary units. The impinging water masses would have also contributed to the small-scale plastered and sheeted drifts that cover the walls and tops of seamounts, when the flow velocities decreased, causing the rapid settling of particles from suspension.

(iii) *Climate and sea-level changes.* The Pliocene was dominated by a general cooling trend (Lisiecki and Raymo, 2005), punctuated by short warming and cooling episodes (Zachos et al., 2001; Becker et al., 2005). The Quaternary was characterised by high frequency and high amplitude glacioeustatic sea-level changes (approximately 40 to 100 m of sea-level fall) with significant increases in the amplitude from 700 ky, as confirmed in the Alboran Sea by various authors (Comas et al., 1996; de Kaenel et al., 1999; Von Grafenstein et al., 1999). A comparison of the thickness of Plio-Quaternary contourite deposits does not reveal an unequivocal match between drift accumulation and sea level changes, but the 100 ky glacial-interglacial cycles with sea-level falls of around 100 m (Miller et al., 2011) may have contributed widening the contouritic terraces located on the uppermost slope. The high-amplitude sea-level changes would have altered the position of the interfaces and of the cores of the water masses. The interfaces and their associated turbulent energy patterns would have descended together with the sea level, enhancing the turbulent and erosive processes on the proximal terrace, and widening the area affected by erosive processes (vertical and horizontal displacements of the interface between the proto-AW and MWs). In this scenario, the amount of resuspended sediment would increase, favouring the progradation of the distal part of the terrace both seawards and in the direction of the current.

5.2. Turbidite sedimentation as a proxy to understand bottom currents

Bottom currents also influence the sedimentation in turbidite systems (Mulder et al., 2008), and in the case of the Alboran Sea specifically influence: i) their regionally uneven formation; and ii) their general recession with time.

(i) *Uneven development of turbidite systems*. These systems are common on the Spanish margin and develop under the influence of bottom currents during the Plio-Quaternary (Ercilla et al., 2019a). This scenario contrasts sharply with the Moroccan margin where turbidite systems are rare and contourites are ubiquitous during that time (Figs. 9 and 10). The initiation of gravity flows needs sufficient sediment supply to create mixtures of suspended sediment and to form high concentration, very near-bed flow moving down-slope under the influence of gravity. In turn, sediment supply is generally related to significant and instantaneous sediment remobilisation from the sea floor or coastal areas due to catastrophic events, such as sedimentary failures, earthquakes, and so on, or related to river discharge forming hyperpicnal flows (e.g., Wright and Friedrichs, 2006; Manica, 2012). In the northern margin of the Alboran Sea, the mapping of turbidite systems points to suspended-sediment concentration from river discharge representing the major sediment source for gravity flows (Ercilla et al., 2019a), due to the correlation of downslope systems and modern river systems delivering sediment directly into the heads of submarine canyons during lowstands (e.g., Alonso and Ercilla, 2003). Taking into account the fact that both the Spanish and Moroccan margins had similar geography, climate, and fluvial systems supplying the sediment load during the Plio-Quaternary (Stanley et al., 1975; Liquete et al., 2005; Fernandez-Salas, 2008; Vázquez et al., 2015b), near-bottom currents may be the main processes dispersing the sediment discharged by the Moroccan rivers. The present-day oceanography indicates that the core of the DMW flows along the Moroccan margin (Pistek et al., 1985; Millot, 2009; Naranjo et al., 2012; Ercilla et al., 2019a), steered by topographic constrictions (Parrilla et al., 1986) and due to the clockwise forcing of the western Alboran gyre and the closeness to the Strait of Gibraltar (Naranjo et al., 2012; Rogerson et al., 2012). This steering would also have favoured a focused branch of the proto-DMW (Fig. 11, inset 4) with high velocities that would pirate the fine sediment (Shanmugam et al., 1993; Mulder et al., 2008) avoiding its convergence and the formation of erosive down-slope gravity flows, therefore inhibiting the formation of turbidite systems (Ercilla et al., 2019a).

(ii) *Recession of turbidite systems.* Literature on the turbidite systems in the Alboran Sea suggests that the main factors controlling their evolution are sea-level changes, the morphostructure of the margins, tectonics, and sediment supply (Alonso and Maldonado, 1992; Ercilla et al., 1994; Estrada et al., 1997; Alonso and Ercilla, 2003). Nevertheless, none of those factors explains the recession of the turbidity activity observed in the WAB and MB during the Quaternary (Figs. 9, 10). The glacio-eustatic sea level changes, uplifting of hinterland sources (Braga et al., 2003) and the related down-slope increases in sediment supply during the Quaternary should have favoured the activity of turbidity flows compared to that of the Pliocene (Figs. 9, 10). This study reveals coexisting contourites and turbidites (Figs. 9, 10 and 11), pointing to a new factor not previously evaluated: bottom current conditions. The above-mentioned strengthening of the proto-MWs after the Late Pliocene, as well as the better-defined density structure between the proto-AW and -MWs during the Quaternary would have affected the turbidity flows due to: i) greater sediment piracy of fine sediments from the river runoff, these being distributed across the water mass interfaces over long distances before finally being deposited (Ercilla et al., 2016); and ii) piracy of the finer tails of the channelised turbidity flows running along the canyons and channels (Shanmugam et al., 1993). Both piracies would have caused gravity flows with low concentration of fine sediments (Jobe et al., 2011), resulting in decreased turbidite activity (He et al., 2008).

5.3. Additional processes controlling down-slope sedimentation

The formation of turbidite systems and mass-wasting deposits suggests that other factors beyond the direct influence of bottom currents also control sedimentation in the Alboran Sea. These are: i) tectonics; ii) topography; and iii) sea-level changes and related sediment supply.

(i) *Tectonics*. The aforementioned changes in the Alboran Basin configuration also influenced the distribution and thickness of the Almeria turbidite system as well as the formation of the mass-wasting deposits. During the Pliocene, tectonic subsidence conditioned the deeper and semi-confined configuration of the eastern sector of the Alboran Trough (Estrada et al., 1997; Alonso and Ercilla, 2003), trapping the gravity flows sourced from the Almeria canyon that filled the available accommodation space, favouring the deposition of thicker Pliocene turbidites (350 ms of channelised lobe deposits) (*Pl2*, Fig. 7). In addition, the progressive uplifting of the Alboran Ridge and other structural seamounts (e.g., Xauen, Petit Xauen, Tofiño, Eurofleet, Ramon Margalef, Francesc Pagès, Pollux, and Sabinar) after tectonic regional pulses controlled the contemporaneous occurrence of mass-wasting deposits, predominantly during the Quaternary (Fig. 10) (Martínez-García et al., 2009; Alonso et al., 2014). In this sense, a medium frequency recurrence interval (40–210 kyr) has been determined to result from tectonic-related seismicity throughout the Quaternary in the eastern Alboran basin (Alonso et al., 2014). Slope failure events could have been triggered by tectonically controlled overstepping and/or seismicity (Ercilla and Casas, 2012; Casas et al., 2015), contributing to the mass wasting of the plastered and sheeted drifts draping the uplifting highs (Martínez-García et al., 2009; Alonso et al., 2014).

(ii) *Topography.* The topography inherited from the Messinian Salinity Crisis (MSC) also controlled the location of most of the turbidite systems along the margins. The location of the canyons feeding the earliest Pliocene turbidite systems coincides with the location of the valleys excavated as conduits for river and stream flows during the MSC subaerial exposure (Estrada et al., 2011). After the Atlantic mega-flood, these subaerial conduits evolved into underwater canyons, facilitating the transport of submarine gravity flows. This evolution was locally favoured by the poor definition of the continental shelf after the MSC as well as by the direct contact between the hinterland drainage system and the Messinian subaerial valleys (Loget and Driessche, 2006). In this scenario, the sediments transported by rivers contributed to the quick infilling of the estuaries (Loget and Driessche, 2006) and together with alongshore transport, contributed to the formation and maintenance of submarine sediment-gravity flows running down the former subaerial canyons and the progressive development of turbidite systems (Bernhardt et al., 2015; Tari et al., 2015).

(iii) *Sea-level changes and related sediment supply*. Sequence stratigraphy studies in the Alboran Sea suggest that the Quaternary sedimentary record of the continental slopes mostly comprises lowstand system tracts, i.e., sediments formed during the sea-level fall and lowstand stages (e.g., Ercilla et al., 1994; Chiocci et al., 1997; Alonso and Ercilla, 2003; Lobo et al., 2008). Based on this, we suggest that the sedimentation was characterised by active and reduced periods of growth (Alonso and Ercilla, 2003) that mostly occurred during sea-level falls and lowstand stages, where the accommodation space was reduced and the hinterland sediment sources (rivers located off canyon heads, and coastal erosion) moved seawards (Fernández-Salas et al., 2003). During those periods of relative lower sea-level, sediment supply increased progressively in all the sedimentary environments on the distal margin and adjacent subbasins (Chiocci et al., 2003) favouring sedimentation (both along-slope and down-slope) regardless of the relative energy of bottom currents. The distance between the canyon heads and sediment sources decreased, favouring the funnelling of large amounts of sediment along the canyons and channels and, consequently, the main building of the turbidites systems. In contrast, reduced periods of growth mainly occurred during transgressions and highstand stages, when the sediment sources retreated landwards (Bernhardt et al., 2015), increasing the distance to the continental slope and canyon heads. This retreat caused the coarser sediment to become trapped in the nearshore environments (infralittoral wedges and prodeltas), while the fine-grained sediments escaped basinwards (Fernández-Salas et al., 2003; Fernández-Salas et al., 2007).

In addition, the rapid sedimentation rate of contourites favours both the low consolidation of the sediments and the slope over-steepening, factors that contribute increasing the shear stress and the risk of slope failures (Casas et al., 2015). The small mass-wasting deposits occurring along the distal escarpments of the growing contourite drifts generate elongated erosional surfaces (Alves, 2010). In this sense, three relevant modern examples stand out in the Alboran Basin: i) the partial dismantlement of the Ceuta drift along the eastern margin of the Ceuta Canyon (Ercilla et al., 2002); ii) the partial dismantlement of the T3 distal escarpment (Fig. 10D), and iii) the dismantlement of the plastered drift built attached to the Habibas High (Figs. 4A and 10D). The resulting narrow and elongated local unconformities, interfingered with hiatuses (Alves et al., 2011) ultimately provide reworked material to distal sedimentary systems (Mulder et al., 2013). In the case of the Alboran Basin, this partial dismantlement is favoured by the tectonic movements (Alonso et al., 2014) and possibly the halokinetic movements characterizing the WAB.

6. Conclusions

The detailed seismic analysis of the Pliocene (*Pl1* to *Pl3* units) and Quaternary (*Qt1* to *Qt4*) units of the Alboran Sea (SW Mediterranean) shows the precise temporal and spatial distributions of a wide variety of along-slope and down-slope features and deposits developed in different context and oceanographic conditions, revealing a complex sedimentary architecture. Our analysis allow building a sedimentary model on the long-term impacts of bottom-current circulations and related processes, that help to understand the stratigraphy and depositional architecture of other Mediterranean marginal seas at the basin scale.

The contourite features have allowed us to elucidate the past bottom currents dynamics as well as their relative energies, and active periods after the Atlantic mega-flood. An increase in the flow energy from the Pliocene to the Quaternary is decoded from the variations in the type of contourite drift (geometry, dimensions, location of escarpments, associated erosive features) and the progressive increase in reflectivity. Furthermore, the progressive increase in density contrast between the water masses, and the long-term occurrence of turbulent processes caused by internal waves as well as their displacement during sea level excursions could explain the widening and flattening of the terraces. The factors influencing the sediment transport by bottom currents comprise (i) the uplift of tectonic features (Alboran Ridge) that changed the basin configuration and favoured the formation of structural passages (Alboran Through, Al Hoceima Valley) dividing and accelerating the flow due to their sectional restriction, (ii) the local topography causing the development of current branches and filaments flowing along post-MSC topography and around seamounts, and (iii) the palaeoclimate and associated glacio-eustatic sea level variations, which were more relevant in the Quaternary and caused the displacement of water masses cores and interfaces, ultimately being responsible for the widening of the submarine terraces.

The turbidite systems also act as a proxy to deduct the evolution of the water masses over time. The scarcity of turbidite systems in the Morocco margin, which shows a similar tectonic context, climate forcing, drainage system and river discharge as the Spanish margin (both are the northern and southern counterparts of the Arc of Gibraltar), may be caused by the dispersal of the sediments by bottom currents. In addition, the Spanish margin shows a general recession in the number of turbidite systems since the Pliocene and a decrease in their sizes towards the late Quaternary, which also could be related to the enhanced water mass action on sediment transport and greater density contrasts since the onset of the Quaternary. Other factors have also influenced the development of turbidite systems over time include (i) the topography, among which the MSC subaereal channels that conditioned the location of most turbidite systems stands out, (ii) the variations in accommodation space (tectonics), which had a great influence in the Almeria turbidite system, and (iii) the sea level changes, which were of uttermost importance in the Quaternary favouring the alternance of active (low sea level, coarser sediment) vs. reduced (high sea level, fine-grained sediment) periods of growth.

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Declaration of competing interest

This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose. All authors have read and approved the final version of the manuscript.

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