

Chapter 6

Seafloor Morphology and Processes in the Alboran Sea



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6.1 Introduction

The Alboran Sea is one of the seas most widely studied by Spanish marine geologists. There are two main reasons: its structural framework and its oceanographic circulation. The Alboran Sea is interesting from a structural point of view because it is the site of collision between the Eurasian and African plates, and the basin is located within the framework of an orogenic process forming the surrounding Betic and Rif mountain belts. The westward displacement of the Alboran Domain (formerly the Alboran Microplate, Andrieux et al. 1971) between the two major plates

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has determined the development of the Arc of Gibraltar, within which the arc-shaped, semi-enclosed basin of the Alboran Sea is formed. The mentioned tectonic collision favours the development and activity of faults with associated crustal earthquakes. It has also contributed to the modelling of a highly irregular seafloor relief that reflects the complexity of the tectonic processes (Galindo-Zaldívar et al. 2018; Estrada et al. 2018). From an oceanographic point of view, the Alboran Sea is interesting because it is where the Mediterranean Waters (MWs) escaping toward the Atlantic Ocean encounter the Atlantic Water (AW) entering the Mediterranean Sea (e.g. Parrilla et al. 1986). This meeting of water masses produces a complex oceanography where the bottom layers of the Atlantic and Mediterranean water masses interact with the complex and irregular seafloor, conditioning the transport, sedimentation, and reworking of the near surface sediments, and forming sedimentary reliefs that increase the topographic complexity of the seafloor (Ercilla et al. 2016).

These geological and oceanographic characteristics of the Alboran Sea make this sea an ideal context in which to analyse the morphological features and sedimentary deposits, from shallow waters, where the continental shelf is generally poorly developed, to deep sea areas, dominated by a highly irregular topography. This contribution summarises the geomorphology of the Alboran Sea, based on recent, local and regional, interdisciplinary studies. After presenting the geological and oceanographic frameworks, we offer an up-to-date summary of the main

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morphological features and near surface sedimentary facies. Then, we look with attention to recent sediment dynamics and tectonic activity using geological and oceanographic approaches. In addition, we assess how the geomorphology of the Alboran Sea offers us clues to determine the main potential geological hazards, as well as how it can play an important role in the bionomy of the seafloor.

6.2 Setting

6.2.1 Geographical and Geological Settings

The Alboran Sea is the westernmost province of the Mediterranean Sea (Fig. 6.1). It is east-west oriented and occupies an area of about 54,000 km². It is 150 km wide and 350 km long, presenting a maximum depth of 2294 m. It is partly land-locked, bounded by the Strait of Gibraltar to the west. To the east, the Alboran Basin gives way to the Algero-Balear Basin.

The origin and present-day setting of the Alboran Sea are controversial due to the geological complexity of the region. It is a Neogene-Quaternary extensional basin located within the Betic (Spain) and Rif (Morocco) alpine cordilleras, connected by the Arc of Gibraltar (Andrieux et al. 1971) (Fig. 6.1b). The geodynamic evolution of the Alboran Basin, still under debate, is determined by the relative motion between Eurasia and Africa (Dewey et al. 1989). The westward displacement of the Betic-Rif orogen during the development of the Arc of Gibraltar has been accommodated by the major Trans-Alboran Shear zone (De Larouzière et al. 1988; Frasca et al. 2015). Faults and folds have formed in the framework of recent NNW-SSE shortening and regional Eurasian-African plate convergence (DeMets et al. 2015) (Fig. 6.1b). Seismicity in the Alboran Sea includes mostly shallow (<30 km depth), but also scarce intermediate (30–120 km depth), and a few deep (600–640 km depth) events (Buforn et al. 1991, 2011, 2017; www.ign.es) (Fig. 6.1b)

The shallow seismicity is characterised by low to moderate magnitude earthquakes (generally $M_w < 5$) and is heterogeneously distributed (www.ign.es; Buforn et al. 2004) (Fig. 6.1b). GPS research shows that the Alboran Sea is undergoing a heterogeneous ENE-WSW extension, increasing towards the Strait of Gibraltar, and an orthogonal NNW-SSE shortening as high as 3.3 mm/year in its central part (Fadil et al. 2006; Koulali et al. 2011; Palano et al. 2015; González-Castillo et al. 2015; Galindo-Zaldívar et al. 2015).

The sedimentation in the Alboran Sea is mostly siliciclastic, primarily from rivers, coastal erosion, and dust from the Sahara Desert (e.g. Moreno et al. 2002; Jiménez-Espejo et al. 2008; Lobo et al. 2015). The Spanish and Moroccan margins bordering the sea are quite similar from the point of view of sediment sources. Many fluvial catchments in the Mediterranean region are characterised by small- to medium-sized rivers and ephemeral streams with abrupt topographies, resulting from the proximity of the mountain ranges and the adjacent coast (Liquete et al. 2009); these erode the Betic Mountains (>3000 m high) and the Rif Mountains

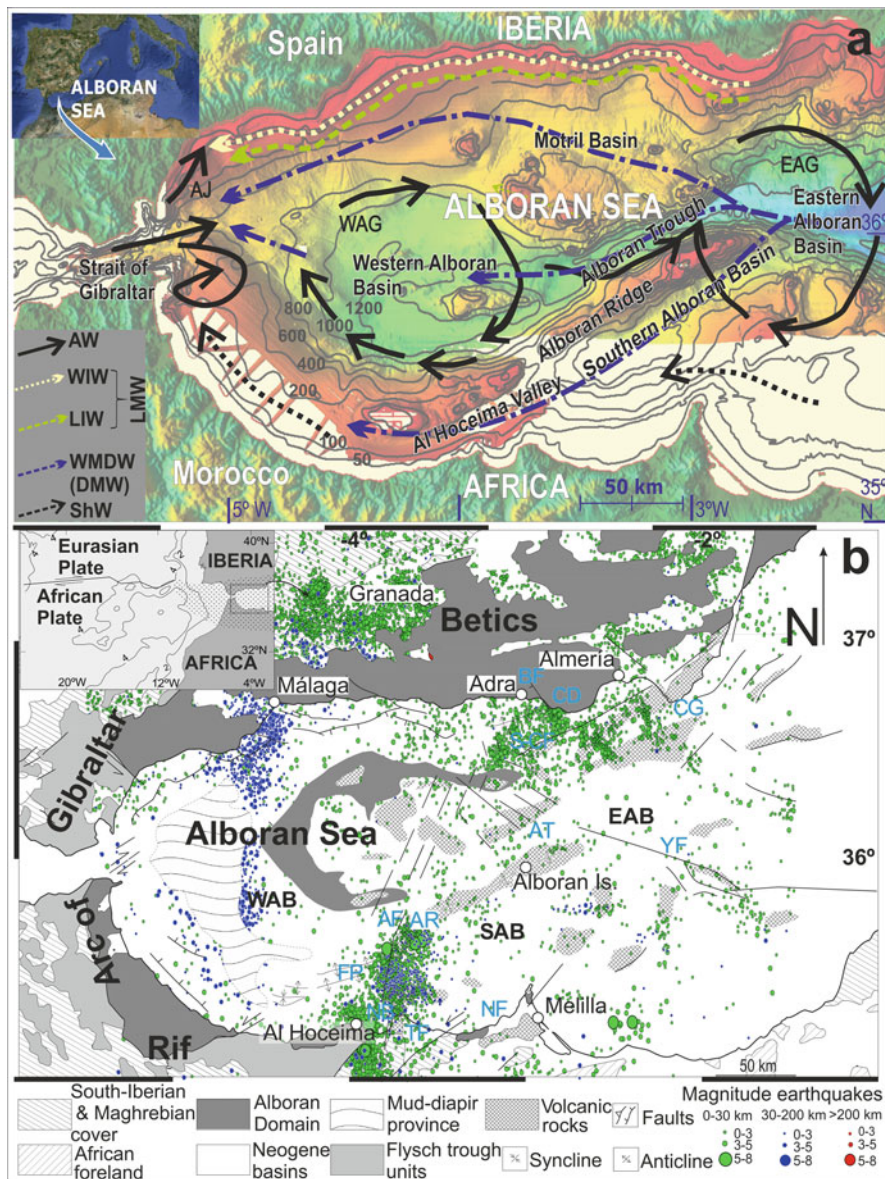


Fig. 6.1 Geographical and geological settings of the Alboran Sea. (a) Bathymetric map of the Alboran Sea with the present-day circulation model of the near-bottom water masses affecting the seafloor (modified from Ercilla et al. 2016). Legend: AW Atlantic water; WIW Western Intermediate Water; LIW Levantine Intermediate Water; LMW Light Mediterranean Water; WMDW Western Mediterranean Deep Water; DMW Dense Mediterranean Water; ShW Shelf Water; WAG Western Alboran Gyre; EAG Eastern Alboran Gyre; AJ Atlantic Jet. (b) Geological map including regional faults and seismicity. Plate boundaries in the Azores-Gibraltar area (modified from Galindo-Zaldívar et al. 2003) and geological sketch of the main structural features and basins of the Alboran Sea (modified from Comas et al. 1999) are shown. Legend: AF Al Idrisi Fault; AR Alboran Ridge; AT Alboran Through; BF Balanegra Fault; CD Campo de Dalías; CG Cabo de Gata; S-CF La

(>2000 m). Flood events in the larger rivers result in influential plumes of fine suspended sediments along both margins (Lobo et al. 2006). In contrast, the shorter rivers and streams remain dry for most of the year but have sporadic torrential regimes, discharging anything from gravels to silty sediments (El Moumni and Gensous 1992; Liquete et al. 2005; Lobo et al. 2006; Fernández-Salas et al. 2007). Most of the rivers flowing into the Alboran Sea display a seasonally contrasting pattern, with maximum water discharges in winter and very low discharges for the rest of the year (Stanley et al. 1975; Liquete et al. 2005; Lobo et al. 2006). In addition, water discharge is also very irregular on an inter-annual basis, with alternating dry and humid years.

6.2.2 Oceanographic Settings

Present-day circulation is largely influenced by the exchange of water through the Strait of Gibraltar, the AW flowing into the Alboran Sea and the MWs flowing out into the Atlantic Ocean (e.g. Parrilla et al. 1986). This exchange of water masses is conditioned by the high evaporation rates of the Mediterranean basin (exceeding precipitation and river runoff), which are compensated for by the inflow of the AW.

The AW flows at a maximum water depth of 150–200 m and describes two anticyclonic gyres (Chap. 4) (Fig. 6.1a). Water masses with a Mediterranean origin can be grouped by density (e.g. Millot 1987, 1999). Intermediate water comprises the Western Intermediate Water (WIW) flowing at a depth of 150–200 m in the western Mediterranean; the Levantine Intermediate Water (LIW), which forms in the western Mediterranean and flows towards the west between depths of 200–600 m; and the lightest part of the Tyrrhenian Deep Water (TDW), formed in the Tyrrhenian Sea and flowing below a depth of 500 m. The properties of this water mass vary from being similar to LIW to more like the Western Mediterranean Deep Water (WMDW). Deep water includes the TDW, the densest; and the WMDW, which fills the Alboran sub-basins at greater depths. On the western Moroccan slope, WMDM mixes locally and seasonally with AW, forming the Shelf Water flowing to the northwest (ShW, Gascard and Richez 1985) (Fig. 6.1a).

In the Alboran Sea, the intermediate Mediterranean water masses (WIW, LIW, and upper TDW) are less dense and saline, and are grouped into the Light Mediterranean Water (LMW) (Fig. 6.1a) (Ercilla et al. 2016). LMW circulates mainly along the Spanish margin. The deep Mediterranean water masses (lower TDW and WMDW) are denser and are grouped into the Dense Mediterranean Water (DMW) (Ercilla et al. 2016). DMW circulates along the Moroccan margin and in the deep basin and is forced upwards by the topography (Fig. 6.1a) (Parrilla et al. 1986).



Fig. 6.1 (continued) Serrata-Carboneras Fault; *DB* Djibouti Bank; *EAB* Eastern Alboran Basin; *FP* Francesc Pagès seamount; *NB* Nekor Basin; *NF* Nekor Fault; *SAB* Southern Alboran Basin; *TF* Trougout Fault; *WAB* Western Alboran Basin; *YF* Yusuf Fault; *Alboran Is.* Alboran Island

6.3 Method

6.3.1 Datasets

The geomorphological study of the Alboran Sea was conducted based on four main databases: (1) the *multibeam bathymetric database*, which consists of high-resolution swath bathymetry data acquired in different expeditions, gridded to a resolution of 25 and 50 m (Fig. 6.1a). The gaps in the bathymetric mosaic were completed with the regional bathymetry from the GEBCO Digital Atlas, resulting in a variable resolution mosaic; (2) the *seismic database* has been compiled in the framework of several Spanish and international research projects, most in collaboration with French and Moroccan institutions, as well as from commercial hydrocarbon exploration projects (<http://gma.icm.csic.es/sites/default/files/geoweb/OLsurveys/index.htm>). The database comprises single- and multi-channel seismic profiles with different degrees of resolution, extending to various depths and resolutions (>1250 profiles) (Fig. 6.2a). All the seismic profiles were integrated into a Kingdom Suite project (IHS Kingdom) for their accurate correlation and interpretation; (3) *sediment cores* recovered in various cruises (<http://gma.icm.csic.es/sites/default/files/geoweb/OLsurveys/samples.htm>) and aligned along seven N-S transects of the Alboran Basin (1–7 in Fig. 6.2b); five cross (transects 1–5) the Western Alboran Basin; one (transects 6) crosses the Motril Basin, Alboran Trough, and Southern Alboran Basin; and the last (transects 7) crosses the easternmost Alboran Trough and Southern Alboran Basin. The N-S transects enable the sedimentary facies to be defined and downslope and alongslope sedimentary processes to be compared; and (4) the *hydrographic database*, which comprises (Fig. 6.2c): (a) more than 3000 CTD (Conductivity, Temperature, and Depth) data points, downloaded from open-access sources (Medatlas II: <http://odv.awi.de/en/data/ocean/medatlasii/>); (Sea Data Net: <http://www.seadatanet.org>), allowing water mass characterisation; Acoustic Doppler Current Profiler (ADCP) data, that provides the module and direction of the different layers of the water column down to a water depth of 700 m.

6.3.2 Data Analysis

Three main types of analysis were carried out using different approaches and techniques: (1) geomorphological and sedimentary analysis combining the multibeam bathymetric mosaic and the seismic profiles; (2) sedimentological analysis of the sediment cores; and (3) descriptive hydrographic analysis. In the *geomorphological and sedimentary analysis* the features were defined based on their overall dimensions, morphology and geometry, along slope and downslope elongations, acoustic facies, and strata patterns; the *sedimentological analysis* consisted of a characterisation of the sedimentary facies, carried out based on grain-size distribution, carbonate content, presence of sedimentary structures, and sand fraction

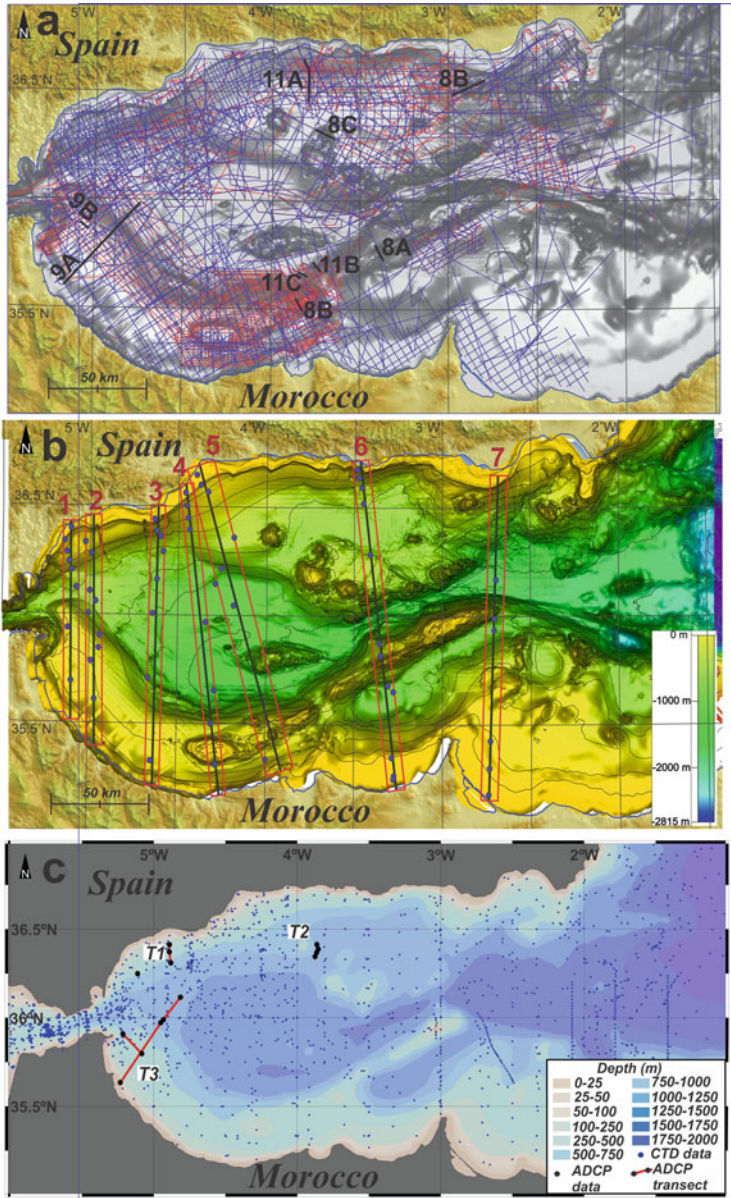


Fig. 6.2 Maps displaying the location of the different datasets used in this study. (a) Location map of single- and multi-channel seismic records with high to low resolution (lines in blue) and very high-resolution records (in red), from the ICM-CSIC database (<http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm>). (b) Transects displaying the location of the sediment cores displayed in Fig. 6.14. These cores are from the ICM-CSIC database (<http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/samples.htm>). (c) Location of the CTDs (Conductivity, Temperature, and Depth) from the Sea Data Net website (<http://www.seadatanet.org>) and ADCPs (Acoustic Doppler Current Profilers) analysed. T1–T3 point to the location of contouritic terraces mapped in the Alboran Sea. For more details see also Fig. 6.6b and explanation in the text

composition. Textural analysis was performed using settling-tube techniques for the coarse-grained fraction ($<50\mu\text{m}$) and Sedigraph 5000D techniques for the silt and clay fractions ($<50\mu\text{m}$). Total carbonate content was determined using a Bernard calcimeter. The sedimentary structures were examined based on digital images of the split cores. The sand fraction composition was examined using a binocular microscope. For the *hydrographic analysis*, the CTD dataset was analysed with the Ocean Data View (ODV) software using T/S diagrams, as well as N-S and E-W transect of the key properties of the water masses. In addition, the ADCP data (Ercilla et al. 2016) also allowed an analysis of the variation in the E and N components of the water flow with depth and the variation in the backscatter intensity of these components along the vessel track.

6.4 Physiography

Four physiographic domains have been defined in the Alboran Sea: continental shelf, continental slope, base of slope, and basins (Fig. 6.3a).

The continental shelf extends down to a depth of 90–115 m on the Iberian margin and 100–150 m on the North African margin. It is characterised by an abrupt outer limit, with the exception of the easternmost African shelf, which has a poorly defined ramp shape. The continental slopes of both margins are irregular: the Iberian margin ranges from 10 to 83 km wide, and the African margin is 10–105 km wide, extending to depths of up to 945 m in the west and 2294 m in the east (Fig. 6.3a). The continental slopes also have intraslope basins, including the Southern Alboran Basin (1180 m deep), and the Motril Basin (920 m deep). The other intraslope basins are the Al-Hoceima Valley (470 m deep), the Habibas Basin (928 m deep), and the Pytheas Basin (880 m deep) (Fig. 6.3a). The base of slope is defined in the Alboran Sea by an important decrease in slope gradients ($<2\text{--}0.8^\circ$). This province is locally defined on the western Iberian margin at water depths of between 600 and 945 m, and on the eastern Iberian margin at water depths of between 1400 and 1850 m. The basin domain comprises the Eastern Alboran Basin (2294 m deep); the Western Alboran Basin (1510 m deep); the northeast/southwest-oriented Alboran Trough (up to 1800 m deep); and the Yusuf Basin (up to 2340 m deep) (Fig. 6.3a).

6.5 Geomorphology

6.5.1 Shelf Features

Most of the observations on shelf geomorphology refer to the northern shelf of the Alboran Sea. However, recent studies have provided geomorphological descriptions of limited sectors of the southern shelf (e.g. Lafosse et al. 2018). The main

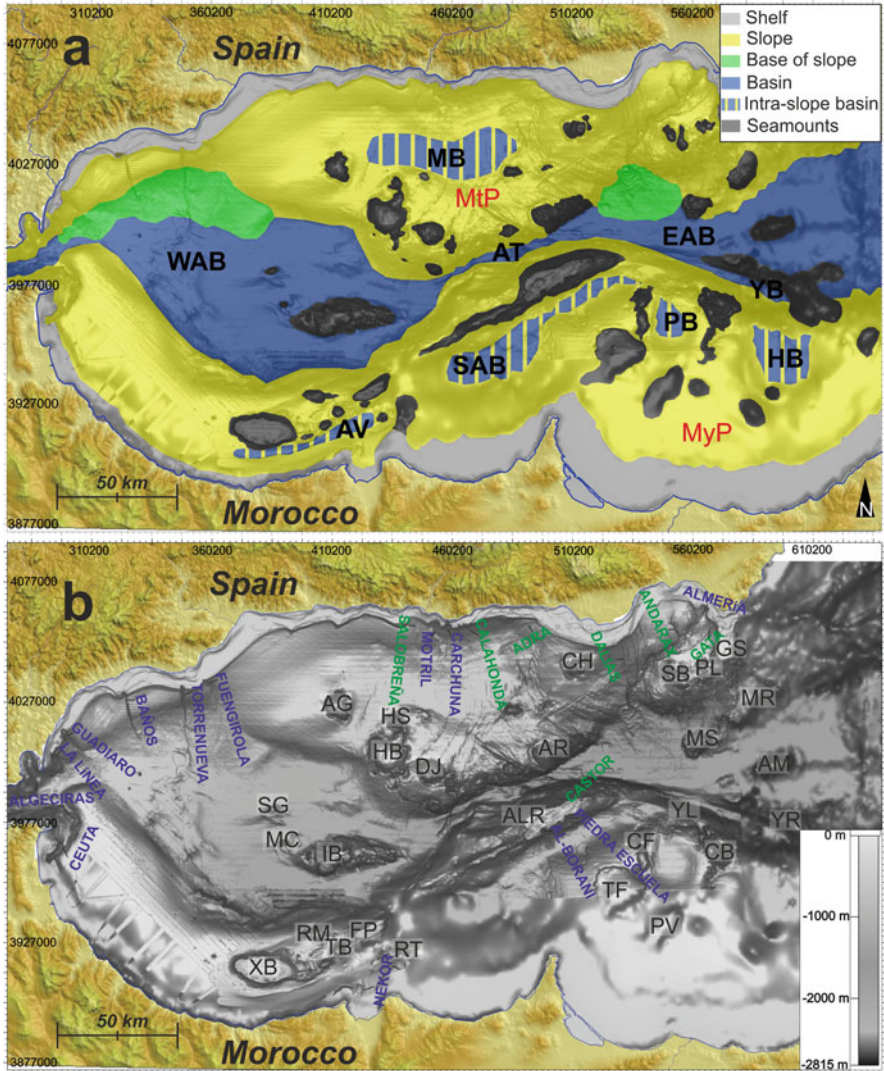


Fig. 6.3 Physiography of the Alboran Sea. (a) Map showing the shelf, slope, base of slope provinces on the Iberian and African continental margins, the basins (*AT* Alboran Trough; *EAB* Eastern Alboran Basin; *WAB* Western Alboran Basin; *YB* Yusuf Basin), the intraslope basins (*AV* Al-Hoceima Valley; *HB* Habibas Basin; *MB* Motril Basin; *PB* Pytheas Basin; *SAB* Southern Alboran Basin) and plateaus (*MiP* Motril Plateau; *MyP* Moulouya Plateau). Modified from Juan et al. (2016); and (b) bathymetric map showing submarine canyon (in blue) and gully (in green) systems, as well as the structural highs dotting the margins and basins. Legend: *AB* Alidade Bank; *AG* Algarrobo Bank; *ALR* Alboran Ridge; *AM* Al-Mansour High; *AR* Adra Ridge; *CB* Câbliers Bank; *CF* Catifas Bank; *CH* Chella Bank; *DJ* Djibouti Bank; *GS* Cabo de Gata Spur; *HB* Herradura Bank; *HE* Habibas Escarpment; *HS* Herradura Spur; *IB* Ibn-Batouta Bank; *MC* Maria del Carmen High; *MS* Maimonides Ridge; *MR* Maimonides Ridge; *PL* Pollux Bank; *PV* Provençaux Bank; *RT* Ras Tarf Ridge; *SB* El Sabinar Banks; *SG* Segoviano High; *TB* Tofiño Bank; *TF* Tres Forcas Cape Ridge; *XB* Xauen Bank; *YL* Yusuf Lineament; *YR* Yusuf Ridge

geomorphological types can be classified according to their genesis in depositional, erosive, gravitational, and anthropogenic origins (Bárcenas et al. 2016).

6.5.1.1 Depositional Features

The most important types are prodeltaic wedges and infralittoral prograding wedges (IPWs). Additionally, bedform fields at various scales have been documented in specific locations (Fig. 6.4).

Prodeltaic bodies are wedge-shaped morphologies with variable seaward extensions, depending on the dimensions of the parent drainage basins (Fig. 6.4a, b, c). They exhibit very narrow topsets (relatively flat proximal segments) bounded seawards by a shallow break of slope, close to the coast. Seawards, the seafloor gradient is higher in the foresets and becomes distally asymptotic in the bottomsets. These geomorphological boundaries are controlled by the wave base levels associated to medium and high-energy conditions (Bárcenas et al. 2015). Overall, the vast majority of cross-sectional geometries are concave-upward (Fig. 6.4c, d). In plain view, these dominant geometries mostly produce lobate and elongate patterns (Bárcenas et al. 2015). The seismic facies of prodeltaic bodies are mainly stratified with progradational and aggradational patterns. The progradational pattern is characterised by an oblique-sigmoidal configuration and varies from perpendicular to oblique to parallel with respect to the shoreline (Lobo et al. 2014). Most of the prodeltaic wedges of the Alboran Sea exhibit superimposed seafloor undulations over the foresets and bottomsets (Fig. 6.4a, b, c, d). The undulations can be up to a few metres high and the wavelengths range between tens and hundreds of metres (Bárcenas et al. 2009; Lafosse et al. 2018). These undulations are generally regarded as sediment waves (Fernández-Salas et al. 2007).

Infralittoral prograding wedges (IPWs) are narrow (i.e. a few kilometres wide) wedge-shaped clinoform bodies which have been mapped in the inner shelf stretches of the Iberian margin (Fig. 6.4c, e). A well-marked break of slope occurs at water depths of about 20–25 m; seawards, a steep slope of greater than 2° extends to water depths of up to 60 m (Hernández-Molina et al. 2000). The characteristic slope break may be relatively linear and continuous or instead be composed of arcuate, discontinuous segments (Fernández-Salas et al. 2009). These wedges have been recognised in several sectors, but the most important bodies occur off Carchuna-Calahonda, Campo de Dalías, and Gata Cape (Hernández-Molina et al. 2000; Fernández-Salas et al. 2009). In some particular cases, such as off the Adra River the infralittoral wedges develop laterally from the main deltaic protuberances, representing the morphological response of an evolving deltaic system (Jabaloy-Sánchez et al. 2010) (Fig. 6.4c). In the Carchuna-Calahonda shelf area (Iberian shelf) and the Nekor Basin shelf (African shelf), marine-built terraces observed at different water depths from the outer to the inner shelf, are regarded as the morphological expression of IPWs (Martínez-Martos et al. 2016; Lafosse et al. 2018).

Fields of large-scale bedforms such as elongated bars and ridges have been described in specific outer shelf settings of the Iberian shelf (Lobo et al. 2006;

of Gibraltar and around the Carchuna Canyon (e.g. the Motril Canyon head) (Alonso and Ercilla 2003; Vázquez et al. 2015a).

Small-scale submarine valleys comprise *prodeltaic channels and/or gullies*, documented in a few prodeltaic deposits along the Iberian shelf (Bárcenas et al. 2016), as well as a *prodeltaic deposit* located in Al-Hoceima Bay, on the African shelf (Lafosse et al. 2018) (Fig. 6.5a, c, d). The gullies are straight and very shallowly incised (Bárcenas et al. 2016). They initiate over the prodeltaic topsets and generally extend over the foresets (Bárcenas et al. 2016; Lafosse et al. 2018), although they may be restricted to the outer shelf, as occurred in the case of the Guadalfeo River prodelta (Lobo et al. 2006).

Wave-cut terraces are represented by abrupt escarpments with high lateral continuity. They are particularly frequent on the westernmost shelf of the northern margin at various bathymetric levels (Hernández-Molina et al. 1996).

6.5.1.3 Gravitational Features

These are mostly represented by scarce shallow-water *slides*, occurring at water depths of more than 60 m (Bárcenas et al. 2016). The slides range from 38 to 1000 m long and 56 to 629 m wide (Fig. 6.5a, e).

6.5.1.4 Anthropogenic Features

These include spherical mounds and straight lineations, usually found in proximity to harbours due to dredge activities (Bárcenas et al. 2016) (Fig. 6.5a, f). Mounds with reliefs of between 25 and 50 m are around 80 m long and up to 100 m wide. The lineations that have been mapped between water depths of 25 and 47 m, are 420–850 m long and have average widths of 20 m.

6.5.2 Deep-Sea Features

These include features of varying genesis that may be grouped as tectonic, seamount, fluid-flow, contourite, mass-movement, and biogenic features (Figs. 6.6 and 6.7).

6.5.2.1 Tectonic Features

The main tectonic structures influencing the seafloor morphology are folds and faults. These affect mainly the central and eastern seafloor of the Alboran Sea (Fig. 6.7).

Folds have a dominant ENE-WSW strike and are up to several kilometres in length, with the most representative being the Alboran Ridge, Francesc Pagès and

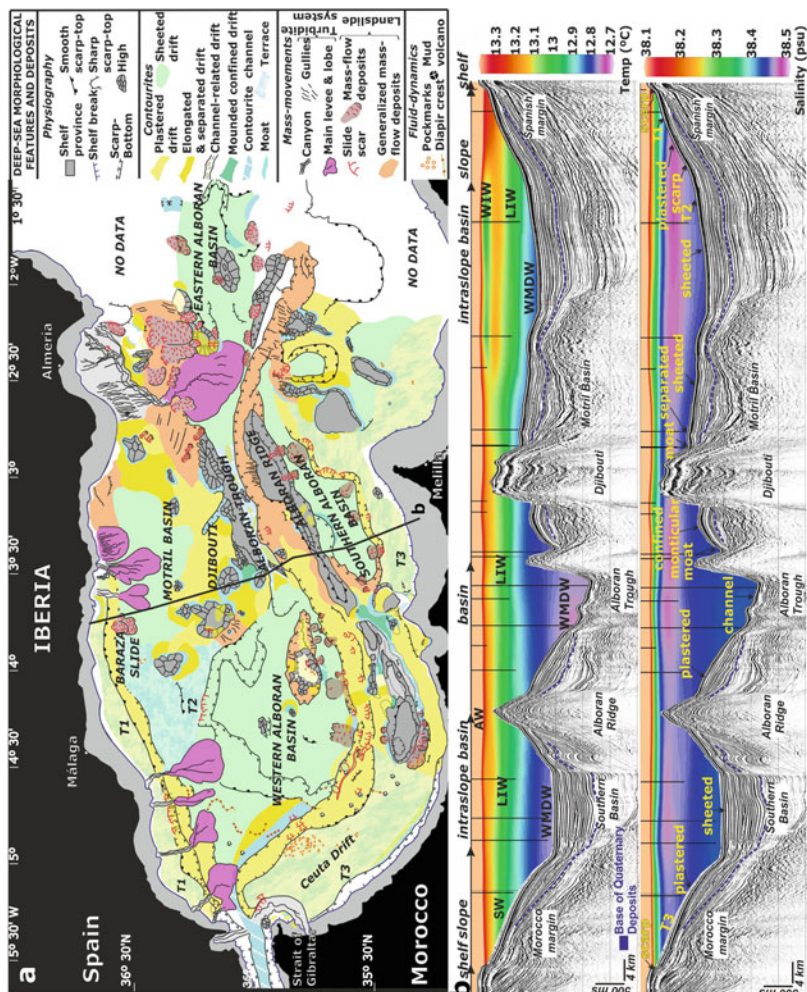


Fig. 6.6 Deep-sea geomorphology and seismic and oceanographic architectures of the Alboran Sea. **(a)** Deep-sea morphological features and deposits mapped from the shelf-break down to the deep-sea areas of the Alboran Sea. Legend: T1–T3 refer to the location of contouritic terraces. **(b)** N–S seismic–hydrographic section crossing the continental margins and some basins (location in **a**). Note the correlation between the water mass interfaces [AW, WIW+LIW (i.e. LMW), WMDW (i.e. DMW)] and the main physiographic domains. Contourite features are indicated on the seismic profile (letters in yellow). Colour-coding: temperature (°C) and salinity (psu, practical salinity units). Black vertical lines within the water column show the vertical and horizontal distribution of CTDs. Legend of water mass names in Fig. 6.1a. Modified from Ercilla et al. (2016)

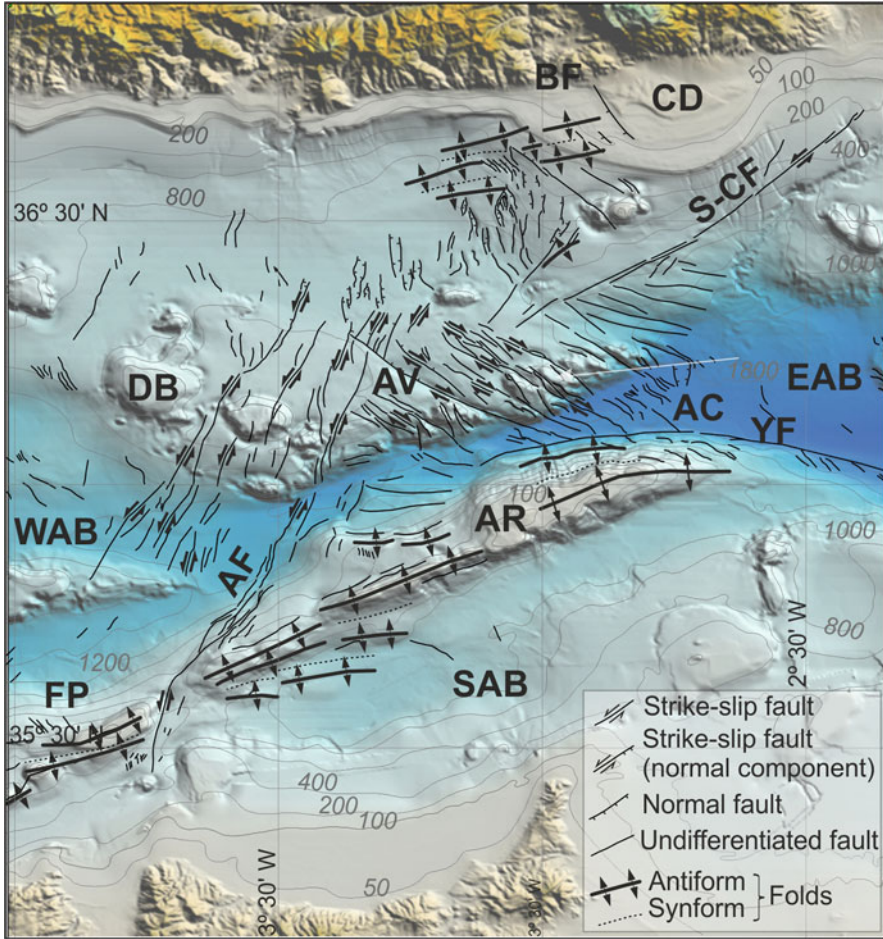


Fig. 6.7 Map showing the main tectonic features (faults and folds), formed in the framework of recent NNW-SSE shortening and regional Eurasian-African plate convergence. Legend: *AF* Al Idrisi Fault; *AR* Alboran Ridge; *AV* Averroes Fault; *BF* Balanegra Fault; *CD* Campo de Dalías; *S-CF* La Serrata-Carboneras Fault; *DB* Djibouti Bank; *EAB* East Alboran Basin; *FP* Francese Pagès seamount; *SAB* South Alboran Basin; *YF* Yusuf Fault

Xauen seamounts, which are three aligned antiforms (Bourgeois et al. 1992; Martínez-García et al. 2011, 2013; Estrada et al. 2018), and the Campo de Dalías folds (Pedrera et al. 2015) (Figs. 6.7 and 6.8a, b). These last folds form three smooth, elongate elevations (N50-60), located to the W of Chella Bank, which are 15–20 km long and 30–80 m high (Vázquez et al. 2016). They are interpreted as anticlines associated with blind thrusts affecting the recent sediments.

Faults are grouped into two main sets of N25° E sinistral and N130° E dextral kinematics (Fig. 6.7). Fault traces are evidenced in the seafloor by different features

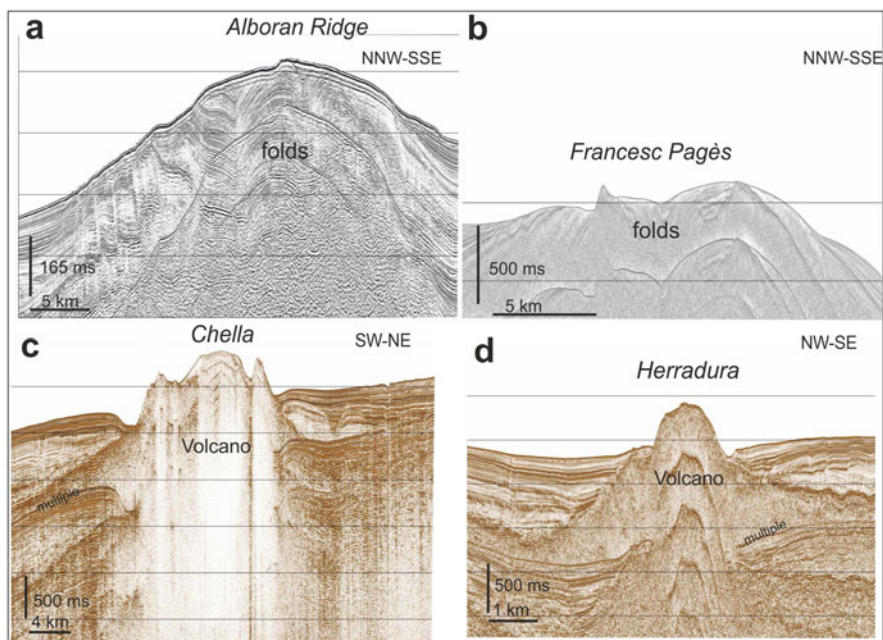


Fig. 6.8 Seamounts in the Alboran Sea. Seismic profiles showing two different types of seamounts: the Alboran Ridge (a) and Francesc Pagès Seamount (b) related to structural folds; and the Chella or Seco de los Olivos (c) and La Herradura (d) volcanic seamounts. Location of profiles in Fig. 6.2a

as scarps, ridges, depressions, and lineations (Vázquez et al. 2014). The N25° E set is mainly located to the NW and W of the Alboran Ridge, comprising a fault zone that is 25 km wide and more than 120 km long. The most significant fault in this set is the Al Idrisi Fault, which has a straight seafloor trace, including continuous segments, more than 38 km long (Martínez-García et al. 2013; d'Acremont et al. 2014). This fault displaces the boundary between the Alboran Ridge and Francesc Pagès seamounts (Figs. 6.1b and 6.7). In the northern margin, the activity of the N25° E faults produces on seafloor marked scarps and sets of longitudinal and rhombic depressions (Vázquez et al. 2018). The N130° E set is mainly located to the N and NE of the Alboran Ridge, in a zone more than 60 km wide. The main structure of this set is the Yusuf Fault, which has a straight trace up to 120 km long (Figs. 6.1b and 6.7). The Averroes Fault is another significant structure in this set, and its trace can be mapped on the seafloor as a straight scarp and related longitudinal depression. Its morphology shows evidence of vertical displacements related to dextral strike-slip at the NW fault edge (Vázquez et al. 2016; Estrada et al. 2018). Several related faults and scarps with similar directions occur on the seafloor to the east of Averroes Fault (Pedrera et al. 2015; Estrada et al. 2018). Moreover, other normal faults trending between N130° E and N170° E have been recognised, mainly west of Campo de

Dalías (longitudes between -3° and -3.5°), with the Balanegra Fault being one of the most significant, and which determine the location of the coastline (Galindo-Zaldívar et al. 2013) (Figs. 6.1b and 6.7). The sinistral Serrata-Carboneras Fault has been identified south of Campo de Dalías, and its straight trace is characterized by push-up ridges and sharp scarps on the seafloor (Vázquez et al. 2016). This sinistral fault extends 80 km offshore towards Cape Gata (Figs. 6.1b and 6.7) and is one of the main faults affecting the northeastern Alboran Sea although its present-day activity is still under discussion (Moreno et al. 2016; Estrada et al. 2018).

6.5.2.2 Seamounts

The Alboran Sea is characterised by the presence of several highs scattered along the continental margin and basins (Figs. 6.3b and 6.6) (Würtz and Rovere 2015). They have different origins and sizes related to the complex geodynamic evolution of the Alboran Sea (e.g. Palomino et al. 2015; Vázquez et al. 2015b). Seamounts mostly consist of a series of folds of Miocene to Quaternary units (almost all represented by the Xauen Bank, Frances Pagès Seamount, and the Alboran Ridge) and/or volcanic bodies (e.g. Ammar et al. 2007; Martínez-García et al. 2013; Vázquez et al. 2015b; Estrada et al. 2018; Galindo-Zaldívar et al. 2018) (Fig. 6.8). They are hundreds of metres high (400–1750 m), with the Alboran Ridge—located in the central sector—being the major elevation that emerges locally, forming Alboran Island and crossing the Alboran Sea obliquely with a NE-SW trend (Figs. 6.3b and 6.6a). The top of the seamounts is relatively flat (in most of the shallowest ones, <300 m water depth) and subrounded, and they usually present folded layers, structural ridges, and biogenic features that favour the settling of benthic species associated with hard bottoms, like cold water corals (Palomino et al. 2011). Indeed, these highs comprise heterogeneous habitat types and are considered hotspots for biodiversity. The seamount walls have high-gradient slopes shaped by downslope features, like turbidite systems and landslides (Fig. 6.6a). At their feet, seamounts are also characterised by along slope features, such as contourite drifts and moats (Fig. 6.6).

6.5.2.3 Features Related to Fluid Outflow

Various fluid outflow related features in the Alboran Sea, including mud diapirs, mud volcanoes, pockmarks, and authigenic carbonates, have been mapped in the Alboran Sea (Figs. 6.6a and 6.9) (e.g. Pérez-Belzuz et al. 1997; Somoza et al. 2012; León et al. 2014; Palomino et al. 2016) mostly piercing contourite deposits. They occur mainly in the western part of the Alboran Basin, mostly affecting the Ceuta contourite Drift.

Diapirs are dome-shaped features that rupture the overlying mobile sediments, which in the Alboran Sea are muddy in nature (Fig. 6.9a). Diapirs are mainly located in the Western Alboran Basin (Pérez-Belzuz et al. 1997). Although most diapirs are buried below the Pliocene-Quaternary sediments, a few produce a morphological

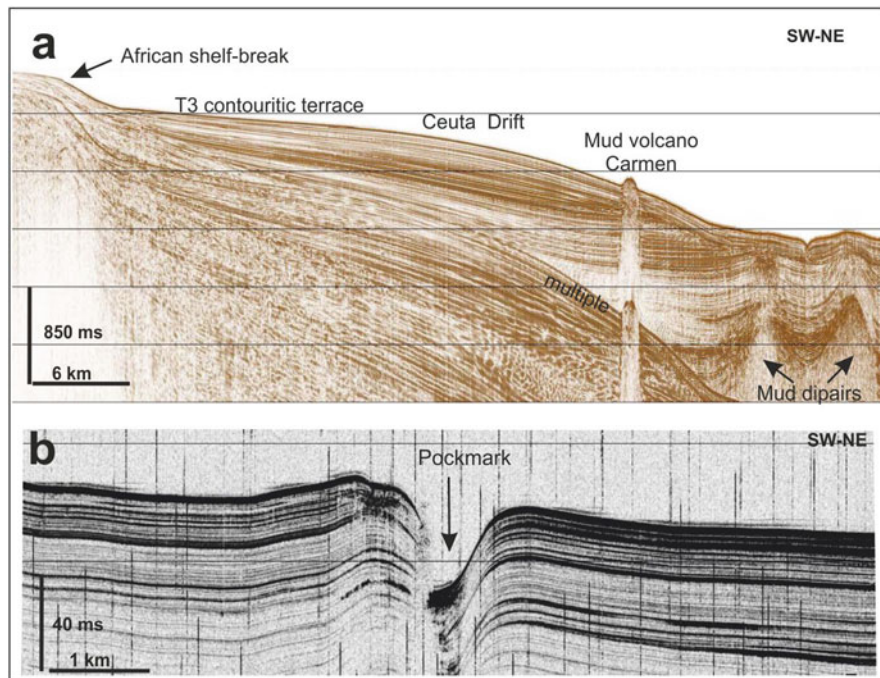


Fig. 6.9 Fluid-dynamic features in the Alboran Sea. (a) Seismic profile showing sub-bottom mud diapirs piercing and deforming the recent sediments of the Ceuta contourite Drift in the western Moroccan continental slope. Mud is forced to move upwards due to overpressures in the subsoil units. Also, the Carmen mud volcano piercing seafloor is shown. (b) Seismic profile showing the cross-section of a pockmark. Location of profiles in Fig. 6.2a

expression on the surface, forming relatively small seamounts tens of metres high (Pérez-Belzuz et al. 1997).

Mud volcanoes can be defined as conical edifices built up by mud sediments and fluids expelled from a deep source layer as the result of degassing processes (Kopf 2002). In recent decades, ten mud volcanoes have been documented in the Western Alboran Basin (Fig. 6.9a) (e.g. Somoza et al. 2012; Kenyon et al. 2000). They present different heights varying from 30 m (Mulhacen volcano) to 185 m (Granada volcano), and diameters of up to 1635 m (Dhaka volcano) (Somoza et al. 2012). It has been documented that some of these volcanoes could be active, or have had recent activity, as methane gas bubbling in the water column and evidence of chemosymbiotic fauna have been observed (Blinova et al. 2011; Hilário et al. 2011).

Two *pockmark fields* have been reported in the Ceuta Drift, and another field has been described in the vicinity of the Avempace Seamount, also on a contourite drift deposit (Palomino et al. 2011; Somoza et al. 2012) (Fig. 6.6a). Pockmark craters form abruptly, when pockets of local overpressured porewater and gas erupt through the seafloor surface sediments (Cathles et al. 2010). Pockmarks in the Alboran Sea

occur as circular and oval depressions on the seafloor, mostly as isolated features, and they vary in size from 50 to more than 500 m in diameter, with a few tens of metres of relief (Fig. 6.9b). The presence of these pockmarks has been attributed to fluid seepage and interstitial fluids from the underlying sediments that in the Ceuta Drift have been detected near the surface sediments (Mathys et al. 2005).

Other seepage fluid flow features, such as hydrocarbon-derived *authigenic carbonate crusts and chimneys* have been identified and sampled in the pockmark field of the Ceuta Drift (Blinova et al. 2011), also pointing to seepage flow emissions as these are necessary for their formation.

6.5.2.4 Contourite Features

The term contourites refers to those deposits formed by the action of alongslope bottom currents, including wind-driven, thermohaline, geostrophic, contour, boundary, and abyssal currents (Rebesco et al. 2014). A wide spectrum of depositional (drifts and sediment waves), erosional (moats, channels, and scarps), and mixed (terraces) contourite features have been characterised from the shelf-break (>90 m water depth) to the basin (Ercilla et al. 2002, 2016; Palomino et al. 2011; Juan et al. 2016) (Fig. 6.6). The drifts differ in magnitude: the largest appear along the slopes, the base of slope, and basin domains. Plastered and sheeted drifts are the dominant largest (a few hundreds of km long, a few to tens of km wide, and tens to a few hundreds of m of relief) type of drifts. The Iberian and Moroccan slopes are mainly characterised by *plastered drifts*. *Sheeted drifts* contribute to shaping the base of the slope and infill the basin irregularities generating a roughly flat and smooth seafloor. With respect to the small-scale drifts (a few to tens of km long and wide and a few hundreds of metres high) they are dispersed throughout the Alboran Sea, particularly around the different seamounts of the northern margin, the Alboran Ridge and highs, in the narrow passages formed by the steep structural walls, within the Alboran Trough and in the Al-Hoceima Valley. In addition to small-scale plastered and sheeted drifts, another type of minor-scale drift includes *channel-related drifts*, *mounded confined drifts*, and *mounded, elongate and separated drifts*. All drifts show similar seismic facies and are defined by stacked layered deposits with regional erosive unconformities. In cross-sections their stacking defines aggradational mounds with upslope-and-downslope prograding clinofolds for the plastered, elongated, separated, an onlap-infilling pattern with subparallel, parallel and deformed strata for the sheeted drifts, and aggrading mounds with subparallel strata for the confined drifts and channel-related drifts (Fig. 6.6b). With respect to the *sediment waves*, they have been locally mapped at the main entrance of the Strait of Gibraltar. They comprise 3D sediment waves mostly characterized as sand waves (metric in relief, and few to tens of metres in length) (Heezen and Johnson 1969; Kelling and Stanley 1972).

Erosive contourite features are also dispersed along the margins and basins (Fig. 6.6). The *moats*, which have U-shaped cross-sections of tens of m of relief, are mainly mapped associated to the separated and confined drifts. Their dimensions

vary between hundreds of m and a few km in length and <6 km in width. *Contourite channels* are represented by the U-shaped structural corridors of Al-Hoceima Valley, formed between the aligned Xauen Bank and Frances Pagès seamounts and the Moroccan margin, and of the Alboran Trough, which could be considered a deep-gateway connecting the east and west basins. They are a few km wide and up to tens of km long. The *scarps* represent the along slope boundaries of terraces. They are narrow (<16 km wide) and steep (2°–11°) escarpments, hundreds of km long, which play a major role in shaping the transition between the physiographic provinces, the shelf-break-upper slope being the most proximal, and the transition from the Iberian slope to the base of slope and the West African slope to the basins, the most distal (Fig. 6.6b). Erosive contouritic features are generally easily recognisable due to the truncation of the underlying deposits, hyperbolic, and prolonged facies with high acoustic reflectivity.

On top of the large slope plastered drifts and sheeted drifts, *contourite mixed terraces* extend, producing flat areas <30 km wide on the Iberian and African slopes, where the truncation of reflectors against the seafloor is easily recognisable in the proximal sectors. Three terraces have been mapped, T1 and T2 on the Spanish margin and T3 on the Moroccan margin (Figs. 6.6 and 6.9a).

6.5.2.5 Mass-Movement Features

The term ‘mass-movement’ used here refers to a general term by Locat and Lee (2000) that defines sediment movement driven by gravity rather than by interstitial fluid motion and comprises a great variety of sedimentary instabilities, from slides to turbidity currents. The main evidence for mapping recent features resulting from mass-movements in the Alboran Sea is the following: the disappearance of deposits, deformation and/or loss of the sedimentary structure, and associations of genetically related features. Based on these criteria three main sedimentary systems comprise these mass-movement features: turbidite systems, lone valleys, and landslides (Fig. 6.6a).

Turbidite systems are one of the most significant clastic accumulations in deep-sea areas of the margins and adjacent basins (Normark et al. 1993). Turbidite systems are formed by various architectural elements, including canyons, main and distributary channels, overbanks/levees, and lobes (Mutti and Normark 1991). In the Alboran Sea, these systems interrupt the lateral continuity of contourites and have only been mapped on the Spanish margin and Alboran Ridge (Fig. 6.6a). Eleven turbidite systems have been defined, with variable dimensions (length/width: 7.7×7 km to 123×25 km), exhibiting two main types of sedimentary models: submarine fans (La Linea, Guadiaro, Baños, Torrenueva, Fuengirola, Sacratif, Almería on the Iberian margin; Al-Borani and Piedra Escuela on the southern face of the Alboran Ridge), and submarine ramps Salobreña and Calahonda) types on the Iberian margin (Fig. 6.10). The submarine fan model comprises a U- or V-shaped feeder canyon, generally with axial incisions at the base (i.e. talwegs), that crosses the continental slope and evolves into a main, leveed

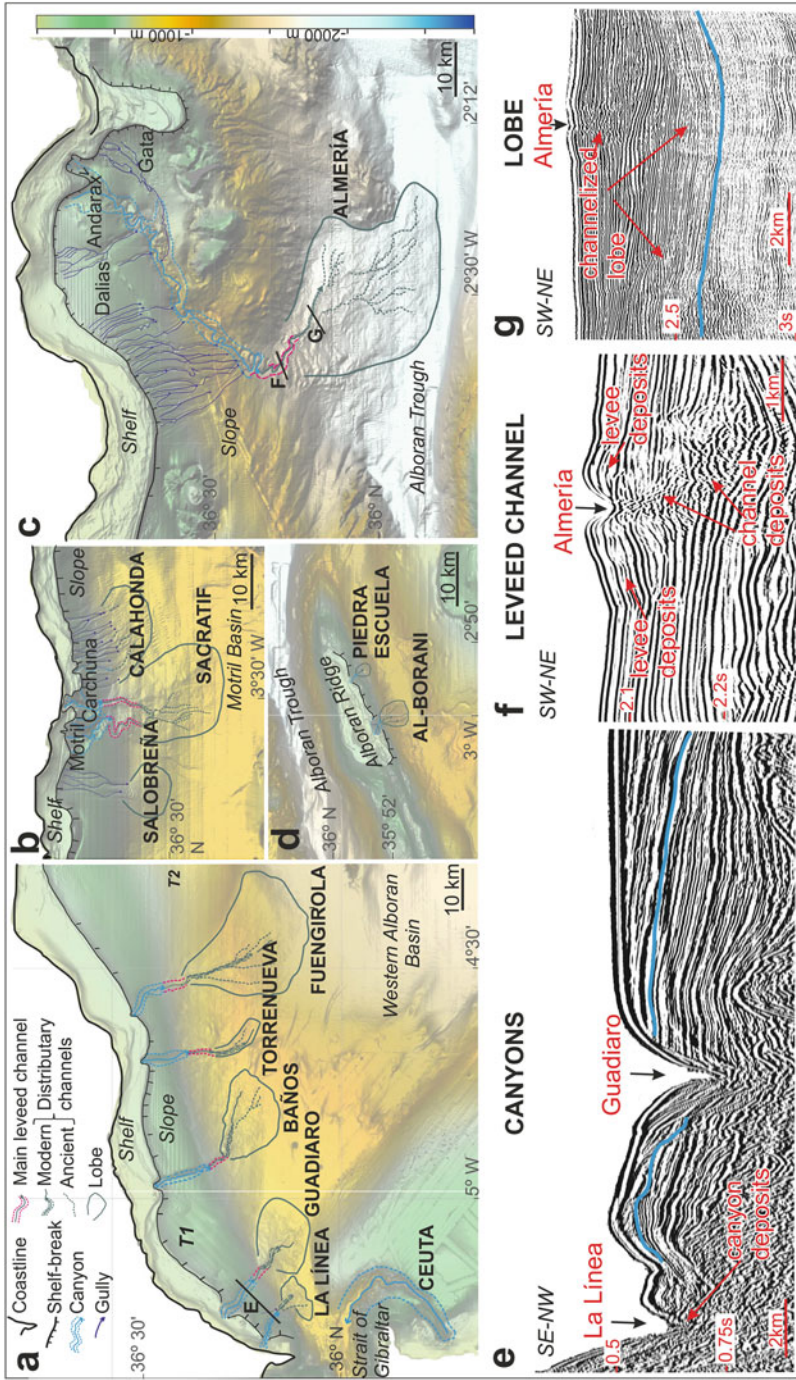


Fig. 6.10 Turbidite systems in the Alboran Sea. (a)–(d) Multibeam bathymetry showing the architecture of the turbidite systems on the present-day seafloor of the Alboran Sea. (a) La Línea, Guadiaro, Baños, Torrenueva, and Fuengirola in the western sector of the Iberian Margin. (b) Salobreña, Sagratif, and Calahonda in the central sector. (c) Almeria in the eastern sector. (d) Piedra Escuela on the southern flank of the Alboran Ridge. (e)–(g) Single-channel seismic records showing the main acoustic facies that characterise the architectural elements (canyon, leveed channel, and lobe) of the turbidite systems. The blue seismic boundary refers to the base of the Quaternary deposits. Modified from Ercilla et al. (2019)

channel on the lower slope that mouths directly into a channelised lobe at the base of slope and basin. The submarine ramp model comprises a feeder system with gullies linked down-dip to amalgamated lobe deposits. Seismic facies analysis of turbidite systems involves complex patterns of chaotic and discontinuous stratified facies with different configurations (prograding-, divergent-, and mounded-fill) for the canyons and channels and vertical stacking of asymmetric and roughly symmetric mound bodies of stratified facies that stand out from the seafloor. The architecture and dimensions of these systems suggest their sedimentary model ranges mostly from sandy to mixed sand-mud fans, and they describe a continuum between both end-member types from west to east.

The *lone valleys* are characterized by the lack of channel leveed and lobe deposits at their mouths and because of that they are considered separately from the turbidite systems. The valleys mapped comprise (Fig. 6.3b): the 10 km long Adra Channel, eroding the uppermost continental slope of the western Iberian margin; the Castor Canyon and gullies on the northeastern side of the Alboran Ridge; and the Ceuta and Nekor canyons, on the African margin. The Ceuta Canyon is 25 km long and widens down the valley (from 4 to 6 km); it has a curved pathway and mouths onto the entrance of the Strait of Gibraltar. The Nekor Canyon is 3 km long and 1.3 km wide, with a rectilinear pathway that extends down to a water depth of 300 m. Seismic facies analysis shows valleys eroding contourite deposits, generally presenting truncated, stratified, and prograding facies on the canyon margins, and chaotic deposits on the canyon floors.

Isolated *landslide* scars as well as landslide scars with associated mass-transport deposits have been mapped on both the Iberian and African continental slopes, in addition to the steep walls of some seamounts (Figs. 6.6a and 6.11). Landslide scars delineate the headscarp of the failed area, and form a relatively steep scarp (a few to tens of km long, with tens of metres of relief) facing seaward, with concave and amphitheatre shapes (Figs. 6.6a and 6.11). These slide scars are associated, in attached and detached forms (Fig. 6.11a, b), to lobate bodies, from around 5 km to <10 km in length and tens of metres in thickness, with chaotic and transparent sediments producing a wavy and irregular seafloor area, which varies roughly in the area from 5 to >100 km². Baraza (110 km²) on the Iberian slope (Figs. 6.6a and 6.11a), and the Montera slide (90 km²) in the SAB, are some of the largest landslides affecting the upper Quaternary deposits (Casas et al. 2011; Vázquez et al. 2013; Rodríguez et al. 2017). The Alboran Ridge, Francesc-Pagès Seamount, Djibouti, Pollux and Sabinar Banks, and Maimonides and Adra Ridges are some of the seamounts whose recent sedimentary record, on their walls and in the surrounding areas, are characterised by the vertical stacking of numerous landslides (Figs. 6.6a and 6.11c) (e.g. Palomino et al. 2009; Alonso et al. 2014; Galindo-Zaldívar et al. 2018).

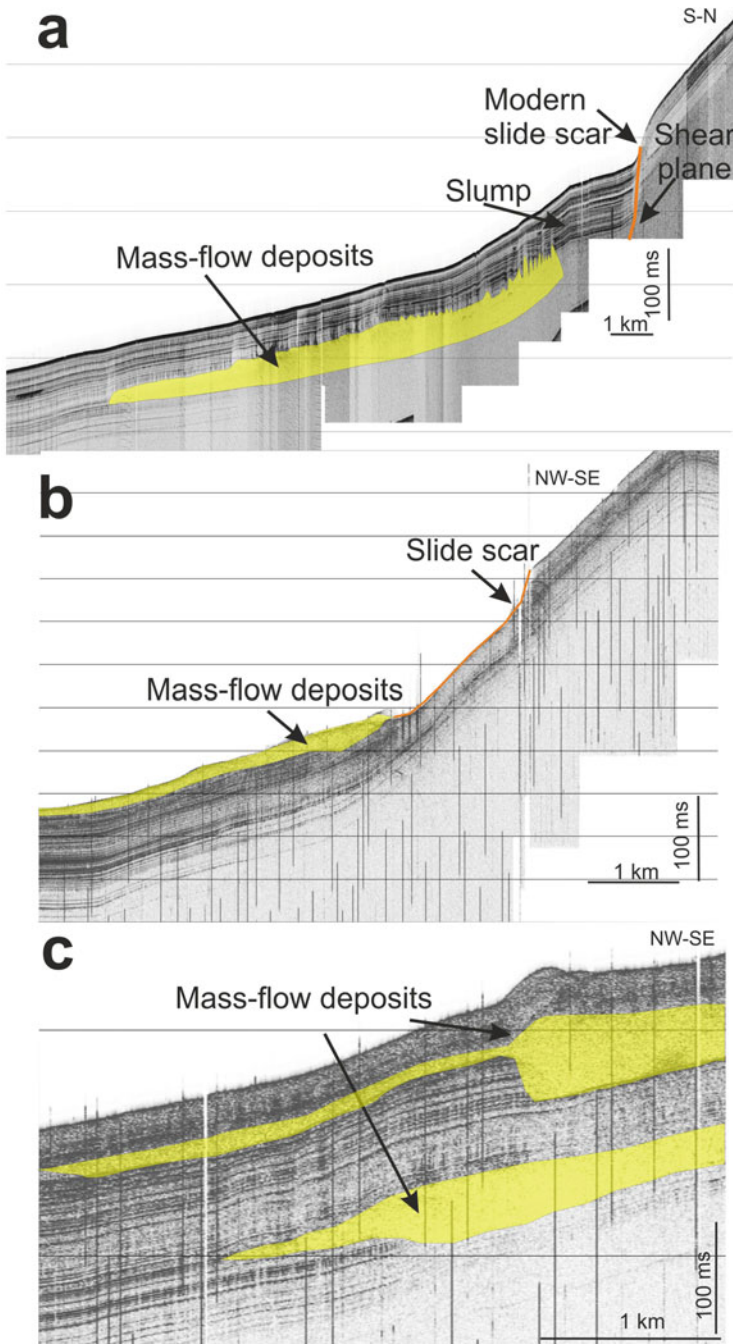


Fig. 6.11 Landslides in the Alboran Sea. Very high-resolution seismic profiles displaying: (a) the Baraza slide and (b) the mass-flow deposits mapped on the Francesc-Pagès Seamount and (c) on the Southern Alboran Basin. Note: The Baraza slide comprises two types of mass-movements—mass-flow type changing to slump type. Location of profiles in Fig. 6.2a. Modified from Casas et al. (2011) and Galindo-Zaldívar et al. (2018)

6.5.2.6 Biogenic Features

Potential clustered carbonate mounds (CM) have been recently reported along the continental slope of the northern and southern Alboran Sea (Fig. 6.12). Three different CM fields with still-undetermined biological activity, are located at similar water depths, on the contouritic terrace of the upper continental slope of the Iberian Alboran Sea (Ballesteros et al. 2008; Sánchez-Guillamón et al. 2018). The Alcantara mounds (Western field) are located at depths of between 250 and 282 m off Estepona (Málaga) (Fig. 6.12b, e), while the Málaga mounds (Central field) (Fig. 6.12c, f), are located between 220 and 282 m off Málaga city. The Aceitunas mounds (Eastern field), are located between 142 and 300 m off El Ejido (Almería) and close to Chella Bank (Fig. 6.12d, g). A total of 150 mounds have been identified in the three fields that range from 2 to 17 m in height, with maximum lengths of 130 m and slopes of between 2° and 18°. Generally, they are circular or NW-SE to N-S elongated, presenting skewed and scalloped distributions. Some have contouritic moats surrounding their basal areas and contourite deposits appear as plastered drifts overlapping and burying the mound flanks (Ercilla et al. 2016).

Two different CM fields also occur in the African Alboran Sea: the West and East Melilla Provinces (WMP and EMP) (Fig. 6.12a). The fields are interpreted as being cold-coral water mounds (Lo Iacono et al. 2014). The WMP is located on the western upper slope sector of the southern Alboran Sea off Cape Tres Forcas, within a water depth range between 130 and 620 m. This field comprises two clusters with a total of 103 mounds, within a depth range of 298–590 m. The main cluster is located between 299 and 420 m water depth, while the second, smaller cluster is located between 347 and 430 m water depth, in the eastern portion of the WMP. The mounds are from 1 to 48 m high, with an average height of 10 m, and maximum slopes of 35°. They are almost circular in outline, with maximum lengths of 476 m, although some are NE-SW elongated in the main cluster and NW-SE elongated in the second cluster, with maximum lengths of 650 m showing a skewed distribution. They also present erosive moats. On the other hand, the East Melilla Province (EMP) is located along the eastern upper and middle slope of the southern Alboran Sea off Cape Tres Forcas, in water depths of between 230 and 450 m (Comas and Pinheiro 2007). Two different CM areas comprise up to 10 mounds and ridges (BigOne, Horse, Elephant, Serpent, Dragon, and New Mounds). BigOne is located at the base of the shallow-water Provencaux Bank, between 300 and 450 mbsl, and comprises three carbonate ridges: Brittlestar Ridge I-III, while the other mounds are located between 230 and 260 mbsl (Hebbeln et al. 2009). They range from 20 to 100 m high, up to 3000 m in length, and always have elongate shapes with varying orientations, mainly E-W and NE-SW. All the mound fields present contourite moats (Comas et al. 2009).

Acoustically, CM are characterized by non-penetrative echoes that produce transparent pinnacles generally buried under a thin (few milliseconds) sediment blanket of variable thickness that stands out from the surrounded layered sediments (Fig. 6.12e, f, g).

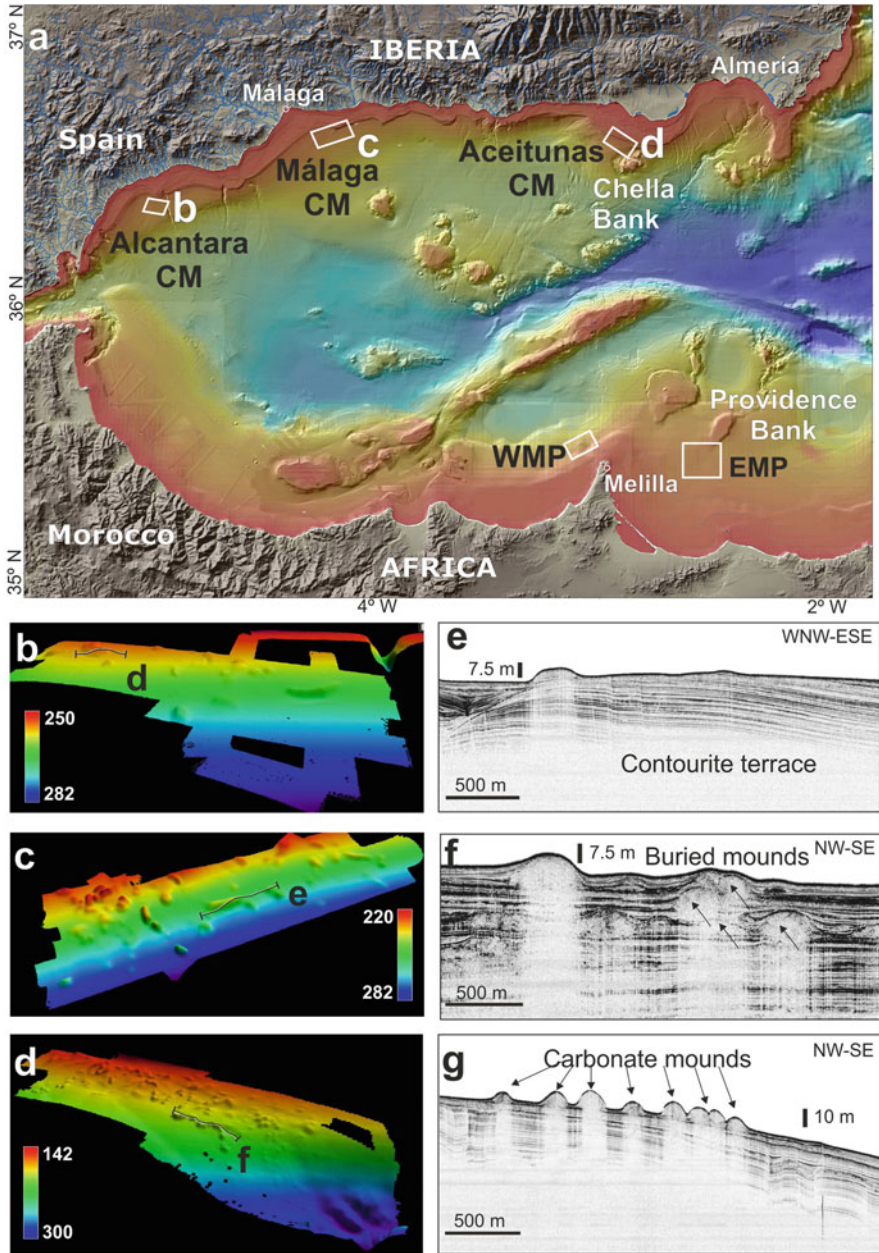


Fig. 6.12 CM in the Alboran Sea. (a) Multibeam bathymetric map showing the location of the CM mapped in the Alboran Sea. (b)–(d) Zooms of multibeam bathymetry showing the Alcantara, Málaga, and Aceituna fields. (e)–(g) Seismic profiles displaying their cross-sections and internal acoustic character of surficial and buried carbonate Mounds. Acoustically, these CM represent transparent pinnacles that stand out from the surrounded layered sediments. Legend: *WMP* CM in the western Melilla province; *EMP* CM in the eastern Melilla province

6.5.3 Recent Sediments: Facies Model

The surface and spatial distribution of recent sediments have been determined by several regional studies (Zamarreño et al. 1983; El Moumni and Gensous 1992; Ercilla 1992; Hernández Molina et al. 1993; El Moumni 1994; Ercilla et al. 1994, 2019; Bárcenas 2002, 2012). Sedimentation is mainly siliciclastic; only locally it is mixed (terrigenous-carbonate) in the eastern Iberian sector (Almería margin) and on the main, shallowest, and isolated seamounts (Alboran Ridge, Xauen Bank, and Frances Pagès Seamount). Five types of sedimentological facies have been characterized in the Pleistocene-Holocene near surface record; these are (1) nearshore, (2) prodeltaic, (3) contourite, (4) turbidite, and (5) mass-flow deposits (Fig. 6.13). These five facies define the vertical succession corresponding to the regional sedimentary environments of the proximal margin (continental shelf), distal margin (continental slope and base of slope), basins, and morphological highs (Fig. 6.14).

The *continental shelf facies* model involves nearshore and prodeltaic facies, the boundary between them being a sharp surface (Fig. 6.14). *Nearshore facies* (1) form homogenous successions of gravels and sands (up to 140 cm thick), as well as fining-upward successions from heterometric gravels to sands, and from sands to sandy muds (Fig. 6.14, profiles 1, 3, 6, 7). The gravels form successions of bioclastic fragments (relict molluscs, bryozoans, and calcareous algae occasionally replaced by glauconite), rounded and subrounded light and heavy minerals, and glauconite grains. Nearshore facies produce a widespread veneer over the entire continental shelf and are exposed mainly in the outer shelf area. The ages obtained for these facies vary between 21,610 years BP at 208 cm core depth and 1240 years BP at 27 cm core depth. The nearshore facies are overlain by *prodeltaic facies* (2), separated by a well-defined unconformity. The overlying prodeltaic facies are characterised by a vertical succession of terrigenous mud (Iberian prodeltas) and sandy mud (African prodeltas) with coarsening and fining-upward sequences

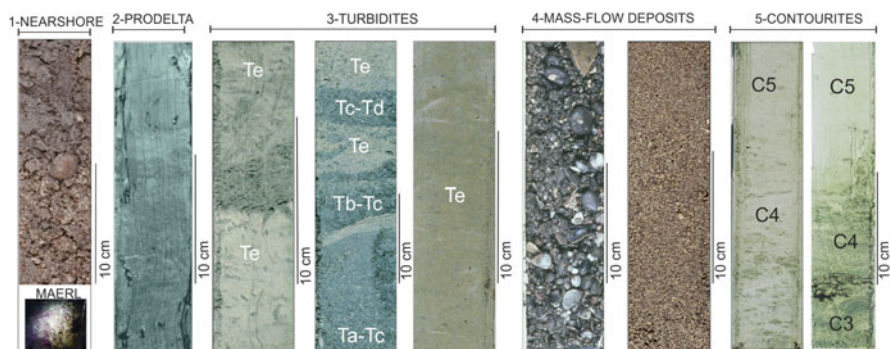


Fig. 6.13 Selected sediments core photos of the recent Alboran sediments and seafloor photo of maerls upholstering the seafloor of Alboran Ridge. Legend: Ta to Te refer to the Bouma divisions, and C3 to C5 refer to the contourite divisions of Stow and Faugères (2008)

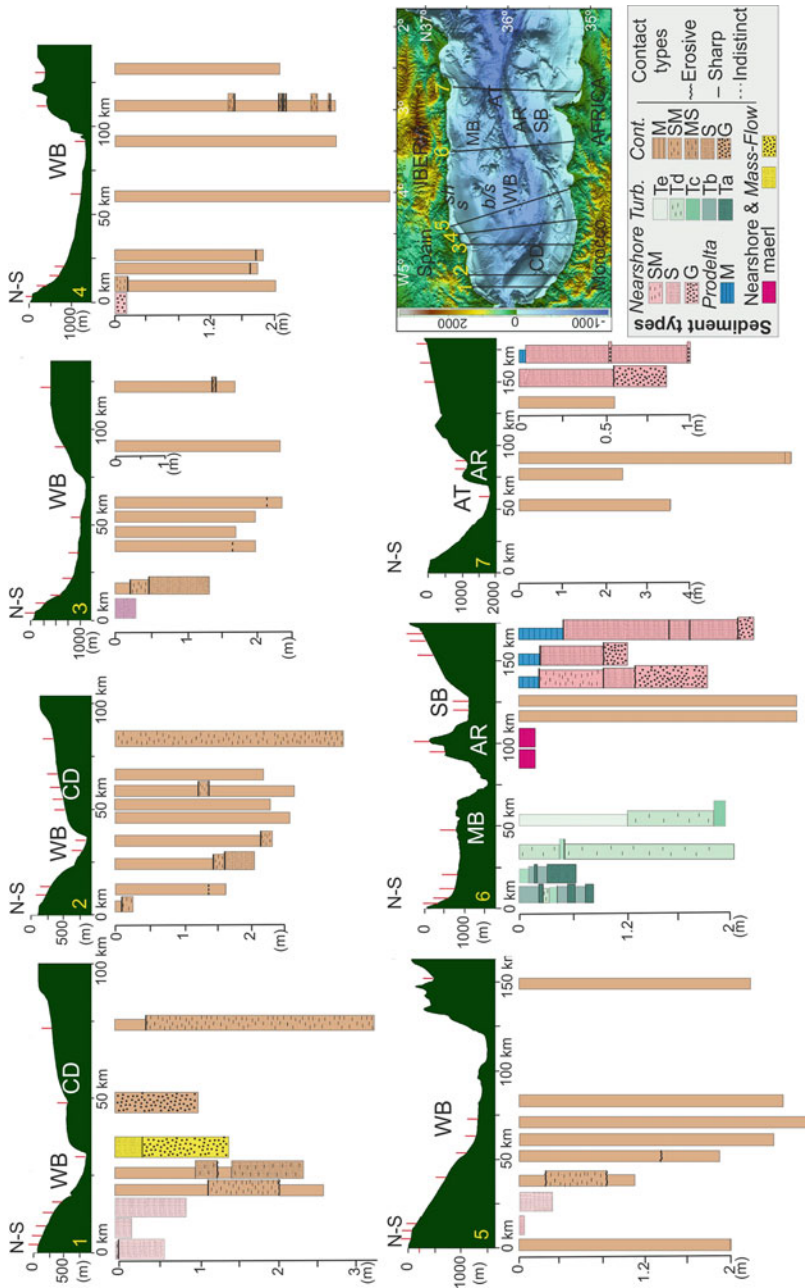


Fig. 6.14 Roughly N-S cross-sections in the Alboran Sea to provided two-dimensional slices of the stratigraphy and distribution of sedimentary facies in the Alboran Sea. Legend: *Turb* Turbidites; *Cont* Contourites; *sh* slope; *s* Sand; *MS* Muddy sand; *SM* Sandy mud; *M* Mud; *WB* Western Alboran Basin; *MB* Motril Basin; *AR* Alboran Ridge; *AT* Alboran Trough; *SAB* Southern Alboran Basin. See also the location of cross-sections and sediment cores in Fig. 6.2b

(Fig. 6.14, profiles 6, 7). These facies occur locally on the inner-middle shelf, off the river mouths in the Iberian (Ercilla et al. 1994; Hernández Molina et al. 1993; Bárcenas 2012) and African (El Moumni 1994) shelf, down to a depth of 70 m, and have a lobate shape in plan-view (Bárcenas 2012). The age obtained for the prodelta sediments analysed is about 1500 years BP at 25 cm core depth.

The *continental slope, base of slope, and basin facies* model consists of contourites, turbidites, and mass-flow deposits. The *turbidite facies* (3) form vertical succession of three textural types (sand, silt, and clay) displaying fining-up sequences (Fig. 6.14, profile 6). These correspond to divisions of the Bouma sequence (Ta to Te). The cores show turbidite sand and silt layers (Ta-d) alternating with mud layers (Te) in the turbidite systems of the Iberian margin (Bozzano et al. 2009; Ercilla et al. 2019). They comprise terrigenous components and, in a minor proportion, the sand fraction contains bivalves and gastropods, similar to those described on the continental shelf (Ercilla et al. 1994). The coarsest-grain size occurs in channel environments, while the finest-grain sizes are in the inter-canyon and levee areas. The *mass-flow facies* (4) form vertical successions of sands and gravels, displaying homogenous sequences with lithic clasts. These are found on the Ceuta and Guadiaro Canyon floors (Ercilla et al. 2019). Coarse and fine contourite facies (5) have been characterised. The *coarse contourite facies* have been sampled from the shelf-break down to about 360 m water depth, on the erosive surface defining the contouritic terrace, on the uppermost Iberian continental slope (Fig. 6.15, profiles 1, 5). There, these facies comprise successions of poorly sorted sand up to 73 cm thick with sparse gravel-size biogenic clasts (shell fragments). The sand fraction of this sediment is terrigenous, mainly comprising subrounded and rounded grains of glauconite (44%) mixed with bioclastic debris (30%). This debris is mainly composed of fragments of molluscs that look old due to their greyish colour and because they show mechanical and chemical abrasion with loss of ornamentation. The *fine contourite facies* form successions of different textures from sandy muds, muds, and silty clays with terrigenous and mixed components (Fig. 6.15 profiles 1 to 7). The vertical succession produces a bi-gradational sequence, with coarsening-up followed by fining-up, and corresponds to the five sediment divisions (C1 to C5) of Stow and Faugères (2008). In addition, there are truncated sequences formed by C1, C3–C4–C5, and C4–C5 (Fig. 6.14). The thickness and vertical/spatial distribution of the contourites indicate that muds (C1 or C5) are predominant, interrupted by levels of sandy muds (C2 or C4). The coarse-grained intervals occur more frequently in the southern and western sectors of the Ceuta Drift (Ercilla et al. 2002). On the other hand, the summits of the *topographic highs* of Tofiño, Xauen, and the Alboran Ridge are surficially covered by nearshore sediments composed mostly of gravels and sands of bryozoans, coralline algae, mollusc fragments, echinoid spines, and foraminifera (benthic and planktonic) with abundant maerl (also known as rhodolith; Bárcenas et al. 2001). The ages obtained for these sediments are around 13,430 to 3085 years (Fig. 6.14, profile 6).

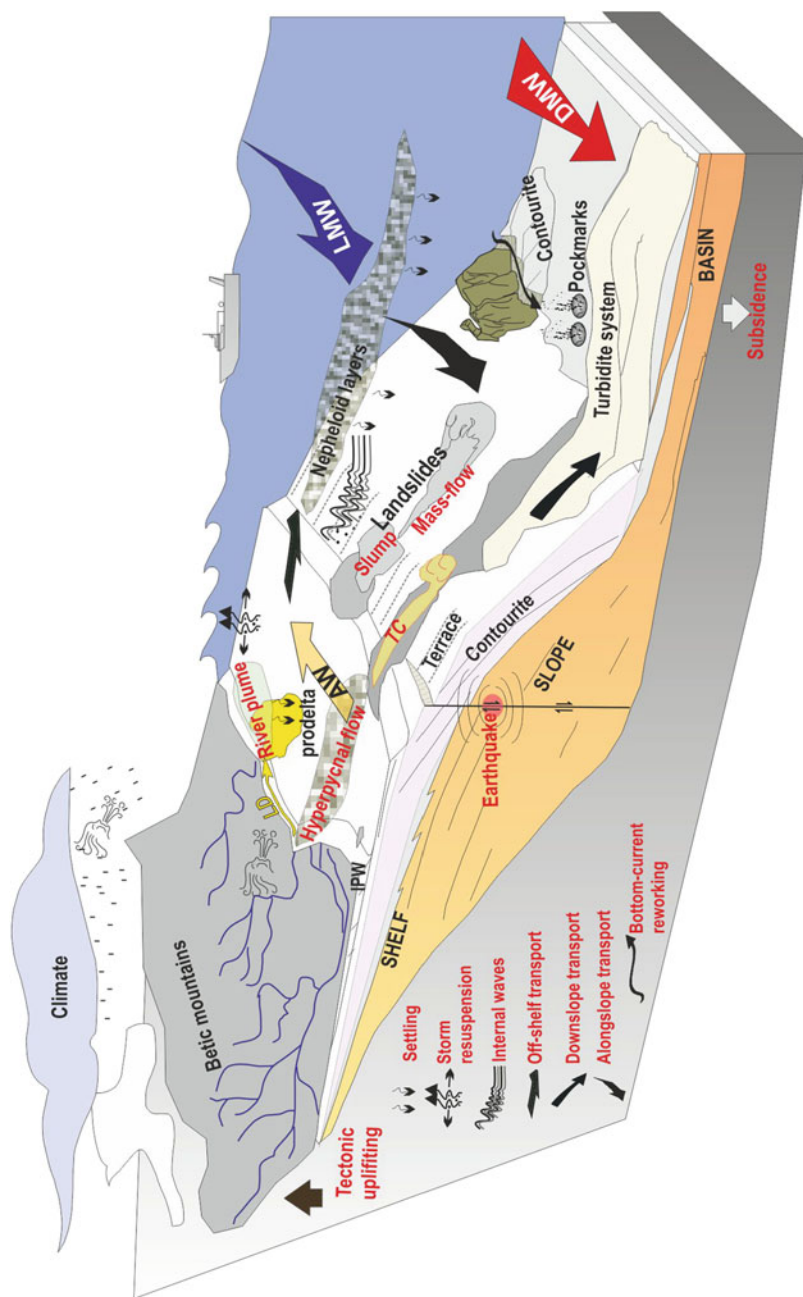


Fig. 6.15 3D diagram summarising the main features and sedimentary dynamics characterising the Alboran continental margins and adjacent sub-basins. Legend: *IPW*: infralittoral prograding wedge; *LD*: Littoral drift; *TC*: turbidity current; *AW*: Atlantic Water; *LMW*: Light Mediterranean Water (*WTW*+*LMW*); *DMW* (*WMDW*) Dense Mediterranean Water. Figure adapted and modified from Piasias and Delany (1999)

6.6 Discussion

6.6.1 Active Tectonics

NW-SE present-day oblique convergence between the Eurasian and African plates at a rate of 4.5 mm/year (DeMets et al. 2015) causes a regional NW-SE shortening and orthogonal extension accommodated by tectonics structures (folds and faults) and that produces a set of seafloor features of structural origin. Basically folded reliefs of different magnitude, push-up ridges, linear scarps and lineations, and rhombic and longitudinal depressions have been mapped (Vázquez et al. 2016).

Tectonics determines the development of large NE-SW to ENE-WSW antiforms that delineates the shape of elongate seamounts (e.g. the Alboran Ridge, Xauen Bank, and Francesc Pagès), the Alboran Trough, as well as smooth bulges anticlines in the Adra margin region (Figs. 6.1b, 6.3b, 6.7 and 6.8a, b). Moreover, plate convergence produced the presence of the two main fault sets, oriented N25° E sinistral and N130° E dextral, where the resistant basement of the African plate indents the thinned continental crust of the Alboran Sea (Estrada et al. 2018) that are strongly marked in the morphology of the seafloor (Fig. 6.7). These faults have a high level of seismic activity and are responsible for the NNE-SSW seismicity band crossing the Alboran Sea, from Campo de Dalías to Al-Hoceima, where the recent 1993–1994, 2004, and 2016–2017 seismic series occurred (Figs. 6.1b and 6.7). The Al Idrisi Fault and new faults developing westwards constitute the present-day most active seismogenic faults in the Alboran Sea (Galindo-Zaldívar et al. 2018), located on the northwestern border of the indenter. The dextral Yusuf Fault constitutes the main WNW-ESE conjugate fault delineating the northern boundary (Figs. 6.1b and 6.7). NW-SE normal faults located along the northern boundary of the Alboran Sea, like the Balanegra Fault (Galindo-Zaldívar et al. 2015) also play an important role in accommodating the ENE-WSW extension related both to the indentation tectonics and rollback processes. The orientation of the ENE-WSW Serrata-Carboneras Fault with respect to the orthogonal NNW-SSE present-day convergence suggests that this fault may currently have limited activity (Figs. 6.1b and 6.7).

The active tectonics is also attested by the fluid-flow features mapped on the seafloor (Fig. 6.9). Fluids flowing from deep layers have been related to regional tectonics. The diapir distribution in the Western Alboran Basin is related to extensional, compressional and strike-slip processes related to the geodynamic evolution of the Alboran Basin (Pérez-Belzuz et al. 1997). Extensional processes reactive though it punctuated diapiric activity during the Pliocene and early Quaternary, and during the late Quaternary that activity was characterized by a generalised collapse phase in many mud ridges (Pérez-Belzuz et al. 1997). The mud volcano activity is related to the tectonically-driven diapirs whose mud forms the source of the focused fluid-flow feeding the volcanoes (Pérez-Belzuz et al. 1997; Somoza et al. 2012). These authors also suggest that active diapirism and mud volcanism was also favoured in the African margin by differential loading generated by a contourite sedimentation, specifically of the Ceuta plastered Drift (Pérez-Belzuz et al. 1997;

Somoza et al. 2012). In contrast, fluids accumulate as reservoirs in near surface sediments and create cold-seep features through fluidification and liquefaction of the unconsolidated sediments; the formation of these structures may also be favoured by the erosion of contourite drifts and sea-level changes (Somoza et al. 2012).

Most of the tectonic deformation of the seafloor has been located in areas of the continental slope or basin, while the tectonic deformation of the continental shelf has been located mostly in the area of the Al-Hoceima Bay. This is consequence first by the source of the tectonic activity which proceeds from the boundaries of the indentation block described by Estrada et al. (2018), where the western limits, the Al-Idrissi Fault, would end up towards the Al-Hoceima area. A second argument must be taken into account, it is the low magnitude of the convergence velocity of Africa-Eurasia convergence (DeMets et al. 2015) that is being accommodated by these structures, so that on the continental shelf the evidences of this deformation can be obliterated by the erosive processes in moments of lowstand level or by deposits related to the last high stand-level episode. In any case, a detailed analysis of the possible tectonic seafloor deformation must still be carried out in areas of the continental shelf.

6.6.2 The Key Role of Alboran Sea Seafloor Morphology in Characterising Sediment Dynamics

The Alboran Sea represents the dumping area for sediments coming from the Betic and Rif mountain belts (Fig. 6.1a). The way sediment has been transported and deposited, at least in recent times, is mainly reflected by the morphosedimentary features that characterise the present-day morphology of the Iberian and North African continental margins and the adjacent deep basins (Figs. 6.5 and 6.6a). Their mapping on the seafloor does not imply present-day activity, although they have been, at least, recently active from a geological point of view. The distribution and lateral relationships between these features reveal that each physiographic province is dominated by a cluster of morphosedimentary features that, based on formation processes, indicate at least two main, different sedimentary environments on the continental margins. These two major environments are: (1) the proximal margin defined by the continental shelf; and (2) the distal continental margin, clustering to the continental slope, base of slope, and adjacent basins.

6.6.2.1 Sediment Dynamics on the Proximal Continental Margin

The proximal continental margin of the Alboran Sea is dominated by coastal and fluvio-marine sedimentary processes. The seafloor morphology of the Alboran continental shelf attests to the influence of these processes in different sedimentary environments, including prodeltas, IPWs, bedforms, and relict nearshore sheets (Fig. 6.4).

The sediment dynamics of the prodeltaic systems are mainly related to settling from the suspension of nepheloid layers, or turbid layers of sediment delivered from rivers and streams or wave-supported gravity flows, all with a dominant cross-shelf transport dynamic (Fig. 6.15). The settling process appears to be continuous, operating on the present-day proximal continental shelf since the installation of the Holocene highstand (6500 years BP to present). The well-defined 2D surficial distribution of the prodelta facies, the age of these facies (1500 years BP), and the well-defined 3D geometry (wedge-shape) of the prodeltaic bodies identified from seismic records indicates strong sediment progradation in the submarine environment and low sediment retention levels in the emerged domain (Fig. 6.4a, b, c, d) (e.g. Ercilla et al. 1994; Hernández-Molina et al. 1994; Bárcenas et al. 2009; Lobo et al. 2015). The plan-view geometries are directly related to hydrodynamic control being greater in those with elongate patterns. In this sense, the Guadalfeo River prodelta exhibits lateral morphological plan-view changes from lobate to elongate, reflecting the temporal modification of the balance between fluvial supply and sediment redistribution by the governing hydrodynamics and/or reworking of pre-existing depocentres (Figs. 6.4a, b and 6.15) (Lobo et al. 2006; Jabaloy-Sánchez et al. 2014).

Many prodeltas are affected by conspicuous seafloor undulations (Fig. 6.4a, d). Morphometric, stratigraphic, and sedimentological data indicate the possible activity of hyperpycnal flows (i.e. a particular type of turbidity current generated by river discharge) as a plausible genetic mechanism (Fig. 6.15) (Lobo et al. 2015). The margins of the southern Iberian Peninsula are mountainous, and the drainage basins are small and steep; in addition, rainfall events are torrential nature in the region; these conditions favour the generation of hyperpycnal flows. There is greater undulation development in prodeltaic settings off river basins with high maximum rainfalls; therefore, a genetic link between fluvial flow and undulation development has been proposed (Bárcenas et al. 2009). In this sense, a relationship is observed between undulation development and river basin parameters, such as river length and basin size (Bárcenas et al. 2009). The most detailed analysis has been conducted on the undulations off the Guadalfeo River, which could be classified as a moderately dirty river (Fig. 6.4a, b, d). There, morphometric differences between undulation fields suggest the occurrence of temporal changes in hyperpycnal flows. Higher undulations could be indicative of intensified river flow, whereas lower and more laterally extensive undulations could indicate their inactivity due to a change in the course of the river (Fernández-Salas et al. 2007; Lobo et al. 2015). On the other hand, the presence of prodeltaic channels and/or gullies would point to relatively high-energy hyperpycnal flows, suggesting a relationship between their development and fluvial flow (Figs. 6.5c, d and 6.15).

Current interpretations also assume that inner IPWs are moulded by relatively recent (i.e. Holocene stillstand) dynamic processes (Figs. 6.4a, c, e and 6.15). The original conceptual model highlighted the major influence of seaward sediment transport patterns induced by downwelling storm resuspension currents that trigger sediment avalanching onto a depositional slope below storm base levels (Fig. 6.15) (e.g. Hernández-Molina et al. 2000; Ercilla et al. 2010). More recent studies stress

the additional influence of alongshore sediment transport, instead of downslope, on IPW development (Fig. 6.15) (Fernández-Salas et al. 2009), particularly on relatively straight coastlines with progradational coastal plains. There, IPW accretion parallel or oblique to the coastline is usually coupled to the progradational story of the adjacent coastal plains and seems to be favoured by significant alongshore currents. Major changes in development of IPWs would be caused by erosional events and/or by significant changes in the direction of prevailing winds, and then wind-forced currents, which ultimately affect littoral drift patterns (Fernández-Salas et al. 2009). In the particular case of the Carchuna IPW, sediment transport and IPW construction seem to be enhanced by the role played by the Carchuna Canyon head (Fig. 6.5a, b), which focuses wave energy during high-energy events and enhances coastline and shoreface erosion. As a consequence of the widespread erosion, sediments would be available in the coastal system for subsequent remobilisation, and these would be finally entrained by along-coast hydrodynamic processes (Ortega-Sánchez et al. 2014).

Sediment dynamics in those shelf areas where relict nearshore facies and wave-cut terraces are exposed (Figs. 6.13 and 6.14), point to domains (mainly on the outer continental shelf) with present-day low levels of sedimentation; in other words, they are shelf areas that do not receive sediment from fluvial sources or major coastal erosion. The ages obtained for the nearshore facies (from $21,610 \pm 350$ to 1249 ± 60 years) suggest that these facies were mainly formed during the last sea-level rise, as the sea-level was about 110 m (Mateu 1992) below its present position at about 18,000 years, and began to transgress the entire continental shelf. The successive coastline migration across the shelf would explain the fact these facies forms a widespread veneer over the entire continental shelf. This migration was pulsed and the stillstands would have favoured the formation of wave-cut terraces (Lobo et al. 2014). The occurrence of different types of bedforms, preferentially in outer continental shelf settings, where relict nearshore facies are exposed, on both the Iberian and African shelves, could be tentatively related to the activity of reworking processes during the course of the postglacial sea-level rise. Specifically, the dune fields reported on the shelf around Al-Hoceima Bay have been genetically linked with a sea-level stillstand at around 15,000 years, predating a major shelf flooding event (Lafosse et al. 2018).

6.6.2.2 Sediment Dynamics on the Distal Continental Margin

The distal margin is dominated by marine sedimentary processes, which mainly include the action of bottom currents and mass-movements.

Bottom Current Processes

Bottom current processes are responsible for the formation of contourite features, both depositional and erosional. The ubiquity of these features (Fig. 6.6a) makes bottom currents as the most important factor controlling sediment patterns in the deep-sea areas in the Alboran Sea (Figs. 6.6b and 6.15). The effect of bottom

currents on sediments is twofold: they move sediments prior to and after deposition. In the first scenario (prior to deposition) sediment is transported and deposited by bottom currents favouring the formation of large-scale, plastered, and sheeted drifts, which contribute to the building of the open continental slope, base of slope, and the infilling of the basins (Fig. 6.6); in this scenario sediment deposition occurs far from the sources of continental sediments, i.e. rivers and streams, coastal erosion, and including Saharan aeolian input (e.g. Jiménez-Espejo et al. 2008; Moreno et al. 2002; López-Gonzalez et al. 2019). This activity has been occurring at least since the opening of the Strait of Gibraltar, at around 5.33 Ma (Ercilla et al. 2016; Juan et al. 2016). When sediment reaches the sea, the AW, LMW, and DMW drive the alongslope transport that provokes the dispersion and distribution of sediment (mostly the fine sediment) over large areas of the Alboran Sea (Fig. 6.15). In addition to this alongslope component of sediment transport, there is a downslope component, also exerted by the water masses, specifically by the water mass interfaces. These interfaces favour the occurrence of nepheloid layers with a relatively high content of fine sediments (e.g. McCave and Tucholke 1986) that move sediment downslope (Fig. 6.15). Deposition occurs when sediment motion velocity decays, producing the rapid settling of the suspended sediment, and thus drift formation. The sediment motion is related to large-scale velocity variations in the AW, LMW, and DMW pathways, which are themselves mostly governed by the interplay between the trend and morphology of the Iberian and African margins and basins (Fig. 6.1a), together with the Coriolis Force. The predominance of fine contourites in the sampled cores (Figs. 6.13 and 6.14) points to the fact they were deposited under generally low-energy conditions, at least in the case of the most recent (Holocene) contourite deposits. The vertical grain-size variations observed in those facies may be the result of changes in bottom current velocity (e.g. Toucanne et al. 2007; Stow and Faugères 2008) and sediment provenance (e.g. Brackenridge 2014; Rebesco et al. 2014).

When bottom currents move sediment after deposition, they contribute to reworking the seafloor. The effects of this reworking activity are seen clearly in erosive (moats, channels) and mixed (terrace) contourite features. Reworking occurs when the bottom current velocity increases enough to erode the seafloor (e.g. Nittrouer et al. 2007) (Figs. 6.6 and 6.15) and it occurs at two different scales in the Alboran Sea: (1) local; and (2) regional. Local accelerations of the DMW occur when this water mass is confined by the Alboran Trough and Al-Hoceima Valley (Fig. 6.1a). Along the Alboran Trough, the seafloor is mostly eroded, although channel-related drifts do form when the velocity decreases. Conversely, in the Al-Hoceima Valley there is only erosion, and the DMW transports the eroded sediment along the African margin, towards the Strait of Gibraltar. Locally, the LMW and DMW also accelerate when they interact with seamounts and steep scarps, producing seafloor reworking at the break of the steep slopes (Figs. 6.6 and 6.15). This reworking contributes to excavating erosive moats that constitute striking depressions at the feet of the seamounts (Palomino et al. 2011; Ercilla et al. 2016). This reworking/erosion contributes to the relatively high concentrations of suspended sediment at the benthic boundary layer that is deposited close to the

moats, where the sediment motion velocities decay sharply, forming mounded, separated, and confined drifts (e.g. Stow et al. 2008; Rebesco et al. 2014).

Reworking at regional scale mainly occurs on the upper continental slope of the Iberian and African margins, where terraces have been mapped (Figs. 6.6 and 6.15). The reworking happens where the interfaces of the AW with LMW and DMW touch the continental slope seafloor. Turbulent motion characterises the interfaces due to the presence of internal waves that alter flow velocity with oscillations of up to 0.4 m/s, producing vertical displacement of water (50 m) above and below the mentioned interfaces (Fig. 6.15) (e.g. Samthein et al. 1982; Pomar et al. 2012; Shanmugam 2013a, b; Chen et al. 2014; Ercilla et al. 2016). Currently, internal waves are mostly formed within the Strait of Gibraltar (e.g. Armi and Farmer 1988; Bruno et al. 2002), and above striking variations in relief, such as the shelf break (e.g. Ercilla et al. 2016). The sediment cores have revealed the presence of wide areas of coarse sediments, free from fine sediments, on the seafloor at the proximal sites of the terrace (Fig. 6.14) (Ercilla et al. 1994), providing evidence for the action of this important turbulent motion. The position of the Atlantic and Mediterranean water mass interfaces would have varied during the past high frequency and high amplitude glacio-eustatic changes in sea level, caused by the three variables of the Earth's orbit (eccentricity/obliquity/precession) (e.g. Ercilla et al. 1994; Chiocci et al. 1997; Lobo et al. 2008). The horizontal displacements of interfaces during the sea-level changes would have favoured the reworking of extensive areas of the upper slope and enlargement of the terraces.

Additionally, the interplay between favourable bottom currents and climatic conditions could have influenced the complex CM development in different phases, possibly related to the last deglaciation (<5400 years) corresponding to the Late Holocene, as suggested by Fink et al. (2013) for the EMP mounds.

Mass-Movement Processes

Mass-movement processes are responsible for the formation of both the turbidite systems and the landslides. The morphology and deposits making up the architectural elements of *turbidite systems* indicate they are mainly formed by the action of channelized turbidity currents and related flows (mass flows), i.e. downslope density flows (Fig. 6.15). The U- and V-shapes of the canyons and related tributary gullies suggest those flows have a significant erosive capacity (Fig. 6.10e). Their energy is mainly related to sediment load characteristics and the relatively high seafloor gradients that directly influence the gravitational force (e.g. Ercilla et al. 1998; Pirmez et al. 2000; Ferry et al. 2005; McHargue et al. 2011). Sediment cores recovered from canyon floors indicate that turbidity and mass flows transport a great variety of grain sizes, from gravels to clay. Most of the canyons (except Torrenueva and Baños) were formed during the Messinian salinity crisis (Estrada et al. 2011; Ercilla et al. 2019), and their present-day morphosedimentary characteristics (Fig. 6.10a–e) are the result of gravitational flows that have been acting on them since that time. Pliocene and Quaternary sedimentary studies suggest that gravitational flows were active, eroding and enlarging the canyons, mainly during the glacial periods, when the sea-level and continental sediment sources were closer

to or below the shelf-break. The occurrence of turbidity and mass flows decreased during interglacial highstand stages (e.g. Alonso and Maldonado 1992; Ercilla et al. 1992, 1994; Chiocci et al. 1997; Estrada et al. 1997; Alonso and Ercilla 2003). The U-shape of many canyons and the presence of sinuous talwegs on the seafloor (Fig. 6.10) suggest alternating deposition and erosion in recent times. The energy of the turbidity and mass flows decreases when they reach the gentle gradients at the base of the slope and in the adjacent basin, and their sediment charge deposits forming leveed channels and lobes, although erosion may continue along the main and distributary channel floors.

Recent studies have indicated that turbidity flow characteristics seem to be locally affected by the action of bottom currents running across the turbidite systems in the westernmost Alboran Sea (Ercilla et al. 2016, 2019). AW, LMW, and DMW contribute to the piracy of the finer sediment travelling in the upper part of the turbidity flows, making the turbidite systems sandier (La Linea and Guadiaro) closer to the Strait of Gibraltar. The action of the DMW also seems to have been more intense on the African margin, probably inhibiting the formation of leveed channels and lobes at the mouth of the Nekor and Ceuta canyons.

Respect to *landslides* shaping the seafloor of the Alboran Sea (Figs. 6.6, 6.11 and 6.15) the literature reveals that most of them formed during the Quaternary (Casas et al. 2011; Martínez-García et al. 2011; Alonso et al. 2014; Rodriguez et al. 2017; Galindo-Zaldívar et al. 2018). Their fresh morphologies indicate that their activity has continued into recent times. Slope sediment failure occurs when their metastable equilibrium is disturbed, causing the sediment to move downslope (e.g. Casas et al. 2011; Ercilla and Casas 2012). Although the causes of landslides are still not fully understood, several triggering factors, acting either individually or jointly, have been tentatively suggested for the Alboran Sea: over-steepening, seismicity, under consolidation due to overpressure by interstitial fluids, stratigraphy, and high sedimentation rates (e.g. Casas et al. 2011; Alonso et al. 2014; Rodriguez et al. 2017).

After failure, the sediment runs downslope, disintegrating, and remoulding as a consequence of the stress and incorporation of water during the movement (e.g. Locat and Lee 2000). Based on this process and the runout distance, the sediment remains as a coherent mass attached to or detached from the slide scar (Fig. 6.11). Detailed studies of the Baraza slide reveal that the type of movement may change through time. This landslide has been affected by two types of movement since its formation during the Upper Quaternary, firstly mass flow-type, followed by a more recent slump-type movement (Casas et al. 2011).

6.6.3 *Geohazards in the Alboran Sea*

The seafloor morphology offers interesting clues to help assess the main potential geological hazards. These hazards can be grouped into two major different categories, endogenic and exogenic. The endogenic are related to tectonic processes, and the exogenic are related to bottom current and mass-movement processes.

Hazards related to tectonic processes (1) are the most relevant in the Alboran Sea. They are related to its complex tectonic context (Fig. 6.1b) caused by the interaction between the Eurasian and African plates. This fact is evidenced by the numerous faults and folds affecting the seabed, in addition to the related seismicity. The central Alboran Sea presents the highest concentration of active tectonic structures (d'Acremont et al. 2014; Estrada et al. 2018; Galindo-Zaldívar et al. 2018) (Figs. 6.1b and 6.7). Historical records suggest that Spanish, Moroccan, and Algerian populations bordering the Alboran Sea have been affected by more than 50 destructive earthquakes in the last 2000 years (Martín-Lechado et al. 2005). The last was on January 25th, 2016, when there was an earthquake of magnitude $M_w = 6.3$ with its epicentre in the Alboran Sea (35.6° N, 3.81° W). This caused material damage in Melilla and other Moroccan cities.

Hazards related to bottom current processes (2) are mainly related to the erosive activity of the Atlantic and Mediterranean waters. This activity is revealed by the erosive contouritic features. Published literature on the present-day characteristics of oceanographic circulation points to the fact seafloor erosion could occur in the vicinity of the Strait of Gibraltar, on both the Iberian and African margins. In this area, the Atlantic and Mediterranean water masses accelerate (e.g. Kelling and Stanley 1972; La Violette 1984; Parrilla et al. 1986; Parrilla and Kinder 1987; Viúdez et al. 1996; Naranjo et al. 2012; Peliz et al. 2013; Sotillo et al. 2016). This results in two hazardous effects: the reworking of slope terrace sediments, rock outcropping, and the presence of a mobile seafloor at the entrance to the Strait of Gibraltar (Kelling and Stanley 1972; Ercilla et al. 2016). Here, sand waves and undefined sediment waves (metre-sized in relief, and a few to tens of metres in length) have been mapped (Heezen and Johnson 1969).

Hazards related to mass-movement processes (3) is revealed by the presence of landslides on the open slope and basins and on the steep walls of valley walls and seamounts (Fig. 6.6a). In spite of the active tectonic context of the Alboran Sea, the relationship between recent earthquake epicentres and submarine landslides is not readily apparent in this basin (Figs. 6.1b and 6.6a). The correlation is only clear on the northern side of the Francesc Pagès seamount and Alboran Ridge, where several landslides have been mapped along the 2016–2017 ENE–WSW seismicity alignment (Fig. 6.1b) (Ercilla et al. 2016; Galindo-Zaldívar et al. 2018). Most of these landslides are located on contourite deposits and the occurrence of alternating layers with different grain sizes and mechanical behaviour could induce slope failures under cyclic and/or static loading conditions. Slope instability may be also related to the presence of a high content of gas bubbles in the interstitial pore water that contributes reduced sediment shear strength. The gas content is mainly evidenced by the presence of pockmarks, as in the case of the Baraza Slide (Fig. 6.6a) (Casas et al. 2011). Many other predisposing factors contribute to the triggering of submarine landslides; for example the interaction of shallow canyon heads (e.g. Algeciras, Guadiaro and Carchuna canyons) (Figs. 6.3b and 6.10a, b) with coastal and fluvio-marine processes that undercut the canyon sidewalls, leading to a progressive slope over-steepening of the canyon heads. On the other hand, sedimentary processes related to the generation of hyperpycnal flows due to the torrential nature of the

region and strong rainfall events may cause local erosion and mobile bedforms, as happens in many Iberian prodeltas (e.g. Bárcenas et al. 2009).

Hazards related to tectonics and slope instability can trigger destructive tsunamis (e.g. Fine et al. 2005; Gisler et al. 2006; Harbitz et al. 2014). The seismic-related risk of tsunamis in the Alboran Sea has not yet been quantified but is considerable. The various coastal regions of the basin have been affected by several tsunamis over the last seven centuries (Kaabouben et al. 2009). Accessible tsunami models, such as the Cornell Multi-grid Coupled Tsunami Model (COMCOT), enable us to assess the areas potentially affected in the Alboran Sea. The most-affected coastal area (involving sources in the south-central area of the Alboran Basin) is located between the cities of Marbella and Almería. In this area, wave elevations (locally exceeding 1 m in height) would reach the coast in less than 30 min (Álvarez-Gómez et al. 2011; Macías et al. 2015). Strike-slip faults like the Serrata-Carboneras and Yusuf faults could generate local tsunamis affecting the coastal infrastructure with a short (5 min) travel time (Álvarez-Gómez et al. 2011). Recently, the Averroes Fault has been suggested to be one of the most important potential tsunamigenic faults in the area (Estrada et al. 2018) (Fig. 6.7). Also, recent studies consider underwater mass-movements as a potential cause of tsunamis, and these have been numerically modelled in order to evaluate the affected areas (Macías et al. 2015; Rodriguez et al. 2017).

6.6.4 Contribution of Geology to Habitat Knowledge

Habitat mapping requires the integration of biological, geological, and oceanographic data. Surficial marine geology is a very important variable for habitat classification purposes and biodiversity studies. Marine geological mapping involves a range of acoustic and ground-truthing methods that provide crucial information for linking substrate characteristics (morphological and textural) with the existence of certain types of habitats. Furthermore, geology affects the environmental conditions of an ecosystem, for example changes in topography generated by slope movements govern the development, or not, of habitats. Also, major natural disasters, like earthquakes, tsunamis, and floods, are key factors affecting habitat settling. All these are specific topics in the study of marine geology.

In recent years, several research articles written from a geohabitat perspective have been published, mainly dealing with the northern margin of the Alboran Sea (Hebbeln et al. 2009; Palomino et al. 2011; Vázquez et al. 2015a; Gofas et al. 2014; Moya-Urbano et al. 2016; Sánchez-Guillamón et al. 2018). Most of these studies form part of the INDEMARES project, a European initiative to define Sites of Community Importance to be included in the Spanish marine Natura 2000 Network, and in which geological studies have played an important role.

In this sense, the studies undertaken to date in the Alboran Sea have focused on the following geomorphological units: prodeltas, bioconstructions, seamounts, and canyon heads. These geological studies have provided information on the depth,

acoustic response, and textural characteristics of the sediment; the seafloor morphology, sediment dynamics, and the angle and orientation of the seafloor, which in combination with assemblages of habitat-forming species enables habitat identification and mapping. In many cases, the high diversity and patchiness of habitats can be explained by the high environmental variability resulting from the broad geomorphological diversity (De La Torriente et al. 2018). The geological contribution has been crucial for these studies, to allow the consistent identification and mapping of the habitats using benthic samples. These examples demonstrate the intrinsic association of geoscience and habitats, and it is from these associations that a better understanding of the total ecosystem can be made and ultimately managed (Barrie and Conway 2008).

6.7 Conclusions

This contribution summarises the geomorphology of the Alboran Sea, based on recent local and regional interdisciplinary studies, and the combined analysis of acoustic, seismic, sedimentological, and CTDs data. The geological and oceanographic characteristics of the Alboran Sea make this sea an ideal context in which to analyse geomorphology and sedimentary deposits from shallow to deep-sea areas.

Four major physiographic domains have been defined in the Alboran Sea: (1) continental shelf, (2) continental slope, (3) base of slope, and (4) intraslope and deep basins. The continental shelf is generally poorly developed, and the deep-sea areas are dominated by a highly irregular topography.

The proximal margin (continental shelf) comprises depositional (*prodeltas*, *infralittoral prograding wedges*, and *bedform fields*), erosive (*submarine valleys*, *wave-cut terraces*), *slides*, and *anthropogenic* features. The distal margins and adjacent sub-basins include features with a different genesis; these can be grouped as tectonic, seamount, fluid outflow, contourite, mass-movement, and biogenic structures. The main tectonic features with seafloor relevance are *folds* with dominant ENE-WSW strikes, and *faults* that can be grouped into two main sets of N25° E sinistral and N130° E dextral kinematics. Both predominantly affect the central and eastern seafloor of the Alboran Sea. Several *seamounts*, with different origins and varying sizes, are scattered along the continental slopes and in the sub-basins. Fluid outflow features include *mud diapirs*, *mud volcanoes*, *pockmarks*, and *authigenic carbonates patches*, which occur mainly in the Western Alboran Basin. A great variety of depositional (*drifts*), erosional (*moats*, *channels*, and *scarps*), and mixed (*terraces*) contourite features have been mapped from the shelf-break (>90 m water depth) to the basins. Mass-movement features comprise *turbidite systems* mapped on the Iberian margin; *canyons* mapped in the Iberian and African continental slopes and in the Alboran Ridge flanks; and *landslides* mostly situated on seamount walls and with a minor presence on the open continental slope. Finally, fields with *bioconstructions* have been identified on the Iberian and African continental slopes.

Folds and faults mapped affecting the seafloor accommodate the present-day convergence between the Eurasian and African plates. This convergence is oblique with NW-SE shortening and orthogonal extension, and the related faults have a high level of seismic activity that determines the NNE-SSW seismicity band crossing the Alboran Sea. Regional tectonics is considered a controlling factor on fluid flows are related to diapirs and mud volcanoes mapped in the WAB.

The morphosedimentary features reflect the way sediment has been transported and deposited. Their near surface sediments indicate that sedimentation is mainly siliciclastic with locally mixed sediments (terrigenous-carbonate) in the eastern Iberian sector (Almería margin). Five types of sedimentological facies have been identified in the Pleistocene-Holocene near surface record: nearshore, prodelta, contourites, turbidites, and mass-flow deposits. The proximal continental margin is dominated by coastal and fluvio-marine sedimentary processes that have been acting since the last glacial sea-level change. Features found on the outer continental margin (relict nearshore facies and wave-cut terraces) mainly formed during the last sea-level rise and today are relict. Modern features (prodeltas, IPWs, and bedforms) generally occur on the inner-middle shelf and have been deposited during the present-day highstand (6500 years BP to present). The distal continental margin is mainly dominated by marine sedimentary processes, with the action of alongslope bottom currents of the AW and MWs being responsible for the ubiquity of contourite sedimentation. On the other hand, channelised downslope turbidity flows and related flows responsible for building the turbidite systems, were dominant during the glacial periods when the sea-level and continental sediment sources were closer to, or below, the shelf-break. The occurrence of landslides is relatively more important on the active structural seamounts and seems to be the consequence of the interplay of several triggering factors, including over-steepening, seismicity, under consolidation due to overpressure by interstitial fluids, stratigraphy, and high sedimentation rates.

The seafloor morphology of the Alboran Sea facilitates an assessment of the main potential geological hazards. These hazards can be categorised into three main groups related to: (1) tectonic processes; (2) slope instability processes; and (3) bottom currents. The main potential hazards are a consequence of seismicity and landslides, which can also trigger destructive tsunamis. The Alboran Sea is an excellent area in which to demonstrate the association of geoscience and habitats, leading to a better understanding of the total ecosystem.

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