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Shelves of the Iberian Peninsula and the Balearic Islands (I): Morphology and sediment types

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ABSTRACT

Here we present a synthesis of bedforms and sediment types on the shelves surrounding the Iberian Peninsula and the Balearic Islands, after the integration several pieces of bathymetric, morphological and sedimentological datasets. The Iberian and Balearic shelves are divided into segments according to the large-scale margin configuration, fluvial sediment supply and hydrodynamic regime. Their geological settings and large-scale sedimentation patterns place the investigated shelves into two broad categories: abrupt, steep and narrow sediment-starved shelves, illustrated by the Cantabrian shelf, and gentle, smooth and wide sediment-fed shelves, such as the shelves off some major flivial systems. An in-depth classification was subsequently attempted, based on morpho-sedimentary types. Under this approach, the Iberian and Balearic shelves can be classified as: (1) storm-dominated shelves, with erosional rocky floors, frequent abrasion surfaces and coarse-grained sediments; (2) current-dominated shelves, showing a good equilibriumbetween sediment fluxes and coastal and shallow ocean circulation, with laterally extensive muddy belts; (3) sediment supply-dominated shelves, where extensive subaqueous deltas develop off river mouths; and (4) wave-dominated shelves that occur off coastal stretches with minor and/or multiple fluvial sediment sources and enhanced littoral current.

Key words: continental shelf, insular shelf, geomorphology, sediment types, Iberian Peninsula, Balearic Islands.

Plataformas de la Península Ibérica y las Islas Baleares (I): Morfología y tipos de sedimentos

RESUMEN

En este estudio se presenta una síntesis de los tipos morfológicos y de los sedimentos superficiales que cubren las plataformas alrededor de la Península Ibérica y las Islas Baleares, integrando datos de distinta naturaleza (datos batimétricos y cartografía de tipos morfológicos y sedimentarios). La plataforma fue subdividida en varios sectores de acuerdo con la configuración general de los márgenes continentales y las condiciones regionales del aporte fluvial y de la hidrodinámica. Las plataformas ibérica y balear se dividen básicamente en dos categorías en función del contexto geológico y los patrones sedimentarios a escala del margen continental: plataformas desnutridas abruptas, inclinadas y estrechas, como la plataforma cantábrica como ejemplo más significativo, y plataformas nutridas suaves, poco inclinadas y anchas, tales como los sectores de plataforma frente a los principales sistemas fluviales. Una clasificación más pormenorizada se realizó teniendo en cuenta la distribución de tipos morfosedimentarios. De esta forma, las plataformas de la península ibérica y de las islas Baleares pueden ser clasificadas en: (1) plataformas erosivas rocosas, controladas por regímenes de tormentas energéticas, caracterizadas por extensas superficies de abrasión y sedimentos groseros; (2) plataformas dominadas por las corrientes, que muestran un equilibrio entre los flujos sedimentarios y la circulación somera, que conduce al desarrollo de cinturones fangosos de elevada continuidad lateral; (3) plataformas dominadas por los aportes, con desarrollo de grandes depósitos deltaicos submarinos frente a ríos grandes y medios; (4) plataformas dominadas por el oleaje, frente a sectores costeros con (múltiples) aportes fluviales menores y condiciones de deriva litoral activa.

Palabras clave: plataforma continental, plataforma insular, geomorfología, tipo de sedimentos, Península Ibérica, Islas Baleares.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

Los estudios realizados desde los años 60 del pasado siglo hasta la actualidad han permitido ir aumentando el conocimiento de la morfología submarina y la naturaleza del sedimento en las plataformas continentales e insulares. La ejecución de proyectos de cartografía sistemática, como el proyecto ESPACE, en las plataformas continentales mediterráneas y del País Vasco, contrasta con la falta de los mismos en otras regiones, donde únicamente se han llevado a cabo estudios parciales en el marco de proyectos de investigación de carácter regional o local. Dicha situación ha generado un claro desequilibrio en el conocimiento de detalle.

Las plataformas continentales ibérica y balear, bañadas por el Océano Atlántico y por el Mar Mediterráneo, están situadas en un complejo contexto geológico que sustenta una notable diversidad en su geomorfología. Además, su posición geográfica y las condiciones climáticas asociadas, así como las características de las cuencas fluviales vertientes, tienen una elevada influencia en el volumen, la naturaleza y la redistribución de los aportes de sedimento. Estos parámetros, junto con los cambios del nivel del mar durante el Cuaternario, han sido determinantes en el desarrollo de la plataforma continental y sus características morfológicas.

La plataforma continental ibérica y balear se ha dividido en siete sectores (Fig. 1) habiéndose recopilado información de numerosos proyectos de investigación y cartográficos, realizados por diferentes instituciones para el conjunto de dichos sectores. El objetivo de este trabajo es la presentación, con carácter general, de los tipos morfológicos y los sedimentos superficiales de las plataformas ibéricas y balear, así como su clasificación en tipos representativos de acuerdo con las condiciones de aporte de sedimento y de regímenes hidrodinámicos, sobreimpuestos al contexto geológico de cada sector.

Geomorfología y tipos de sedimentos

A efectos descriptivos, la plataforma ibérica y balear se ha dividido en 7 sectores, para cada uno de los cuales se han considerado las características geológicas, el régimen hidrodinámico, las aportaciones de sedimentos, las morfologías principales y la distribución de los sedimentos superficiales. Siguiendo el sentido contrario de las agujas del reloj tenemos los siguientes sectores de la plataforma:

Cantábrico

Está localizada sobre un margen abrupto con aportes sedimentarios provenientes de ríos montañosos de *corto recorrido, afectado por un levantamiento tectónico reciente (Cadenas* et al.*, 2012). Su régimen hidrodinámico es muy energético, con grandes tormentas y fuerte oleaje del noroeste. Su régimen mareal es semidiurno macro- o mesomareal. La plataforma, estrecha y en pendiente, está dominada por morfologías erosivas (Fig. 2): superficies de abrasión, afloramientos rocosos (Fig. 3B) y escarpes o terrazas, con un predominio de los sedimentos gruesos en el lecho de la plataforma.*

Galicia

Situada en un margen de tipo pasivo con aporte sedimentario relativamente escaso, y con una compleja configuración como resultado de su evolución tectónica y de los procesos de formación del relieve (Fig. 4). Hay que destacar las rías, valles fluviales del Terciario, que fueron inundados en la última transgresión y que actúan como trampas de sedimentos, y donde se favorece la expulsión de gas desde el sedimento (Fig. 3C). Dominan los procesos oceanográficos de alta energía en un régimen mesomareal. En la distribución de sedimentos tienen especial importancia las corrientes que fluyen en dirección norte. Presenta una gran diversidad geomorfológica, tanto en el interior de las rías como en la plataforma media y externa, destacando el cinturón fangoso de la plataforma media.

Portugal

Está situada sobre un margen pasivo, al que vierten ríos de importancia regional. Su clima marítimo es de alta energía, dominado por temporales del oeste y el noroeste, con mareas semidiurnas de rango mesomareal. Las corrientes litorales distribuyen el sedimento a lo largo de la plataforma, de anchura variable y compartimentada por cañones submarinos profundamente encajados. Destacan los depósitos fangosos de la plataforma septentrional media y las superficies de abrasión (Figs. 3D y 5), tanto en el norte como en el sur, en la plataforma media y externa. Predominan los sedimentos de tamaño arena, con afloramientos rocosos y acumulaciones de sedimentos más gruesos paralelas a la costa.

Golfo de Cádiz

Es un margen con una actividad tectónica activa situado en el límite de las placas africana y europea, afectado por el emplazamiento de la Unidad Alóctona u olistostroma del golfo de Cádiz, debido a la convergencia de ambas placas y al desplazamiento hacia el oeste del arco bético-rifeño. El oleaje es de intensidad media a baja y el régimen de mareas es mesomareal, con un aumento de la velocidad de las corrientes mareales hacia el Estrecho de Gibraltar. La principal fuente de sedimentos es el río Guadalquivir, y en menor medida, el río Guadiana. La anchura de la plataforma y su pendiente son menores en la parte portuguesa y en la más cercana al Estrecho, incrementándose la anchura en su parte central (Fig. 6). El elemento morfosedimentario dominante es el prodelta del río Guadalquivir, aunque en dirección al Estrecho también son importantes las morfologías generadas por corrientes como son los campos de ondas (Fig. 3E). Los sedimentos se distribuyen en bandas relativamente continuas a lo largo de la plataforma, con predominio de los depósitos fangosos.

Mar de Alborán

Al igual que en el golfo de Cádiz, su desarrollo ha estado condicionado por la colisión entre la placa europea y la africana. La presencia de la Cordillera Bética condiciona el clima y los aportes sedimentarios. El régimen hidrodinámico es bajo a moderado y las mareas varían desde un rango meso a micromareal, disminuyendo conforme aumenta la lejanía al Estrecho de Gibraltar. La plataforma es estrecha con una pendiente media-alta (Fig. 7). Las morfologías más destacadas son los prodeltas aguas afueras de los ríos principales, y las cuñas progradantes infralitorales en las zonas de poco o nulo aporte sedimentario y mayor influencia de las tormentas (Fig. 3F). La sedimentación es principalmente siliciclástica.

Sudeste y Baleares

Es un margen situado en el dominio tectónico Bético-Baleárico, con afloramientos volcánicos del Neógeno. Su régimen hidrodinámico está dominado por tormentas en un ambiente micromareal con una deriva litoral predominantemente en dirección sur. El aporte de sedimentos proviene de ríos de tamaño medio o pequeño, siendo más significante su influencia en la mitad norte. La plataforma es estrecha y abrupta al sur, aumen-

tando significativamente su anchura al norte de Cabo de Palos (Fig. 8). Las morfologías dominantes son los prodeltas, en las zonas donde hay aportes fluviales, y las cuñas progradantes infralitorales, en el resto. Destacan las praderas de fanerógamas marinas (Fig. 3G) sobre todo en la mitad sur. La cobertera sedimentaria es silicicoclástica, con predominios de los fangos al norte, arenas en su parte media, y arenas gruesas y gravas al sur. Tanto en Cabo de Gata como en las Islas Baleares, abundan los depósitos biogénicos de tamaño arena y grava.

Noreste

La configuración actual del margen noreste como margen pasivo, que comprende las regiones de Valencia y Cataluña, se alcanzó durante el Oligoceno superior-Mioceno inferior determinada por la apertura del surco de Valencia. La plataforma está dominada por el oleaje en un régimen micromareal con una marcada deriva litoral hacia el sur. Los ríos son principalmente de tamaño medio o pequeño, a excepción del río Ebro que aporta la mayor parte de los sedimentos. La plataforma es relativamente estrecha al norte del Ebro, aumentando su anchura frente y al sur de su desembocadura. La morfología de este sector es compleja y está determinada por la presencia de prodeltas, cuñas progradantes infralitorales y afloramientos rocosos, así como por la presencia de cañones submarinos con cabeceras muy próximas a la costa en el margen central y septentrional de Cataluña (Fig. 9). En la plataforma externa, existen grandes campos de dunas sumergidas, como las existentes frente a Valencia (Fig. 3H) en las Islas Columbretes. Al norte abundan los sedimentos gruesos y los afloramientos rocosos, interrumpidos por los depósitos más fangosos de los prodeltas. Hacia el sur predominan los depósitos más fangosos, con un papel preponderante de los aportes del río Ebro que son transportados en dirección sur por la acción de la fuerte deriva litoral.

Discusión y conclusiones

La fisiografía, los tipos morfológicos y la distribución de los sedimentos superficiales en la plataforma continental están controlados por el contexto tectónico y geodinámico, los cambios climáticos y eustáticos, y los procesos sedimentarios y oceanográficos a diferentes escalas de tiempo.

Los márgenes continentales de la Península Ibérica y Baleares muestran una gran variedad de estilos con un control tectónico subyacente y la mayoría de aquellos configurados desde el Cenozoico. A grandes rasgos, se pueden distinguir dos tipos de plataformas continentales: a) plataformas estrechas, abruptas, inclinadas y con poco espesor de sedimentos; y b) plataformas anchas, suaves, con poca pendiente y con predominio de procesos sedimentarios.

De acuerdo con las condiciones dominantes en relación con el aporte de sedimentos y el régimen hidrodinámico, las plataformas ibéricas y baleáricas se pueden adscribir a cuatro categorías: a) plataformas rocosas erosivas, representadas por la plataforma cantábrica, cuyas morfologías dominantes son de carácter erosivo, principalmente, superficies de abrasión y afloramientos rocosos; b) plataformas dominadas por corrientes, siendo Galicia y la parte norte de la plataforma portuguesa los mejores ejemplos, con notables depósitos fangosos de plataforma media; c) plataformas dominadas por la sedimentación de origen fluvial, situadas aguas afuera de los ríos grandes y medianos, cuyos aportes sedimentarios cubren buena parte de la plataforma continental con depósitos prodeltaicos; y d) plataformas dominadas por el oleaje, con escasos aportes sedimentarios y con un oleaje lo bastante fuerte para resuspender y removilizar el sedimento, lo que da lugar al predominio de cuñas progradantes infralitorales.

El estudio de las variaciones locales de los factores de control a diferentes escalas de tiempo, de los tipos morfológicos de la plataforma, y de la distribución y naturaleza de los sedimentos en la plataforma ibérica y balear aportan una perspectiva amplia y necesaria acerca de su evolución dentro de un amplio rango de condiciones ambientales, así como información relevante acerca de su dinámica y estado actuales.

Introduction

Shelf bathymetry provides key information about the morphology, the distribution of sediment facies (Posamentier *et al.*, 1988) and sedimentary processes that have and may continue to affect continental margins (Driscoll *et al.*, 2000). Initial exploratory studies collecting submarine geomorphology information started during the 1940s (Kennet, 1982). In recent years, an understanding of the shape of the seabed (i.e. bathymetry) and the type of seabed forms (i.e. geomorphic features) is considered fundamental information needed for better planning, managing and protecting the marine environment and its resources (Maestro *et al.*, 2013), and for the understanding of the seafloor evolution by surface processes acting over geological time scales (Pratson *et al.*, 2007).

The Iberian and Balearic shelves are washed by the Atlantic Ocean and the Mediterranean Sea, which are characterized by fairly different hydrodynamic regimes. The distinct shelf sectors are allocated in complex geological settings that exert a major influence on their highly diverse seafloor geomorphology. In addition, their geographical positions dictate to a large extent the regional climatic conditions which in turn affect the amount of sediments that eventually may reach the shelf environment, moulding its morphological features.

In this study, the Iberian and Balearic shelves have been divided into seven sectors (Fig. 1): 1) The Cantabrian shelf located in the northern abrupt margin of the Iberian Peninsula, is considered as a sediment-starved shelf since the sediments supplied by the small mountain rivers bypass the shelf and are deposited in deeper provinces of the margin. 2) The Galician shelf is sediment-starved with a highly complex geomorphological configuration across the shelf from the rias to the shelf break. 3) The western Portuguese shelf is long and narrow, locally disrupted by off the mouth of the most important rivers such as the Miño, Douro and Tagus. 4) The northern shelf of the Gulf of Cadiz displays variable width, more abrupt in the Portuguese coast and close to the Gibraltar Strait, and increases its width between the Guadiana River mouth and Cape Roche. The most significant sediment supplier is the Guadalquivir River. 5) The northern Alboran Sea shelf is narrow, with numerous small mountainous rivers and streams draining the Betic Ranges. 6) The southeastern and Balearic shelves show a southward evolution from a prograding shelf off the Cape La Nao to an abrupt shelf in the vicinity of Cape Gata, reflecting both the increasing influence of the Betic Ranges. 7) The northeastern shelf comprises the wide Ebro shelf, supplied by the main fluvial source in the Iberian Peninsula, and the Catalan shelf, which shows less development as it receives the supplies of smaller rivers draining the Catalonia coastal ranges and the Pyrenees.

The first descriptions of the Iberian and Balearic shelf morphology and surficial sediments had started by the end of the 1960s based on the Galician shelf (Nonn, 1966; Pannekoek, 1966; Koldijk, 1968). However, systematic marine geology studies based on single-beam echo sounder and side scan sonar data, seismic reflection profiles and bottom samples were extended in the late 1980s, and especially in the 1990s, to other numerous shelf sectors (e.g., Maldonado *et al.*, 1983; Rey and Díaz del Río 1983; Moita, 1986; Dias, 1987; Rey and Díaz del Río, 1987; Rey and Medialdea, 1989; Díaz and Maldonado, 1990; Díaz *et al.*, 1990; Rodrigues *et al.*, 1991; Ercilla, 1992; Hernández-Molina *et al.*, 1993; Rey, 1993; Catafau *et al.* 1994; Ercilla *et al.*, 1994a, b; Rey and Fumanal 1996; Rey *et al.,* 1999; Fernández-Salas *et al.*, 1999; Nelson *et al.*, 1999; Vilas *et al.*, 1995, 1996, 1999; García-Gil *et al.*, 2000). Recent advances in both sonar resolution and GPS positioning, as well as the availability of vessels equipped with high-resolution geophysical techniques have allowed us to study seafloor morphology in increasing detail (e.g., Muñoz *et al.*, 2005; Vilas *et al.*, 2005; Lobo *et al.*, 2006; Amblas *et al.*, 2006; Fernández-Salas *et al.*, 2007; Liquete *et al.*, 2009; Galparsoro et al, 2010; Lo Iacono *et al.*, 2010; Urgeles *et al.*, 2011; Lastras *et al.*, 2011; Bárcenas, 2013; Durán *et al.*, 2014). Advances in seafloor mapping and extensive surveys with widespread shelf coverage (e.g., the ESPACE project whose main subject was the systematic cartography of the Spanish continental shelf) achieved over the past decade are outstanding landmarks in this regard. Geomorphological studies conducted along different segments of the Iberian and Balearic shelves mainly depend on data collection density, which is very uneven; there are areas with abundant information available, such as the Gulf of Cadiz and extensive parts of the Mediterranean shelves. In contrast, there is a significant lack of information from the Cantabrian shelf. The reasons for this unevenness among areas include the lack of systematic coverage of the shelf environment and the overlapping of research efforts in specific sectors.

The basic information for this paper is provided by systematic projects, such as the following: FOMAR maps at a scale of 1:200,000, compiled from 1982 to 2003 by the Spanish Geological Survey for the Catalan margin and the southeastern and Balearic, and northeastern shelves; (2) the ESPACE project (Spanish Continental Shelf Research Project, initiated in 1999) which studies the Spanish continental shelf, producing a high-resolution map of the south and south-eastern Spanish continental shelf produced by the Spanish Oceanographic Institute and the General Secretariat of Maritime Fishing. (3) Ecocartography projects, funded by the Ministry of Agriculture, Food and Environment, carried out between 2000 and 2012 on the Gulf of Cadiz, Alboran Sea and the southeastern and Balearic continental shelves. (4) Map of the Mediterranean seabed released by the International Commission for the Scientific Exploration of the Mediterranean Sea (CIESM) in a 1:2,000,000 multibeam bathymetric syntheses (MediMap Group, 2005). (5) EMODnet (European Marine Observatory and Data Network). (6) Geomorphological Map of the Iberian Continental Margin at 1:2,000,000 scale, and (7)

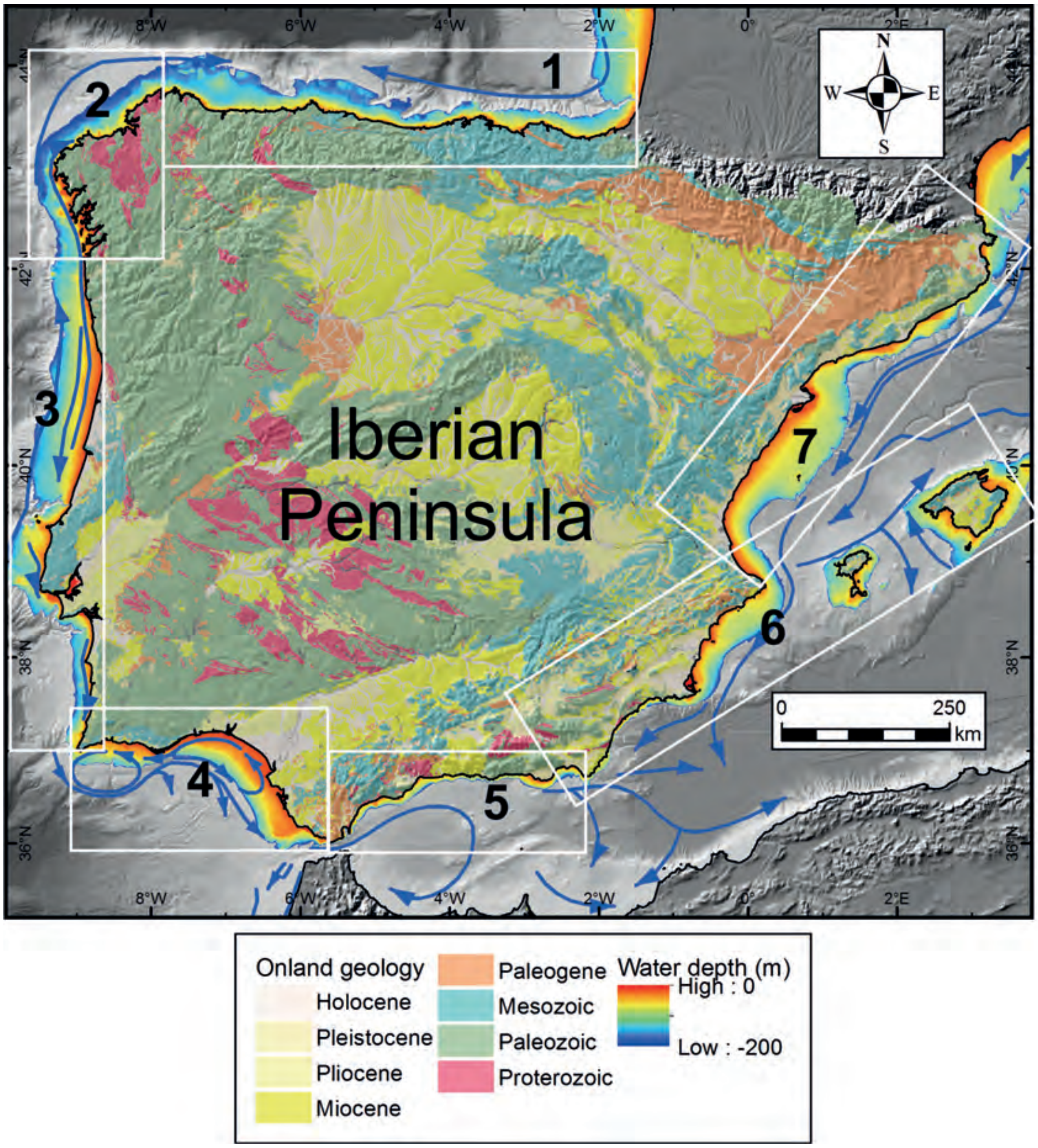


Figure 1. Shaded-relief map of the Iberian and Baleares margins showing inland geology and the gross bathymetry of the continental shelves. Blue arrows outline the ocean surface circulation. White boxes refer to the seven continental shelf sectors considered in this study. The inland geological map was extracted from the One Geology Project (http://www.onegeology.org/). The topographic data were extracted from the Global Topography Database (http://topex.ucsd.edu/index.html). The bathymetric data were extracted from the EMODnet portal (http://www.emodnet-hydrography.eu/). Surficial circulation patterns were compiled from several studies: Millot (1999), Peliz *et al.* (2002, 2005) and García-Lafuente *et al.* (2006).

Figura 1. *Mapas del relieve sombreado de los márgenes de Iberia y Baleares mostrando la geología de la zona emergida y la batimetría de las plataformas continentales. Las flechas azules indican la circulación oceánica superficial. Las cajas blancas muestran la localización de los 7 sectores de la plataforma continental estudiados. El mapa geológico terrestre proviene del Proyecto One Geology (http://www.onegeology.org/). Los datos topográficos son de la Global Topography Database (http://topex.ucsd.edu/index.html). Los datos batimétricos provienen del portal EMODnet (http://www.emodnet-hydrography.eu/). Los modelos de circulación superficial se han obtenido con datos de diferentes estudios: Millot (1999), Peliz et al. (2002, 2005) and García-Lafuente et al. (2006).*

MeshAtlantic project (Mapping European Seabed Habitat).

The goal of this paper is to present a wide picture of surficial morphological types and sediments along the Iberian and Balearic shelves, and to extract end-member cases according to the prevailing conditions of sediment supply and hydrodynamic regimes, superimposed to the background geological context.

Shelf sectors

The Cantabrian shelf: morphology and sediments

(a) Geological and oceanographic setting

Geological setting

The Cantabrian continental shelf is located in the northern margin of the Iberian Peninsula (Fig. 1). This margin is an abrupt type (Heezen, 1974) and has an east-west direction in relation to the tectonic events during the Palaeocene and Eocene, together with the Tertiary alpine orogeny (Ercilla *et al.*, 2008).

The north-south convergence of Europe and Iberia during the Cenozoic formed the Pyrenean-Cantabrian range, a collisional mountain chain composed of the Pyrenees in the east and its structural prolongation on land along the Cantabrian Cordillera in the west (Pulgar *et al.*, 1996). The latter consists of a Variscan basement block uplifted during the Alpine and the inverted Basque Cantabrian basin.

The southern margin of the Bay of Biscay became active during the Cenozoic convergence, producing an accretionary wedge at the base of the actual continental slope, the shortening and steepening of the continental slope and the partial inversion of the Mesozoic basins of the continental shelf. The syntectonic deposits of the accretionary wedge have been tentatively dated Eocene to Lower Miocene (Alvarez-Marrón *et al.*, 1996, Gallastegui *et al.*, 2002). Since the late Oligocene, the plate boundary between Europe and Africa shifted to the south, and the Bay of Biscay became part of the passive Atlantic margin. Recent uplift in the shelf and minor present day seismicity associated to NW-SE compression suggests that slight deformation persists (Cadenas *et al.*, 2012).

Structural features dominate the morphology of the continental shelf. Horsts and anticlines, found generally in Cretaceous rocks, form areas starved of soft Neogene sediments. Faults and synclines, filled with Tertiary materials, underlie sandy depressions (Pascual *et al.*, 2004). The outer section of the continental shelf is a sedimentary Neogene and Pleistocene prism, developed by progradation (Boillot *et al.*, 1984).

Climate and oceanography

The maritime climate along the Cantabrian coast is related mainly to its location within the Bay of Biscay and the NE Atlantic (González *et al.*, 2004b). In relation to its location and orientation, this part of the coast is exposed to large storms from the northwest, produced by evolution of the North Atlantic low-pressure systems. Northwestern strong swell waves dominate and are the most common sea state within the study area. During summer, with the extension of the Azores high-pressure system, the North Atlantic low-pressure formation sequence slows down, as its intensity lessens. On the basis of the Bilbao offshore buoy, Liria *et al.* (2009) summarised the wave climate, as described below.

(i) Summer (June-August): wave periods of less than 10 s over 75% of the time, with representative wave heights of 1.5 m, exceeding 2 m within less than 10% of the measurements.
(ii) Winter (December-February): high wave periods (i.e. 13 sec), with wave heights greater than 2 m over more than 50% of the time.
(iii) Spring and autumn are transitional periods, with intermediate characteristics.
(iv) Under extreme offshore wave conditions, significant wave heights can exceed 5 m (several times a year) and, occasionally, 10 m (with return periods of 20 years).

The tidal wave is semi-diurnal in character within the Cantabrian coast (Uriarte *et al.*, 2004). Along the Basque coast, the mean tidal range is approximately 1.65 m on neap tides and 4.01 m on spring tides (REDMAR, 2005). Despite the importance of tidally-induced surface water fluctuations, the contribution of the tides to the generation of currents is somewhat modest (except within the estuaries) (Uriarte *et al.*, 2004). Away from the estuaries, the tidal currents decrease, with water circulation being governed mainly by wind forcing fluctuations, over a wide range of meteorological frequencies, within the surface and sub-surface waters (Fontán *et al.*, 2009; Fontán *et al.*, 2008); however, even these are incapable of generating littoral sediment transport along the Basque coast (González *et al.*, 2004b).

The main water mass that affects the continental shelf is the Eastern North Atlantic Central Water (ENACW), which extends to depths of about 600 m.

Sediment sources

The Cantabrian margin can be considered as sediment-starved due to the great sediment evacuation over a relatively steep depositional profile. Sediment is eroded mostly from the Cantabrian Cordillera and transported by small streams/rivers to the sea. It bypasses the continental shelf and when the sediment reaches the slope it is transported through a major submarine drainage system down to the continental rise and adjacent Biscay abyssal plain (Ercilla *et al.*, 2008).

The main rivers in this margin are the Nervion, Deva, Navia and Nalon whose courses have a lengths ranging between 72 and 159 km and their river basins vary between 1 196 km^2 and 3 692 km^2. In terms of sediment supply, the 12 main rivers draining the Basque Country, discharge 1.57 10^6 t yr^{-1} of suspended material (Ferrer *et al.*, 2009; Uriarte *et al.*, 2004). The geomorphological and hydrological characteristics of the Basque estuarine water bodies are described in Valencia *et al.* (2004) and Borja *et al.* (2006).

(b) Shelf physiography

The Cantabrian continental shelf is very narrow (Fig. 2A), extending down to 180-245 m water depth and morphologically its edge is a sharp break, displaying a sinuous pathway in plan view (Ercilla *et al.*, 2008). The width varies between 4 and 17 km, tending to increase toward the west. The narrowest shelf sector is to the east of Lastres-Llanes Canyon, so that in the Basque Country it ranges from 7 km off Cape Matxitxako, to 25 km off the Oria River estuary (Uriarte, 1998). Its average slope is 1.6° and its maximum slope is 80° (Janeau, 2012).

In the shallow water zone, a continuous belt of a rocky seafloor is present, which is intersected only by sediment accumulations off the main estuary mouths (Fig. 2C). This shallow and highly roughened bedrock is associated with the coastal topography; it presents a slope of approximately 5.7°, following an inflexion point at 35-40 m water depth. Further offshore, the shelf extends with a milder slope (varying between 0.86° and 1.14°) and the rock shows lower rugosity (Galparsoro *et al.*, 2010).

The continental shelf break has been identified at an average depth of 185 m, presenting an average gradient value of 12°. Most of the slope area is carved by submarine canyons or gullies and thus has variable patterns (Janeau, 2012).

(c) Shelf morphology

A rocky seafloor represents 35% of the shelf area. The rock strata present different orientations in relation to the coastline. Over the western part, rock strata lie mainly perpendicular to the coastline, producing a low slope seafloor: the presence of coarse sand patches is common between the rock outcrops. Over the eastern part, the rock strata lie mainly parallel to the coastline (Fig. 3B), with a high dip generating a rectilinear coastline and the presence of cliffs. In this zone, a thin veneer of sand cover overlies the rock outcrop, which leaves the structural features of the underlying rock still visible. This seafloor type is complex and patchy, so it has been defined as a mixed bottom type (Galparsoro *et al.*, 2010).

There are several localized zones of rock outcrops, rising some 40 m above the surrounding seabed and 130 m wide.

Eight shoreline terraces have been identified on the rocky seafloor, corresponding to periods of sea-level still-stand, at approx.: -37 m, -52 m, -56 m, -70 m, -73 m, -75 m, -87 m and -92 m water depth (relative to the Local Datum, which is 2,016 m above spring low-tide level). The shallower terrace is the steepest and longest and extends continuously along the inner continental shelf (Galparsoro *et al.*, 2010). Above this water level, the rocky seafloor is very rough and constitutes the shallow rock belt (as described previously). Deeper shore terraces are gentler, whilst the rocky seafloor is flatter, in response to erosion at still-stand periods.

The rocky seafloor shows numerous incisions, of various sizes, that correspond to paleo-river channels (Fig. 3B). The channels are oriented generally shore-normal and are most likely associated with geomorphological features of the modern shoreline. Some of them incise across the entire width of the rocky shelf, up to a water depth of 85 m (Galparsoro *et al.*, 2010).

Infra-littoral prograding wedges (IPW) are present, associated with the mouths of the main rivers. The IPWs form a low-angle slope (0.6° on average), which represents the infralittoral prograding environment, extending to a strong break in slope at water depths of 30-35 m. This water depth corresponds to the mean level of the storm wave base (Galparsoro *et al.*, 2010). Another IPW is observable between -180 m and -225 m depth. This implies 45 m of vertical difference along a distance of 250 m creating a 10° gradient (Janeau, 2012).

Sorted bedforms (Diesing *et al.*, 2006; Lo Iacono and Guillén, 2008), or so-called "rippled scour depressions" (Cacchione *et al.*, 1984), are present as slightly depressed, elongated features, which lie perpendicular to the isobaths. The seafloor surface on the sorted bedforms is oriented mainly towards the north (approximately shore perpendicular); meanwhile, the surrounding sedimentary seafloor is oriented to the northwest, as a response to sediment remobilisation by wave action. Sorted bedforms are slightly depressed by up to 0.5 m with respect to surrounding fine sands. Most of the bedforms develop just outside the fair-weather surf zone water depth (20-25 m), up to water depths of 90-100 m. The largest of the bed-

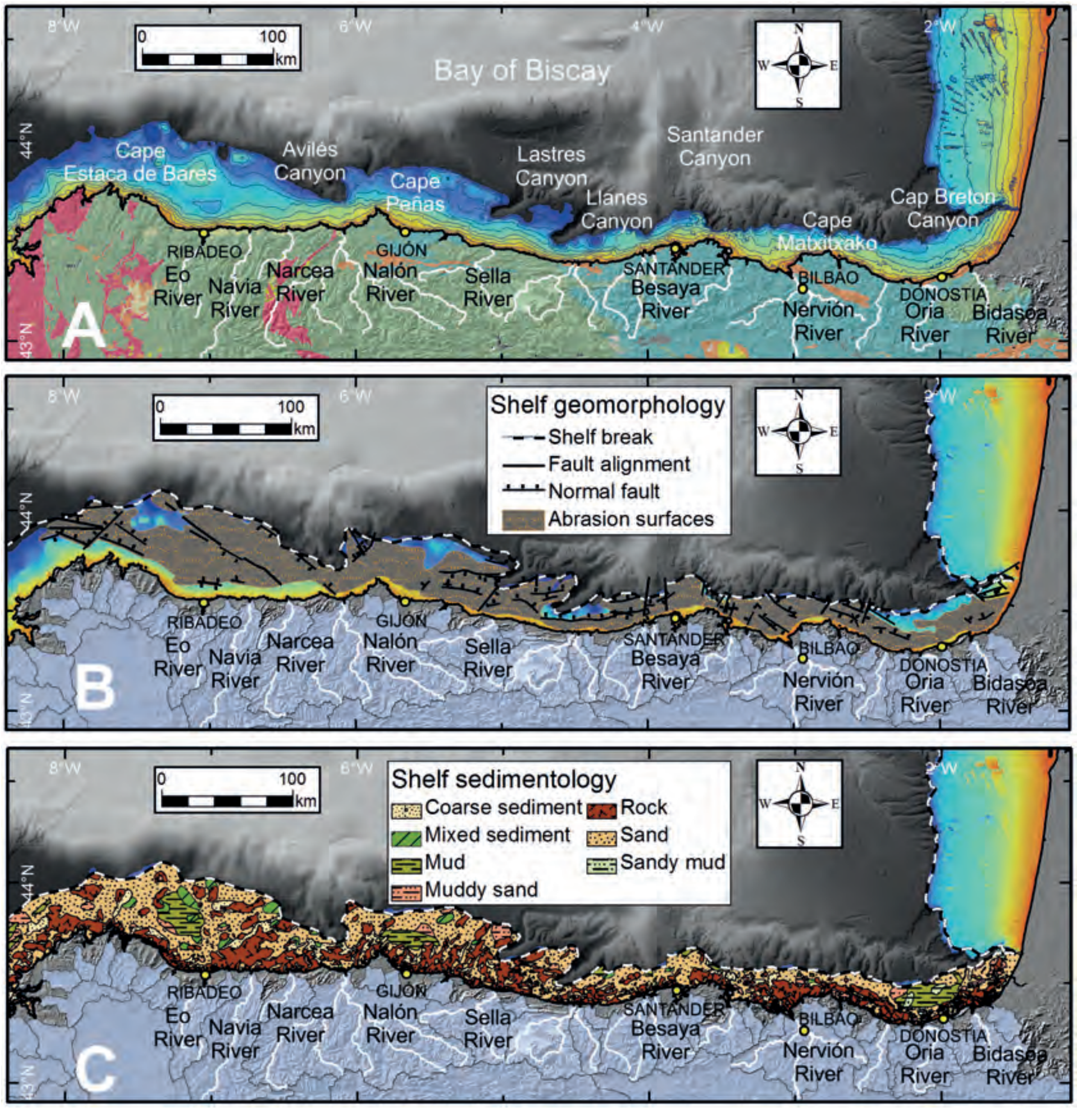


Figure 2. Synthetic morpho-sedimentary mapping of the Cantabrian shelf. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Shelf surficial sediment distribution; river systems and drainage basins are represented. Inland geology information included in Figure 2A extracted from the One Geology Project (http://www.onegeology.org/). Topographic data extracted from the Shuttle Radar Topography Mission portal (http://www2.jpl.nasa.gov/srtm/). Bathymetric data extracted from the EMODnet portal (http://www.emodnet-hydrography.eu/). Morphological features extracted from the Geomorphological Map of the Iberian Continental Margin at 1:2,000,000 scale by Maestro *et al.* (2013). Surficial sediment distribution extracted from the MeshAtlantic portal (http://www.searchmesh.net/).

***Figura 2.** Mapa morfosedimentario sintético de la plataforma continental cantábrica. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 2A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen del portal Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/). Los datos batimétricos son del portal EMODnet (http://www.emodnet-hydrography.eu/). Los tipos morfológicos se extrajeron del Mapa Geomorfológico del Margen Continental Ibérico a escala 1:2.000.000 realizado por Maestro et al. (2013). La distribución de sedimentos superficiales proviene del portal MeshAtlantic (http://www.searchmesh.net/).*

forms are around 1 650 m in width and 4 400 m in length (Galparsoro *et al.*, 2010).

Alongshore bars are identified as crescentic bars (quarter-moon type patterns, with the horns of the moon facing shoreward), as a result of the interaction with an alongshore rhythmic circulatory pattern

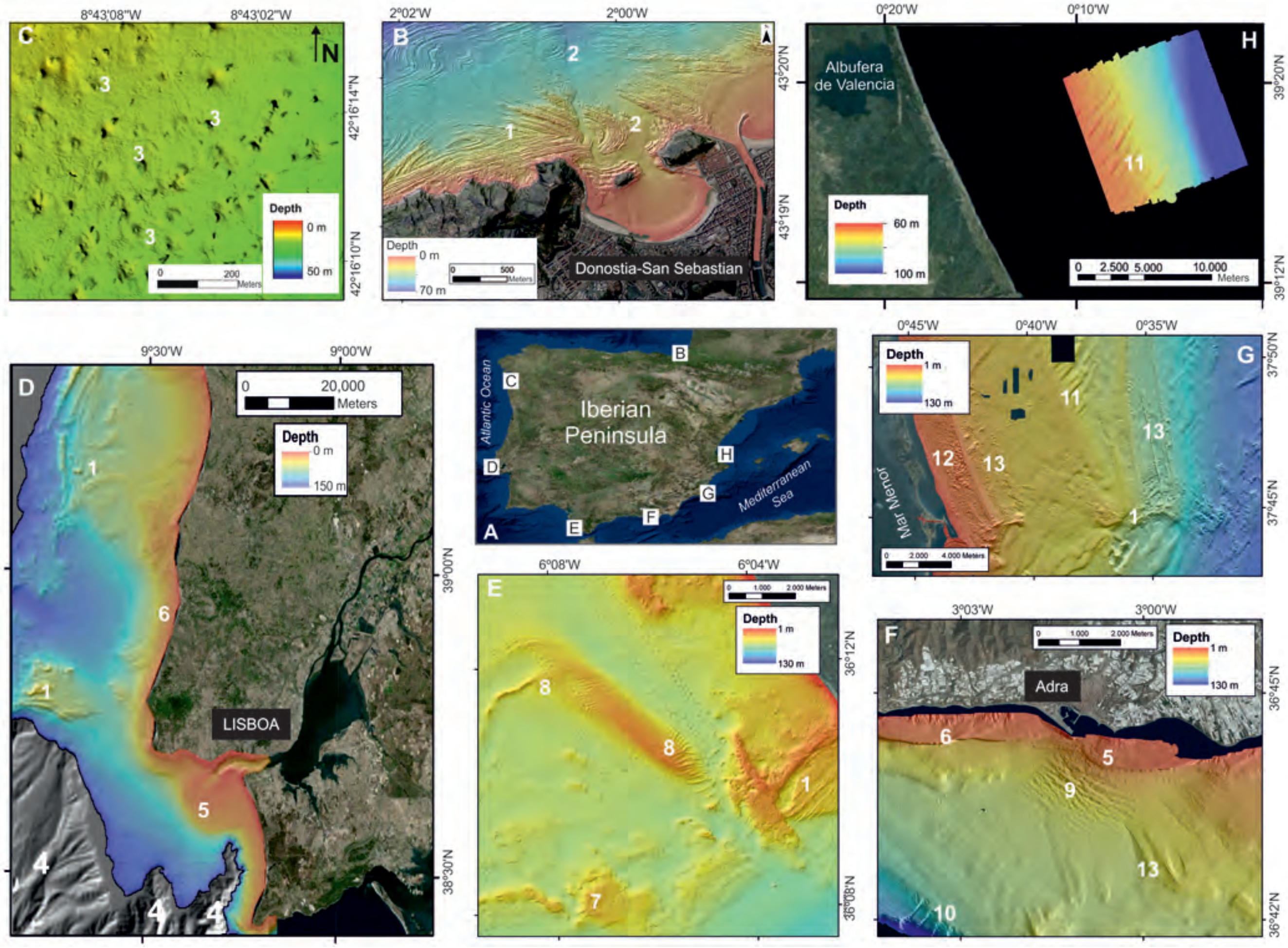


Figure 3. Colour-scaled bathymetry maps showing the main geomorphic features from different zones of the Iberian continental shelf. A) Geographical location of these zones marked with white boxes. B) Cantabrian shelf: structural features dominate the morphology of the rocky seafloor off La Concha Bay and surrounding area. The paleochannel corresponding to the Urumea River can be observed. C) Galician shelf: Pockmarks field identified in the Ria de Vigo (modified from Martínez-Carreño and García-Gil, 2013). D) The Portuguese shelf: Rocky outcrops predominate on the northern middle and outer shelf and depositional bodies prevail in the inner shelf. The shelf is interrupted by numerous canyons. E) Gulf of Cadiz shelf: rocky outcrops, erosional surfaces and large-scale bedforms (superimposed submarine dunes) cover the Barbate shelf. F) The Alboran shelf. Submerged deltaic bodies and infralittoral prograding wedges dominate the inner shelf. The seafloor undulations are common in the Mediterranean prodeltaic environments. Sand ridges and slumps are mainly located on the middle and outer shelf. G) The southeastern shelf. Seagrass meadows, sand ridges fields, elongated rocky ridges and outcrops are frequent off the Mar Menor area. H) The northeastern shelf. Sand ridges on the Valencia outer shelf (modified from Simarro *et al.,* 2015). Main geomorphic features: 1. Rocky outcrops. 2. Paleo-channel. 3. Pockmarks. 4. Submarine canyon. 5. Submerged deltaic body. 6. Infralittoral prograding wedge. 7. Erosional surfaces. 8. Bedform field. 9. Seafloor undulations. 10. Slumps. 11. Sand ridges. 12. Seagrass meadows. 13. Rocky ridges.

Figura 3. *Mapas batimétricos en escala de color mostrando los principales tipos geomorfológicos de diferentes zonas de la plataforma continental ibérica. A) Localización geográfica de estas zonas marcadas con unas cajas blancas. B) Plataforma continental Cantábrica: las morfologías de origen estructural dominan la morfología del fondo del mar rocoso frente a la bahía de La Concha y área adyacente. Se puede observar el paleocanal correspondiente al Río Urumea. C) Plataforma continental de Galicia: Campo de pockmarks identificados en la Ría de Vigo (modificado de Martínez-Carreño y García-Gil, 2013). D) Plataforma continental portuguesa: Los afloramientos rocosos predominan en la plataforma media y externa del norte y los depósitos sedimentarios prevalencen en la plataforma interna. La plataforma se interrumpe por la existencia de numerosos cañones. E) Plataforma continental del Golfo de Cádiz: Afloramientos rocosos, superficies de erosión y formas de fondo de gran escala (dunas submarinas superimpuestas) cubren la plataforma frente a la localidad de Barbate. F) Plataforma continental de Alborán: Depósitos deltaicos sumergidos y cuñas progradantes infralitorales dominan la plataforma interna. Las ondulaciones del fondo del mar son morfologías comunes en los ambientes prodeltaicos mediterráneos. Dorsales de arena y deslizamientos se localizan principalmente en la plataforma media y externa. G) Plataforma del sureste: Praderas de fanerógamas marinas, campos de dorsales de arenas, dorsales rocosas alargadas y afloramientos rocosos son frecuentes en la plataforma frente al Mar Menor. H) Plataforma noreste: Dorsales de arenas en la plataforma externa de Valencia (modificado de Simarro et al., 2015). Principales tipos morfológicos: 1. Afloramiento rocoso. 2. Paleocanal. 3. Pockmark. 4. Cañón submarino. 5. Depósitos deltaico sumergido. 6. Cuña progradante infralitoral. 7. Superficie de erosión. 8. Campo de formas de fondo. 9. Ondulaciones del fondo del mar. 10. Deslizamiento. 11. Dorsales de arena. 12. Praderas de fanerógamas marinas. 13. Dorsales rocosas.*

(Masselink and Short, 1993; Santiago *et al.*, 2013). Water depths vary between 2 and 4 m and the bars occur from 230 to 250 m from the shoreline; they range in width from 150 to 230 m. Bar crests in many of the locations follow the 4 m isobath (referred to local datum). It has been observed that single to double alongshore bars, together with troughs associated with the bars, originate as 1.5 m depressions (Galparsoro *et al.*, 2010).

(d) Shelf sediments

The sedimentary seafloor area corresponds to 64% of the shelf area. The continental shelf is a sedimentary Neogene and Pleistocene prism, developed by progradation (Boillot *et al.*, 1984). The shelf is covered by sandy sediments; these, in turn, isolate the exposed rocky areas of the seabed (Rey and Sanz, 1982) (Fig. 2C). Ten main sandbanks have been identified, which represent the extension of the present estuaries and have been identified as infra-littoral prograding wedges (IPW) (Galparsoro *et al.*, 2010). An extended shelf mud belt covers the middle and outer eastern Basque continental shelf (Jouanneau *et al.,* 2008).

The Galician shelf: morphology and sediments

(a) Geological and oceanographic setting

Geological setting

The Galician margin is a passive type continental margin connecting the northwestern corner of the Iberian Peninsula to the Atlantic Ocean (Fig. 1). It comprises, from land to sea, the rias (set of prolonged inlets in the shore), a narrow continental shelf, and a steep slope crossed-cut by several canyons (i.e. O Ferrol, A Coruña, Laxe, Muxia, Muros, Arousa, Pontevedra and Vigo).

The Galician region is a sediment-starved passive type margin with highly complex configuration as a result of successive tectonic episodes (Montadert *et al.*, 1974; Sibuet and Ryan, 1979; Mougenot *et al.*, 1984). It comprises the northwest part of the Variscan orogenic domain, characterized by the presence of deformed metamorphic and igneous rocks of Precambrian to Silurian age. Metasediments are glandular Gneisses of granitic origin formed from Variscan Granites and granodiorites resulting from the general magmatic evolution of the northwest of Spain (Capdevilla, 1980).

Two main phases of deformation associated with the Variscan Orogeny resulted in an axial schistosity plane followed by wide folding with N-S orientation. Post-Variscan evolution is mainly represented by the reactivation of many of the Variscan structures by Pyrenean tectonism associated with southerly-directed subduction along the southern side of the Bay of Biscay (Muñoz *et al.*, 2003). Many of these structures appear to have been rejuvenated during the Neogene Betic Orogeny (Muñoz *et al.*, 2003). Deformation on the shelf mainly comprises normal faulting, with possible compression (reverse faulting) being limited to the outer shelf (Muñoz *et al.*, 2003). This system of normal faults results in elongated and narrow blocks, which tilt northwards and slightly eastwards (Mauffret *et al.*, 1978; Boillot and Malod, 1988). Some of these faults were reactivated during the Miocene and Pliocene producing blocks tilting, and may even have been active until the Quaternary (Pannekoek 1966; De Aguirre and Butzer 1967; García-Gil *et al.* 1999).

The Rias Baixas (Fig. 4A) are structurally controlled by Tertiary river valleys, bounded by steep hills and mountains, incised during the low sea-level stands of the Quaternary and then drowned during the last transgression (Rey, 1993). They are characterized by SW-NE trending main structural axis (Fig. 4A) limited to the main fault systems and fractures (NE-SW, N-S and NNW-SSE), which appear as a result of a period of brittle deformation during the late stages of the Variscian and post-Variscian tectonic evolution. From a geological point of view, the basement corresponds to the Variscian Orogenic Belt, represented by the "Central Iberian Zone" and the "Galicia-Trás-os-Montes Zone" (Vera, 2004).

Climate and oceanography

High-energy oceanographic processes in a mesotidal regime characterize the Galician shelf (Vitorino *et al.*, 2002a). The meteorological dynamics are highly conditioned by the seasonal evolution of two atmospheric systems, the Azores High and the Iceland Low (Wooster *et al*,. 1976; Fiúza, 1982; Vitorino *et al.*, 2002a). In winter, the Azores High is displaced to the south and the Iceland Low is stronger, leading to highly energetic wave conditions, with significant wave heights exceeding 5 m during storms (Pires, 1985; PO-WAVES Group 1994), and to westerly winds, that often show a southerly component (Fiúza, 1982), establishing a downwelling regime over the shelf.

In summer, the Azores High is located offshore of the Iberian Peninsula and the Iceland Low is weaker, avoiding the storms that affect the Galician region. The summer wave regime is characterized by low energy wave conditions, with less significant wave heights of about 2 m (Vitorino *et al.*, 2002a).

The main surface current in the region is the Portugal Current (also named as the Canaries Current), which flows southwards at average speeds of 0.9-1.4 km/h (Dias *et al.*, 2002a, 2002b). On the continental slope, the main surface current is the Iberian Poleward Current (IPC) that flows northwards over 1,500 km along the Iberian margin (Frouin *et al.*, 1990; Haynes and Barton, 1990). In the middle continental shelf, persistent poleward bottom currents transport the fine-grained sediment resuspended by storms northwards (Drago *et al.*, 1998; Dias *et al.*, 2002a, 2002b).

Circulation in the Rias Baixas is characterized by a positive residual circulation pattern controlled by water exchange with the Atlantic Ocean, which results in a circulation in two layers. The upper current flows

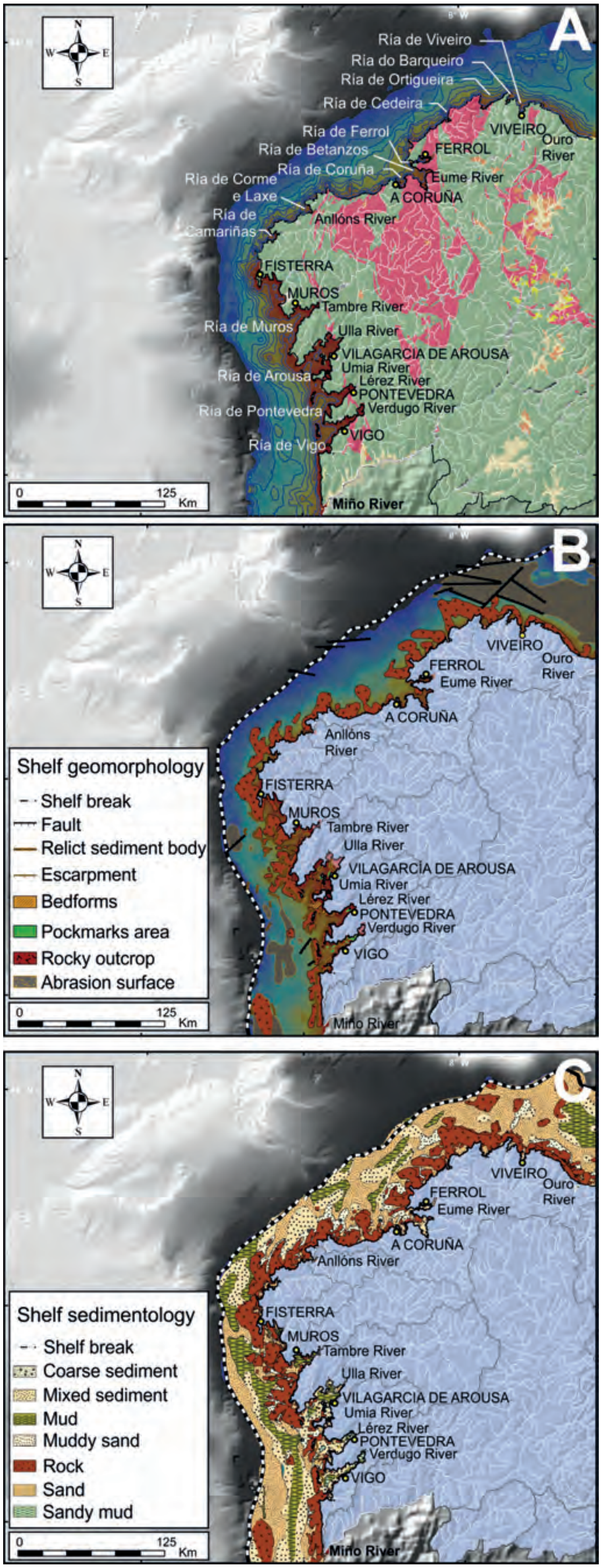


Figure 4. Synthetic morpho-sedimentary mapping of the Galician shelf. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Shelf surficial sediment distribution; river systems and drainage basins are represented. Inland geology information included in Figure 4A extracted from the One Geology Project (http://www.onegeology.org/). Topographic data extracted from the GEBCO digital database (IOC *et al.*, 2003). Bathymetric data extracted from the EMODnet portal (http://www.emodnet-hydrography.eu/). Morphological features compiled from different sources: Durán *et al.* (2000, 2001), Dias *et al.* (2002a, 2002b), García-García *et al.* (2003), Ferrín (2005), IGME (2005), Vilas *et al.* (2005), Díez *et al.* (2007), Lantzsch *et al.* (2009a, 2009b), Martínez-Carreño and García-Gil (2013) and the Geomorphological Map of the Iberian Continental Margin at 1:2,000,000 scale by Maestro *et al.* (2013). Surficial sediment distribution extracted from the MeshAtlantic portal (http:// http://www.meshatlantic.eu/).

Figura 4. *Mapa morfosedimentario sintético de la plataforma continental de Galicia. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la Figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 4A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen del portal de la base de datos digital GEBCO (IOC et al., 2003). Los datos batimétricos son del portal EMODnet (http://www.emodnet-hydrography.eu/). Los tipos morfológicos se extrajeron de diferentes fuentes: Durán et al. (2000, 2001), Dias et al. (2002a, 2002b), García-García et al. (2003), Ferrín (2005), IGME (2005), Vilas et al. (2005), Díez et al. (2007), Lantzsch et al. (2009a, 2009b), Martínez-Carreño and García-Gil (2013) y del Mapa Geomorfológico del Margen Continental Ibérico a escala 1:2.000.000 realizado por Maestro et al. (2013). La distribución de sedimentos superficiales proviene del portal MeshAtlantic (http://www.searchmesh.net/).*

towards the mouth of the rias, and the compensating bottom current circulates from the outer to the inner part of the rias (Rosón *et al.*, 1995). Connection with the ocean mainly takes place through the southern mouth delimited between the islands and the south coast of the ria. The rias coast experiences seasonal upwelling of cool nutrient-rich water from depths of less than 500 to 1 000 m along the coast and into the rias (Fraga, 1981). Upwelling generally occurs during spring-summer as the result of favourable southerly winds along the coast (Fraga, 1981) pumping cold nutrient-rich deep-water mass Eastern North Atlantic Central Water (ENACW) into the rias (Ríos *et al.*, 1992, Fiúza *et al.*, 1998). However, recent studies report autumn and winter upwelling (De Castro *et al.*, 2006) originating from the poleward current that flows along the Galician shelf (Alvarez *et al.*, 2003).

Sediment sources

The Miño River is the most important river supplying the Galician shelf region with a catchment area of 17 081 km^2 (Araújo *et al.*, 2002; Dias *et al.*, 2002a, 2002b; Sousa *et al.*, 2013) (Fig. 4). From the smaller rivers discharging into the rias very little sediment reaches the shelf, since the rias themselves trap most of the sediment (Rey, 1993; Ferrín, 2005).

The small size of the rivers and basins draining into the Rias Baixas is noteworthy, with the largest being the Ulla and Umia rivers, with drainage basins of 2 803 and 440 km^2 and mean flow rates of 79.3 and 16.3 m^3/s, respectively (Río and Rodríguez, 1996). In the Pontevedra and Vigo rias, the Lérez and the Oitavén-Verdugo rivers respectively, have lesser drainage basins (450 and 334 km^2) and mean flow rates (21 and 17 m^3/s).

Drainage networks have not been the subject of much research in Galicia in terms of suspended sediment loads and erosion rates of sediment budget. In spite of the importance of quantifying the different sedimentary loads of the rias, scarce budget data is available, particularly regarding the Vigo and the Pontevedra rias (e.g. Méndez and Rey, 2000; Pérez-Arlucea *et al.*, 2000, 2005).

(b) Shelf physiography

The Galician margin comprises a narrow continental shelf (30 km, with a shelf break at a depth of approximately 150 m) (Fig. 4A). The shelf is divided into three zones based on both depositional environments and morphologies (Vanney, 1977; Rey, 1993; Ferrín, 2005): the inner shelf (0-60 m) that includes the rias, the middle shelf (60-90m) and the outer shelf (from 90 m to the shelf edge). The islands located at the rias mouth represent the transition between the inner and middle shelf.

The inner shelf shows highly variable width due to the presence of the rias. The rias have valley geometry, with the deepest part located along the central axis. The seafloor relief of the rias displays high variability, especially the Ria de Arousa (Diez, 2006). The physiography is very irregular offshore rocky coasts, the northern entrance of the rias, and the surrounding the islands (gradients between 1.6 and 3.4°) due to the widespread occurrence of rocky outcrops (Fig. 4B) (Durán, 2005; Diez, 2006). Along the axis, the rias display a smooth seafloor (0.4° on average) that deepens seawards down to 60 m water depth at the entrance of the rias.

Outside the rias, the inner shelf is characterized by an irregular physiography determined by positive relieves corresponding to rocky outcrops, particularly off coastal headlands and cliffs, such as Costa da Vela or the coastline between the Ria de Vigo and the Miño River mouth; and smooth areas off beaches, such as La Lanzada, in Pontevedra. From the rias to the middle shelf, a series of bathymetric highs coincide with the alignments of the Cies, Ons and Salvora islands.

The middle shelf presents an average slope of 0.14° with a small increase to the north due to the presence of isolated rocky outcrops. The outer shelf extends to the shelf break, with water depths of between 165 and 200 metres (Fig. 4A). It forms a re-entrant arc between 42° and 42°40'N, which can be indicative of large-scale slumping (Ferrín, 2005).

(c) Shelf morphology

The Galician shelf is considered to represent a low-accumulation sedimentation system (Ferrín, 2005; Lantzsch *et al.*, 2009a). It displays a complex morphology with varying characteristics across the shelf from the rias to the slope that is strongly controlled by tectonic features.

The rias show a complex morphology determined by the occurrence of erosional and/or non- depositional and depositional features, such as rocky outcrops, clastic wedges corresponding to infralittoral prograding wedges and delta-like shape morphologies, large areas of fine and coarse sediment, and sediment waves (García-Gil *et al.*, 2000; Durán *et al.*, 2000, 2001; García-García *et al.*, 2003). Rocky outcrops, both igneous and metamorphic, dominate the shallower areas of the rias, mostly surrounding coastal headlands, near the islands and in the rias mouths, particularly the northern margins of the rias (Fig. 4C). Elongated to curved morphological steps corresponding to infralittoral prograding wedges have been described along the inner shelf. Additionally, delta-like shape morphologies have been observed at the east face of the islands, such as Cies and Ons, showing mainly eastward progradation (García-Gil *et al.*, 1999, 2000; 2011; García-García, 2001; Durán, 2005).

Different types of bedforms have been identified in areas of sandy sediments; these include sorted bedforms and subaqueous dunes (Durán *et al.*, 2001; Diez, 2006). They are mostly located in the outer part of the rias and particularly between the Pontevedra and Arousa rias. Finally, morphological features associated with gas, such as pockmarks are common in the rias (Fig. 3C). Many of them are small (< 10 m in diameter), but they can be even larger than 50 m in diameter (García-García *et al.*, 1999; García-Gil *et al.*, 2002; García-Gil, 2003; Ferrín *et al.*, 2003; Diez *et al.*, 2007; García-Gil *et al.*, 2011; Martínez-Carreño and García-Gil, 2013). They appear distributed along the main axis of the Ria de Vigo, in the innermost part of the Ria de Pontevedra and covering large areas in the Ria de Arousa (Fig. 4B).

A gravelly sand belt parallel to the lineation of plutonic and/or metamorphic outcrops separating the shelf from the rias characterizes the transition between the inner and the middle shelf (Ferrín, 2005). In the continental shelf, the basement is displaced by normal faults into narrow (10-20 km), elongated (60-100 km) tilted blocks trending northward and slightly eastward, forming a series of half graben that control the present day morphology (Montadert *et al.,* 1974; Sibuet and Ryan, 1979).

Outer shelf sediment bodies comprise both relict deposits (Pannekoek, 1966, 1970; Hinz, 1970) as well as recent deposits, which have originated different bottom structures, mainly wavy bottoms and thin sandy bars (Ferrín, 2005). Multiple erosional surfaces coexist along the modern shelf depositional profile. These are related to superimposed periods of erosion, which affected the rocky basement and the Tertiary outcrops (Dupeuble and Lamboy, 1969; Lamboy and Dupeuble, 1971, 1975).

(d) Shelf sediments

Grain-size distribution of sediments in the rias seems to be conditioned by bathymetry, waves, river and tidal currents. Generally, fine sediments characterize the inner zone of the rias (Fig. 4C). Muddy sediments also align with the central axis of the rias, with increasing concentrations in those areas protected from wave action. Biogenic carbonate content decreases in estuarine areas or near the river mouths, where siliciclastics predominate. Spatial distribution of facies varies between different rias, giving discharge and river drainage differences. The Ria of Arousa presents the highest siliciclastic content, controlled by the Ulla and Umia rivers. In the Pontevedra and Vigo rias, however, the Lérez and the Oitavén-Verdugo rivers respectively, have smaller drainage basins and mean flow rates, deriving in a lesser siliciclastic content (Vilas *et al.*, 2005). Large, smooth areas of coarse sediment occur in the outer part of the Ria de Vigo and Ria de Arousa suggesting high-energy deposition (García-García *et al.*, 2003; Diez, 2006). In the Ria de Pontevedra, these areas of coarse sediment occupy almost the whole seafloor (up to 55% of the seafloor) (Durán, 2005). Smooth areas of fine sediment occur along the main axes of the Ria de Vigo and Ria de Arousa (covering almost 45 % of the seafloor), as well as in the innermost part of the Ria de Pontevedra, suggesting a low-energy deposition.

At the middle shelf, a large patch of muddy sediment, named as "Galicia mud patch" or "Galicia mud belt" (GMB), is located at an average depth of 120 m (Fig. 4C; Dias *et al.*, 2002a, 2002b; Ferrín, 2005; Lantzsch *et al.*, 2009a, 2009b) with the central part of the GMB situated between the Ria de Pontevedra and the mouth of the Minho River. The polewar current that moves river-derived fine sediments northwards can explain the GMB location. Sediments discharged by the Miño River are transported onto the Galician shelf. Coarse-grained sediments delivered by the Miño River settle near the river mouth, whereas fine-grained particles can be carried to greater distances. Fine-grained fluviogenic sediments are frequently resuspended by winter storms and transported to the north by the poleward-flowing bottom current (Dias *et al.*, 2002a, 2002b). This availability of fine sediments leads to the development of well-defined areas of mud deposition at around 100 to 120 m modern water depth (Dias *et al.*, 2002a, 2002b; Oliveira *et al.*, 2002a).

The Portuguese shelf: morphology and sediments

(a) Geological and oceanographic setting

Geological setting

The genesis and morpho-structural evolution of the western Portuguese continental margin is closely linked with the formation of the Lusitanian Basin. By the end of the Carboniferous and during the Lower

Permian intense deformation and fracturing associated with the Variscan Orogeny occurred. Continental rifting began in the Late Triassic related to the opening of the North Atlantic and spanned until the Early Cretaceous due to extensional forces. The post-rift phase initiated with oceanic crust formation in the Late Cretaceous, when a passive margin was finally set. During the Paleogene the extensional basins formed during the Mesozoic rifting phases were inverted due to the compressional regime imposed by the Alpine orogeny with consequent formation of the Pyrenees and the Betic chains. The Miocene was marked by localized subsidence of some individual sectors of the continental margin, whereas others suffered uplift related to the last betic phase (Lepvrier and Mougenot, 1984; Mougenot, 1989). Finally, this compressional phase was then responsible for higher sediment inputs that culminated in the progradation and establishment of the western Portuguese continental margin as a general monocline structure characterized by diversified outcropping lithologies.

The northern continental margin down to Cape Mondego is mainly characterized by formations of Cretaceous and Cenozoic age that lie on top of Variscan Pre-Cambrian and Palaeozoic rocks (Fig. 1). The stratigraphic contact between them corresponds to an inversion fault (Rodrigues and Ribeiro, 1992, 1993, 1994) of SSE-NNW to N-S direction that is the likely prolongation of the Porto-Tomar fracture zone (Lefort *et al.*, 1981; Cabral and Ribeiro, 1989). In the middle shelf, from the mouth of the Minho River to Aveiro these younger formations correspond to Upper Eocene-Pleistocene lithologies, and to Cretaceous lithologies from Aveiro to near Cape Mondego. In the outer shelf there are a series of outcrops following the general N-S alignment of the adjacent coast that date back to the Miocene and Pleistocene (Boillot *et al.*, 1978). Immediately to the south of Cape Mondego, the shallower shelf domains are characterized by Plio-Pleistocene formations, whilst formations of Palaeogene, Neogene and Pleistocene age outcrop on the middle and outer shelf. Deposits from the Jurassic and Cretaceous occupy most of the continental margin south of the Nazare Canyon and until close to Ericeira. Between Ericeira and the Tagus estuary mouth Mesozoic lithologies constitute the inner-middle shelf domain, whilst Neogene and Pleistocene formations dominate the outer shelf. Between Setubal and Cape Sao Vicente, Mesozoic and Cenozoic formations dominate the continental shelf. These formations are affected by late-Variscan fault systems (oriented NE-SW to NNE-SSW) of Carboniferous age (Boillot *et al.*, 1975) that were reactivated during the Atlantic second episode of rifting (Mougenot *et al.*, 1979). The detritic formations from the Neogene and the Quaternary that outcrop throughout the middle and outer shelf to the north of Arrifana lie in discordance over Variscan and Mesozoic rocks.

Climate and oceanography

The climate is Mediterranean with Atlantic influence, characterized by hot, dry summers and mild winters during which most of the rain falls. Average annual rainfall is higher in the north and lower in south of Portugal, ranging between 2 212 mm in the Cavado and 667 mm in the Mira River basins, respectively (Dias, 1987). The western Iberian margin is subject to the influence of larger-scale annual and decadal changes such as the North Atlantic Oscillation (NAO) (e.g. Hurrell, 1995; Luterbacher *et al.*, 2001). A more persistent positive phase of the NAO enhances upwelling, conditions (e.g. Abrantes et al, 2005; 2011; Lebreiro *et al.*, 2006; Bartels-Jónsdóttir *et al.*, 2009), whereas a persistent negative phase results in more rainfall and subsequent enhanced floods in winter (e.g. Trigo *et al.*, 2002; 2004).

The wave regime is characterized by high, energetic conditions that exceed 5 m during winter and low, energetic conditions of about 2 m during summer (Costa et al, 2001; Vitorino *et al.* 2002a, b). It is dominated by swells from the northwest, with 73% of the occurrences at Figueira da Foz (north-western coast) and 77% at Sines (south-western coast). The annual average peak is around 11s in both locations. Less frequent are western waves making up about 19% of the occurrences (Costa et al, 2001). However, periods of extreme wave conditions (significant wave height >5 m), promoted by storms, are associated with prevailing southerly winds and downwelling conditions (Vitorino *et al.*, 2002a). Tides are semidiurnal and the regime is mesotidal. The average neap tidal range is 1 m and the average spring tidal range is 2.8 m, however, significant tidal variations occur along particular segments of the coast, especially at estuaries and lagoons.

The Portugal Current System, a descending branch of the North Atlantic Drift, dominates the Atlantic Iberian coast. However, the patterns of circulation are complex, showing different behaviour in summer and in winter. During the summer, the Portugal Coastal Current is 30- 40 km wide and 50-100 m deep, flowing southwards in the vicinity of the shelf break (Ambar and Fiúza, 1994; Álvarez-Salgado *et al.*, 2003). This current is driven by the upwelling, which is favoured by northerly winds during the summer, in connection with the dynamics of the Azores anticyclone and the seasonal migration of the subtropical front (Fiúza *et al.*, 1982; Fiúza, 1983; Relvas *et al.*, 2007). During the upwelling season, a warm, counter current may occur over the inner shelf in the south of the west coast, coming from the Gulf of Cadiz and associated with periods of weakening or relaxation of the upwelling due to the favourable winds (Relvas and Barton, 2002; 2005). During the winter, outside the upwelling season, a poleward current flows along the Iberian slope and the outer shelf (Peliz *et al.*, 2005 and references therein). Additionally, prevailing southerly winds may also force a downwelling regime over the middle shelf (Vitorino *et al.*, 2002a). The continental fresh-water input, which is mainly to the northern continental shelf, can result in buoyant plumes that develop into inshore currents (Peliz *et al.*, 2002; 2005; Relvas *et al.*, 2007; Otero *et al.*, 2008).

Sediment sources

The principal sediment source to the western Portuguese continental shelf is fluvial supply, with the most important contributions coming from (from N to S) the Minho, Lima, Cavado, Ave, Douro, Vouga, Mondego, Tagus, Sado and Mira rivers (Fig. 5). In the north, the Douro and the Minho rivers are the main sources of fine sediments to the shelf, the Douro being responsible for about 80% of this supply (e.g. Araújo *et al.*, 2002; Dias *et al.*, 2002a, b; Jouanneau et al, 2002; Oliveira *et al.*, 2002b), estimated to be about 2.25×10^6 t year^{-1} (Oliveira *et al.*, 1982) and with an average transport capacity of 0.5×10^6 m^3 year^{-1} at the river mouth (Portela, 2008). To the south, the Tagus River delivers the highest average of suspended sediment load to the shelf of approximately 4×10^5 t year^{-1} (Vale and Sundby, 1987). The Sado River is the second most significant source, although the concentration of suspended particulate matter at its mouth is four times lower than at the Tagus mouth (Jouanneau *et al.*, 1998). The sediment input of these rivers to the shelf is very irregular, with the highest inputs occurring during winter floods (e.g. Dias and Nittrouer, 1984).

The other important regional sediment source is the southward littoral drift, induced by the waves from W-NW, with a potential transport capacity of 2×10^6 m^3 year^{-1} (Oliveira *et al.*, 1982). This potential transport is variable along the coast, according to the coastline orientation, gradually decreasing southwards (e.g. Andrade *et al.*, 2002).

(b) Shelf physiography

The Atlantic Portuguese continental margin covers an area of around 23 500 km^2 (Dias, 1987). The margin is ca. 550 km long (Dias, 1987), and narrow, with widths varying from less than 5 km in front of Cape Espichel to more than ca. 80 km off Vila de Nova de Milfontes (Magalhães, 2001) (Fig. 5A). The general water depth of the shelf edge is somewhat irregular as it varies between about 120 m and over 500 m at a few locations (Magalhães, 2001). The average slope of the shelf is between ca. 0.17° and 0.63° (Monteiro, 1971) and the relief is in general regular and smooth, with the bathymetry being approximately parallel to the coastline. This configuration is only disturbed off the mouth of the most important rivers, where submerged deltas (Fig. 3D) may develop, and near the submarine canyons that cut through the shelf.

From the Minho River mouth down to near the Nazare Canyon, the continental margin has a mean width of between 35 km and 60 km (Dias, 1987), broadening southwards and reaching its maximum value in front of Cape Mondego, where the shelf edge is well marked at a water depth around 160 m (Musellec, 1974) (Fig. 5A). In this area, the bathymetry has simple contours and runs parallel to the coastline. Three main submarine structures are defined in the shelf, namely the Porto, Aveiro and Nazare canyons, at water depths of 130 m for the first two, and of 50 m for the latter (Dias, 1987). Between the Nazare Canyon and Cape Raso, the shelf mean width varies from only 15 km near the canyon, to 70 km in the area of Ericeira which is more or less at mid-distance from those locations. The margin follows a much more irregular bathymetry in this area, although the only important geomorphological feature is the Nazare Canyon, at its northern limit. From Cape Raso to the Setubal Canyon, the continental margin assumes a very complex bathymetrical configuration that is conditioned by the submerged deltas of both the Tagus and the Sado rivers, and also by the presence of three important submarine canyons (Fig. 3D). The Cascais, Lisbon and Setubal canyons are set at water depths of 150 m, 40 m and 50 m, respectively (Dias, 1987). The range of values for the width of the shelf is the smallest in this area, from only 5 km to 30 km (Dias, 1987). Finally, the shelf between the Setubal Canyon and Cape Sao Vicente is again regular. The mean width ranges from ca. 20 km to 90 km (Dias, 1987), the narrower areas being near the Setubal Canyon, to the north, and Cape Sao Vicente, to the south, whilst the more extensive area is immediately southwards of Cape Sines. The only significant geomorphological feature

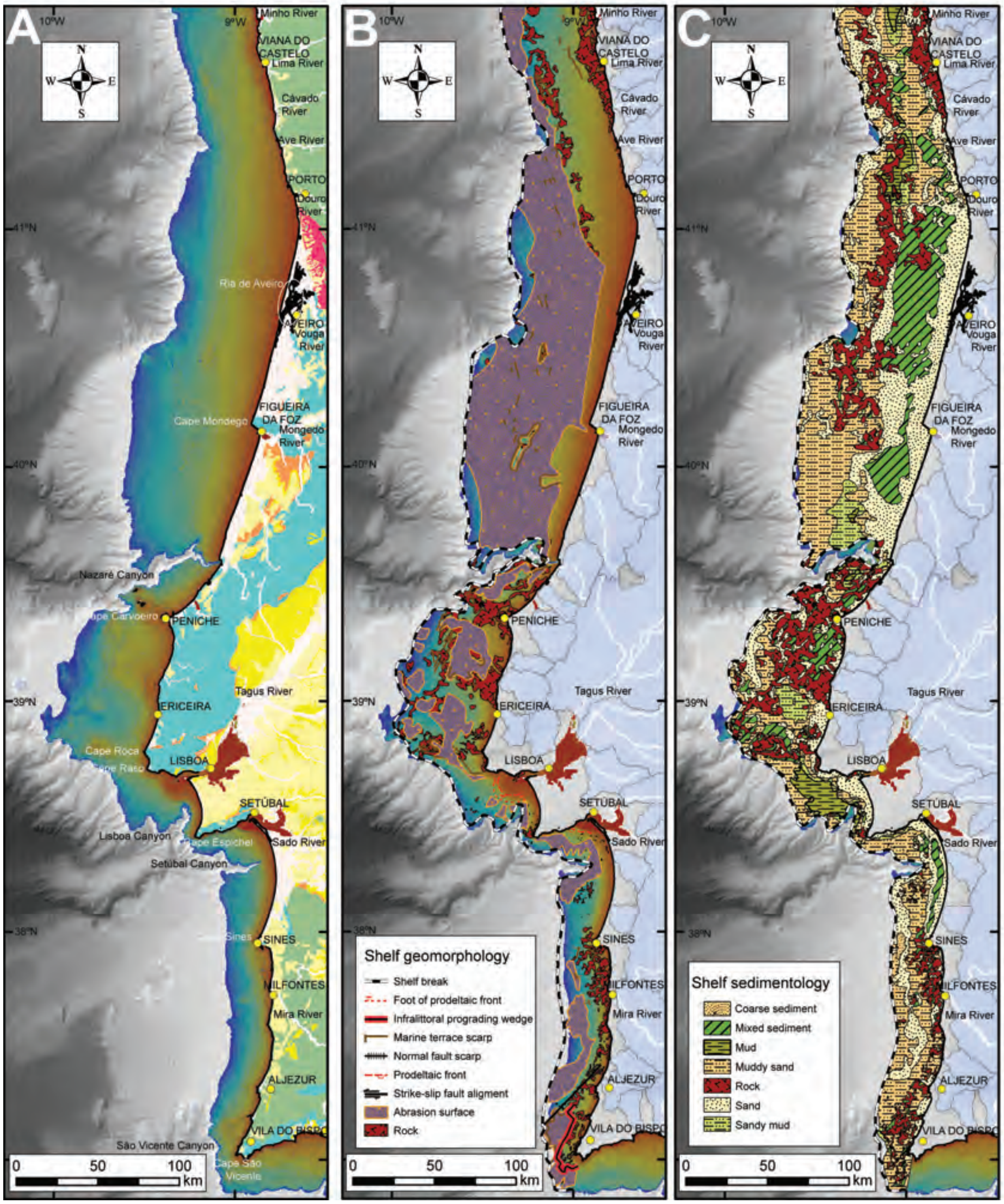


Figure 5. Synthetic morpho-sedimentary mapping of the western Portuguese shelf. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Shelf surficial sediment distribution; river systems and drainage basins are represented. Inland geology information included in Figure 5A extracted from the One Geology Project (http://www.onegeology.org/). Topographic data extracted from the Shuttle Radar Topography Mission portal (http://www2.jpl.nasa.gov/srtm/). Bathymetric data extracted from the EMODnet portal (http://www.emodnet-hydrography.eu/). Morphological features extracted from the Geomorphological Map of the Iberian Continental Margin at 1:2,000,000 scale by Maestro *et al.* (2013). Surficial sediment distribution extracted from the MeshAtlantic portal (http://www.meshatlantic.eu/).

Figura 5. *Mapa morfosedimentario sintético de la plataforma continental al Oeste de Portugal. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la Figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 5A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen del portal Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/). Los datos batimétricos son del portal EMODnet (http://www.emodnet-hydrography.eu/). Los tipos morfológicos se extrajeron del Mapa Geomorfológico del Margen Continental Ibérico a escala 1:2.000.000 realizado por Maestro et al. (2013). La distribución de sedimentos superficiales proviene del portal MeshAtlantic (http://www.searchmesh.net/).*

is the São Vicente Canyon, north of the cape with the same name, which is at a water depth of 300 m (Magalhães, 2001), thus being the deepest along the whole western Portuguese margin.

(c) Shelf morphology

On the northern Portuguese shelf outcrops of Palaeozoic rocks appear along the entire inner shelf, extending down to water depths of 70 m, and of Late Cretaceous to Pleistocene rocks on the outer shelf (Rey, 1993; Dias *et al.*, 2002a, b; Oliveira *et al.*, 2002b). Two main mud deposits occur on the mid-shelf, the Douro and Galicia mud bodies, strongly influenced by the shelf morphology as the rocky outcrops act as sediment traps (Dias *et al.*, 2002a, b; Lantzsch *et al.*, 2009b; 2010). Furthermore, pocket deposits also occur related with the rocky outcrops (Dias, 1987). Additionally, the shelf is marked by specific littoral morphologies associated with relict deposits that correspond to ancient coast lines situated at different depths, which are related with sea-level variations (Rodrigues *et al.*, 1991). The margin in front of the Tagus and Sado rivers is characterized by a narrow shelf incised by numerous canyons and by a large mud deposit that is supplied by the inputs of both estuaries (Jouanneau *et al.*, 1998) (Fig. 5B). The southern shelf from the Setubal Canyon to Cape São Vicente has a general morphology composed of a series of inclined surfaces that correspond to 300 m-thick deposits from the Neogene. These deposits coincide with large plateaus and progradational surfaces that spread along the margin (Baldy, 1977; Vanney and Mougenot, 1981; Magalhães, 2001). The continental shelf north of the Nazare Canyon drains into Iberian abyssal plain, mainly through the three submarine canyons (Porto, Aveiro and Nazare). The outflow from the shelf between the Cape Raso and the Cape São Vicente is directed towards the Tagus abyssal plain. The exception occurs in the São Vicente Canyon, which is connected to the Ferradura abyssal plain (Dias, 1987).

(d) Shelf sediments

Sand-sized sediments generally dominate the western Portuguese shelf (Dias, 1987). Gravel-dominated deposits occur only to the north of Cape Raso (near Lisbon) in several inner- to mid-shelf areas, whereas clayey sediments dominate some deposits to the south of Cape Raso, associated with predominantly silty deposits (Dias, 1987). These fine sediments form significant mud bodies that develop in the mid-shelf around water depths of 100-120 m, off the main rivers (Minho, Douro, Tagus and Sado), usually being oriented N-S due to the northwards transport of the fine sediments along the mid- and outer-shelf by a poleward flowing bottom current (Dias, 1987; Magalhães, 2001; Jouanneau *et al.*, 2002; Dias *et al.*, 2002a, b) (Fig. 5C). Particularly in the northern shelf, several rocky outcrops are aligned to the coastline, around the 70 m isobath and act as barriers that prevent the drift of the fine-grained material to the west (Fig. 3D), towards the shelf break (Dias, 1987; Dias *et al.*, 2002a, b). Sand-sized deposits tend to dominate the inner shelf, where they are reworked and transported southwards by high energy currents associated with the littoral drift (Jouanneau *et al.*, 1998; Dias *et al.*, 2002a, b). A mixture of sandy and muddy sediments typically dominates the outer shelf down to the shelf break (Dias, 1987; Jouanneau *et al.*, 1998; 2002; Magalhães, 2001). However, in many areas both on the north and on the south outer margins, coarser (sandy and gravelly sands) relict sediments that are remnants of an ancient shoreline with ca. 16,000 years appear as seabed features (Dias, 1987; Jouanneau *et al.*, 1998; Magalhães, 2001; Dias *et al.*, 2002a).

The Gulf of Cadiz shelf: morphology and sediments

(a) Geological and oceanographic setting

The Gulf of Cadiz is a wide embayment of the northeast Atlantic Ocean connected to the Mediterranean Sea through the Strait of Gibraltar. The Iberian margin of the gulf stretches from Cape São Vicente in the west to the Strait of Gibraltar in the east (Fig. 1).

Geological setting

The Gulf of Cadiz is located close to the eastern end of the Azores-Gibraltar Fracture Zone that is part of the Eurasia-Africa plate boundary (Sartori *et al.*, 1994). A tectonically active margin was established from the Late Eocene to the Early Miocene, as Iberia became a plate independent from Africa and the gulf was part of the extensive area of deformation located along a transcurrent fault system (Maldonado *et al.*, 1999). The most significant tectonic event affecting the gulf was the emplacement of a giant allochtonous unit off the Strait of Gibraltar, or olistostrome in early studies (Maldonado *et al.*, 1999), interpreted by Gutscher *et al.* (2003) and Duarte *et al.* (2013) as an accretionary wedge during the Late Miocene as a consequence of the N-S to NNW-SSE convergence between Iberia and Africa and the westward displacement of the Betic-Rifean Arc (Roberts, 1970; Torelli *et al.*, 1997; Medialdea *et al.*, 2004). Since then, this seismically-active area has been under convergence, and it is the source of large earthquakes and tsunamis (e.g. the 1755 Lisbon earthquake) (Gràcia *et al.*, 2003).

Climate and oceanography

The climate is Mediterranean with Atlantic influence. Average annual rainfall is below 600 mm, with two maxima in autumn and spring (Cendrero *et al.*, 2005). Episodic floods play a major role in the supply of sediment from the river basin to the continental shelf (Morales, 1997; Portela, 2006).

Wave climate can be classified as of medium to low energy. Dominant waves approach from the west and southwest (about 71% of occurrences); southeast waves are less frequent (about 23% of occurrences) but more energetic (Costa *et al.*, 2001). The coast is mesotidal with a tidal range between 0.2 m and 3.8 m (e.g., González *et al.*, 2001). On the shelf, bi-directional tidal currents show increasing intensity toward the Strait of Gibraltar, with measured velocity values of around 1 m/s (Besio and Losada, 2008).

The surface circulation is governed by a branch of the larger-scale Portuguese-Canary Eastern Boundary Current (core N2), which leads to a general anticyclonic circulation due to the southeastward movement of the surface Atlantic water (SAW) (Criado-Aldeanueva *et al.*, 2006; García-Lafuente *et al.*, 2006). This branch enters the Mediterranean Sea through the strait (i.e., Atlantic Inflow) to balance evaporation and buoyancy losses within this sea and countering the outflow of Mediterranean water (Criado-Aldeanueva *et al.*, 2006).

Warm shelf waters (WSW) may occur on the shelf, when the SAW is influenced by continental freshwater inputs, generating warmer water masses (Criado-Aldeanueva *et al.*, 2006). A cyclonic circulation occurs to the east of Cape Santa Maria, generated by a shelf-break front (core N1) seaward and by a coastal counter-current (CCC) composed of WSW. A cyclonic eddy (SVE) is identified between capes São Vicente and Santa Maria (García-Lafuente *et al.*, 2006).

Sediment sources

In the coast between Cape São Vicente and the town of Quarteira, Mesozoic cliffs are made up of fossiliferous carbonate sandstones of early middle Miocene age, and progressively substituted to the east by less-consolidated late Miocene sandstones (Vanney and Mougenot, 1981), only interrupted by small fluvio-estuarine systems, such as the Arade Estuary (Moita, 1986).

The erosion of those poorly-consolidate cliffs acts as a source of coarse sediments to the shelf and to the Ria Formosa barrier islands, composed of five barrier islands and two peninsulas extending about 50 km between Quarteira and Tavira (Rosa *et al.*, 2013). Low-lying sandy beaches and some small estuaries, such as the Gilao Estuary, make up the coast between Tavira and the Guadiana River mouth.

The most significant fluvial supplies to the northern Gulf of Cadiz occur in the middle section, sourced by the Guadiana, Piedras, Tinto-Odiel and Guadalquivir rivers. The Guadalquivir River is the fluvial system with the highest mean water discharge (164 m^3s^{-1}) (Palanques *et al.*, 1995). Piedras and Tinto-Odiel rivers feed the coastal stretch between the Guadiana and Guadalquivir rivers, with low mean annual discharges, i.e. 1-10 m^3s^{-1} (Borrego *et al.*, 1995; Palanques *et al.*, 1995).

The fluvial discharge of rivers of this area is very irregular, with significant seasonal and interannual variability. As an example, the Guadiana River peak discharges occur in winter months, with values higher than 3,000 m^3s^{-1}, and very low discharges, of around 10 m^3s^{-1}, in summer months (Palanques *et al.*, 1995; Morales, 1997).

To the south of the Guadalquivir River, the main coastal forms are extensive beaches interrupted by small cliffs, whose erosion provides most of the sediment supply (López-Galindo *et al.*, 1999). The main rivers are the Guadalete River sourcing the Bay of Cádiz and the Barbate River. To the south of Cape Trafalgar, abrupt cliffs carved on the Betic Ranges dominate the coast.

Another important regional sediment source is the littoral drift, which produces an eastward- and southeastward-directed sediment transport from the southern Portuguese coast toward the eastern part of the gulf of around 180×10^3 m^3yr^{-1} (Morales, 1997; González *et al.*, 2001).

(b) Shelf physiography

The western shelf of the gulf off the Portuguese coast is narrow with variable widths; its minimum width (5-7 km) occurs off Cape Santa Maria (Moita, 1986). Its average slope is 0.4° and its maximum slope is 1.5° (Roque, 1998). The shelf break is located at water depths of 110-150 m (Vanney and Mougenot, 1981) (Fig. 6A).

Shelf width increases to the east of the Guadiana River, attaining more than 30 km off the Guadalquivir River and a maximum shelf width of 41 km off Cape Roche. Average shelf slopes decrease to the east, <0.3° off the Guadiana River, and <0.2° off the Guadalquivir River (Lobo, 2000). The shelf break occurs at about 130±20 m water depth (Nelson *et al.*, 1999; Maldonado *et al.*, 2003), with the maximum depth (150 m) off the Guadiana River and off Cape Roche (Lobo, 2000; Maldonado *et al.*, 2003).

To the southeast of Cape Roche the average shelf width is 35 km, and the shelf break occurs at 120-140 m water depth. A relatively flat, shallow platform up to 50 m water deep named as the Barbate High or Platform occurs between capes Roche and Trafalgar (Lobo *et al.*, 2000, 2010). To the south of Cape Trafalgar, the shelf width decreases to 15 km, and the shelf break occurs at a depth of 100 m. Further south, the shelf becomes narrower towards the Strait of Gibraltar (Maldonado *et al.*, 2003).

(c) Shelf morphology

The inner shelf between Cape São Vicente and Quarteira exhibits depositional bodies such as the Arade River pro-delta. Mesozoic rocky outcrops and abrasion platforms are widespread on the mid to outer shelf, although depositional bodies occur in paleo-valleys or as ancient coastal deposits (Vanney and Mougenot, 1981). The shelf between Faro and Tavira shows shallow-water deposits interpreted as

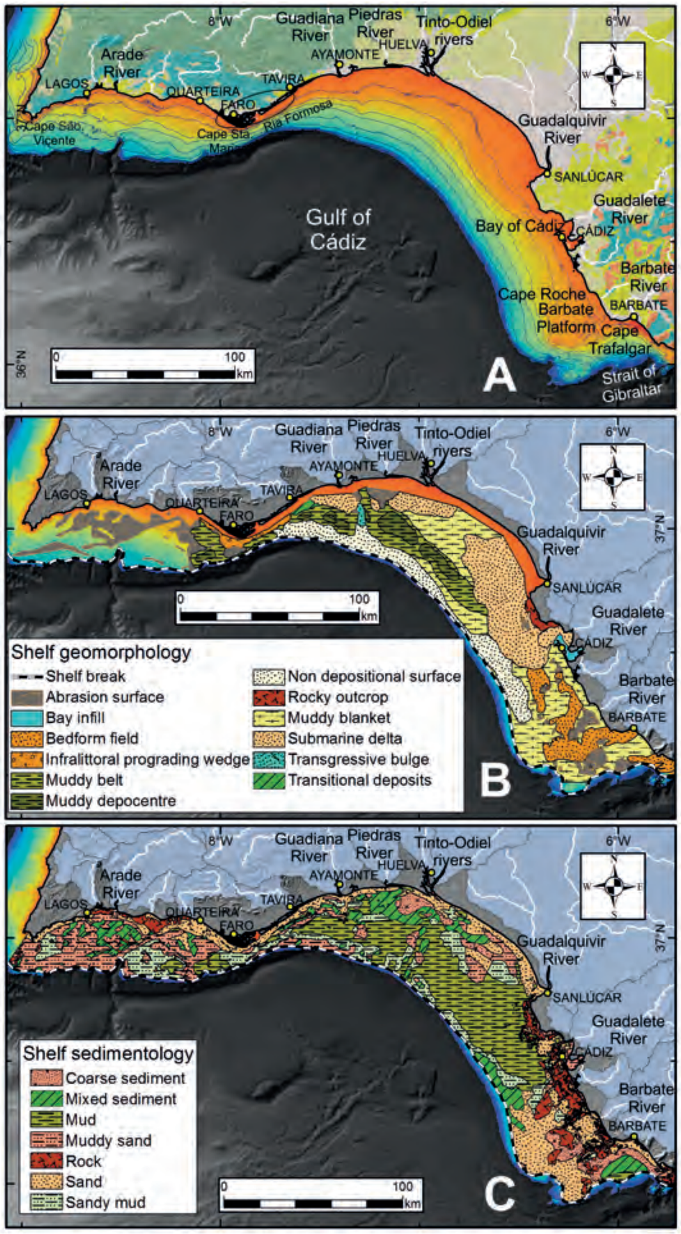


Figure 6. Synthetic morpho-sedimentary mapping of the northern shelf of the Gulf of Cadiz. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Shelf surficial sediment distribution; river systems and drainage basins are represented. Inland geology information included in Figure 6A extracted from the One Geology Project (http://www.onegeology.org/). Topographic data extracted from the Shuttle Radar Topography Mission portal (http://www2.jpl.nasa.gov/srtm/). Bathymetric data extracted from the EMODnet portal (http://www.emodnet-hydrography.eu/). Morphological features compiled from different sources: Vanney and Mougenot (1981), Lobo (1995), Roque (1998), Nelson *et al.* (1999) and Lobo *et al.* (2004). Surficial sediment distribution extracted from the MeshAtlantic portal. (http://www.meshatlantic.eu/).

Figura 6*. Mapa morfosedimentario sintético de la plataforma continental del Golfo de Cádiz. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la Figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 6A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen del portal Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/). Los datos batimétricos son del portal EMODnet (http://www.emodnet-hydrography.eu/). Los tipos morfológicos se extrajeron de diferentes fuentes: Vanney and Mougenot (1981), Lobo (1995), Roque (1998), Nelson et al. (1999) and Lobo et al. (2004). La distribución de sedimentos superficiales proviene del portal MeshAtlantic (http://www.searchmesh.net/).*

an infralittoral prograding wedge that extends more than 10 km in the along-shelf direction (Hernández-Molina *et al.*, 2000). The inner shelf between Tavira and the Guadiana River is partially covered by a poorly developed inner shelf pro-delta connected to the Guadiana River; seaward, most of the mid to outer shelf is covered by muddy belts, except for several wave-cut terraces that occur at water depths of 50-84 m (Roque, 1998).

The inner shelf between the Guadiana River mouth and Cape Roche is partially covered by elongated prodeltaic lobes off the main rivers, such as the Guadiana, Tinto-Odiel and Guadalquivir (Fernández-Salas *et al.*, 1999; Nelson *et al.*, 1999) (Fig. 6B). Inter-prodeltaic areas are characterized by the common occurrence of erosional features such as erosional surfaces and Pliocene-Quaternary rocky outcrops (Fig. 3E). (Gutiérrez-Mas *et al.*, 1996; Fernández-Salas *et al.*, 1999). Other depositional morphologies such as infilled depressions and bedform fields show a patchy distribution (Fig. 3E) (Nelson *et al.*, 1999; Lobo *et al.*, 2000). The middle shelf is covered by several muddy depocentres extending from the shelf to the east of the Guadiana River to the Bay of Cadiz (Nelson *et al.*, 1999). The middle shelf off the Guadiana River, however, exhibits a more irregular morphology and a step-like profile, due to the occurrence of several backstepping sediment wedges laterally related to marine terraces (Fernández-Salas *et al.*, 1999; Lobo *et al.*, 2001).

Several large-scale sandy sediment bodies with superimposed submarine dunes cover the Barbate shelf (Nelson *et al.*, 1999; Lobo *et al.*, 2000, 2010) (Fig. 3E). To the southeast, the shelf in the vicinity of the Strait of Gibraltar shows an abrupt physiography generated by outcropping flysch units (Esteras *et al.*, 2000; Luján *et al.*, 2011).

(d) Shelf sediments

From the Cape San Vicente to the Bay of Cadiz, shelf sediments occur as relatively continuous bands from the inner shelf to the shelf break (Fig. 6C). The depth of the middle shelf is limited to water deeper than 40 m and shallower than 90 m, and the outer shelf spans water depths of 90 m to 120 m, constituting the shelf break. The inner shelf, between coastline and 30-40 m depth, is covered by a sandy sediment belt, with local occurrence of gravels and rocky outcrops (Rey and Medialdea, 1989; Gutiérrez-Mas *et al.*, 1996; Fernández-Salas *et al.*, 1999; Nelson *et al.*, 1999; Maldonado *et al.*, 2003; González *et al.*, 2004; Rosa *et al.*, 2013), and muddy patches in the proximity of the most important river mouths (e.g. López-Galindo *et al.*, 1999; González *et al.*, 2004a). An elongated, laterally-continuous muddy layer covers most of the mid to outer shelf (Nelson *et al.*, 1999). Sandy sediments may also occur in distal settings, such as the middle shelf to the west of Cape Santa Maria (Moita, 1986) and the middle shelf off the Guadiana River (Fernández-Salas *et al.*, 1999; González *et al.*, 2004a). Different types of sediments such as clayey sands, sandy and silty clays occur on the outer shelf. Large patches of sands and gravels occur around the shelf break, becoming more widespread to the southeast (López-Galindo *et al.*, 1999; Nelson *et al.*, 1999; González *et al.*, 2004a).

Southeast of the Bay of Cadiz most of the shelf sediment cover is composed of reworked relict sands with a high content of heavy minerals and bioclastic remains (Gutiérrez-Mas *et al.*, 1994; López-Galindo *et al.*, 1999). Toward the Strait of Gibraltar, gravel content increases and Gibraltar flysch rocky outcrops become more common (Rey and Medialdea, 1989; López-Galindo *et al.*, 1999; Nelson *et al.*, 1999).

The northern Alboran Sea shelf

(a) Geological and oceanographic setting

The Alboran Sea is the southwesternmost basin in the Mediterranean Sea, and its origin and development are closely related to the Alpine orogenic belt (Betic-Rif Cordilleras). It extends west- east between Europe and Africa and ensures the connection of the Mediterranean Sea and the Atlantic Ocean which results in prominent oceanographic features, such as the Alboran gyres, the Almeria-Oran Front and coastal upwelling. The northern shelf of the Alboran Sea extends between Cape Gata to the east and the Strait of Gibraltar to the west (Fig. 1).

Geological setting

The Alboran Sea has been interpreted as a back-arc basin that developed during the Neogene as a consequence of the continental collision between the African and European plates. This collision began in the Late Cretaceous (Dewey *et al.*, 1989; Comas *et al.*, 1992; Maldonado and Comas, 1992) and continues at present (Vázquez, 2001). The co-occurrence of compressional and extensional phases, probably related to processes of lithospheric delamination (Seber *et al.*, 1996) characterizes the tectonic history of this area. An inversion in tectonic style, from the Late

Pliocene to Quaternary, activated the strike-slip faulting systems, trending NNW-SSE and NNE-SSW, which affect both onshore and offshore domains, as evidenced by geological and geophysical data (Masana *et al.*, 2004; Martínez-Díaz and Hernández-Enrile, 2005; Gràcia *et al.*, 2006; Moreno *et al.*, 2006). Tectonic activity persists today, with the occurrence of continuous, shallow seismic events of low to moderate magnitude (Mw<5.5) (Stich *et al.*, 2003).

Climate and oceanography

The regional climate is characterized by high seasonal variability, with maximum rainfall in winter in coincidence with the passage of Atlantic fronts and low to negligible rainfall the rest of the year due to the influence of the Azores anticyclone (Senciales and Málvarez, 2003). The Betic Cordillera acts as a natural barrier defining two climatic zones: a) in the coastal fringe where the average temperature is around 20° C and the maximum rainfall is about 500 $mmyr^{-1}$ and b) in the mountains where the climatic conditions are more severe, with lower temperatures (average annual value of 13° C) and higher rainfall (1,000 mm yr^{-1}) with frequent snowfalls (Liquete *et al.*, 2005).

The entrance of Atlantic water across the Strait of Gibraltar determines the characteristics of tides in this area, with a main semidiurnal periodicity (Parrilla and Kinder, 1987). Dominant wind directions alternate from the west and from the east, generating a low-to-moderate wave climate (Puertos del Estado, 2007).

The location of the Alboran Sea to the east of the Strait of Gibraltar greatly influences its oceanography, as surface current patterns are controlled by the entrance of Atlantic waters designed either the Atlantic inflow (AI) or surface Atlantic water (SAW) through the strait with an estimated speed of 1 m/s. The AI is mixed with variable amounts of water masses of Mediterranean origin generating the Atlantic jet (AJ) that feeds two anticyclonic gyres, the quasi-permanent western Alboran gyre (WAG) and the more elusive eastern Alboran gyre (EAG) (Tintoré *et al.*, 1988; Perkins *et al.*, 1990). The AJ originates a strong thermohaline front between cold and dense Mediterranean waters to the left and Atlantic waters to the right of the jet (Vargas-Yáñez and Sabatés, 2007).

Sediment sources

The proximity of the Betic Cordilleras to the Mediterranean coast influences the geomorphology of the drainage basins, with short rivers (while river length varies between 4.7 and 154.2 km) and steep slopes (river slope ranges from 0.4° to 8.2°) (Liquete et al, 2005; Bárcenas, 2013). The coastlines of the northern Alboran Sea margin are mostly supplied via relatively short, mountainous rivers and creeks. The longest rivers with the most extensive drainage basins are, from west to east, the Guadiaro, Guadalhorce, Guadalfeo, Adra and Andarax rivers. Most of these rivers show a contrasting seasonal pattern, with maximum water discharges in winter and very low discharges the rest of the year. In addition, water discharge is also very irregular on an inter-annual basis, with alternating dry and humid years. Average water discharge is less than 11 m^3s^{-1}, with maximum monthly values of about 130 m^3s^{-1} for the Guadalhorce River. An inverse relationship was found between sediment discharge and the extent of the drainage basins due to the capacity of the rivers to react to sudden floods and the absence of areas in the drainage basins where sediments could be stored (Liquete *et al.*, 2005). Average sediment discharge is between 0.1 and 4.8 kgs^{-1} for the water courses under consideration, the maximum value being in the Adra River.

Overall, mean discharges decrease from west to east, but in contrast mean sediment loads and yields tend to increase to the east, indicative of an increasing torrential character (Liquete *et al.*, 2005). This supply pattern is conditioned by: (a) the abrupt coastal physiography, as the Betic Ranges occur at short distance from the coast, and in several places show recent tectonic activity leading to steepening of physiographic profiles and river incision (Carvajal and Sanz de Galdeano, 2008); (b) the Mediterranean climate, with increasing aridity toward the east. Due to their torrential character, most of the rivers are very effective in transporting sediments from the drainage basins toward the shelf and eventually into deeper water (Liquete *et al.*, 2005).

Littoral drift shows a high variability, although an eastward drift is more common (Lario *et al.*, 1999; Goy *et al.*, 2003) due to the interaction between prevailing waves and coastline configuration. Beach ridges and spit bars have been constructed during the Holocene highstand in coastal sectors dominated by along-shore processes (Lario *et al.*, 1999; Goy *et al.*, 2003).

(b) Shelf physiography

The northern Alboran Sea shelf is narrow (several kilometres wide), mainly the area located between

Nerja and Adra, with a minimum of 2 km width off Cape Sacratif, where several submarine canyons incise the shelf (Carter *et al.,* 1972) (Fig. 7A). In this area the average shelf width is around 4.5 km. The shelf is also narrow and abrupt towards the Strait of Gibraltar (Vázquez, 2005). For the rest of the shelf, the average width value is higher (about 9 km wide), although it may locally reach a width of more than 20 km off Malaga and Almeria, due to the sediment supply by the main rivers (Muñoz *et al.*, 2008). In addition, a Neogene volcanic and/or structural seamount has generated a 28 km wide north-trending platform off Cape Gata (Medialdea *et al.,* 1982; Vázquez, 2005; Muñoz *et al.,* 2008).

The shelf break is located at a mean water depth of 110 m (Vázquez, 2001) but off the Cape Gata it is at a depth of 175-200m (Muñoz *et al.,* 2008). The shelf has a regular morphology mainly due to the influence of shelf-margin deltas; on the western shelf an abrupt morphology is observed due to faulting (Muñoz *et al.,* 2008).

(c) Shelf morphology

The majority of the river sediment loads in Andalusia are channelled directly to deltaic systems (Liquete *et al.*, 2005). The most significant inner-shelf morphologies include prodeltaic or submarine deltaic bodies in front of the main fluvial inputs and infralittoral prograding wedges (IPWs) laterally from the main fluvial entries (Hernández-Molina *et al.*, 1993; 1995; Lobo *et al.*, 2006; Fernández-Salas, 2008; Barcenas *et al.*, 2009; Bárcenas, 2013) (Figs. 3F and 7B). These prodeltaic deposits have steep slopes, both in the foresets and bottomsets, and the offlap-breaks are more abrupt and shallower than in most Mediterranean prodeltas (Lobo *et al.*, 2006; Fernández-Salas, 2008; Bárcenas, 2013).

Wide segments of the outer shelf are covered by depositional morphologies, such as bedform fields or by erosional and/or tectonic morphologies such as abrasion surfaces, escarpments, slumps (Fig. 3f) and canyons (Ercilla, 1992; Hernández-Molina *et al.*, 1994; Vázquez, 2005; Lobo *et al.*, 2006). The abrasion surfaces are mostly observed on the western part of the shelf (Fig. 7B).

The bedform fields are mainly located in the eastern part of the inner shelf, from the town of Nerja to Cape Gata (Fig. 7B). Generally, the largest fields are composed of sandy ridges. The minor fields are mainly associated with seafloor undulations (Fig. 3F) generated by strong sediment flows normal to bathymetric contours coupled with slight sediment deformation (Fernández-Salas *et al.* 2007; Urgeles *et al.*, 2011; Bárcenas, 2013). This is a common phenomenon in many prodeltaic environments, where the influence of the river inputs is higher than the influence of the dominant currents.

Basement outcrops are widespread in several shelf sectors (Hernández-Molina *et al.*, 1995). The shelf in the central area is completely dissected off Cape Sacratif by the head of the Carchuna Canyon with a main N-S trend, showing several distributaries (Lobo *et al.*, 2006).

The morphology of the shelf located in the western and central part of the Alboran Sea shows a clear tectonic control, highlighted by the presence of NW-SE trending scarps (Vázquez, 2001).

(d) Shelf sediments

Present-day sedimentation is mainly siliciclastic on the northern Alboran sea shelf. The terrigenous supply of rivers and creeks has generated muddy and/or sandy-muddy deposits covering most of the postglacial transgressive sandy deposits (Hernández-Molina, 1993) mainly in the area between Malaga and Adra (Fig. 7C). In shallow water areas, however, the average grain size is larger due to the combined action of waves, rip currents, and littoral drift (Kelling and Stanley, 1972; Hernández-Molina, 1993). The sediments are transported laterally either by littoral drift or by surface Atlantic water influence. Postglacial relict sediments composed of reworked sands and gravels carpet the outer shelf (Ercilla *et al.*, 1994a; Hernández-Molina *et al.*, 1994). Spillover facies mainly composed by sands tend to occur in the proximity of the shelf break; these facies are related to reworking and resuspension by storm currents and by upper slope gravitational processes (Ercilla *et al.* 1994).

Backscatter intensities are correlated with average grain sizes along the northern shelf of the Alboran Sea (Bárcenas *et al.*, 2011; Bárcenas, 2013). High backscatter intensities are related to sandy sediments (>70%) with moderate amounts of gravels (≈25%). Medium backscatter intensities correspond with very coarse to coarse sands mixed either with gravels (>34%) or with muds (<42.29%). Low backscatter intensities are indicative of coarse to fine sands with mud content locally above 50% and very low gravel content (Bárcenas *et al.*, 2011; Bárcenas, 2013).

Maximum current velocity and bed shear-stress indicate a very high correlation with gravelly sands, thus strongly controlling the location of storm-dominated environments. Mixed and fluvial-dominated environments occur in response to the competing

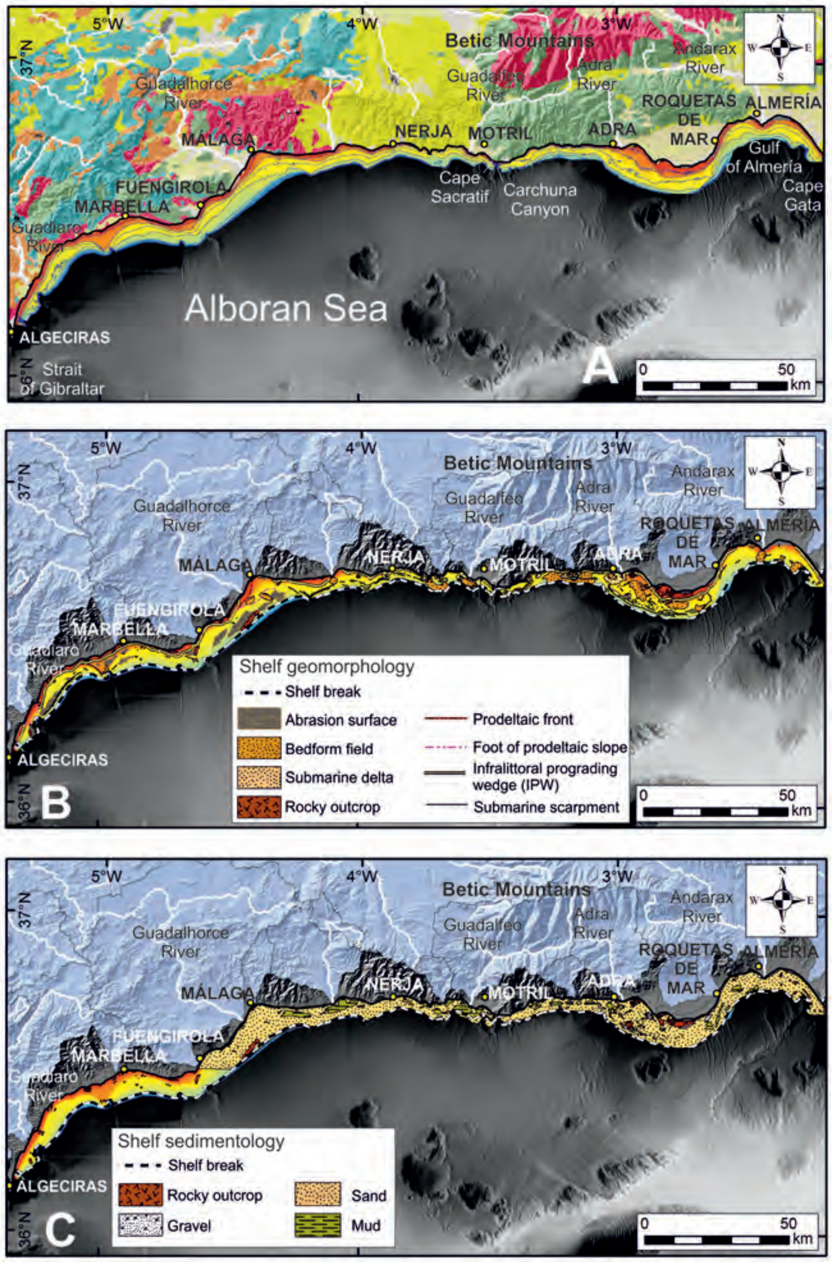


Figure 7. Synthetic morpho-sedimentary mapping of the northern Alboran Sea shelf. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Shelf surficial sediment distribution; river systems and drainage basins are represented. Inland geology information included in Figure 7A extracted from the One Geology Project (http://www.onegeology.org/). Topographic data extracted from the Shuttle Radar Topography Mission portal (http://www2.jpl.nasa.gov/srtm/). Bathymetric data extracted from the EMODnet portal (http://www.emodnet-hydrography.eu/). Morphological features and surficial sediment distribution compiled from different sources: Sanz *et al.* (2003, 2004a, 2004b, 2007a, 2007b, 2007c, 2007d), IGME (2005), Lobo *et al.* (2006), Fernández-Salas (2008), Bárcenas *et al.* (2009, 2011) and Bárcenas (2013). Surficial sediment distribution extracted from the MeshAtlantic portal (http://www.meshatlantic.eu/).

Figura 7. *Mapa morfosedimentario sintético de la plataforma continental del Mar de Alborán. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la Figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 7A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen del portal Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/). Los datos batimétricos son del portal EMODnet (http://www.emodnet-hydrography.eu/). Los tipos morfológicos se extrajeron de diferentes fuentes: Sanz et al. (2003, 2004a, 2004b, 2007a, 2007b, 2007c, 2007d), IGME (2005), Lobo et al. (2006), Fernández-Salas (2008), Bárcenas et al. (2009, 2011) and Bárcenas (2013). La distribución de sedimentos superficiales proviene del portal MeshAtlantic (http://www.searchmesh.net/).*

influence of fluvial supplies and moderate hydrodynamic conditions (Bárcenas *et al.*, 2011). Off from the coast of the northern Alboran Sea, infralittoral bands of gravelly sands are generated by storm conditions. Seaward, a lateral segmentation is evident, primarily conditioned by the Carchuna Canyon head dissecting the shelf, but also by the interaction between an active, bi-directional flow regime and local fluvial supplies from mountainous, small rivers. The shelf sector to the west of the canyon is dominated by the contribution of fluvial systems; in contrast, the shelf sector to the east of the canyon is mainly influenced by the hydrodynamic regime (Bárcenas *et al.*, 2011; Bárcenas, 2013).

The southeastern and Balearic shelves

(a) Geological and oceanographic setting

The southeastern and Balearic shelves extend northward from Cape Gata to Cape La Nao in the Iberian Peninsula, and include the shelf of the Balearic promontory (Fig. 1).The southwestern end of the promontory is attached to the Iberian margin, while to the northeast the Valencia trough separates it from the Ebro margin. The Valencia trough is a northeast-trending aborted rift collecting the terrigenous inputs from the Ebro River mainly (Roca and Guimerà, 1992). For the most part, this margin is of intermediate type, although in the south from the Mallorca and Menorca islands and between Cape Gata and Cape Palos, the margin is abrupt.

Geological setting

The eastern Iberian margin is characterized by the superposition of several Mesozoic structural units developed on a Variscian basement (Roca and Guimerà, 1992). The Betic-Balearic tectonic domain is generated during the Miocene when both extension and compression phases occurred in the eastern Iberian Plate. The eastern and Balearic Promontory continental margins are passive margins whose current geomorphological configuration is related to pre-Oligocene subduction of Africa beneath Eurasia and an Oligocene-Early Miocene rifting phase (Maillard and Mauffret, 1999; Roca *et al.*, 1999). On its southern side, the Valencia trough is flanked by the Betic-Balearic Domain, constituted by the easternmost sector of the External Zones of the Betic Cordillera (Dañobeitia *et al.,* 1990). The promontory was affected by the superposition of different rifting episodes during the Late Tertiary (Fontboté *et al.*, 1990). The current configuration of the Balearic promontory is related to the clockwise rotation of the Mallorca and Eivissa blocks which are related to the westward migration of the Alboran block (e.g. Auzende *et al.*, 1973; Vegas, 1992). The Almeria-Murcia and Valencia-Catalan continental margins show zones with Neogene volcanic outcrops. Volcanism corresponds to submarine emissions related to the evolution of the Betic Cordillera and dates from the Miocene to the Late Quaternary. Southward from Cape La Nao, tectonic features related to the Betic Cordillera have modified the uplift/subsidence shelf regime, limiting the thickness of the sediment cover (Maldonado and Zamarreño, 1983). The acoustic basement outcrops are very shallow off the main coastal promontories such as Cape La Nao and Cape Palos (Rey and Díaz del Río, 1983). In addition, thick Neogene-Quaternary depocentres occur in coincidence with a series of fault-controlled horsts and grabens affected by differential subsidence to the south of Cape La Nao (Medialdea *et al.,* 1982; Rey and Díaz del Río, 1983; Catafau *et al.,* 1994)

Climate and oceanography

High temperatures, scarce rainfall (<700 mm per year) and the wind regime produce an extremely arid climate. Summer temperatures are high (average value of 20-30° C), although winter temperatures are mild in the nearshore region (January average temperature is 10° C).

Littoral drift is mainly directed southward (Catafau *et al.,* 1994). Several spit bars enclose relatively large coastal lagoons, such as the Mar Menor. On the shelf, the main present-day sedimentation processes are linked to the action of major storms, when sediments are remobilized and transported offshore. In addition, the biogenic production is significant in the shelf around the Balearic Islands and in the vicinity of Cape Gata (Maldonado and Zamarreño, 1983).

A surface layer extends down to water depths of 150-300 m. The surface water is the product of both local and remote mixing processes influencing the properties of the water of Atlantic origin along its path across the Mediterranean Basin (Millot, 1999). The surface layer is highly variable due to the thermocline variability and to the local fresh water inputs from rivers and precipitation (Salat and Cruzado, 1981). Within this surface layer, two permanent density fronts designed as the Catalan and Balearic fronts control the regional surface circulation. The Catalan front is constant throughout the year and is associated with a plume of cool water that originates from the north. The front frequently spawns energetic filaments associated with the plume of cool water, and whose development is closely related to the location of submarine canyons. The Balearic front is less documented, although it seems to be less variable and weaker (Font *et al.,* 1988).

Sediment sources

Small rivers and streams, with very irregular discharges and seasonal and irregular flow regimes and a markedly torrential nature, mainly feed the southeastern and Balearic shelves. The most significant fluvial supplies are in the northern part, close to the Cape La Nao, with the contribution by the Segura (26.3 m^3s^{-1} mean discharge) and Jucar (49.22 m^3s^{-1} mean discharge) rivers together with other medium-sized rivers. Southward, between Cape Palos and Cape Gata, the presence of rivers is less influential and abrupt cliffs dominate the coasts. The main river in this sector is the Almanzora River, with infrequent flood events and discharges of typically <40 m^3s^{-1} (Stokes *et al.*, 2012).

(b) Shelf physiography

The peninsular sector comprises two arc-shaped segments, northern and southern, bounded by Cape Palos (Fig. 8A). The northern arc extends between Cape La Nao and Cape Palos and the shelf width decreases southward; the maximum extension (40 km) occurs off Altea, decreasing to 23 km off Cape Torrevieja. Accordingly, seafloor slopes increase southward from 0.1° to 0.2°. The shelf break occurs at water depths from 100 to 130 m (Rey and Díaz del Río, 1983; Catafau *et al.,* 1994).

The southern arc is a more abrupt margin with a narrow shelf located between Cape Palos and Cape Gata. The shelf width is 10 km in the vicinity of Cape Palos, but the shelf tends to be narrower (<6 km) to the south, where it is cut by shelf-indenting canyons that have tributaries with heads located at a short distance from the coastline off Garrucha, Mojacar and Carboneras. Off Cape Gata, the shelf width reaches approximately 17 km. The shelf break ranges in depths from 100 to 110 m (Medialdea *et al.,* 1982; Rey and Díaz del Río, 1983; Catafau *et al.,* 1990) (Fig. 8A).

The Balearic shelf comprises the larger Mallorca-Menorca shelf to the east and the smaller Eivissa-Formentera shelf to the west. The Mallorca and Menorca islands have a common shelf including the smaller Cabrera Island with a total surface of 6418 km^2. The Eivissa and Formentera islands sit on top of a shelf with a total area of 2 709 km^2. The northern shelf of the Balearic Islands is 10-20 km wide, with the shelf break at water depths ranging between 139 and 160 m (Acosta *et al.,* 2003). The southern shelf of the Balearic Islands shows an abrupt morphology, with a minimum width of 3 km and the shelf break at water depths of between 120 and 150 m delineated by the Emile Baudot Escarpment along the island of Mallorca.

(c) Shelf morphology

In the southeastern and Balearic shelves, the surface distribution of geomorphological types has been provided by several regional studies (Medialdea *et al.,* 1982; Rey and Díaz del Río, 1983; Catafau *et al.,* 1994; Rey and Fumanal, 1996; Díaz del Río and Fernández-Salas, 2005). Lobulate pro-deltas occur off the main rivers (e.g. Segura, Almanzora). The Segura pro-delta is located on the inner and middle shelf, but the Almanzora pro-delta reaches the shelf break. Laterally, the pro-delta bodies evolve to elongate infralittoral prograding wedges (IPW), the geomorphic feature with greatest continuity along the eastern margin. The IPW forms a narrow zone seaward of the shoreface, which extends over a distance of 1 to 5 km from the coast and shows a sharp slope break at water depths of 20 to 25 m. On the continental shelf of the Valencia, Balearic Promontory and Betic continental margins, seagrass meadows (Fig. 3G) are capable of generating elongated sand banks (Fig. 3G) parallel to the coastline with lengths that vary from 1 to 50 km (Pérez-Ruzafa and López-Ibor, 1986; Díaz del Río, 1989).

Other depositional features controlled by the present-day or ancient hydrodynamics, such as littoral bars, ridges and bedforms (ripples, megarriples and dunes), are frequent on inner to outer shelf areas (Fig. 3G). These depositional seafloor features are observed in the northern arc, off Cape Aguilas and Cape Gata (Fig. 8B).

As regards the erosive features, some features are interpreted as being associated with wave and current activity, channelised flows along and/or across the shelf. A widespread abrasion surface is located to the south of Alicante, indicating the scarcity of fluvial supply. On the outer shelf, several shelf-margin deltas have been identified; however, most of the middle and outer shelf is covered by either erosional (escarpments and submarine terraces remnants of previous coastlines, abrasion and undulating surfaces, wavy

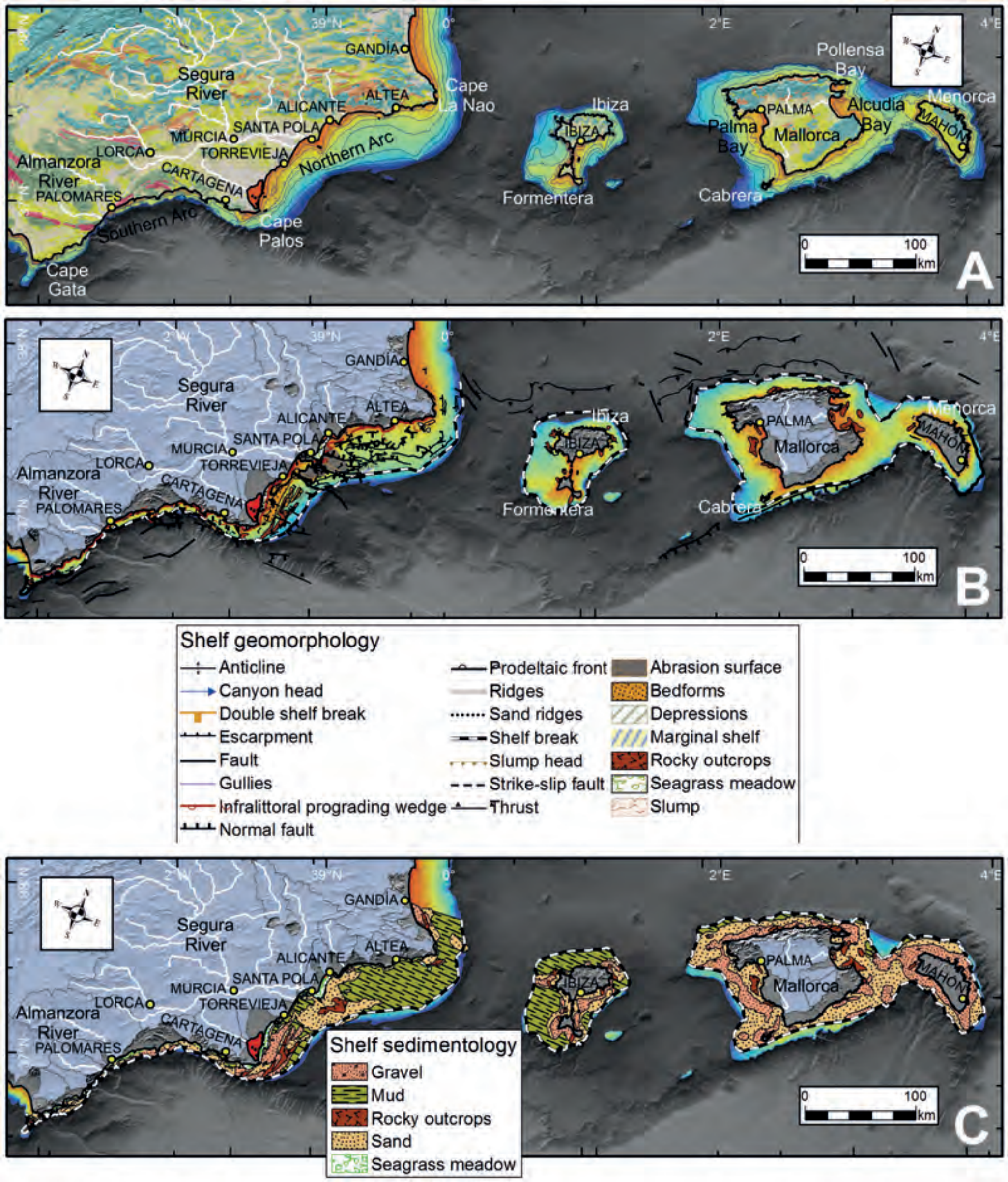


Figure 8. Synthetic morpho-sedimentary mapping of the southeastern and Balearic shelves. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Sediment surficial distribution; river systems and drainage basins are represented. Inland geology information included in Figure 8A extracted from the One Geology Project (http://www.onegeology.org/). Topographic data extracted from the Shuttle Radar Topography Mission portal (http://www2.jpl.nasa.gov/srtm/). Bathymetric data extracted from the ESPACE project database (restricted access) and "Ecocartografia" project in format KMZ files (http://www.ecocartografias.com/). Morphological features and surficial sediment distribution were obtained through the interpretation of multibeam bathymetric data collected in the framework of the ESPACE and "Ecocartografia" projects, and were completed with previous interpretations contained in different sources, such as Sanz *et al*., (2002, 2003a, 2003b, 2003c) and IGME (2005).

Figura 8. *Mapa morfosedimentario sintético de las plataformas continentales del Sureste y de Baleares. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la Figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 8A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen del portal Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/). Los datos batimétricos son de la base de datos del proyecto ESPACE (acceso restringido) y del proyecto de Ecocartografía en formato KMZ (http://www.ecocartografias.com). Los tipos morfológicos y la distribución de sedimentos superficiales se obtuvieron mediante la interpretación de los datos de batimetría multihaz de los proyectos ESPACE y Ecocartografía, y se completaron con interpretaciones previas de diferentes fuentes, como Sanz et al., (2002, 2003a, 2003b, 2003c) and IGME (2005).*

surfaces, depressions and channel-like morphologies) or tectonically-controlled features (faults, step-like escarpments, terraces, and hard bottoms).

Biogenic sands, with a mid-shelf continuous belt of littoral bars, mostly cover the Balearic shelf. In contrast, the northern Eivissa Shelf is controlled by structural lineaments (Acosta *et al.,* 2003; Díaz del Río and Fernández-Salas, 2005). The central shelf of the Balearic Islands exhibits several bays (Mallorca, Pollensa, Alcudia) covered with extensive *Posidonia* meadows, as well as diverse depositional (bedforms, bars and channel infillings) and erosional-tectonic features (escarpments, terraces and abrasion surfaces) (Palomino *et al.*, 2009). Terrace-like reefal build-ups are frequent on the southern shelf of the Balearic Islands (Díaz del Río and Fernández-Salas, 2005).

(d) Shelf sediments

The surficial sedimentary cover in the peninsular northern arc is mainly composed of siliciclastic sediments and three sectors could be differentiated (Fig. 8C). A northern sector located from Cape La Nao to Alicante, where a muddy sheet covers the middle and outer shelf and a sandy sediment belt covers the inner shelf. A central sector, situated from Alicante to Torrevieja, where the sandy sediment prevails on the whole of the shelf. A seagrass meadow covers the inner shelf and a rocky outcrop is located in the middle shelf. Palimpsest coarse-grained sediments and rocky outcrops cover most of the shelf in the southern sector, from Torrevieja to Cape Palos (Catafau *et al.,* 1994). A well-developed coastal belt of seagrass meadows cover the inner shelf in this sector.

Widespread terrigenous sediments also occur in the northern half of the southern arc, where sandy and gravelly sediments prevail. In the central part of this arc, the fine sands are mostly concentrated around the most important river mouths (e.g. Almanzora) and streams. In contrast, biogenic coarse-grained carbonates and rocky outcrops prevail in the southernmost shelf next to Cape Gata (Maldonado and Zamarreño, 1983; Zamarreño *et al.,* 1983). Scattered seagrass meadows are located on the inner shelf.

Shelf sediments around the Balearic Islands are mainly composed of biogenic sands and gravels, with a variable, low content of fine components (Alonso *et al.,* 1988; Fornós and Ahr, 1997). There are some differences between the surficial sediment distribution of the Eivissa and Formentera shelf and the Mallorca and Menorca shelf. In the first, the inner shelf is composed of sandy sediments, the middle shelf by gravels, and muddy sediments cover the outer shelf and shelf break. In contrast, scattered gravels and sands cover most of the shelf of the second sector, and the muddy sediment is only located along the northern shelf break.

The northeastern shelf

(a) Geological and oceanographic setting

The northeastern Iberian margin extends from the Cap de Creus to Cape La Nao and comprises the Catalan and the Valencia margins (Fig. 1). Its lower limit, at depths from 2 000 to 2 600 m, corresponds to the Valencia trough, a mid-ocean type submarine valley.

Geological setting

The present configuration of the northeastern Iberian margin was acquired during the Late Oligocene-Early Miocene opening of the Valencia trough, and subsequently modified by the Messinian Salinity Crisis at the end of the Miocene and the Plio-Quaternary glacio-eustatic fluctuations. The Cenozoic structure and associate depositional features resulted from two successive episodes (Maillard *et al.*, 1992; Roca *et al.*, 1999). The first episode was compressional and related to the development of the Pyrenees orogen from Early to Late Oligocene. The main geological structures developed during this tectonic event correspond to thrusts and associated folds that are approximately E-W oriented (Muñoz *et al.*, 1986). The second episode was extensional, linked to the opening of the SE-NW oriented Valencia trough from Late Oligocene to Early Miocene, and gave rise to the present NE-SW oriented horst-and-graben structure of the Catalan margin (Maillard *et al.*, 1992; Roca *et al.*, 1999). The post-rift stage was characterised by an increasing accommodation space allowing the deposition of thick sedimentary sequences (Clavell and Berastegui, 1991). The Early Miocene to Present depositional evolution was temporarily truncated during the late Messinian regression. The isolation of the Mediterranean Sea from the Atlantic Ocean after the closure of the Gibraltar Strait during the Messinian caused a dramatic sea level fall that stimulated the rejuvenation of the newly emerged reliefs, including the development of submarine canyons in the entire western Mediterranean Basin (Hsü *et al.*, 1977; Lofi *et al.*, 2005; García et al, 2011; Cameselle *et al.*, 2013). Atop of the Messinian erosional surface, the construction of the modern river-fed continental shelf and slope in the study area was modulated by the

Plio-Quaternary glacio-eustatic sea level changes (Díaz and Maldonado, 1990; Liquete *et al.*, 2008).

Climate and oceanography

The northeastern Iberian continental shelf is a wave-dominated, microtidal (<0.2 m) environment that has a seasonal wave climate. Strong northerly winds mostly occur during December and January, whilst easterly winds are more frequent during February, March, April and November (Bolaños *et al.*, 2009). Cold, dry northerly winds are responsible for the formation of dense shelf water over the Gulf of Lion and the northern Catalan continental shelf that flows southward along the shelf and cascades down the continental slope through submarine canyons (Dufau-Julliand *et al.*, 2004; Canals et al, 2006; Puig *et al.*, 2008; Palanques et al, 2009; Ribó et al, 2011). Humid easterly winds are associated to large swells that cause intense sediment resuspension along the coastline (Mendoza and Jiménez, 2008; Sanchez-Vidal *et al.*, 2012). Because waves approach the coast at oblique angles during eastern storms, they generate an intense southwestward alongshore transport of sediment that can be up to 45 000 m^3y^{-1} (DGPC, 1986) or even 83 000 m^3y^{-1} (Copeiro, 1982) off the Maresme coast, north of Barcelona.

The general circulation is dominated by the baroclinic north current flowing southward over the continental shelf-break and slope (Millot, 1999). At the entrance of the Gulf of Valencia, the northern current is fragmented into two branches as result of the intrusion of light water coming from the south through the Eivissa and Mallorca channels (Fig. 1) (Font *et al.*, 1988; Salat, 1995). A significant part of the flow proceeds southward through the Ibiza Channel, but the other part flows eastwards with the Balearic Current. The northern current often develops meanders or eddies eventually invading the continental shelf in the Catalan margin (Font *et al.*, 1995; Rubio *et al.*, 2005) and the Valencia margin (Castellón *et al.*, 1990; Pinot and Ganachaud, 1999; Pinot et al, 1995, 2002; Ribó *et al.*, 2013).

Sediment sources

The northeastern Iberian watershed consists of medium-to-small rivers and ephemeral streams opening directly into the Mediterranean Sea with their headwaters in the eastern Pyrenees and the Catalan coastal ranges. From north to south, these include the Muga, Fluvia, Ter, Tordera, Besos, Llobregat, Foix, Gaia, Francoli, Ebro, Turia and Jucar rivers (Fig. 1). Most of these river systems show an extremely variable regime, with most of the discharge concentrated in short-lived flood events (Martín-Vide, 1985; Martín-Vide *et al.*, 2008).

From Cap de Creus to the Llobregat delta, sediments from medium-to-small rivers (Muga, Fluvia, Ter and Tordera) and ephemeral streams feed into the continental shelf (ACA, 2000; Liquete *et al.*, 2009). From these rivers, Ter, Fluvia and Tordera represent the main long-term source of terrestrial inputs delivering annually 1 266 and 159 t of terrestrial organic carbon and nitrogen, respectively, to the marine environment (Sanchez-Vidal *et al.*, 2013). The Llobregat and Besos rivers discharge represents the largest fluvial input in terms of water and sediment discharge to the Barcelona shelf (Fig. 1). The catchment area of these rivers (6 074 km^2) represents the 6.1 % of the Catalan river basins (Liquete *et al.*, 2009). Both rivers form deltas at their mouths; the Llobregat delta which covers an area of 80 km^2 with a coastal development of 21 km, and the Besos delta, covering an area of 8.3 km^2 defined by a coastline of 7 km (Liquete *et al.*, 2009).

Southwards, the Ebro River represents the most significant fluvial supplies to the Catalan margin draining an area of 85 534 km^2 (86.4 % of Catalan river basins). The sediment budget of the lower Ebro River has been reduced during the last decades due to regulation. Recent studies have reported a mean annual suspended sediment load of around 0.1 x 106 t during recent years (Négrel *et al.*, 2007; Tena *et al.*, 2011). This represents 1% of the sediment load estimated for the beginning of 20th century by Nelson (1990), prior to dam construction. As a consequence, sediment transported downstream from the dams is entrained from the riverbed and the erosion of the flanks, which results in a mean riverbed incision of 30 mm per year (Vericat and Batalla, 2006), and the enhancement of marine erosion processes in the delta (Guillén and Palanques, 1992).

In the southern part of this sector, the main basins are of the Jucar and Turia rivers, draining 22 378 km^2 and 6 913 km^2, respectively. The mean annual discharge of the Jucar River is 0.81 km^3. The discharge shows high seasonality and interannual variability. Discharge decreased between the period 1952-1983 (~100 Mm^3) and the period 1984-2006 (~58 Mm^3) (Sabater *et al.*, 2009).

(b) Shelf physiography

The Catalan margin displays the typical shelf, slope and rise physiographic provinces of passive margins

(Amblas *et al.*, 2006). It is divided into three segments based on morphological sedimentological and tectonic characteristics: northern Catalan (NCM), southern Catalan (SCM) and Ebro margin (EM) (Amblas *et al.*, 2006).

The NCM extends from the Cap de Creus Canyon to the Blanes Canyon and displays the most complex geomorphology of the northeastern Iberian margin. It displays an irregular continental shelf (Fig. 9A) that shows a variable width and finishes in a steep (7° on average) and complex slope (Amblas *et al.*, 2006; Lastras *et al.*, 2011; Durán *et al.*, 2014). The shelf edge is located at depths between 60-100 m around the canyon rims and 135-145 m off the Costa Brava shoreline. The shelf width is highly variable, mostly related to the irregular morphology of the coastline and the presence of submarine canyons incising the shelf (Canals et al, 2004). The shelf is narrow, less than 2.6 and 0.8 km near the Cap de Creus and La Fonera canyons respectively, but it is wider off the Roses Bay (30 km) and the Costa Brava (25 km).

According to its physiographic characteristics, the continental shelf can be divided into three zones: the inner shelf (0-60 m), the middle shelf (60-90 m) and the outer shelf (from 90 m to the shelf edge). The inner shelf displays an irregular topography with positive relieves and variable gradient. The seafloor gradient is homogeneous off the main bays (0.6° on average), but it is on the heterogeneous offshore rocky coasts, near the submarine canyons, where rocky outcrops occur (Durán *et al.*, 2014). As occurs in the continental shelf, the seafloor gradient at the shelf break shows mean values of 0.7° when approaching the smoother continental slope off the main bays, but it is 8° (even locally up to 47°) when entering the canyon heads (Amblas *et al.*, 2006; Lastras *et al.*, 2011; Durán *et al.*, 2014).

The Blanes canyon to the north and the Valldepins canyon to the south limit the SCM. It is characterized by a wide continental shelf (up to 24 km wide) that evolves into a gentle slope with mean gradients of less than 4° (Amblas *et al.*, 2006; Liquete *et al.*, 2007, 2010). In contrast to the NCM, the SCM continental shelf is not significantly incised by submarine canyons (Amblas *et al.*, 2006; Tubau *et al.*, 2013). The shelf width is highly variable; it is 4 km near the Blanes canyon head, 6 km off the Llobregat River mouth and up to 24 km off the Maresme coast. The shelf edge depth ranges from 140 m to the north to only 110 m off the Llobregat pro-delta (Durán *et al.*, 2014). Overall, the shelf displays a smooth seafloor disrupted by the presence of several 1-25 m high morphological steps and narrow ridges (Liquete *et al.*, 2007, 2010; Ercilla *et al.*, 2010; Durán *et al.*, 2014).

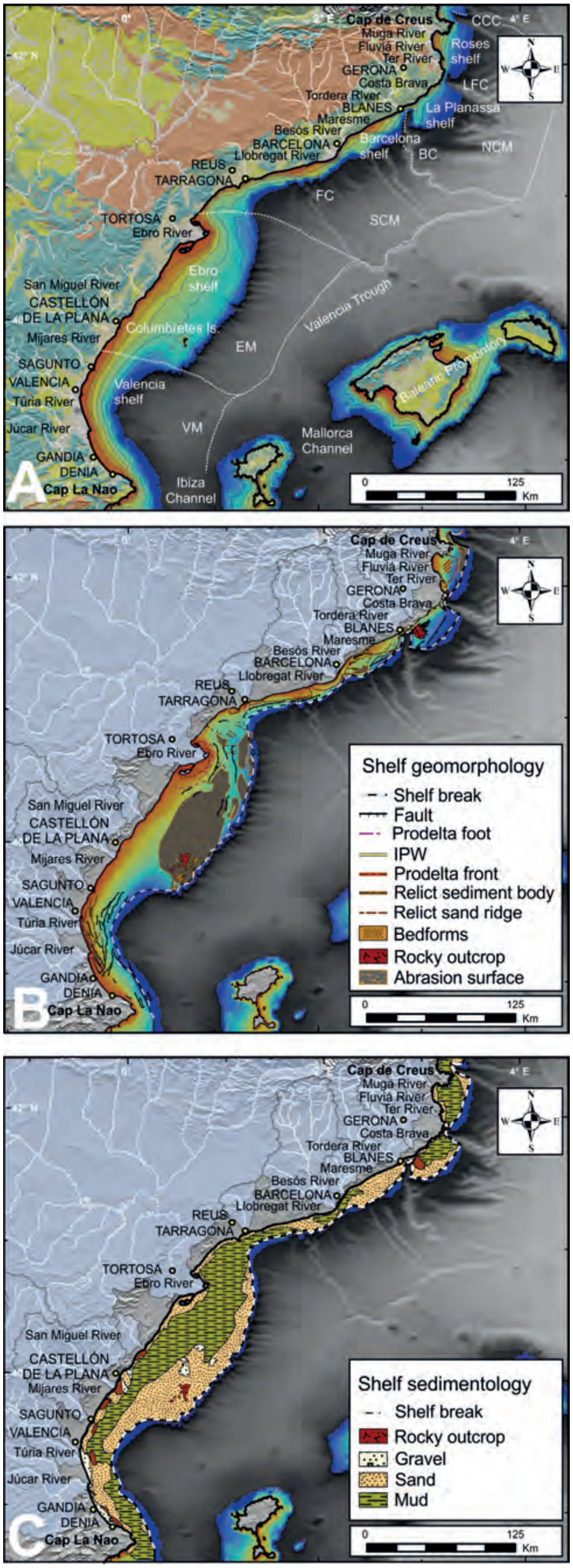
The Foix canyon bounds the EM to the north and the southern limit of the Columbretes Islands to the south. It comprises a broad continental shelf (up to 70 km wide) that finishes in a well-defined shelf break at a water depth of 120 m. The continental shelf shows a uniform gentle gradient (< 0.6 °) only disrupted by isolated features, such as sand shoals (Díaz *et al.*, 1990; Farrán and Maldonado, 1990) and the Columbretes Islands (Muñoz *et al.*, 2005; Amblas *et al.*, 2006). The Columbretes Islands constitute a volcanic field located along a north-south topographic high at the outer shelf off Castellon (Fig. 9A). This high is 12 km long, 4 km wide and has a relief of 60 m (Muñoz *et al.*, 2005). The maximum width of the northeast Iberian shelf is reached in the Ebro margin (70 km off the Ebro Delta). The shelf edge depth ranges from 100 to 140 m. It is subparallel to the coast but it turns landward south of the Columbretes Islands, reducing the shelf width to almost 20 km off Valencia (Lo Iacono *et al.*, 2010). The continental slope is steep (up to 10°) and narrow (up to 8 km). It is incised by great number of canyons, some of them are slightly incised (up to 6 km) into the shelf and their down-cutting rarely exceeds 300 m into the slope (Amblas *et al.*, 2006).

The shelf of the Valencia margin (VM, Fig. 9A) dips gently (<0.3°) towards the shelf break with no marked relief. The average shelf width is 35 km, and the shelf break occurs at water depths ranging from 140 to 170 m. The shelf width is higher to the N (47 km off Sagunto) and to the S (42 km off Gandia) (Díaz del Río *et al.,* 1986). It reaches its minimum width at the southern end, off Cape La Nao (15 km).

(c) Shelf morphology

The northeast Iberian continental shelf displays a complex morphology determined by the presence of large seafloor features such as pro-deltas, infralittoral prograding wedges (IPWs) and rocky outcrops on the inner shelf (Fig. 9B), and large sediment bodies and rocky outcrops on the middle to outer shelf. Smaller seafloor features, such as sediment waves, lineations, elongate and oval depressions, and obstacle marks appear superimposed to these morphologies.

From north to south, the main pro-deltas described in the continental shelf include the Muga-Fluvia, Ter, Tordera, Besos-Llobregat, Ebro and Jucar. In addition, smaller prodelta-like wedges (0.7 km wide along-shelf) have been recognized at the mouth of coastal torrents, such as Tossa de Mar and Lloret de Mar, in the Costa Brava (Durán *et al.*, 2014). The Muga-Fluvia and Ter prodeltas show similar charac-



teristics; both have a wedge-shaped geometry and show a depocentre of about 25 m thick located offshore of the river mouth (Ercilla *et al.*, 1994b). The Tordera prodelta extends almost 5 km along-shelf and 0.4 km seawards, ending in a steep slope down to a depth of 40 m (Durán *et al.*, 2014). The Besos-Llobregat joint pro-delta extends 35 km along the shelf covering and area of 35 km^2 down to 47 m off the Besos River mouth and at 96 m water depth off the Llobregat River mouth (Liquete *et al.*, 2007, 2008). The Ebro pro-delta covers most of the inner shelf from the present Ebro Delta down to a depth of 80 m (Díaz *et al.*, 1990).

Most of these pro-deltas such as the Muga-Fluvia, Ebro and Llobregat show undulated sediment features (Fig. 9B). In the Muga-Fluvia prodelta, sediment undulations are oblique to the bathymetric contours and occur between 60 and 100 m (Urgeles *et al.*, 2011; Durán *et al.*, 2014). In the Llobregat prodelta, a large field of undulations parallel to the bathymetric contours covers an area of 25 km^2 (Urgeles *et al.*, 2007; 2011). The prodelta undulations have a wavelength of 60-100 m, are 0.3-0.8 m high (Urgeles *et al.*, 2007) and have been interpreted as sediment waves (Urgeles *et*

Figure 9. Synthetic morpho-sedimentary mapping of the northeastern shelf. A) Bathymetric map highlighting the shelf environment (i.e., up to 200 m water depth); inland geology is also included (see Figure 1 for bathymetric and geological legends). B) Main shelf morphological features; river systems and drainage basins are represented. C) Shelf surficial sediment distribution; river systems and drainage basins are represented. Inland geology information included in Figure 9A extracted from the One Geology Project (http://www.onegeology.org/). Topographic and bathymetric data extracted from GEBCO digital database (IOC *et al.*, 2003). Morphological features and surficial sediment distribution compiled from different sources: IGME (2005), Muñoz *et al.* (2005), Amblas *et al.* (2006), Liquete *et al.* (2007, 2010), Serra *et al.* (2007), Ercilla *et al.* (2010), Lastras *et al.* (2011), Urgeles *et al.* (2011), and Durán *et al.* (2013, 2014). Geological map modified from IGME (1994).

***Figura 9.** Mapa morfosedimentario sintético de la plataforma continental del Noreste. A) Mapa batimétrico destacando el ambiente de plataforma continental (hasta los 200 m de profundidad) y también se incluye el mapa geológico de la zona emergida (ver la Figura 1 para las leyendas de la batimetría y de la geología). B) Principales características morfológicas de la plataforma continental; se incluye los sistemas fluviales y cuencas de drenaje. C) Distribución de los sedimentos superficiales en la plataforma, se incluyen sistemas fluviales y cuencas de drenaje. La información geológica terrestre incluida en la Figura 9A se extrajo del proyecto One Geology (http://www.onegeology.org/). Los datos topográficos provienen de la base de datos GEBCO* (IOC et al., 2003). *Los datos batimétricos son del portal EMODnet (http://www.emodnet-hydrography.eu/). Los tipos morfológicos y la distribución de los sedimentos superficiales se compilaron de diferentes fuentes: IGME (2005), Muñoz et al. (2005), Amblas et al. (2006), Liquete et al. (2007, 2010), Serra et al. (2007), Ercilla et al. (2010), Lastras et al. (2011), Urgeles et al. (2011), and Durán et al. (2013, 2014). El mapa geológico se modificó de IGME (1994).*

al., 2007). In the Ebro prodelta, the undulations are also oblique to the general bathymetry and develop between 8-15 m, covering an area of 3.7 km^2 (Urgeles *et al.*, 2011).

The IPW develops from the lower edge of the shoreface to a strong break in slope at 30-35 m water depth (Fig. 9B). From the Cap de Creus to the Tordera River mouth, the IPW appears in the form of isolated bodies that are best developed in bays and pocket beaches (Durán *et al.*, 2014). In contrast, south of the Tordera River mouth the IPW appears as a continuous, coast-parallel to coast-oblique sediment body that extends along the Maresme coast (Liquete *et al.*, 2007; Ercilla *et al.*, 2010). Locally, the IPW is characterized by very-high backscatter with elongate patches of lower backscatter interpreted as sorted bedforms (Durán *et al.*, 2013).

The uneven seafloor of the inner shelf is also related to the presence of rocky outcrops that appear as the submerged toe of coastal cliffs showing continuity with the Variscian granites outcropping inland (Fig. 9B). Widespread rocky outcrops locally extend down to the middle shelf, as occurs to the north of the Blanes canyon head, where rocky outcrops cover a large area of the shelf (more than 100 km^2; Durán *et al.*, 2013).

The middle shelf displays a high variability from north to south. In the continental shelf closer to the Cap de Creus canyon head, the middle to outer shelf is characterised by numerous rocky ridges and shoals with erosive and erosive-depositional features, such as lineations, elongate and oval depressions (Durán *et al.*, 2014). To the south of the Cap de Creus canyon head, the main feature that dominates the middle shelf corresponds to an NNE-SSW oriented shallow channel that extends from the narrowed shelf offshore from the Cap de Creus, south of the southern rim of the canyon upper course, to the La Fonera canyon head, showing a relief of almost 15 m (Lastras *et al.*, 2011; Durán *et al.*, 2014). In contrast, the morphology of the La Planassa middle shelf displays a featureless, gentle seafloor characterized by low backscatter, suggesting fines covering the shelf floor there. This trend is disrupted near the canyon heads by the presence of large rocky outcrops and large areas of high backscatter, mostly indicative of coarse sediment pointing to erosion or non-deposition and sorting of fines (Fig. 9B; Lastras *et al.*, 2011; Durán *et al.*, 2014). Southwards, the Barcelona shelf is dominated by large positive relieves corresponding to relict pro-deltas and sediment bodies (Díaz and Maldonado, 1990; Serra *et al.*, 2007; Liquete *et al.*, 2007, 2008) and narrow ridges interpreted as cemented beach-rocks (Liquete *et al.*, 2007).

In the Ebro outer shelf, a recent study has revealed the presence of three relict sand bodies at 80-116 m depth that have interpreted as relict shoreline features (Lo Iacono *et al.*, 2010). Large and very large 2D and 3D subaqueous dunes have been identified above these morphologies. The dunes show asymmetric and slightly asymmetric profile. Their wavelength ranges from 150 to 760 m and the height between tens of centimetres to 3 m (Lo Iacono *et al.*, 2010).

IPWS have been described in the Gulf of Valencia with vast, elongated seagrass meadows settled on the infralittoral domain, playing a very important role in the sediment stabilization and in the formation of biogenic deposits (Giró and Maldonado, 1983). On the middle Valencia shelf some linear bedforms are highlighted and are interpreted as sand ridges of between 50 and 80 m water depth (Fig. 3H) (Albarracín *et al.*, 2014; Simarro *et al.*, 2015). The wavelength between bedforms ranges from 443 m and 1791 m (Albarracín *et al.*, 2014). The shelf in this sector is tectonically controlled by faults.

(d) Shelf sediments

The seafloor morphology and sediment characteristics of the north-east Iberian continental shelf vary along the shelf as a result of the interplay of several controlling factors, such as the geological setting, the volume and nature of sediment input, and the local oceanography. From the Cap de Creus to Cape La Nao, seafloor facies have been interpreted by acoustic backscatter and bottom samples.

At the northernmost limit of the north-east Iberian shelf, close to the Cap de Creus canyon head, the seafloor is characterized by the presence of rocky outcrops and erosional features with high backscatter corresponding to very coarse sediment (Lo Iacono *et al.*, 2012; García-García *et al.*, 2012; Durán *et al.*, 2014). Deposition occurs to the south of the Cap de Creus and off the main river mouths, as is clearly shown by a large patch of low backscatter data and the predominance of silty sediment along the inner to middle shelf (Fig. 9C) (Lo Iacono *et al.*, 2012; Durán *et al.*, 2014). Along the outer shelf, south the Cap de Creus canyon, the sediment is composed of coarse and medium sand or detritic bioclastic gravels interpreted as relict facies (Ercilla *et al.*, 1994b; Lo Iacono *et al.*, 2012).

Southwards, large depositional features, such as pro-deltas and IPWs, characterize La Planassa inner shelf. Backscatter is very high, which fits with the coarse nature of sediment inputs from the Tordera River and coastal torrents, and the action of eastern waves against this exposed coastal stretch (Durán *et al.*, 2013). Modern fine deposition occurs at the middle shelf, as evidenced by a large belt of very low backscatter (Fig. 9C; Durán *et al.*, 2014). The Barcelona shelf is fed by sediment from the Tordera River, the Maresme coastal torrents, and the Besos and Llobregat rivers (Liquete *et al.*, 2007; 2010; Ercilla *et al.*, 2010). The Tordera River releases coarse sand into the Barcelona shelf that is distributed along the inner shelf feeding the Maresme beaches (Serra *et al.*, 2007; Durán *et al.*, 2009; Ercilla *et al.*, 2010). The Besos and Llobregat rivers represent the most important fluvial sources of sediment into the Barcelona shelf. The sediment distribution of the Barcelona shelf has been well described by Liquete *et al.* (2010) from the integration of backscatter data with sediment cores. These authors revealed the occurrence of two large mud patches extending southwestward 6.5 and 13 km from the Besos and Llobregat rivers, respectively.

Fine sediments characterize the grain size distribution of the Ebro shelf, pro-delta mud extending along the inner and middle shelf down to a water depth of 60 m (Díaz *et al.*, 1990). Seawards, the outer shelf is mostly dominated by relict coarse sand, palimpsest carbonate facies, to the north of the Ebro Delta, and hard ground mounds composed of carbonate cemented sand and shell debris partially covered by mud (Díaz *et al.*, 1990).

The Valencia continental shelf is mainly composed of siliciclastic sediments showing a seaward decrease of grain sizes (Giró and Maldonado, 1983; Maldonado and Zamarreño, 1983). Sands and gravels composed of mixed amounts of clastics and carbonates cover the inner shelf, where rocky outcrops also occur locally. A muddy sheet covers most of the mid-to-outer shelf, blanketing a sandy central area. These surficial sediments rest over a basal layer of gravels and coarse to very coarse sands exposed in the vicinity of a coast-parallel belt (Maldonado *et al.,* 1983). Terrigenous mud prevails on the mid-to-outer shelf, north of Alicante, whereas to the south palimpsest coarse-grained sediments cover most of the shelf (Catafau *et al.,* 1994).

Discussion

The physiography, the morphological features and surficial distribution of the sediments on the Iberian and Balearic continental shelves are controlled by a number of factors such as the geodynamic setting, tectonic features, climatic and eustatic changes, and oceanographic and sedimentary processes operating at different time scales.

Large-scale shelf morphology

The Iberian Peninsula and Balearic Islands show a great variety of styles of continental margins, mainly configured during the Cenozoic. Based on the large-scale morphology, two main types of shelves can be distinguished: a) abrupt, steep, narrow shelves; and b) gentle, smooth, wide shelves.

The Cantabrian and Atlantic shelves are controlled by tectonics. Two types of margin can be distinguished: 1) the Cantabrian margin is an E-W trending abrupt margin, related to the Alpine orogeny (Boillot *et al.*, 1974), characterized by its rugged relief and its scarce sedimentary cover (Maldonado, 1995). This margin was active during the Early Tertiary, but at present is not affected by active tectonics. The convergence between the Iberian and European plates caused the progressive uplifting and deformation of the Cantabrian margin. The uplift of the margin is reflected in the steep (with average slope of 1.6° and maximum slope reaching 80°; Janeau (2012)) and narrow (4-17 km width) shelf physiography. 2) The origin of the N-S Atlantic passive margin, including the Galician and Portuguese shelves, is related to the Jurassic rifting stage. The Cenozoic deformation of the Galician and Portuguese margin has reactivated the faults as reverse structures, which seem to be currently active as suggested by the occurrence of seafloor scarps (Pereira *et al.*, 2011). The western Iberian margin exhibits a moderate seismicity associated to major morpho-structural accidents, such as the Galicia Bank or the Tore Seamount and along the offshore extensions of the late Variscan basement and active faults (Ercilla and Vilas, 2008; Pinheiro *et al.,* 1996).

The Gulf of Cadiz and Alboran shelves also show a strong tectonic control because of their position at the boundary between the Iberian and African plates (Maestro *et al.*, 2013). The physiography and morphology of the continental shelf of the Gulf of Cadiz is conditioned by huge allochtonous masses (Roberts, 1970; Torelli *et al.*, 1997; Medialdea *et al.*, 2004). The Alboran margin, off the Betic Ranges, is a passive margin but with significant neotectonic activity, located inside an isolated basin (Maldonado, 1992, 1995). Offshore of the Algarve coast, to the south of Cape Trafalgar towards the Strait of Gibraltar and along the Alboran Sea, the shelf is steep and narrow, with widths of between 2 and 7 km and a maximum slope reaching 1.5-2° (Lobo *et al.*, 2000; Bárcenas *et al.*, 2011).

Seafloor features associated with uplifted or subsided areas related to active tectonics include areas controlled by normal faulting which caused a basinward progressive sinking on the Valencia continental shelf (Díaz del Río *et al.*, 1986) and the Emile Baudot Escarpment (Acosta *et al.*, 2003) in the Balearic promontory. Listric faults parallel to the margin also control the Catalonian margin (Nelson and Maldonado, 1990), although the northern shelf influenced by the Pyrenean Cordillera is affected by thrusts and associated folds that are approximately E-W oriented (Muñoz *et al.*, 1986).

Other large-scale factors affecting the Iberian and Balearic shelf morphology and sedimentation are climatic and sea level changes during the last climate cycle. Long-term sediment fluxes to continental shelves mainly depend on the hydrology of contributing rivers which in turn is controlled by climate and drainage basin characteristics (Syvitski and Morehead, 1999). It is thus noteworthy to mention the differences between Atlantic and Mediterranean shelves, as the latter are influenced by a strong seasonal variability that influences the hydrologic behaviour of the rivers. Due to the torrential character of the Mediterranean rivers, the sediment transport from the drainage basins toward the shelf is very effective (Liquete *et al.*, 2005), the velocities of the flow are high and the sediment input to river mouths is favoured, thus generating well-developed prodeltaic wedges (Fig. 3F), even off small mountain rivers.

The different types of morphologies are directly related with sea-level changes, in particular during the Late Pleistocene-Holocene period. For example, maximum shelf depth is primarily controlled by the amount of relative sea level change.

During falling sea levels and lowstand intervals of the last cycle, the Iberian and Balearic shelves were emerged and exposed by erosion, mainly by the river systems that produced incised valleys. Regressive shelf-edge wedges recording intervals of sea-level fall and lowstand have been described in many sectors of the Iberian and Balearic shelves (Hernández-Molina *et al.*, 1993; Lobo *et al.*, 2001, this issue; Ercilla *et al.*, 2008).

During the postglacial sea level rise, erosional surfaces and terraces and/or extensive sand sheets were generated at different water depths across the shelf. Sand ridges found in the middle shelf normally are relict forms abandoned during these rising sea-level periods. Sand ridge fields have been found on the Gulf of Cadiz and along the Mediterranean shelves (Figs. 3G, 7B, 8B and 9B).

During the last sea-level highstand, the sea flooded the fluvial valleys and consequently wide estuaries were originated. Later, the sea level was stabilised and depositional morphologies, as pro-deltas and infralittoral prograding wedges were favoured in the mouth of the rivers and infralittoral adjacent areas, respectively (Lobo, 1995, Fernández-Salas, 2008). These morphologies have been described on the Mediterranean and Gulf of Cadiz shelves (Figs. 3F, 6B, 7B, 8B and 9B), on the western Portuguese shelf (Fig. 3D and 5B), along the coasts of the rias on the Galician shelf (Fig. 4B) (Garcia-Gil *et al.*, 1999), and on the Cantabrian shelf (Galparsoro *et al.*, 2010).

Morpho-sedimentary types of shelves

According to the prevailing conditions of sediment supply and hydrodynamic energy, the Iberian and Balearic shelves can be classified into different morpho-sedimentary types that are end-members cases, as there are areas with mixed and combined characteristics. These environmental factors are superimposed onto the background geological context and are modulated by the eustatic changes on the shelf.

Erosional rocky shelves

This type of shelf is exposed to a high-energy hydrodynamic regime and the fluvial sediment supplies are limited, therefore the dominant processes are erosional in origin. Waves and currents act to modify the profile of the shelf by redistributing the sediments deposited there (Wright, 1995). This group of shelves includes geomorphological features generated by erosion processes associated with wave and tide activity, channelised flows along/across the shelf, as well as shallow currents. Erosional areas typically display a rough bathymetry that corresponds to rocky outcrops and erosional features such as terraces, abrasion surfaces and linear incisions.

The best example of this type of shelf is the Cantabrian shelf which is clearly dominated by the large storms from the northwest; by strong northwest swell waves, by a meso- to macrotidal tidal range and by limited sediment supplies from small mountainous streams or rivers. In shallow water zones, a continuous rocky belt is intersected by sedimentary seafloors off the major estuary mouths and the presence of large rocky blocks is related to coastal cliff erosion produced by the action of the storm waves (Fig. 3B) (Galparsoro *et al.*, 2010). The main morphological features are the abrasion surfaces which extensively cover the surface of the shelf (Fig. 2A). Escarpments and terraces at different water depths related to stillstand periods are also frequent. Coarse sediments cover the rest of the Cantabrian shelf as a result of the strong erosional activity of the waves and currents (Fig.2C).

Abrasion surfaces indicative of the dominant activity of erosional processes occur in other shelf settings, such as extensive sectors of the outer and middle western Portuguese shelf (Fig. 3D), the inner Galician shelf, the western part of the northern shelf of the Gulf of Cadiz (Fig. 3E), off Santa Pola on the south-eastern shelf and south of the Ebro River mouth (Figs. 4, 5, 6 and 9). These surfaces are generated by erosion processes associated with wave and current activity combined with low-accumulation sedimentation regimes (Roque, 1998; Ferrín, 2005; Lantzsch *et al.*, 2009a) or with conditions that prevent the sedimentation over relict coarse sands and palimpsest coarse-grained sediments located on the middle and outer shelf (Díaz *et al.*, 1990; Catafau *et al.*, 1994).

Sediment-fed shelves

The main distinctive feature of this type of shelf is the prevalence of fluvial sediment supply over shelf hydrodynamic processes. This situation favours the development of extensive muddy prodeltaic deposits seaward, which in certain circumstances may reach the shelf break. These deposits develop off the main sources of sediment and are characterized by clinoforms with a smooth bathymetry. The morphology and surficial distribution of the prodeltaic deposits are controlled by the interplay of the inertial force of fluvial flow and the oceanographic regime (winds, waves and currents). A radial distribution pattern is indicative of prevailing fluvial influence, evolving to elongated patterns as wave and/or current activity affects the dispersal mechanisms.

This type of shelf essentially occurs off the large Iberian rivers, such as the Tagus, Guadiana, Guadalquivir and Ebro rivers. The two most significant examples occur off the Guadalquivir and Ebro rivers, where prodeltaic deposits are deeply influenced by shelf hydrodynamics and cover the entire shelf environment (Figs. 6B and 9B). However, the morpho-sedimentary pattern with significant development of prodeltaic facies is also observed off medium or small Mediterranean rivers with regional significance, such as the Guadalhorce, Guadalfeo, Adra (Fig. 3F), Jucar, Turia, Segura and Llobregat rivers (Figs. 5B, 6B, 7C, 8C and 9C).

It is noteworthy to mention the important role of the discharges of medium and small rivers, especially from coastal mountain ranges, where prodeltaic deposits cross the shelf and even reach the shelf break. Prodeltaic deposits thus show superimposed undulation fields (Fig. 3F) in numerous Mediterranean shelf settings, usually characterized by abrupt margin physiography and marked climatic seasonality. The origin of such undulation has been related to strong sediment flows normal to bathymetric contours (Fernández-Salas *et al.*, 2007; Urgeles *et al.*, 2007, 2011; Bárcenas *et al.*, 2009).

Current-dominated shelves

Shelves with sedimentary belts parallel or subparallel to the coast or with bedforms generated due to the action of strong currents and energetic wave conditions are part of this group.

Along the Iberian and Balearic shelves, this type is represented by the Galician and the northern part of the western Portuguese shelves. These shelves are underlain by graben systems which act as sediment traps. In particular, fine sediments that are not trapped in the estuaries or rias reach the shelf during storm events and are transported by bottom currents, such as the Iberian poleward current that flows northwards on the middle shelf. As a consequence, muddy belts or patches (e.g., Galician and Douro) are deposited on the middle shelf (Figs. 3C, 4C). The coarser sediments (i.e., sands and gravels) are kept closer inshore where they are transported southwards during storms and heavy wave action (Dias *et al.*, 2002).

Other important currents that produce seafloor features are tidal currents. These currents may produce enough bottom shear stress to generate bedforms composed of coarse sediments or even erode the seafloor.

This is particularly clear on the southeastern Gulf of Cadiz shelf (Fig. 3E) where the tidal regime is mesotidal and the bidirectional tidal currents show increasing intensity toward the Strait of Gibraltar, with measured velocity values of around 1 m/s (Besio and Losada, 2008). These strong tidal currents on the shelf can generate enough bottom shears which might explain the rocky outcroppings and bedform fields near Strait of Gibraltar (Ortega-Sánchez *et al.*, 2008; Lobo *et al.*, 2010) (Figs. 3E, 6B and 6C).

Wave-dominated shelves

On the Iberian and Balearic shelves, the main present-day sedimentation processes are linked to the action of major storms, when sediments are remobilized and transported offshore (Maldonado and Zamarreño, 1983). Currents produced during the passage of storm events control the erosion and transport of unconsolidated sediment on the continental shelf surface (Harris, 1995) and during storms, the bottom currents transport the sediment resuspended along and across the Iberian and Balearic shelves (Drago *et al.*, 1998; Hernández-Molina *et al.*, 2000; Dias *et al.*, 2002a, 2002b; Galparsoro *et al.*, 2010).

IPWs constitute the main depositional features in wave-dominated shelves where there is a low supply of sediments or the fluvial courses are inexistent together to a moderate wave climate. IPWs may also be formed where the contribution of multiple small and medium mountain rivers feed a margin, forming a lineal source (Jaeger and Nittrouer, 2000).

This type of shelf is located mainly on the Mediterranean (Alboran Sea, Murcia, Alicante, Valencia and Catalonia) and the Gulf of Cadiz shelves (Figs. 6B, 7B, 8B and 9B) where the wave climate is classified as of medium to low energy.

Small and medium mountain rivers are characteristics of the Mediterranean coastal ranges, and their sediment supplies should be enough to develop IPWs. However, the low significance of direct fluvial input in areas with IPW deposits, where only discontinuous and ephemeral streams are present, indicates the activity of other genetic processes, such as alongshore sediment transport by lateral advection and cross-shore sediment transport induced by downwelling storm currents (Hernández-Molina *et al.*, 2002; Lobo *et al.*, 2006). In addition, IPWs are periodically affected by storm-driven flows generating a coarse-grained proximal belt, covering the IPWs and the shallower parts of laterally equivalent prodeltaic wedges (Fig. 3F) (Bárcenas *et al.*, 2011). Indeed, the depths of IPW offlap breaks are considered to be indicative of storm wave base levels (Hernández-Molina *et al.*, 2000; Fernández-Salas, 2008).

Conclusions

The great diversity of the morphological features and the patterns of surficial sediments described in this study reveal the complexity of the Iberian and Balearic shelves. They are controlled by tectonic, geodynamic, climatic and eustatic factors at large time scales, and by oceanographic and sedimentary supplies at recent time scales.

Considering the large-scale morphology of the Iberian and Balearic shelves, two main types of shelves can be distinguished: 1) abrupt, steep, sediment-starved narrow shelves, and 2) gentle, smooth, sediment-fed wide shelves.

According to the prevailing conditions of sediment supply and hydrodynamic regimes, the Iberian and Balearic shelves can be classified in different end-members cases: 1) erosional rocky shelves, represented by the Cantabrian shelf; 2) current-dominated shelves, mostly represented by the Galician and the north-western Portuguese shelves; 3) supplied-dominated shelves, with various cases around the Iberian Peninsula, mainly off large rivers; and 4) wave-dominated shelves, where the fluvial sediment supply is low and the wave climate is both strong enough to allow sediment remobilization and weak enough to permit the sedimentation.

The local variations of the factors at different time scales affecting the distribution of surficial morphologies and sediments around the Iberian Peninsula and Balearic Islands, allow us to achieve a broad perspective of the response of the shelves under different environmental conditions.

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