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# Seamounts along the Iberian continental margins

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ABSTRACT

Seamounts are first-order morphological elements on continental margins and in oceanic domains, which have been extensively researched over recent decades in all branches of oceanography. These features favour the development of several geological processes, and their study gives us a better understanding of their geological and morphological domains. The seamounts around Iberia are numerous and provide excellent examples of the geodiversity of these morphological elements. Here we present a compilation of 15 seamounts around the Iberian Peninsula. These seamounts have different origins related to the geodynamic evolution (volcanism, extensional or compressive tectonics, and diapirism) of the domains where they are located. The current configuration of their relief has been influenced by Neogene-Quaternary tectonics. Their positioning controls the current morpho-sedimentary processes in the basins and on the margins, and highlights the fact that downslope processes on seamount flanks (mass flows, turbidite flows, and landslides) and processes parallel to seamounts (contouritic currents) correspond to the major geological features they are associated with them. Biogenic structures commonly develop on the tops of seamounts where occasionally isolated shelves form that have carbonate-dominated sedimentation.

Key words: Iberia, morphology, seamounts, sedimentary environments, tectonics.

## *Los montes submarinos en los márgenes continentales de Iberia*

*RESUMEN*

*Los montes submarinos son rasgos morfológicos singulares, cuyo estudio tiene gran relevancia desde el punto de vista de las distintas ramas de la oceanografía. Su presencia favorece el desarrollo de diferentes procesos geológicos y proporciona un mejor conocimiento de los dominios geológicos y morfológicos en los que se encuentran. En el entorno de Iberia, los montes submarinos tienen una amplia representación y tipología. En este trabajo, se presenta una recopilación geológica de 15 montes submarinos (ocho en el Mar Mediterráneo y siete en el Océano Atlántico) de los márgenes continentales de Iberia y en el dominio Oceánico Atlántico, utilizándose levantamientos batimétricos y geofísicos. El origen de estos montes es muy diferente y está relacionado con la evolución geodinámica del dominio geológico en el que aparecen (volcanismo, tectónica extensional o compresional y diapirismo). La configuración actual del relieve ha sido controlada por la actividad tectónica en el Neógeno-Cuaternario. Su presencia controla el desarrollo de los procesos morfosedimentarios recientes de márgenes y cuencas. Los principales procesos sedimentarios asociados a estos montes se relacionan con procesos longitudinales (flujos en masa, flujos turbidíticos, deslizamientos) y transversales a dichos montes (corrientes de contorno). Además es frecuente en ellos el desarrollo de cuerpos biogénicos sobre sus cimas e incluso de plataformas con sedimentación carbonatada. Los* *montes submarinos de Iberia muestran una gran geodiversidad y constituyen un elemento morfológico de primer orden para comprender los procesos geológicos que tienen lugar en sus márgenes continentales y dominios oceánicos adyacentes.*

*Palabras clave: Iberia, morfología, montes submarinos, ambientes sedimentarios, tectónica.*

*VERSION ABREVIADA EN CASTELLANO*

***Introducción***

*Los montes submarinos (MS) son rasgos morfológicos que se elevan sobre los fondos adyacentes con desniveles superiores a 1 000 m, y pueden aparecer como montañas aisladas o formando cadenas de montes. En sentido amplio también se consideran elevaciones menores (colinas) con desniveles inferiores a 1 000 m. Recientemente existe la tendencia de englobar dentro del concepto de monte submarino todas las elevaciones sobre los fondos marinos que alcancen al menos 100 m de relieve sobre los fondos adyacentes. Se trata de elementos singulares del relieve submarino que tienen gran relevancia en las diferentes disciplinas de la oceanografía. Desde el punto de vista geológico, la caracterización y distribución de los montes submarinos ha permitido una mejor comprensión de la evolución del fondo de los océanos, de las dorsales oceánicas y de la tectónica de placas, así como un incremento del conocimiento de los procesos geológicos (tectónicos, sedimentarios) de cada región.*

*Los montes submarinos en torno a Iberia se localizan en los márgenes continentales de Iberia, y dominios oceánicos adyacentes. Se han identificado 51 montes submarinos, si bien existen otros muchos de menores dimensiones (Fig. 1). Los estudios sistemáticos de la geología y oceanografía (Fig. 2) de estos montes son escasos exceptuando aquellos trabajos realizados en el marco de proyectos para caracterizar la Zona Económica Exclusiva y la Plataforma Continental de España y Portugal, o de caladeros pesqueros. Este trabajo tiene por objetivo la realización de un catálogo geológico de los montes submarinos del entorno de Iberia, representando su geodiversidad, si bien esta recopilación nace con la vocación del inicio de un catálogo futuro más completo.*

***Descripción de los montes submarinos: Geomorfología***

*Se han seleccionado 15 montes submarinos de entre los 51 identificados (números del 1 al 51 de la Fig. 1) entorno a Iberia en base a sus dimensiones, relevancia científica, nivel de conocimiento y a su inclusión en propuestas de "Áreas Protegidas Marinas" (Fig. 1 y Tabla 1): en el noreste de Iberia los Montes submarinos de Ses Olives (6), Ausiàs March (7) y Emilie Baudot (8), localizados en el Promontorio Balear (Fig. 3); en el sureste de Iberia la Dorsal de Alborán (13) y los montes submarinos de Avempace (14.1), Herradura (14.2), Herradura Spur (14.3) y Djibouti Ville (14.4) (Bancos de Djibouti), situados en el Mar de Alborán (Figs. 4 y 5); en el suroeste de Iberia los Bancos de Guadalquivir (27) y Portimao (28), localizados en el Golfo de Cádiz (Figs. 6 y 7); en el dominio atlántico al oeste de Iberia el Monte de Coral Patch (29) situado en la placa de África y separa las llanuras abisales de Sena y La Herradura, el Banco de Gorringe (31) localizado en la prolongación suroccidental del margen continental del suroeste de Portugal que separa las llanuras abisales de La Herradura y del Tajo, y el Monte de Tore (33) que separa las llanuras abisales del Tajo y de Iberia (Fig. 8); al noroeste de Iberia el Banco de Galicia (36) localizado en el dominio distal del margen continental de Galicia (Fig. 9); y al norte de Iberia el Banco Le Danois (40) situado en el margen Cantábrico (Fig. 10).*

*Los montes submarinos estudiados están localizados en un amplio rango de profundidades (20-5 200 m), con pendientes suaves en sus cumbres (0.3-3°) y elevadas en sus flancos (hasta 53°) (Tabla 1). Presentan gran diversidad de tipos morfológicos y sedimentarios que se agrupan en siete tipos (Figs. 3 a 10): i) estructurales (escarpes, crestas, altos, fallas), ii) volcánicos, iii) de dinámica de fluidos (estructuras de colapso, ondulaciones y pockmarks), iv) de movimientos en masa (cárcavas, canales, deslizamientos, depósitos de derrubios), v) de corrientes de fondo (surcos, canales, ondas de sedimento, depósitos contorníticos y terrazas); vi) biogénicos y vii) mixtas, incluyendo fondos de "maërl" (acumulaciones de algas rojas cálcareas) en plataformas aisladas.*

***Procesos genéticos***

*La formación de los montes submarinos de Ses Olives y Ausiàs March (Fig. 3) se relaciona con la compartimentación del borde meridional del Promontorio Balear, generado durante la apertura del Mediterráneo Occidental a lo largo del Mioceno. Este proceso tectónico desarrolló sistemas de fallas normales de dirección*

*NE-SO, entre las que destaca el límite suroriental del promontorio conocido como escarpe Emile Baudot. El monte de Emile Baudot (Fig. 3), situado sobre la parte superior de este escarpe, es un "guyot" que presenta la misma orientación y se formó en la prolongación de la sierra meridional de la isla de Mallorca, además ha sido inyectado por estructuras volcánicas. Los montes submarinos estudiados del Mar de Alborán fueron inicialmente altos estructurales y/o volcánicos formados durante la extensión transarco de la cuenca (Oligoceno superior-Mioceno) (Figs. 4 y 5), si bien su actual relieve es consecuencia de la reactivación tectónica compresiva de estos altos durante el Plioceno-Cuaternario. Los montes submarinos del Golfo de Cádiz (Figs. 6 y 7), fueron inicialmente altos estructurales de basamento en el contexto de un margen continental transformante (Triásico-Cretácico inferior), si bien su última elevación se ha producido durante el emplazamiento de las unidades Béticas en el Mioceno y la reactivación de todo el sistema durante el Plioceno-Cuaternario. En el dominio atlántico del oeste de Iberia, el monte submarino de Coral Patch está formado por actividad magmática en el Eoceno, en relación con la traza del punto caliente de Madeira; el Banco de Gorringe se relaciona con el desarrollo del margen transformante Suribérico durante la apertura de la cuenca del Atlántico Central; y el Monte submarino de Tore se debe al emplazamiento de crestas volcánicas alcalinas en el Cretácico superior, si bien el relieve de todas estas estructuras se han realzado como resultado de la actividad tectónica durante la compresión alpina (Fig. 8). El Banco de Galicia es un "horst" tectónico formado durante la fracturación extensional del margen en el Mesozoico (Fig. 9), si bien el patrón actual del relieve se ha interpretado con una reactivación de la fracturación y abovedamiento causado por la elevación del margen durante la orogenia Alpina. El Banco Le Danois fue producido por la inversión y levantamiento del margen que tuvo lugar durante la compresión del Terciario (Fig. 10) previamente fracturado durante la etapa de rifting Mesozoico.*

### *Procesos geológicos asociados*

*Los montes submarinos controlan la morfoestructura y arquitectura local del margen y causan modificaciones, de diversa escala, de las condiciones oceanográficas (Fig. 2). Altos morfológicos como la Dorsal de Alborán compartimentan la fisiografía de la cuenca y otros como el Banco de Gorringe o el Monte submarino de Tore, separan las actuales cuencas abisales atlánticas al oeste de Iberia. Cabe señalar el papel ejercido por el Banco de Guadalquivir que obstaculizó el avance de la unidad Alóctona del Golfo de Cádiz, emplazada durante el Tortoniense, y el Banco Le Danois que ha favorecido la formación y el desarrollo de subsidencia en la cuenca intratalud Asturiana. La configuración reciente de los montes submarinos también ha sido remodelada por los procesos sedimentarios que les afectan y se agrupan en cuatro tipos en base al mecanismo de transporte de sedimento: i) los procesos pendiente abajo de los montes (flujos en masa, flujos turbidíticos, y deslizamientos) dominan en la Dorsal de Alborán y en los bancos de Gorringe, de Portimao y de Galicia aunque aparecen en mayor o menor medida en todos los montes; ii) los procesos que actúan paralelos a los montes (corrientes contorníticas) dominan en los bancos de Djibouti, de Guadalquivir, de Galicia y Le Danois. La acción de estas corrientes, junto con los cambios del nivel del mar, esculpen niveles de terrazas en la cumbre de los montes submarinos más someros y forman plataformas aisladas (v.g. Dorsal de Alborán, Monte submarino de Emile Baudot); y iii) los procesos mixtos.*

### *Conclusiones: recopilación de los montes submarinos de Iberia*

*Se presenta una recopilación de 15 montes submarinos en el entorno de los márgenes continentales de Iberia y del dominio oceánico Atlántico que representan bien la geodiversidad de estos rasgos morfológicos. Se clasifican estos montes en dos grupos en base a su origen: i) los originados por estructuras de primer orden (tectónicas o volcánicas) que incluyen los montes de grandes dimensiones (longitudes superiores a 50 km) y linealidad, representados por la Dorsal de Alborán y la mayor parte de los montes submarinos de los márgenes y dominios oceánicos atlánticos); y ii) los originados por altos de basamento y elevaciones magmáticas más puntuales, con dimensiones menores (longitudes inferiores a 20 km), que aparecen en forma solitaria o formando alineaciones de montes, representados por el resto de los montes submarinos estudiados en los dominios mediterráneos. Aunque el origen de los montes submarinos estudiados es diverso (elevaciones de basamento asociadas a fallas extensionales, cabalgamientos, volcanismo y diapirismo), existe una importante reactivación posterior de tipo tectónica que ha tenido lugar a lo largo del Oligoceno-Mioceno (bancos Le Danois y de Galicia), del Plioceno (bancos de Gorringe y Portimao), e incluso del Cuaternario (Dorsal de Alborán). La presencia de los montes submarinos en el entorno de los márgenes de Iberia ha favorecido, tanto en el pasado como en el presente, el desarrollo de procesos relacionados con inestabilidades sedimentarias y flujos en masa, corrientes de fondo y procesos de construcciones biogénicas como son los arrecifes de corales de aguas frías y acumulaciones de fondos de "maërl" en plataformas carbonatadas sobre los montes más someros.*

## Introduction and state of the art

Seamounts (Smt.) are morphological sea-floor features characterised as isolated mountains, or chains of successive highs with reliefs of at least 1 000 m (Kennet, 1980; International Hydrographic Organization, 2008) but today there is a trend towards using this term for reliefs of heights up to 100 m (Staudigel *et al.,* 2010; Staudigel and Clague, 2010; Würtz *et al.,* 2014); researchers recognise smaller seamounts as being from 50-100 m (Smith and Cann, 1990; Wessel *et al.,* 2010), and nowadays, Mediterranean seamounts are being catalogued according to this criteria (Würtz *et al.,* 2014). In a general sense, any smaller mounts that rise up to 100 m from the seafloor, the so called hills or knolls, may be also considered seamounts, however, when these occur on continental margins they are usually referred to as banks. Their origins are varied. They can be formed by tectonic structures (faults and folds), caused by diapiric movements, mud volcanism and biostromes, although the majority correspond to magmatic constructions, especially in the oceanic crust domain. On continental margins, the major seamounts, *sensu strictu,* have been observed for example, on the Atlantic margin of the Iberian Peninsula (Galicia Bank; Ercilla *et al.,* 2011), the Cantabrian margin (Le Danois Bank; Ercilla *et al.,* 2008a), the northern margin of the British Isles (Hatton Bank; Hitchen, 2004), and the eastern margin of North America (Flemish Cap Bank; Piper, 2005).

Historically, since seafarers began to encounter seamounts centuries ago, they have captured the curiosity of researchers from many disciplines, for instance Charles Darwin was the first person to describe the processes of guyot formation in oceanic domains (Menard, 1984). However, the detailed exploration of seamounts has only been possible over the past few decades thanks to technological advances. The development of swath bathymetry in the 1990s caused an explosion in deep sea exploration that allowed the discovery and mapping of many seamounts. The application of bathymetric techniques using satellite altimetry enabled us to build up a picture of seamount distribution in the oceans (Smith and Sandwell, 1997). The characterisation and distribution of seamounts have led to a better understanding of the deep ocean, seafloor spreading, and plate tectonics. Subsequently, numerous geological, physical and biological characteristics of seamounts have been described, including their important role in global oceanic circulation and the biogeography of the deep seas (Turnewitsch *et al.,* 2013). A significant increase in seamount research resulted from the United Nations General Assembly mandate on sustainable fishing, which was implemented from 2004 to 2009. The mandate urged fishing nations and Regional Fisheries Management Organisations to identify and protect vulnerable marine ecosystems, as well as assess the impact of deep-sea fishing in the high seas beyond national jurisdictions (Durán Muñoz *et al.,* 2012). This came in response to the global expansion of commercial deep-sea fishing in the mid-1950s, when seamounts became the focus of intensive commercial exploitation. Despite more than 100 years of study, many questions remain unanswered.

The relatively small dimensions of seamounts make them excellent subjects for geological study; they represent reference zones for analysing marine geological processes on a larger scale. Seamounts control surrounding geo-environmental processes and interfere with water-mass dynamics, producing upwelling currents and improving nutrient availability. Furthermore, they have a high biological productivity related to the development of interesting habitats and dynamic changes with respect to the adjacent margins. They are little influenced by continental sources and this makes them key in palaeo-oceanographic and palaeo-climatalogical studies. In addition, they can be natural laboratories for studying marine "source-to-sink" relationships as they present all the elements of this chain: source area, sediment transference systems and final deposition, as well as re-sedimentation systems. Seamounts provide an integrated and interesting view of the majority of marine sedimentary systems, including sedimentary instability, pelagic, hemipelagic, turbiditic and contouritic systems. Tectonic reactivation can modify the original structures, either by increasing their elevation or favouring their break-up, and this provides information on local and regional deformation regimes. Lastly, seamounts favour the local and regional pattern of subsurface fluid migration, influencing the development of sedimentary instabilities and/or specific habitats.

Since the 1970s, the Iberian seamounts (e.g., the Gorringe Bank and Tore Seamount) have been surveyed using seismic reflection profiling, as well as other techniques (magnetic anomalies, bathymetry, dredging and gravity profiles). However, there was no detailed knowledge of these seamounts until the improvement in data acquisition techniques in the 90s, particularly multibeam bathymetric data. Historic and recent bathymetric surveys from Spanish national projects (e.g., TASYO, PRESTIGE, ERGAP, CONTOURIBER, SAGAS bis and MONTERA), international research projects (MVSEIS, MOUNDFORCE, SWIM, WESTMED, SEAMOUNT, OASIS, HERMES, SIMoN), Economic Exclusive Zone and Outer Continental Shelf Delimitation projects from Spain and Portugal, and the Spanish national plan for fisheries, have contributed to our knowledge of the morphostructure of seamounts and their sedimentary record. Geophysical studies are enabling us to gain more detailed information on the structural evolution of the Iberian margins. In addition, characterising the sediment types on seamount tops and walls allows us to understand the sedimentary processes of the Iberian deep sea areas.

Several authors have looked at particular seamounts, including noteworthy contributions by Acosta *et al.* (2001a) and Acosta *et al.* (2003) on the seamounts of the Balearic Promontory; Palomino *et al* (2011) who studied the role of the Djibouti Banks within the basin's general morphosedimentary scheme; Ferranti *et al.* (2014) made a detailed morphostructural analysis of the Gorringe Bank; and Ercilla *et al.* (2008b) and Ercilla *et al.* (2011) focused on the Le Danois and Galicia banks, providing a current view of their sedimentary processes. Recently, Maestro *et al.* (2013) have presented a complete review of the geomorphology of the continental margins of Iberia which also address general aspects of many seamounts considered in this work.

Seamounts are widespread across all the Iberian margins and adjacent oceanic domains (Figs. 1 and 2). Their characteristics and origins are different and they represent a complete catalogue of the global geodiversity characterising these features. Current scientific knowledge of seamounts is relatively moderate; there is a lack of systematic geological studies on the Iberian examples, with the exception of the surveys carried out as part of the Portuguese and Spanish Exclusive Economic Zone programs. Seamount research is at the beginning of a steep data-collection curve.

The main aim of this paper is to present, for the first time, an overview of the seamounts in the Iberian region; their occurrence, size and distribution are presented as well as the associated geological processes. This paper offers a broad perspective of the geological research on the seamounts around Iberia. A total of 15 selected seamounts have been analysed and these have been assigned the numbers that appear in Figure 1: the Ses Olives (6), Ausiàs March (7) and Emile Baudot (8) seamounts from the Balearic Promontory; the Northern Alboran Ridge (13), and the Djibouti Banks (comprising the Avempace -14.1, Herradura -14.2, Herradura Spur -14.3 and Djibouti Ville -14.4 seamounts) in the Alboran Sea; the Guadalquivir Bank (27), Portimao Bank (28), Gorringe Bank (31) and Coral Patch Seamount (29) from the Gulf of Cadiz and adjacent Atlantic oceanic domains; the Tore Seamount (33) in front of the Portuguese margin; the Galician Bank (36) from northwest Iberia, and the Le Danois Bank (40) from the Cantabrian margin (Fig. 1 and Table 1). In this regard, it is noteworthy that we have used new, unpublished data on the Gulf of Cadiz and the Alboran Sea seamounts, which were obtained through the project MONTERA.

## Geological setting

The margins and adjacent oceanic basins around the Iberian Peninsula are differentiated into two well-defined geodynamic domains: the Mediterranean margins developed in the context of the Alpine Orogeny from the Upper Oligocene onwards, and the Atlantic domain whose margins formed by rifting from the Late Triassic to the Upper Cretaceous. The most recent morphogenetic episode of most of these seamounts, even the Atlantic ones, may be linked to their evolution during the Alpine orogeny, which greatly influenced the Iberian margins from the Eocene to Miocene, and right up to the present day (Fig. 1). This is due to the successive compressive deformation affecting the Iberian Peninsula, both northwards (the Pyrenean orogen) and southwards (the Betic-Rif orogen) (De Vicente and Vegas, 2009). Since the Upper Tortonian, the Iberian Peninsula has been located just north of the present-day boundary between the African and Eurasian plates (Srivastava *et al.,* 1990). Recent geodynamic models shows the existence of a NW-SE to WNW-ESE oblique convergence at a rate of about 4 mm/yr between these plates (e.g., Nocquet and Calais, 2004; Stich *et al.,* 2006). This plate boundary extends from the western Azores triple junction through the Gloria Fault, located westwards of the Gorringe Bank, and continues eastwards into the Gulf of Cadiz along the SWIM fault zone as suggested by recent models (Zitellini *et al.,* 2009). This fault zone connects with the Rift-Tell System on the southern boundary of the Mediterranean Orogenic Belt (Mauffret *et al.,* 2007; Terrinha *et al.,* 2009; Zitellini *et al.,* 2009; Cunha *et al.,* 2012; Rosas *et al.,* 2012) (Fig. 1). Recently it has been proposed that in the south-western Iberia margin a new subduction zone of the Atlantic oceanic crust beneath Iberia may be forming, resolved with north-western verging thrusts of the Gorringe Bank and the Horseshoe Abyssal Plain and connected by the SWIM fault zone to the Betic-Rif orogen (Duarte *et al.,* 2013).

In the Mediterranean domain, seamounts have been identified in the Balearic Promontory and the

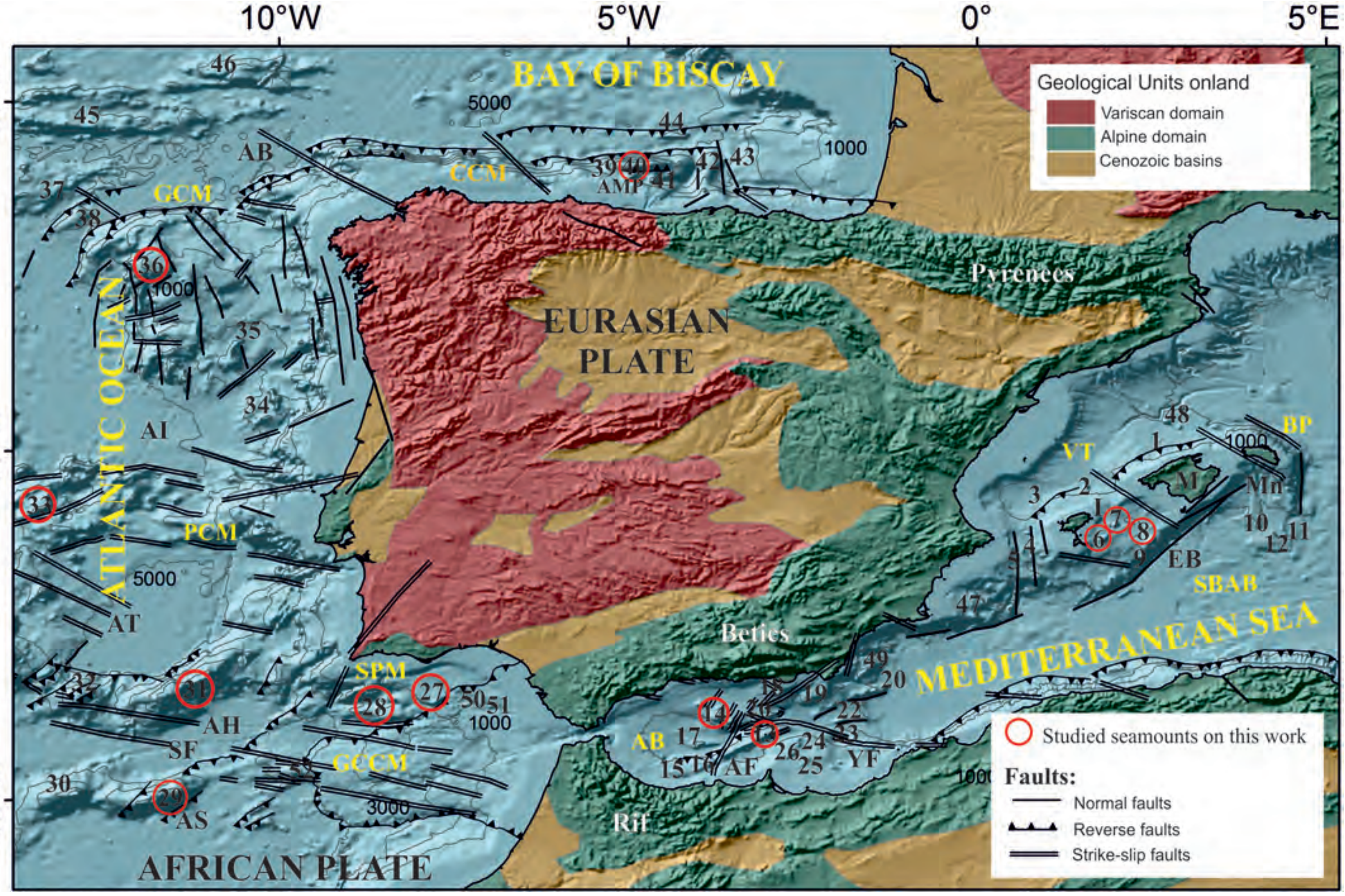


**Figure 1.** Location of the main seamounts (Smt.,) along the Iberian margins: 1- Soller Smt., 2-Morrot de Sa Dragora Smt., 3- MS1-S or Stony Sponge Smt., 4-MS-2 or Xabia Smt., 5-Cabo de la Nao Smt, 6-Ausiàs March Smt., 7-Ses Olives Smt., 8-Emilie Baudot Smt., 9-MS-3 or Bel Guyot, 10-Jaume I Smt., 11-MS-4 or Vallseca Smt., 12- Colom Smt., 47- Seco de Palos Bank, 48-Cresques Smt. (NE Iberia); 13-Northern Alboran Ridge, 14-Banks of Djibouti, 15-Xauen Bank, 16-Tofiño Bank, 17-Ibn Batouta Smt., 18-Chella or Seco de los Olivos Bank, 19-Pollux Bank, 20-Adra Ridge, 21-Maimonides Ridge, 22-Al Mansour Ridge, 23-Yusuf Ridge, 24-Les Cabliéres Bank, 25-Provençaux, Bank 26-Tres Forcas Promontory, 49-Abubacer Ridge (SE-Iberia); 27-Guadalquivir Bank, 28-Portimao Bank, 50- Cadiz Diapiric Ridge, 51-Guadalquivir Diapiric Ridge (SW-Iberia); 29-Coral Patch Smt., 52-Coral Patch Ridge, 30-Ampere Smt., 31-Gorringe Bank, 32-Hirondelle Smt., 33-Tore Smt. (W-Iberian); 34-Porto Smt., 35-Vigo Smt., 36-Galicia Bank, 37-La Coruña Smt., 38-Finesterre Smt. (Galician or NW-Iberian); 39-Vizco High, 40-Le Danois Bank, 41-Ecomarge High, 42-Santander Promontory, 43-Landes Smt., 44- Jovellanos Smt., 45-Charcot seamounts, 46- Vizcaya Smt., (Cantabrian or N-Iberian). BP: Balearic Promontory; Mn: Menorca Island; M: Mallorca island; I: Ibiza island; VT: Valencia Trough; SBAB: South Balear-Algerian Basin; EB: Emile Baudot Escarpment; AB: Alboran Basin; YF: Yusuf Fault; AF: Al Idrissi Fault; GCCM: Gulf of Cadiz continental margin; SPM: South-Portuguese Margin; AS: Seine Abyssal Plain; SF: SWIM Fault Zone; AH: Horseshoe Abyssal Plain; AT: Tajo Abyssal Plain; PCM: West-Iberian or Portugal continental margin; AI: Iberia Abyssal Plain: GCM: north-west-Iberian or Galician continental margin; AB: Gulf of Biscay Abyssal Plain; CCM: north-Iberian or Cantabrian Continental Margin; AMP: Asturian Marginal Plateau.

***Figura 1.*** *Localización de los principales montes submarinos (MS) en los distintos márgenes de Iberia: 1-MS Soller, 2-MS Morrot de Sa Dragora, 3-MS1-S o MS Stony Sponge; 4-MS-2 o MS Xabia, 5-MS Cabo de la Nao, 6-MS Ausiàs March, 7-MS Ses Olives, 8-MS Emilie Baudot, 9-MS-3 o Guyot Bel, 10-MS Jaume I; 11-MS-4 o MS Vallseca; 12-MS Colom, 47-Seco de Palos Bank, 48-MS Cresques (NE Iberia); 13-Dorsal de Alborán Norte, 14-Bancos de Djibouti, 15-Banco de Xauen, 16-Banco de Tofiño, 17-MS Ibn Batouta, 18-Banco de Chella o Seco de los Olivos, 19-Banco de Pollux, 20-Dorsal de Adra, 21-Dorsal de Maimonides, 22-Dorsal de Al Mansour, 23-Dorsal de Yusuf, 24-Banco de Les Cabliéres, 25-Banco Provençaux, 26-Promontorio Tres Forcas, 49-Dorsal de Abubacer (SE-Iberia); 27-Banco del Guadalquivir, 28-Banco de Portimao, 50-Dorsal Diapírica de Cádiz, 51-Dorsal Diapírica del Guadalquivir (SO-Iberia); 29-MS Coral Patch, 52-Dorsal de Coral Patch, 30-MS Ampere, 31-Banco de Gorringe, 32-MS Hirondelle, 33-MS Tore (O de Iberia); 34-MS Porto, 35-MS Vigo, 36-Banco de Galicia, 37-MS La Coruña, 38-MS Finesterre (Margen de Galicia o del Noroeste de Iberia); 39-Alto Vizco, 40-Banco de Le Danois, 41-Alto Ecomarge, 42-Promontorio de Santander, 43-MS Lande, 44-MS Jovellanos (N-Iberia), 45-Montes submarinos de Charcot, 46-MS Vizcaya (Margen Cantábrico o del Norte de Iberia). Otros rasgos geográficos y geológicos mencionados en el texto: BP: Promontorio Balear; Mn: Isla de Menorca; M: Isla de Mallorca; I: Isla de Ibiza; VT: Cuenca de Valencia; SBAB: Cuenca Algero-Balear; EB: Escarpe de Emile Baudot; AB: Cuenca de Alborán; YF: Falla de Yusuf; AF: Falla de Al Idrissi; GCCM: Margen continental del Golfo de Cádiz; SPM: Margen Surportugués; AS: Llanura Abisal de Sena; SF: Zona de falla SWIM; AH: Llanura Abisal de La Herradura; AT: Llanura Abisal de Tajo; PCM: Margen continental de Portugal o del Oeste de Iberia; AI: Llanura Abisal de Iberia; GCM: Margen continental de Galicia o del Noroeste de Iberia; AB: Llanura Abisal del Golfo de Vizcaya; CCM: Margen continental Cantábrico o del Norte de Iberia; AMP: Plataforma Marginal de Asturias.*

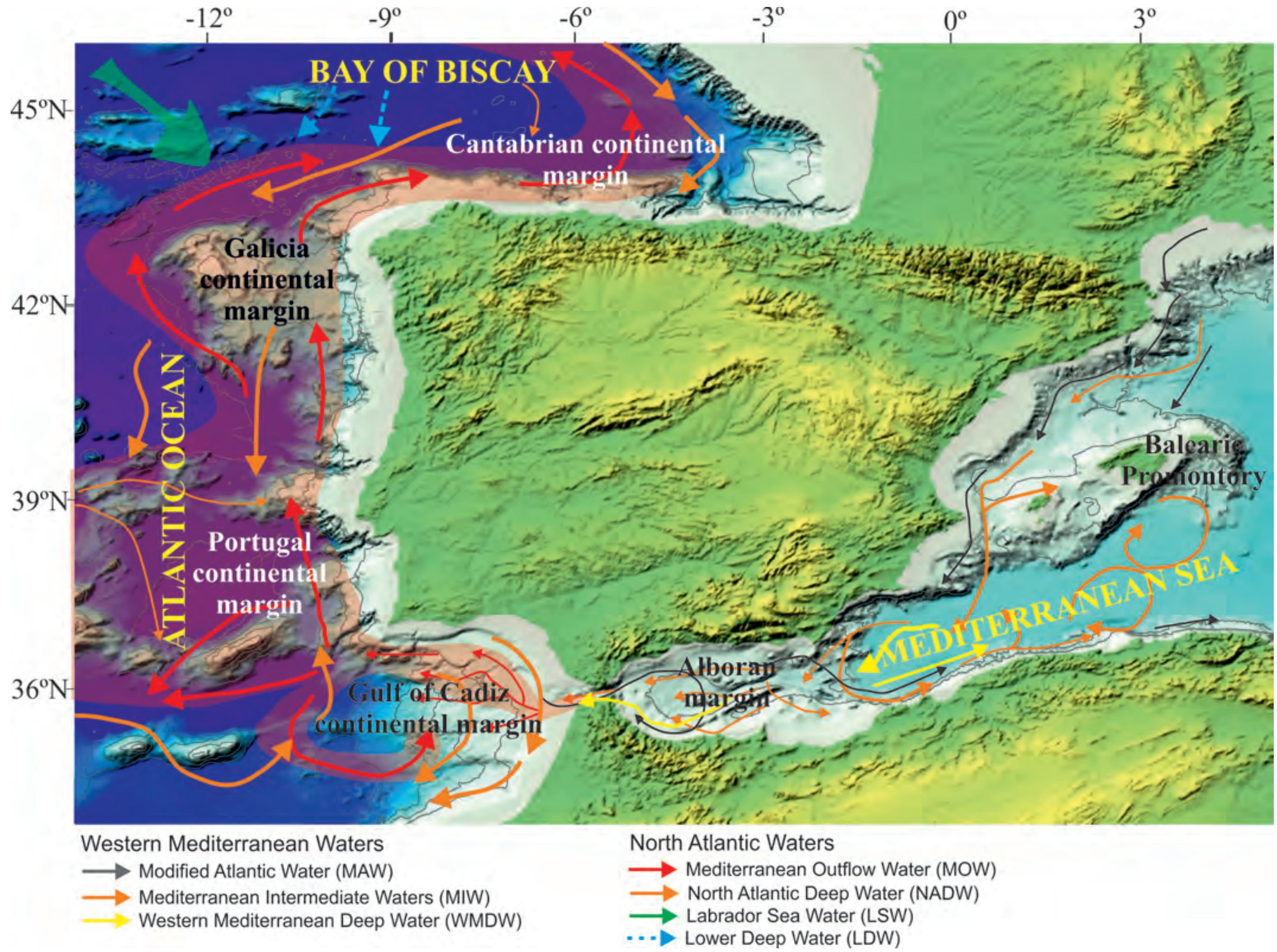


**Figure 2.** Main water masses around Iberia cited in the text. Taken from Hernández-Molina *et al.,* (2011).
***Figura 2.*** *Principales masas de agua alrededor de Iberia tal como se citan en el texto. Tomado de Hernández-Molina* et al., *(2011).*

Alboran Sea Basin (Fig. 1). Both areas formed in the context of the western Mediterranean back-arc Upper Oligocene-Miocene rifting (Jolivet and Faccena, 2000), which resulted from the splitting of a previous Eocene Alpine Belt (Carminati *et al.,* 2012). The Balearic Promontory is 350 km long, 105 km wide and its flanks are approximately 2 000 m high. The promontory is flanked on its south-eastern side by the NE-SW oriented Emile Baudot Escarpment that separates it from the south Balearic-Algerian Basin to the southeast (Acosta *et al.,* 2003). The promontory is a large terrestrial and submarine elevation in the western Mediterranean Basin which corresponds to a continental block located in the north-eastern prolongation of the External Betic Belt (Rehault *et al.,* 1985). Its northern boundary has thrust faults that principally verge in the Valencia Trough, and the southern boundary is dissected by NE-SW normal faults related to oceanic spreading in the western Mediterranean (Vegas, 1992a; Acosta *et al.,* 2001a). The Alboran Sea Basin was formed inside the Gibraltar Arc (Betics-Rif orogen) during the Late Oligocene and Miocene (Platt *et al.,* 2003), and it has been under compression from the Late Miocene to the present (Martínez-García *et al.,* 2013). Stretching and normal faulting in the extensional phase produced thinning of the continental crust accompanied by several andesitic volcanic episodes (Duggen *et al.,* 2004; Gill *et al.,* 2004).

In the Atlantic domain, seamounts have been identified in several geological domains: the Gulf of Cadiz, especially in its northern part (South Portuguese Margin), and the adjacent Atlantic realm, western Iberia (Portugal), north-western Iberia (Galician) and the northern Iberian margins (Cantabrian) (Fig. 1).

The southern Portuguese margin began to be

| Id. N° | Location | | Seamount Name | Latitude | Longitude | Max/Min. water depth (m) | Lenght/ Width (km) | Height (m) | Area (km2) | Max/Min. slope (°) |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | NE Iberia | Balearic Promontory | Ses Olives Smt | 38°58 N | 02°02 E | 995/250 | 11.5/6.4 | 775 | 59 | 40.2/0.3 |
| 7 | NE Iberia | Balearic Promontory | Ausiàs March Smt | 38°44 N | 01°49 E | 583/86 | 13.2/5.9 | 497 | 73 | 32.3/0.1 |
| 8 | NE Iberia | Balearic Promontory | Emile Baudot Smt | 38°44 N | 02°29 E | 702/80 | 15.2/7.6 | 620 | 98 | 31.7/0.0 |
| 13 | SE Iberia | Alboran Sea | North Alboran Ridge | 35°53.33’N | 03°02’W | 1 600/+16 | 105/22 | 1 600 | 2 100 | 57/0.2 |
| 14 | SE Iberia | Alboran Sea | *Banks of Djibouti* | | | | | | | |
| 14.1 | SE Iberia | Alboran Sea | Avempace Smt | 36°22`N | 03°58°`W | 970/250 | 12.5/10 | 700 | 83 | 53.3/0.01 |
| 14.2 | SE Iberia | Alboran Sea | Herradura Smt | 36°12`N | 03°45`W | 930/270 | 17.8/16 | 660 | 202 | 52/0.02 |
| 14.3 | SE Iberia | Alboran Sea | Herradura Spur Smt | 36°18.56’N | 03°41.96’W | 867/436 | 6.1/4.9 | 431 | 22.5 | 22.8/0.8 |
| 14.4 | SE Iberia | Alboran Sea | Djibouti Ville Smt | 36°08`N | 03°33’W | 870/200 | 10.5/9.7 | 670 | 77 | 43.5/0.02 |
| 27 | SW Iberia | Gulf of Cadiz Margin | Guadalquivir Bank | 36°22.89`N | 7°46.33`W | 670-1115 | 11.15/0.275 | 395-840 | 82 | 40/3 |
| 28 | SW Iberia | Gulf of Cadiz Margin | Portimao Bank | 36°12.55 N | 8°39.34’W | 3 800-<br>3 200 | 93/18-25 | 400-900 | 1 800 | 12/0.01 |
| 29 | SW Iberia | Portuguese Margin | Coral Pacth Smt | 34°56.100 N | 11°52.917’W | 5 000-560 | 120/70 | 400 | 8 400 | 20/3 |
| 31 | SW Iberia | Portuguese Margin | Gorringe Bank | 36°38.750 N | 11°18.417’W | 4 800/20 | 200/70 | 4 700 | 14 000 | 30/5 |
| 33 | W Iberia | Portuguese Margin | Tore Smt | 39°23.567’N | 12°53.867’W | 5 200/<br>2 300 | 239/130 | 2 900 | 31 000 | 11/3 |
| 36 | NW Iberia | Galicia Margin | Galicia Bank | 42°41,73’N | 11°45,16’W | 4 100/605 | 84/60 | 3 000 | 2 946 | 49/0.15 |
| 40 | W Iberia | Cantabric Margin | Le Danois Bank | 44° 4.78’ N | 4° 47.07’ W | 4 400 /510 | 72 / 15 | 3 900 | 1 150 | 20/0.1 |

**Table 1**. Summary of the location, geometric parameters (depth, length, width, height, area, and slope gradient) that characterise the 15 studied Iberian seamounts (Smt). Length and width are measured as the longest and shortest axes, and heights from the shallowest part of each seamount to the adjacent seabed.
***Tabla 1****. Resumen de la localización y parámetros geométricos (profundidad, longitud, anchura, altura, área, y pendiente) que caracterizan los 15 montes submarinos de Iberia estudiados. La longitud y la anchura se miden como los ejes de mayor y menor longitud respectivamente, y la altura desde la parte más superficial de cada monte hasta la profundidad del fondo marino adyacente.*

formed during Triassic-Late Cretaceous rifting phases related to the opening of the Neo-Tethys and Central Atlantic Ocean (Terrinha, 1998). The initial formation of this margin took place during the early stages of the opening of the central Atlantic (Late Triassic-Middle Jurassic) in a transtensional continental shear zone which evolved into a rifted transform margin during the Cretaceous (Vegas *et al.,* 2004). The general extensional regime was punctuated by short-lived compressional periods during the Jurassic and near the boundary Jurassic-Cretaceous. From the end of Late Cretaceous and through Late Miocene, the southern Portuguese margin suffered multiphased tectonic inversion, controlled mainly by the N-S convergence between the Eurasian and African plates and the formation of the Betic-Rif orogenic arc in the Gulf of Cadiz (Maldonado *et al.,* 1999; Rosenbaum *et al.,* 2002; Terrinha *et al.,* 2009).

The formation of the western Iberian margin is related to the multiphased rifting that separated the the western Iberian and Newfoundland conjugate margins, from the Late Triassic to Early Cretaceous, leading to the opening of the North Atlantic Ocean. Both margins have been highlighted as classic examples of poor magma rifted margins (Sibuet *et al.,* 1979; Boillot *et al.,* 1995; Pinheiro *et al.,* 1996; Péron-Pinvidic *et al.,* 2007; Reston *et al.,* 2007; Péron-Pinvidic *et al.,* 2007; Tucholke *et al.,* 2007; Péron-Pinvidic and Manatschal, 2009). The first rifting phase occurred from the Late Triassic into early Jurassic, characterized by extension without continental separation. The second phase occurred from the Late Jurassic through the Early Cretaceous and had three episodes (Whitmarsh *et al.,* 2001; Sibuet *et al.,* 2007; Tucholke *et al.,* 2007): 1- rifting and continental crust breakup in the southern part of the rift (Late Jurassic-Berriasian); 2- rifting and continental crust breakup in the northern part of the rift and rifting of sub-continental mantle lithosphere in the southern part (Valanginian-Hauterivian); 3- rifting and exhumation of the continental lithosphere mantle (Barremian-Aptian), forming the zone of exhumed continental mantle (ZECM). According to a recent work by Sallarés *et al.* (2013), the serpentinized peridotites found in the basement of Gorringe Bank may be part of an older ZECM, recording the northwards migration of the rifting. Thus, the rifting and later the oceanic spreading progressively migrated from the Gorringe Bank area northwards, reaching the north-western Iberian margin at about 112 Ma (Pinheiro *et al.,* 1996). Moreover, the Gorringe Bank has been a geodinamic key point since Mesozoic times, due to its location between the domains of the western Iberian and southern Portuguese margins and currently near to the Eurasian (Iberia)-African (Nubia) plate boundary (Jiménez-Munt *et al.,* 2010).

Since the Late Cretaceous the western Iberia margin has been affected by several episodes of alkaline magmatism, which extended from the Tore seamount (~104-80Ma) through the Tore-Madeira Rise and reached the Madeira Islands (~5 Ma) located in the central Atlantic Ocean (Geldmacher *et al.,* 2006; Merle *et al.,* 2006). Several alkaline magmatic episodes have also been recognized onshore, for instance, at Monchique (~72 Ma) located in the south-west mainland of Portugal and offshore in the Ormonde Smt. (~66-60 Ma) on the Gorringe Bank, the Coral Patch seamount (32 Ma) and the Ampere Smt. (31 Ma) (Merle *et al.,* 2009; Geldmacher *et al.,* 2011). This magmatic activity has been interpreted as the trace of the Madeira hotspot (e.g., Geldmacher *et al.,* 2011). Several compressional episodes associated with changes in the convergence direction between the African and Eurasian plates, since the Eocene until the Present, have been accommodated by thrusting along major structures. This is the case for the north-westwards thrusting of the Gorringe Bank over the Tagus Abyssal Plain (Terrinha *et al.,* 2003), and of the Coral Patch Smt. in the same direction over the Horseshoe Abyssal Plain (Hayward *et al.,* 1999; Martínez-Loriente *et al.,* 2013; Martínez-Loriente *et al.,* 2014).

The north-western Iberian (Galician) margin formed near the triple junction between North America, Iberia and Eurasia in the Upper Cretaceous from magnetic anomalies MO to C33o (118 to 80 Ma), which allowed the oceanic opening in the Bay of Biscay (Sibuet and Collette, 1991; Sibuet *et al.,* 2004). Finally, the northern Iberian (Cantabrian) margin, the youngest Atlantic margin in Iberia, was formed in the Upper Cretaceous and Palaeogene during the early opening of the Bay of Biscay (Le Pichon *et al.,* 1971; Sibuet *et al.,* 2004). Offshore, the Pyrenean orogeny (Late Cretaceous to Eocene) caused the partial closure of the Bay of Biscay and the uplift of the margins by thrusting (Gallastegui *et al.,* 2002), simultaneously, in part, with seafloor spreading in the basin (Sibuet *et al.,* 2004). These processes migrated westwards, also inverting the north-western Iberian margin in the Lower Miocene (Alvarez-Marrón *et al.,* 1997; Sibuet *et al.,* 2007; Vázquez *et al.,* 2008a).

## Methods

This paper is based on the study of combined data obtained by means of multibeam echo sounders (Kongsberg-Simrad EM-12S, EM-120, EM300, EM1000 and ATLAS Hydrosweep DS), ultra-high (parametric TOPAS PS 018 echo sounder and ATLAS Parasound P-35) and high reflection seismic systems (EG&G sparker and 3-channel Airgun). The data has been compiled from several oceanographic expeditions sponsored by Spanish projects (TASYO, MOUNDFORCE, PRESTIGE, ERGAP, SAGAS bis, CONTOURIBER, MONTERA) and Portuguese national programmes developed on the Iberian margins by various governmental organisations. In particular, complete multibeam coverage of the floor of the Balearic Sea and the Galicia Margin was recorded during the Spanish Exclusive Economic Zone surveys (IEO-IHM-ROA, 1999; Gómez-Ballesteros, 2000).

The morphography of the seamounts has been systematically analysed using the geographic information system ArcGis software. This considers location and a series of geometric parameters (depth, length and width, height, area, and slope gradient) where the lengths and widths are the longest and shortest axes respectively of these features in the bathymetric cartography, and relief is the measure of height from the adjacent seafloor to the summit of the seamount. Table 1 summarises this characterisation.

## Seamounts in the Balearic Promontory

### *Morphology*

Fourteen seamounts (Soller, Morrot de Sa Dragora, MS1-S or Stony Sponge, MS-2 or Xabia, Cabo de la Nao, Ausiàs March Smt., Ses Olives, Emilie Baudot, MS-3 or Bel Guyot, Jaume I, MS-4 or Vallseca, Colom, Cresques seamounts, Seco de Palos Bank) have been recognised in the Balearic Promontory and Valencia Trough (numbers 1 to 12, 47 and 48 in Fig. 1). In this section, three selected seamounts (numbers 6, 7 and 8 in Fig. 1), which are under consideration as "Protected Marine Areas" of Spain, are described. These are: the Ses Olives (6) (also known as Monte Norte) (Fig. 3A), Ausiàs March (7) (also called Monte Sur) (Fig. 3B) and Emile Baudot (8) seamounts (Fig. 3C). They are located to the east of the islands of Ibiza and Formentera on the Balearic Promontory (Fig. 1).

The Ses Olives Smt. (summit at 250 m water depth) is approximately NE-SW trending, rectangular in shape, and occupies an area of 50 km$^2$ (11.5 km long and 6.4 km wide) (Table 1). The top of the seamount is flat (< 2°) and displays three small elevations (< 30 m high). Its flanks slope up to 40°. The main morphological features identified on this seamount are: a slide scar, slumps, and pockmarks (Fig. 3A). An amphitheatre-like scar is observed on the south-western flank where deposits have been eroded and transported south-westwards. Slump deposits occur on the south-eastern flank where NE-SW faults are found bounding this seamount. An extensive pockmark field has been identified on the western and southern flanks. The pockmarks are circular (150 to 500 m in diameter; 10 to 35 m in relief), giving the seafloor an "orange peel" texture, and tend to group into chains following the main tectonic trend (Fig. 3A) (Gómez-Ballesteros, 2000; Acosta *et al.,* 2001b).

The Ausiàs March Smt. (summit at 86 m water depth) is approximately NE-SW trending, has an elongated shape, and occupies an area of about 73 km$^2$ (13.2 km long and 5.9 km wide) (Table 1). The planar top of this structure has moderate slope gradients (2° to 4°). The main morphological features identified on this seamount are: fault scarps, scars, slumps, mounds, and pockmarks (Fig. 3B). The most striking feature is a NE-SW fault with a topographic expression of more than 25 m dissecting the top (Gómez-Ballesteros, 2000; Acosta *et al.,* 2001b). Slide scar and slump deposits occur on the north-eastern flank. Elongated circular mounds forming chains aligned with the NE-SW fault are recognised in the northern sector. The pockmark field occurs in the north-eastern sector of the seamount (Fig. 3B), individual pockmarks ranging 150-500m in diameter and have 10-35 reliefs, and tend to group into chains aligned to NE-SW faults.

The Emile Baudot Smt. (summit at 80 m water depth) is approximately NE-SW trending, has an elongated shape and occupies an area of about 98 km$^2$ (15.2 km long and 7.6 km wide) (Table 1). The top is planar (0-2°) and the flanks have important slope gradients (up to 31°) (Acosta *et al.,* 2001a). The main morphological features identified on this seamount are: erosional surfaces, biogenic patches, gullies, slumps, scars and volcanic intrusions. Erosional surfaces, as well as biogenic patches formed by accumulations of coralline algae (maërl) and carbonate clasts (rodoliths) are recognised on the top (Acosta *et al.,* 2003). A network of NW-SE orientated gullies and slide scars have been identified on the upper sector of the flanks (Gómez-Ballesteros, 2000; Acosta *et al.,* 2001a), and slumped and blocky sediments are present at their bases. A volcanic field (513 km$^2$) has also been mapped on the flanks (Gómez-Ballesteros, 2000; Acosta *et al.,* 2001a; Acosta *et al.,* 2004) (Fig. 3B). This comprises 118 pointed and flat-topped, cone-shaped pinnacles from 8 to 501 m in height and 141 to 1741 m in diameter (Acosta *et al.,* 2001a,b) (Fig. 3 C, D).

### *Genetic processes*

The Ses Olives and Ausiàs March seamounts are structural highs which are caused by the conjugate fault system oriented NE-SW and NW-SE (Gómez-Ballesteros, 2000; Acosta *el at.,* 2001a). The Emile Baudot Smt. is a NE–SW elongated guyot formed by the south-west prolongation of the southern mountain ranges of Mallorca Island, probably intruded by volcanics (Acosta *et al.,* 2001a), as indicated by geomagnetic data (Palomo *et al.,* 1974; IEO-IHM-ROA, 1999). Some of the differentiated pinnacles around this seamount are almost perfectly conical in shape; these are Middle Miocene-Recent and intrusive in nature (Martí *et al.,* 1992; Gómez-Ballesteros, 2000; Acosta *et al.,* 2003). An olivine basalt sample taken on the top of this seamount has led to a similar origin being ascribed to the other volcanic features (Acosta *et al.,* 2004). The southern limit is marked by the Emile Baudot Escarpment, a NE-SW linear scarp that suffered extensive erosion in the Messinian (Rehault *et al.,* 1985; Acosta *et al.,* 2001a).

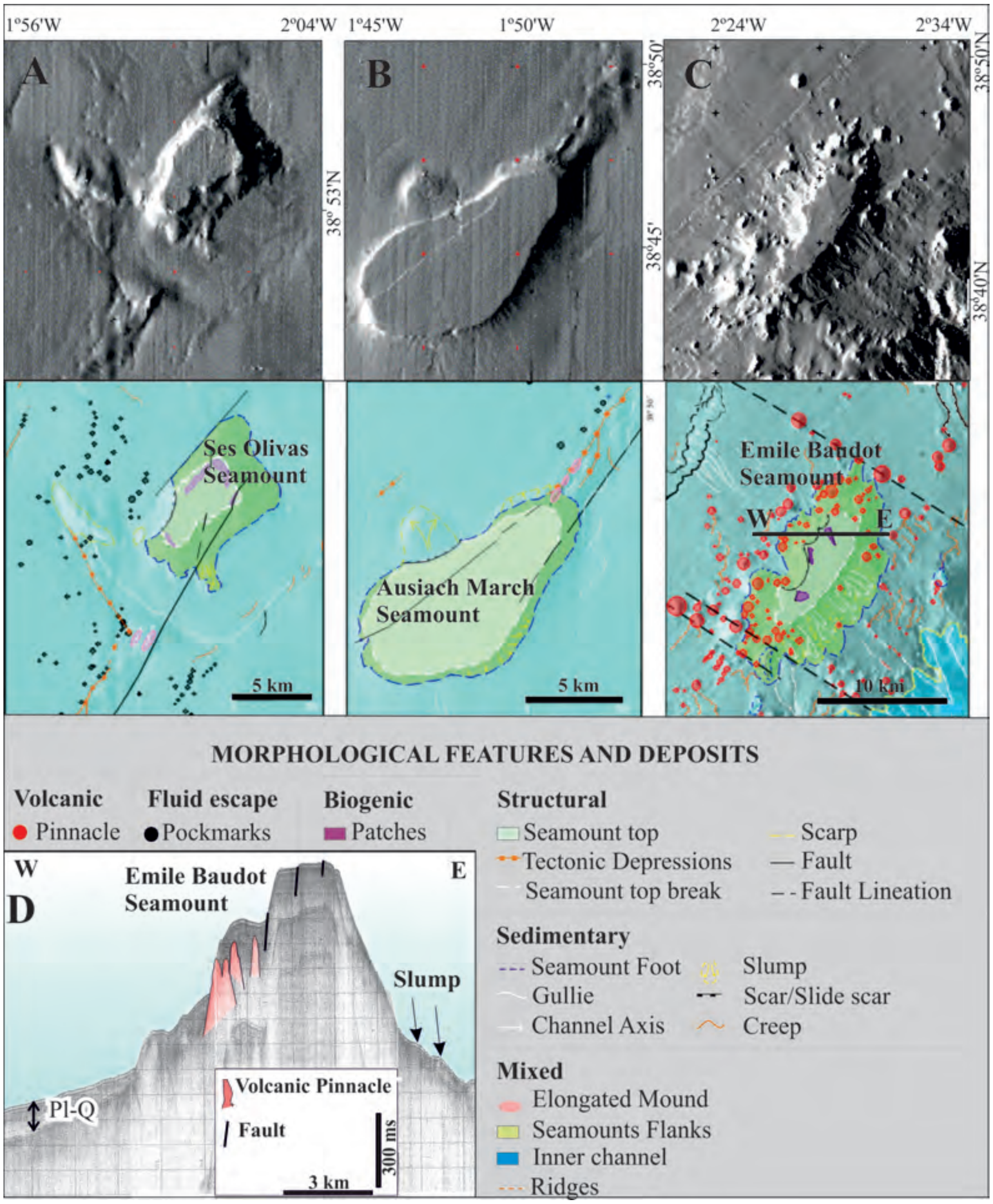


**Figure 3.** The Balearic Promontory seamounts (NE-Iberian): hill-shade and geomorphological maps of (A) the Ses Olives (B) the Ausiàs March and (C) the Emile Baudot Seamount and (D) selected single channel seismic of the Emile Baudot Smt. Profile location in C. Legend: Pl-Q, Plio-Quaternary deposits. Modified from Gómez-Ballesteros (2000).

***Figura 3.** Montes submarinos del Promontorio Balear (NE-Iberia): Mapas de Sombras y Geomorfológicos de los Montes submarinos de (A) Ses Olives, (B) Ausiàs March y (C) Emile Baudot; y (D) Perfil de sísmica monocanal a través del Monte Submarino de Emile Baudot. Localización del perfil en C. Leyenda: Pl-Q, Depósitos Plio-Cuaternarios. Modificada de Gómez-Ballesteros (2000).*

### *Recent geological processes*

The main geological processes affecting the three Balearic seamounts studied are sedimentary instability, volcanism, seepage, and carbonate formation (Fig. 3). Numerous areas of instability related to tectonics, erosion at head scarps and sediment remobilisation by slumps and slides have been identified (Gómez-Ballesteros, 2000: Acosta *et al.,* 2001a,b). Middle Miocene-Recent volcanic activity has been located close to the Emile Baudot Escarpment (Martí *et al.,* 1992) and associated extensional tectonics is evidenced by a folded sequence on south-western flank of the Emile Baudot Smt. Evidence of seepage (gas/water) is characterised by pockmark depressions and this may be due to a subsurface gas/water pressure factor that favours, if not triggers, the sediment failures (Acosta *et al.,* 2003). The recent volcanic structures present in the region suggest that most of the pockmarks observed may have formed due to the migration of gas and associated water from a residual sub-bottom hydrothermal field, via neo-tectonic faults (Acosta *et al.,* 2001b). Most water masses in the basin interact with the surface of the seamounts (Fig. 2). In particular, the shallow-water mass, the Modified Atlantic Water (MAW), interacts with the shelf and upper slope and results in the formation of coralline algae accumulations (maërl) on the top of the seamounts. These are made up of round, centimetre-sized carbonate clasts (rodoliths) which carpet the seafloor (Acosta *et al.,* 2003).

## Seamounts in the Alboran Sea

### *Morphology*

Fifteen major seamounts (Northern Alboran Ridge, Djibouti Banks, Xauen Bank, Tofiño Bank, Ibn Batouta Smt., Chella or Seco de los Olivos Bank, Pollux Seamount, Adra Ridge, Maimonides Ridge, Abubacer Ridge, Al Mansour Ridge, Yusuf Ridge, Les Cabliéres Bank, Provençaux Bank, and Tres Forcas Promontory) have been recognised in the Alboran Sea (numbers 13 to 26 and 49 in Fig. 1). Two selected areas are described here: the Northern Alboran Ridge (number 13 in Fig. 1 and Table 1) and the Djibouti Banks (numbers 14.1 to 14.4 in Fig. 1 and Table 1), because of their oceanographic and geological location in the central part of the basin (Figs. 4 and 5). The northern Alboran Ridge (NAR) is the north-eastern segment of the Alboran Ridge chain which follows an ENE-WSW trend (Figs. 1 and 4) between the Yusuf Fault escarpments to the northeast and the Xauen Bank to the southwest (Fig. 1). It is bounded to the north by the Alboran Trough and the Western Alboran Basin, to the south by the Southern Alboran Basin and to the west by the Al Idrisi Fault. The Djibouti Banks are located on the Djibouti-Motril Marginal Plateau (Palomino *et al.,* 2011), on the northern margin of the Alboran Basin, where four major seamounts have been recognised forming a NW-SE trending chain at the south-western boundary of this marginal plateau: Avempace Bank (14.1), Herradura Bank (14.2), Herradura Spur (14.3) and Djibouti Ville Bank (14.4) (500 m on the north-eastern flanks to 1 000 m on the south-western flanks) (Fig. 5A).

The NAR can be divided into three sectors based on the differences in the water depth of its summits (Fig. 4): the shallowest (summit at 0-115 m water depth) is in the north-eastern sector, and is trapezoidal in shape (75 km length, 22 km width); the intermediate (summit at 83-115 m water depth) is in the central sector and has a strongly linear crest (32 km long and 23 km wide); and the deepest (summit at 257-400 m water depth) is in the south-western sector and has a smooth crest (28 km long and 20 km wide). The NAR occupies an area of around 21 000 km$^2$. The top of the NAR is relatively flat (<2°) but locally reaches up to 5°; the lowest gradients occur in the north-eastern and central sectors which are configured as isolated shelves (Bárcenas *et al.,* 2001). The small Alboran Island (642 m long, 265 m maximum wide and 15 m maximum height) is the culmination of a rhombohedral submarine structure on the shelf area. The flanks of the NAR display important gradients (up to 57°) more abrupt (8-27°) in the north-eastern sector, meanwhile the central and south-western sector gradients are gentler, ranging (2-24°). The base of the northern flank is located at depths of approximately 1 400-1 700 m water and in the southern flank varies from water depths of 1 160 to 1 060 m. The main morphological features identified on this seamount are: erosive terraces, crests, tectonic scarps and depressions, as well as sedimentary waves on the top of the shelf (Bárcenas *et al.,* 2004a,b), and scars, mass-movement deposits, linear erosive features (e.g., canyons, gullies) and contourite deposits, ridges and valleys sets and a intraslope marginal plateau on the flanks.

Several erosive terraces have been located in the north-eastern sector of the top of the shelf and they could be grouped at least four levels at water depths of between 65 and 90 m (Bárcenas *et al.,* 2004a,b). Minor crests (between 1 and 6 km in length and 1.5 to 25 in height) associated to basement outcrops have been differentiated in the north-eastern sector (Bárcenas *et al.,* 2004a,b). Tectonics scarps and depressions of ENE-WSW, WNW-ESE, NW-SE and NNE-SSW trends are related to faults (Maestro-Gónzalez *et al.,* 2008). Sedimentary waves may appear as solitary features around the main reliefs or grouped in a field on the southern part of the shelf (Bárcenas *et al.,* 2004a, b).

Scars (3 to 10 km in length sub-parallel to the flank) and mass-movement deposits (from slides to turbidites) are more developed on the southern flank where two short NNW-SSE canyons (7 km length) also occur (Bárcenas *et al.,* 2001), however a large arc-shaped feature on the northern flank of the central and north-eastern sectors has been interpreted as the header scar of an old slide (Martínez-García *et al.,* 2011). Linear erosional features, oriented NNW-SSE to N-S, occur on the northern flank of the north-eastern sector of the NAR, where a major canyon (9.5 km

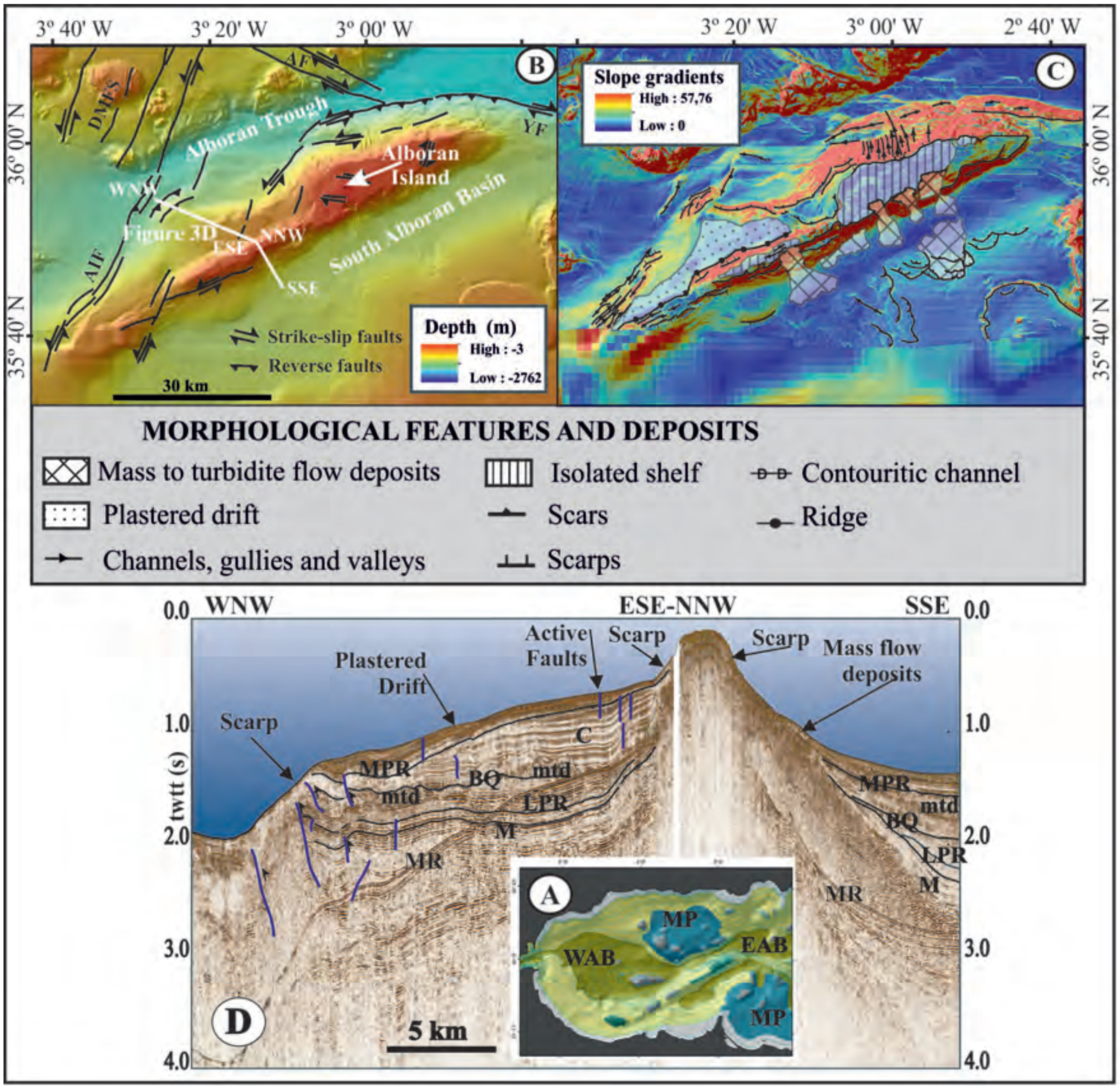


**Figure 4**. The North Alboran Ridge (SE-Iberian) : (A) physiographic domains of the Alboran Sea Basin (EAB: Eastern Alboran Basin; WAB: Western Alboran Basin; MP: Marginal Plateau), (B) Bathymetric and tectonic map (AF: Averroes Fault; AIF: Al Idrissi Fault; DMFS: Djibouti-Motril Fault System; YF: Yusuf Fault), (C) Slope gradients and geomorphological map showing the main structural, mass-movement and bottom current features, and (D) Airgun high-resolution seismic profile crossing the North Alboran Ridge (see location on Fig. 4B). Legend: MPR, Mid-Pleistocene Revolution; BQ, Quaternary Base; LPR, Lower Pliocene Revolution; M, Pliocene Base; CU, contouritic deposits; mtd; mass transport deposits; MR, multiple reflector; twtt in seconds.

***Figura 4**. Dorsal de Alborán Septentrional (SE-Iberia): (A) Dominios fisiográficos de la cuenca del Mar de Alborán (EAB: Cuenca Oriental de Alborán; WAB: Cuenca Occidental de Alborán; MP: Plataforma Marginal), (B) Mapa Batimétrico y Tectónico (AF: Falla de Averroes; AIF: Falla de Al Idrissi; DMFS: Sistema de fallas de Djibouti-Motril; YF: Falla de Yusuf), (C) Mapa de Pendientes y de los principales rasgos geomorfológicos de tipo estructural, movimientos en masa y corrientes de fondo y (D) Perfil sísmico de alta resolución (cañones de aire) atravesando la Dorsal de Alborán Septentrional (localización en la Fig. 4B). Leyenda: MPR, Revolución del Pleistoceno Medio; BQ, Base del Cuaternario; LPR, Revolución del Plioceno Inferior; M, Base del Plioceno; CU, depósitos contorníticos; mtd, depósitos de transporte en masa; MR, Reflector múltiple.*

long and 0.6 km wide) and several secondary canyons (3-5 km in length) and gullies (0.7 km in length) have been identified.

Two sets of ridges and valleys have been differentiated, the first one is an E-W set located in the northern flank of the north-eastern sector (15 km in length) and is related to the northern boundary faults of the NAR, and the second set is a series of ridges and valleys of NNE-SSW mapped on the western boundary of the NAR. These reliefs have been interpreted as a consequence of the Quaternary activity of the Al Idrissi fault (Gràcia *et al.,* 2010; Martínez-García *et al.,* 2013). The upper slopes of the northern flank of the central and south-western sector are linear and abrupt linear but an intraslope marginal plateau occurs on the middle slope (0.4-3°) at 400-800 m

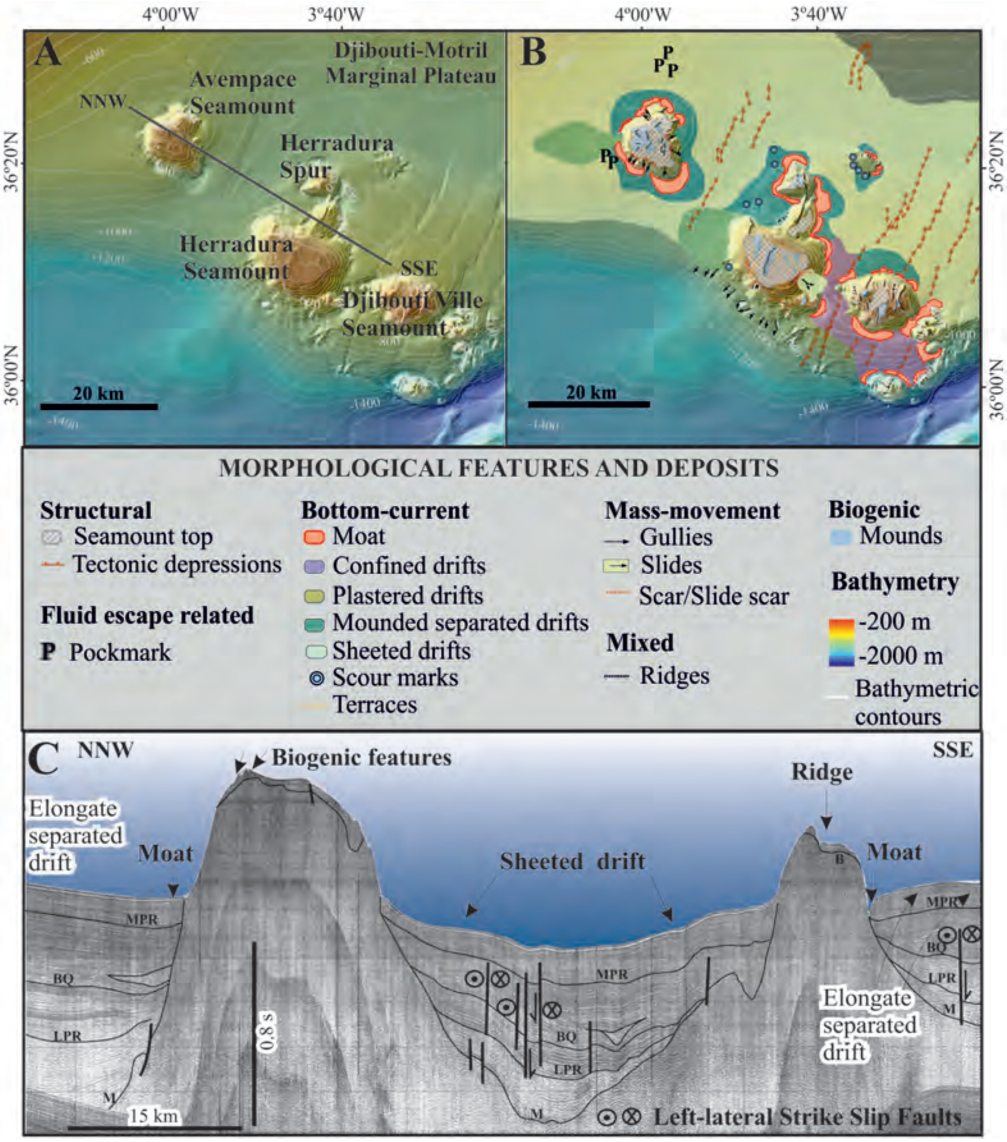


**Figure 5**. The Banks of Djibouti on the Alboran Sea (SE- Iberian) : (A) Bathymetric map, (B) Geomorphological map showing the main structural, fluid escape, mass-movement, bottom current and biogenic features and (C) Sparker seismic profile crossing the Avempace and La Herradura banks. Legend: MPR, Mid-Pleistocene Revolution; BQ, Quaternary Base; LPR, Lower Pliocene Revolution; M, Pliocene Base. Fig. 5B is modified from Palomino *et al.,* (2011).

***Figura 5****. Bancos de Djibouti en el Mar de Alborán (SE-Iberia): (A) Mapa Batimétrico, (B) Mapa Geomorfológico mostrando los principales rasgos estructurales, escape de fluidos, movimientos en masa, corrientes de fondo y estructuras biogénicas y (C) Perfil sísmico de Sparker a través de los Montes submarinos de Avempace y Herradura. Leyenda: MPR, Revolución del Pleistoceno Medio; BQ, Base del Cuaternario; LPR, Revolución del Plioceno Inferior; M, Base del Plioceno. La Fig. 5B está modificada de Palomino* et al., *(2011).*

water depth) where plastered drift deposits and a discontinuous moat are defined over the marginal plateau (Fig. 4D) (Ercilla *et al.,* 2012).

Most of the Djibouti Banks (summits at 200-500 m water depth) display truncated cone geometries, except in the case of the Herradura Spur Smt. which is pyramid-like in shape. They occupy areas of around 73-83 km$^2$, with the exception of the La Herradura Bank which is greater in extent (202 km$^2$). The tops of these seamounts are relatively flat (< 5°) and their flanks display higher slope gradients (up to 53°) (Table 1). The main morphological features identified on these seamounts are: crests, terraces, gullies, slides, mass movement deposits, and contourite deposits (Fig. 5B). Minor NNE-SSW scarps cross these seamounts as is the case of the La Herradura Banks: these scarps are related to the Quaternary activity of the Djibouti-Motril fault system. Outcropping crests and superimposed biogenic features composed of carbonate-rich sediments are found on the top (Fig. 5B, C). Several terraces (up to 6.5 km in length) have been identified on the top-flank at various water depths (280 m to 450 m) and on the south-western flank of the La Herradura Bank. Several gullies (2 km in length and 1.5 km in width) occur on variably steep slopes (5° to 20°) on the La Herradura and Avempace banks and are radially oriented in relation to the summits (Fig. 5B). Small (2 km$^2$) and moderate-sized (13 km$^2$) slides have been identified mainly on the southern flank of the La Herradura Bank (300 m to 800 m water depth). The four seamounts are surrounded by narrow contouritic moats (1-2 km in width and 5.5-10 km in length) as well as drifts (Palomino *et al.,* 2011) (Fig. 5B).

### *Genetic processes*

The seamounts studied in the Alboran Sea formed in two main episodes. One period corresponds to the Late Oligocene-Miocene extension which generated structural highs sub-parallel to the back-arc trend and volcanoes, which are part of the highest summits in this basin, particularly in the eastern Alboran region (Comas *et al.,* 1999). The other period is related to the Late Miocene to present compression (Martínez-García *et al.,* 2013), which is responsible for the latest elevation of the main seafloor reliefs. On the NAR, volcanism involving tholeiitic basaltic andesites (Gill *et al.,* 2004) dates from 9.4 to 9.3 Ma, indicating that the eastern sector of this high, around the Alboran Island, was an active volcanic edifice during the Late Miocene (Fernández Soler *et al.,* 2000; Duggen *et al.,* 2004). A last compressive phase produced a shortening of the orogenic systems, mountain uplift on the main land, reduction of the initial Alboran Sea Basin, tilting of basement margins and the structural uplift of previous basement morphological highs (Avempace Bank) and other, volcanic features (the La Herradura, La Herradura Spur and Djibouti Ville banks). This phase involved the formation of the NAR as a tectonic relief, uplifted by means of folding and laterally-compressive faulting that follow the same ENE-WSW trend as the seamount, including previous Miocene volcanic elements such as the Alboran Island (Bourgois *et al.,* 1992; Vegas, 1992b; Woodside and Maldonado, 1992; Watts *et al.,* 1993).

### *Recent geological processes*

The main geological processes affecting the NAR and the Djibouti Banks are: bottom current activity and its interference with the seamounts and sedimentary instabilities on the flanks, and debris flow deposits at the foot of the slope and current tectonic activity. Dense deep Mediterranean water masses and intermediate waters (including the Winter Intermediate Water and Levantine Intermediate Water) interact with the seamounts favouring the formation of moats at the foot and the associated drift deposits (Fig. 2). Elongated and plastered drifts have been described around the Djibouti Banks (Palomino *et al.,* 2011), whereas on the north-western flank of the NAR only plastered drifts have been identified (Ercilla *et al.,* 2012). Other processes related to water-mass dynamics include the presence of several guyots, some of them corresponding to current isolated shelves (NAR, Xauén Bank) characterised by carbonate sedimentation, particularly coralline algae and rodoliths related to Atlantic water flow and sea level oscillations (Milliman *et al.,* 1972; Bárcenas *et al.,* 2001). The sedimentary instabilities that produce mass movements at various scales are evidenced by slide scars on the seamount flanks and debris flow deposits at the foot of the slope. These are evident on the southern flank of the NAR, where several mass movement deposits, varying from slides to turbidites, have been identified (Vázquez *et al.,* 2010). The intense sedimentary instability processes are related to continuous moderate seismic activity (Stich *et al.,* 2006) and the reactivation of relief gradients caused by Quaternary tectonics. Several tectonic structures show current activity in this area: i) inverted characteristics on the eastern sector of the northern flank of NAR (Estrada *et al.,* 2014), ii) Quaternary movements in the NW-SE Yusuf fault to the east of the NAR, as well as in the Averroes and Adra fault systems on the Djibouti-Motril marginal plateau (Gràcia *et al.,* 2012; Estrada *et al.,* 2014; Vázquez *et al.,* 2014), and iii) a modern left-lateral NNE-SSW trending strike-slip fault system cuts the main reliefs, in this sense the Al Idrissi fault divides the Alboran Ridge into two parts and also generates two sets of ridges and valleys with the same trend (Gràcia *et al.,* 2010; Martínez-García *et al.,* 2013), and the Djibouti-Motril fault system affects the Djibouti Banks (Vázquez *et al.,* 2008b).

## Seamounts in the Gulf of Cadiz

### *Morphology*

Four seamounts (Guadalquivir Bank, Portimao Bank, Cadiz Diapiric Ridge and Guadalquivir Diapiric Ridge) have been recognised in the Gulf of Cadiz (numbers 27, 28, 50 and 51 in Fig. 1). In this section, two main seamounts (numbers 27 and 28 in Fig. 1), Guadalquivir Bank (27) and Portimao Bank (28) (Figs. 6 and 7, Table 1), are described because of their oceanographic and geological location in the northern part of the Gulf of Cadiz. The Guadalquivir Bank is an isolated high, located at the edge of the continental slope of the distal Portuguese margin, 75 km to the south Portuguese coast (Vegas *et al.,* 2004). The Portimao Bank or Plateau, described as the westernmost part of the Guadalquivir Bank (Terrinha *et al.,* 2009; Matias *et al.,* 2011), is also located at the edge of the continental slope of the southern Portuguese margin, about 100 km from the coast.

The Guadalquivir Bank trends NE-SW, is elongated in shape, and occupies an area of 82 $km^2$ (11.2 km long and 8.75 km wide) (Table 1) with two summits at different water depths (275 m in the northeast and 410 m in the southwest). The top is relatively flat (3°) and the flanks have higher slope gradients (up to 40°). The main morphological features identified on this bank are: crests, terraces, scarps, slides, gullies, biogenic mounds, moat and drift deposits (Fig. 6 B, C, D). These features have a NE-SW main trend, except the slides and gullies, which are NW-SE. The crests and terraces appear on the top whilst the scarps, slides, and gullies are located on the southern flank. The Guadalquivir contouritic channel is oriented ENE-WSW and is around 4 km wide, and a deformed contouritic drift bounds the southern base of this bank (Llave *et al.,* 2007a, b) (Fig. 6 B, C, D). Towards the northwest a second countouritic channel (0 to 2 km wide) developed from northeast to southwest bounds the southern base and separates the bank from the Bartolomeu Dias Plateau (Fig. 6 B, D).

The Portimao Bank (summit at 1 500 m water depth) is W-E trending, has an elongated shape and occupies an area of about 1 800 $km^2$ (93 km long and 15-28 km wide) (Fig. 7A). The top is flat (approximately 0.2°) in the eastern sector, whilst in the central and western sector gradients are higher (2°-4°). The top increases in depth towards the west, from 1 500 to 3 500 m. The slope gradient increases on the flanks (4-15°). The southern flank is the steepest (12°-15°) and presents escarpment morphology, whilst the north-eastern flank is less steep (4-5°). The main morphological features identified on this bank are: crests, depressions, bulges, domes on the top, slide scars and mass movement deposits, and escarpments on the flanks (Fig. 7 B, C). In particular, a 32 km-long crest feature oriented W-E has been mapped on the top towards the north of the bank, probably related to recent tectonics and salt mobility (Terrinha *et al.,* 2009; Matias *et al.,* 2011). Two bulges have been identified in the central sector of the bank top, the most prominent being related to the Don Carlos Diapir (Terrinha *et al.,* 2009). This is a circular dome-shaped area (47 $km^2$) rising around 320 m above the high and surrounded by a circular depression (Fig. 7B). This feature marks the boundary between the western and eastern structural styles of the bank. The other bulge, located 4 km towards the northwest of the Don Carlos diapir, is cone-shaped, occupies a smaller area (2.5 $km^2$) and is 100 m high. Slide scar features are located on the northern and southern flanks, those in the north being smaller (4-5 km in length and 1.5-2 km in width) than those located on the southern flank (17 km in length and 1-3 km in width). These slide scars seem to originate from the Don Carlos diapir, extending downslope on the southern flank. Escarpments are identified on the north-eastern part of the Portimao Bank, which are 28 km long and rise 170 m above the seafloor (Fig. 7B).

### *Genetic processes*

The southern Portuguese margin acted as the northern boundary, in the Gulf of Cadiz, of the compressive western front of the Betic-Rif orogen. The current structure and morphology of the Guadalquivir Bank is a relict of its evolution in a rift-transcurrent margin type (Medialdea, 2007), and Paleozoic rocks have been dredged (Vegas *et al.,* 2004). Nevertheless, the last important uplift is related to the Betics-Rif development and occurred in the Late Tortonian to Early Messinian, and even during the Pliocene-Quaternary as revealed by anticlinal and synclinal folds affecting Pliocene and Pleistocene sedimentary units along the south-eastern flank of this bank (Gràcia *et al.,* 2003; Medialdea *et al.,* 2004). Seismotectonic activity has been described by Negredo *et al.* (2003) and is characterised by shallow and intermediate depth seismic events which present reverse faulting with a strike-slip component and horizontal NNW-SSE compression. Structurally, the Portimao Bank has been interpreted as a pop-up structure (Terrinha *et al.,* 2009) related to thrust faults resulting from the tectonic inversion of Mesozoic rift faults (Mougenot *et al.,* 1988, Zitellini *et al.,* 2004, Duarte *et al.,* 2011) with marked diapiric activity. A basement high has been observed in the south-eastern sector that has been interpreted as a reactivated reverse fault which uplifted Pliocene-Quaternary units, and in the northern sector a crest delimited at the seafloor surface, generated by an anticlinal fold related to a blind thrust or diapirism, has caused deformation of the current sedimentary units (Vázquez *et al.,* 2013).

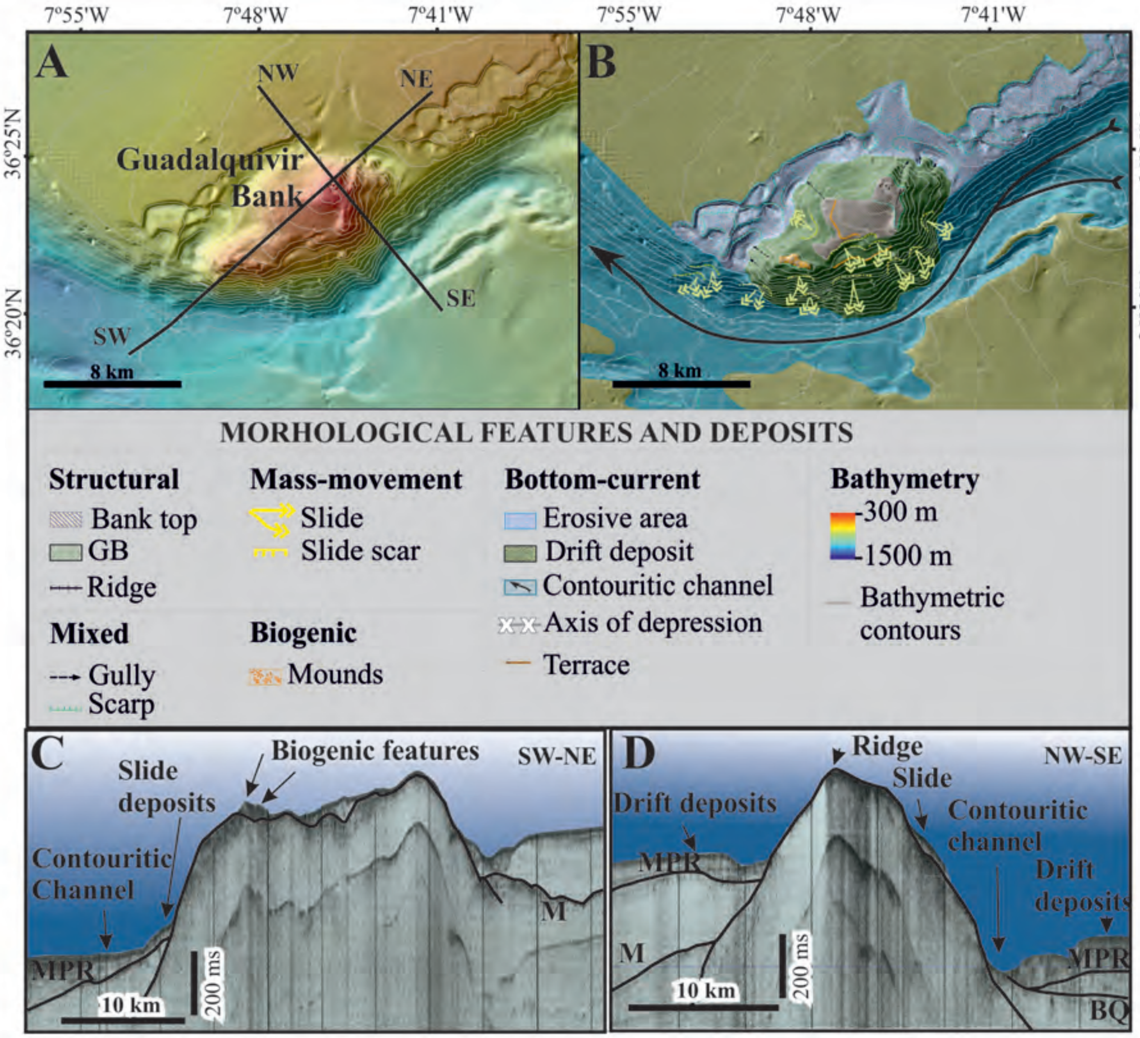


**Figure 6.** The Guadalquivir Bank of the Gulf of Cadiz margin (SW-Iberian): A) Bathymetric map, B) Geomorphological map showing the main structural, mass-movement, mixed, biogenic and bottom current features, and (C, D) Sparker seismic profiles showing the architectural features. MPR, Mid-Pleistocene Revolution; BQD, Quaternary Base Discontinuity; M, Pliocene Base.

***Figura 6.*** *Banco del Guadalquivir en el margen del Golfo de Cádiz (SO-Iberia): (A) Mapa batimétrico, (B) Mapa geomorfológico mostrando los principales rasgos estructurales, de movimientos en masa, mixtos, biogénicos y de corrientes de fondo, y (C, D) Perfiles sísmicos de Sparker mostrando los rasgos arquitectónicos. MPR: Revolución del Pleistoceno Medio; BQD: Discontinuidad de la Base del Cuaternario; M: Base del Plioceno.*

### *Recent geological processes*

The two Gulf of Cadiz seamounts studied play an important role in the morphostructure and architecture of the margin, as well as modifying sedimentary and oceanographic processes due to their geographic location (Figs. 1, 2, 6 and 7). Structurally, the southern sector of the Guadalquivir Bank acts as an obstacle for the advance of the Gulf of Cadiz allocthonous unit (Medialdea *et al.,* 2004), emplaced during the Tortonian, and therefore in some way it controls the detachment and elevation of the thrust wedges which deformed this unit. A Pliocene-Pleistocene uplift episode is evidenced by the south-eastern scarp of the Guadalquivir Bank that displaces the lateral ramp of the allocthonous unit (Medialdea *et al.,* 2004). To the northwest the Portimao Bank constitutes also a barrier to the sediment flow supplied by the Portuguese margin mainly through the Portimao Canyon and the Faro Canyon, meanwhile the northern sector of the Guadalquivir Bank is covered by the Neogene-Quaternary Bartolomeu Dias Drift, which is related to the Mediterranean Outflow Water (MOW) (Llave *et al.,* 2001; Hernández-Molina *et al.,* 2006; Roque *et* al., 2012) (Fig. 6). On the southern flank, since the Pliocene, the MOW has eroded and shaped

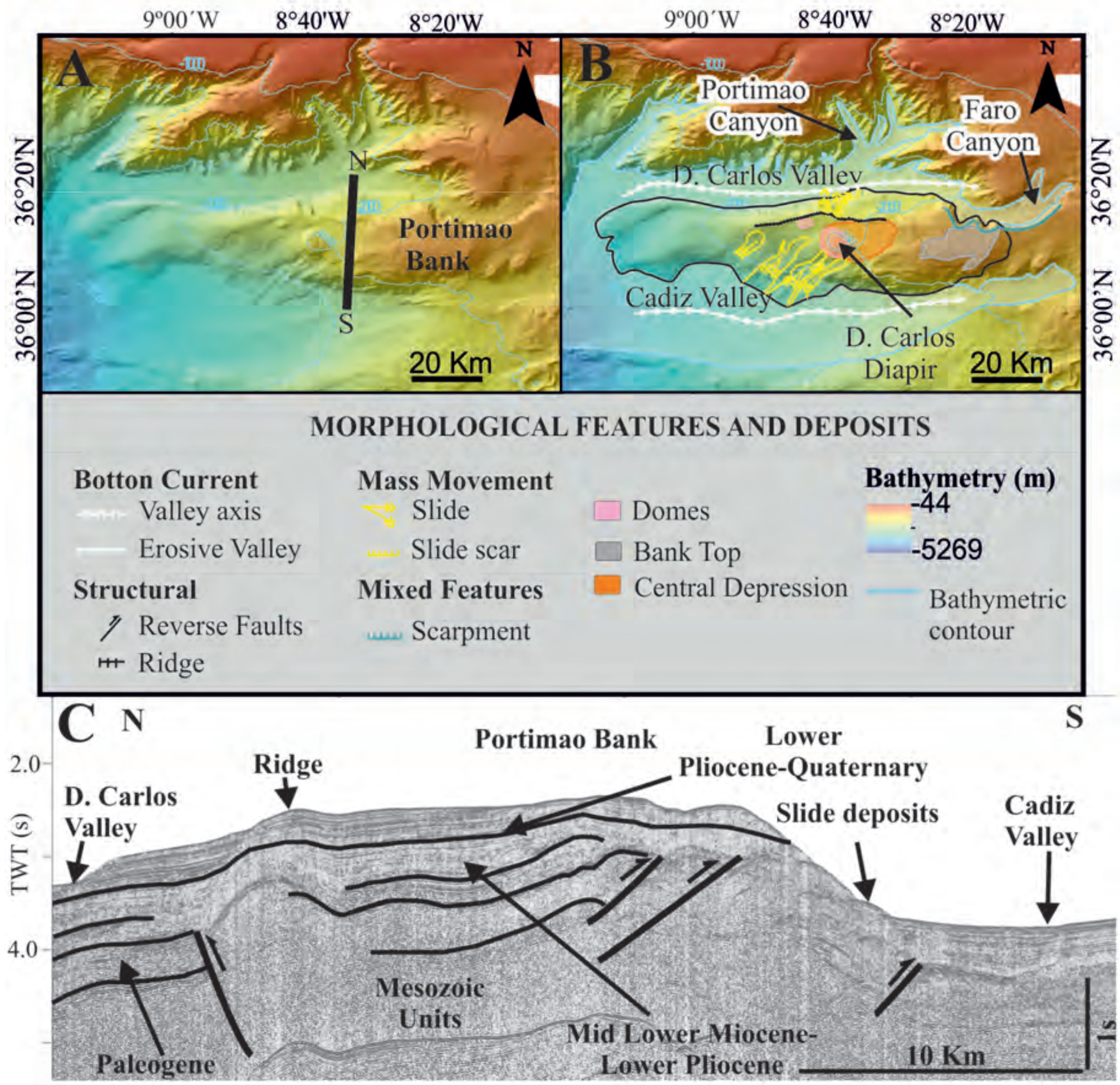


**Figure 7.** The Portimao Bank of the Gulf of Cadiz margin (SW-Iberian): (A) Bathymetric map (from SWIM bathymetric data base, Zitellini *et al.*, 2009), B) Geomorphological map showing the main structural, mass-movement, mixed, and bottom current features, and (C) Sparker seismic profile showing the architectural features.

***Figura 7.*** *Banco de Portimao en el margen del Golfo de Cádiz (SO-Iberia): (A) Mapa batimétrico, (de la base de datos batimétricos SWIM, Zitellini* et al., *2009), (B) Mapa geomorfológico mostrando los principales rasgos estructurales, de movimientos en masa, mixtos, biogénicos y de corrientes de fondo, y (C) Perfil sísmico de alta resolución (cañones de aire) mostrando los rasgos arquitectónicos.*

the Guadalquivir contouritic channel (Hernández-Molina *et al.,* 2006; Llave *et al.,* 2007a; García *et al.,* 2009; Hernández-Molina *et al.,* 2014). Instabilities and mass movement processes are responsible for the slide scars located on both flanks of this bank. On the southern flank, the slide scars are mainly linked to recent and present-day diapirism, whereas the slide scars and escarpment on the northern flank are both related to the uplift of blind thrusts (Terrinha *et al.,* 2009).

## Seamounts in west Portugal

### *Morphology*

Six main seamounts (Coral Patch Seamount, Coral Patch Ridge, Ampere Smt., Gorringe Bank, Hirondelle Smt. and Tore Smt.) have been identified to the west of Portugal (numbers 29 to 33 and 52 in Fig. 1). Three seamounts (numbers 29, 31 and 33 in Fig. 1), selected due to their large dimensions, are described here: the

Coral Patch Smt. (29), the Gorringe Bank (31) and the Tore Smt. (33) (Fig. 8, Table 1). The Coral Patch Smt. is located southwards of the SWIM Fault Zone (Rosas *et al.,* 2012) (Fig. 1). It is limited to the north by the Horseshoe Abyssal Plain, to the south by the Seine Abyssal Plain, and to the west by the Ampere Smt. (Fig. 1). The Gorringe Bank, the major morphological feature of the south-western Iberian margin (Auzende *et al.,* 1978), is located approximately 120 km WSW off Cape Saint Vicente (Fig. 1). To the south it is surrounded by the Horseshoe Abyssal Plain at depths of 4,800 m, and to the north by the Tagus Abyssal Plain which reaches depths of 5 100 m (Fig. 8B). This seamount is located northwards of the SWIM Fault Zone (Zitellini *et al.,* 2009), and is considered as one of the main seismogenic sources in southwest Iberia (Borges *et al.,* 2001). This feature is also associated with one of largest positive free-air gravity anomalies in the world (300 m Gal) and a 9 m positive gravity anomaly in the geoid (Souriau, 1984). The Tore Smt., the least known seamount of the western Iberian margin, is located approximately 300 km west of the Portuguese coast. It

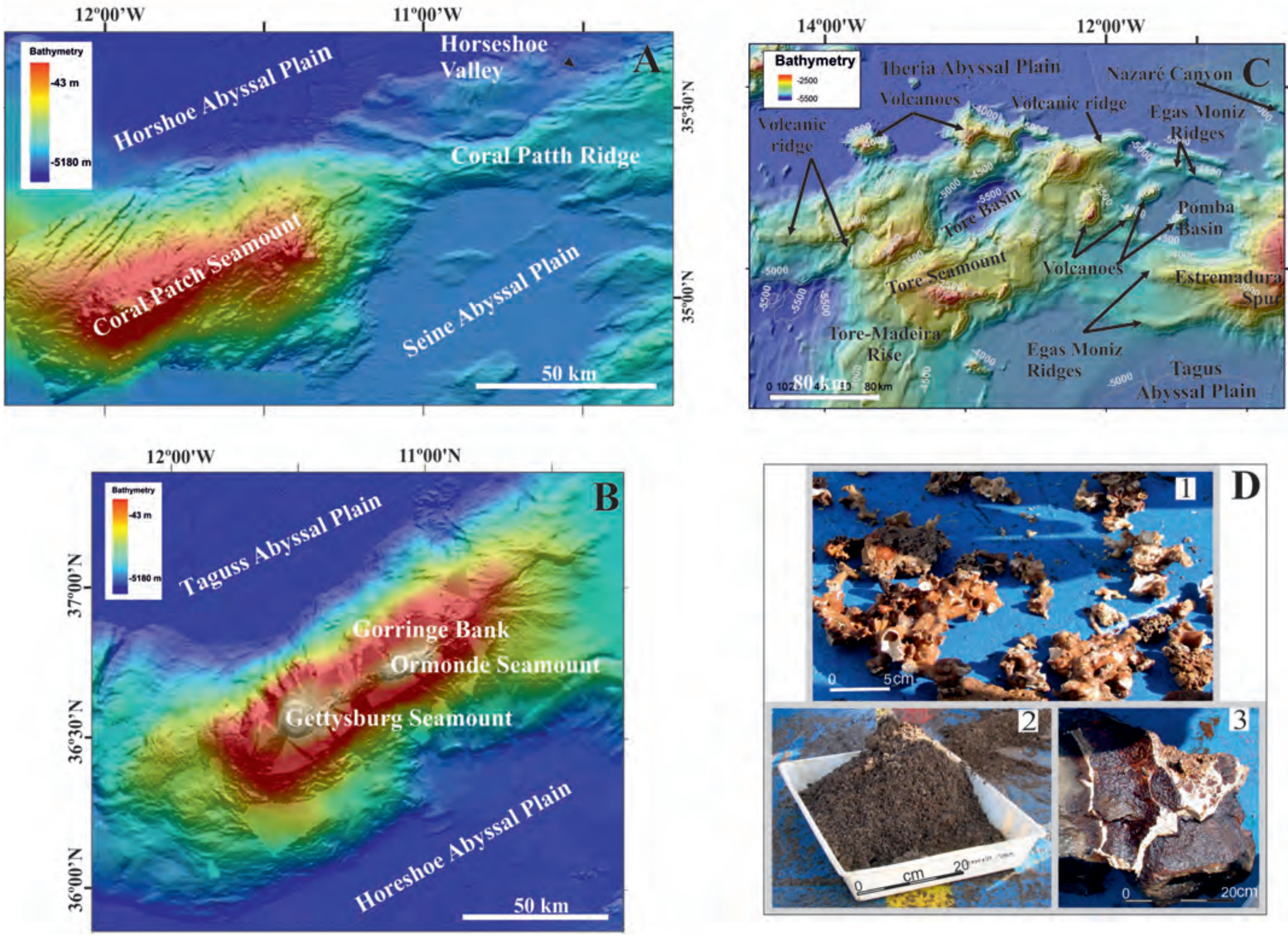


**Figure 8.** Seamounts of the Atlantic oceanic domain (W-Iberian): Bathymetric maps of the (A) Coral Patch Smt., (B) the Gorringe Bank (both from SWIM bathymetric data base, Zitellini *et al.,* 2009), and (C) the Tore Smt. (the bathymetric metadata and Digital Terrain Model data products have been derived from the EMODnet Hydrography portal-http://www.emodnet-hydrography.eu), and (D) photos of the sedimentary cover on the Coral Patch Smt. displaying fragments of (1) deep-water corals, (2) bioclastic sands and (3) fragment (~40 cm long) of pillow-lava with pelagic carbonates filling the veins.

***Figura 8.*** *Montes submarinos del dominio oceánico Atlántico (O-Iberia): Mapas batimétricos de (A) el MS de Coral Patch, (B) del Banco de Gorringe (de la base de datos batimétricos SWIM, Zitellini* et al., *2009), (C) del MS de Tore (los metadatos batimétricos y el Modelo Digital del Terreno proceden del portal EMODnet Hydrography-http://www.emodnet-hydrography.eu), y (D) Fotos de la cobertera sedimentaria sobre el MS de Coral Patch mostrando fragmentos de (1) corales de aguas profundas, (2) arenas bioclásticas y (3) fragmentos (~40 cm de longitud) de lavas almohadilladas con carbonatos pelágicos en venas rellenando fisuras.*

is bounded to the north by the Iberian Abyssal Plain and to the south by the Tagus Abyssal Plain (Figs. 1 and 7C). It represents the northern end of the Tore-Madeira Rise, a ~1 000 km long submarine volcanic elevation crossing the Eurasian and African plates (Merle *et al.,* 2006; Miranda *et al.,* 2009).

The Coral Patch Smt. (summit at 560-750 m water depth) is WSW-ENE trending, has an elongated shape and occupies an area of 8 400 km$^2$ (120 km long and 70 km wide) (Table 1). The slope of the western flank is gentle (< 5°), whereas the south-eastern flank is steeper (5°-20°) (D'Oriano *et al.,* 2010). The main morphological and structural features identified on this seamount are: volcano thrust-faults, linear scours, scarps, and ridges. Nine small volcanoes have been mapped on the summit using swath bathymetry and ROV images. These minor volcanic edifices reach widths of 3-5 km and heights of 100-300 m, but the largest has a diameter of about 8 km. These features are well preserved and present typical sub-circular and conical shapes with associated radial features on the slopes, and have been interpreted as lava flows (D'Oriano *et al.,* 2010). A major WSW-ENE thrust-fault overthrusts the Horseshoe Abyssal Plain towards the north and limits the northern flank (Martinez-Loriente *et al.,* 2013). Small linear scours cut the eastern sector of the flanks, whilst the shallower central part presents a flat area and the deeper section displays several northward-verging scarps (D'Oriano *et al.,* 2010). A series of sub-parallel crests spaced from 1.5 to 4.0 km, trending NE-SW have been identified in the north-western area of this seamount. These features reach 15-50 km in length, 2-3 km in width and heights of ~100 m. The crests correspond to large-scale folds with wavelengths of ~20 km, associated with steep faults affecting the uppermost sediments and the seafloor (Martínez-Loriente *et al.,* 2013).

The Gorringe Bank (summit at 20 m water depth) has a NE-SW trending elongated ridge and occupies about 14 000 km$^2$ (200 km long and 70 km wide) (Table 1). It is formed by two minor seamounts, the Ormonde Smt. (summit at 33-46 m water depth) in the northeast and the Gettysburg Smt. (summit at 20-28 m depth) in the southwest (Fig. 8B). The average slope gradients of the flanks range from 5° to 10°, but higher values are observed locally. The south-eastern flank of the Ormonde Smt. has gradients of up to 20°, whereas on the north-western flank they reach 30°. A clear depositional shelf break can be seen at 140 m depth, and locally an erosional shelf break occurs between 130 and 170 m depth characterised by increasing gradients (> 6°-8°) (De Alteriis *et al.,* 2003). The main morphological and structural features identified on this seamount are: terraces, slope failures and a thrust-fault. The terraces display sub-horizontal surfaces (< 3°-4°) at depths of between 60 m and 100-120 m, which were probably generated during the partial emersion of the Gorringe Bank in the Last Glacial cycle (De Alteriis *et al.,* 2003; Ferranti *et al.,* 2014). Several scars related to slope failures have been located on both flanks of this seamount with a sub-parallel trend. On the northern flank, one of these scars has been associated with a main landslide deposited as an avalanche at the foot of slope of the seamount (Lo Iaccono *et al.,* 2012). The northern flank is bounded by a major northward-verging thrust-fault (Terrinha *et al.,* 2003).

The Tore Smt. (summit at 2,300 m water depth) trends NE-SW to NNE-SSW, and has an elongated shape enclosing a central elliptical depression, the Tore Basin (Fig. 8C). This complex seamount occupies a very broad area, 31 000 km$^2$ (239 km in length and 130 km wide) and to the east is morphologically connected to the Estremadura Spur by means of four E-W ridges, the Egas Moniz Ridges, which are asymmetric highs trending E-W to WNW-ESE, and varying from 46 to 90 km in length. The summits of these ridges are deeper towards the north, ranging from about 3 050 m water depth in the south to 4 540 m in the north. The Egas Moniz Ridges and the eastern flank of the Tore Seamount enclose a small basin about 4,900 m deep, known as the Pomba Basin (Fig. 8C). The main morphological and structural features observed on this seamount are crests and isolated, volcanically-originated small seamounts, arranged in E-W to ENE-WSW trends, and which have summits between water depths of 2 300 and 3 000 m (Roque *et al.,* 2009). These features surround the central asymmetric NE-SW-trending Tore Basin (Fig. 8C).

### *Genetic processes*

The genesis and formation of the Coral Patch Smt. is linked to Cenozoic magmatism (32 Ma) that probably represents the trace of the Madeira hotspot (Geldmacher *et al.,* 2005; Merle *et al.,* 2009; Geldmacher *et al.,* 2011). This seamount is part of the larger Coral Patch Ridge-Coral Patch Smt. which has been recently described by Martínez-Loriente *et al.* (2013; 2014). The Pliocene and Quaternary convergence between the African and Eurasian plates deformed the basement and the uppermost sediment cover, forming faults and folds (Hayward *et al.,* 1999). This compression was accommodated by the northwards thrusting of the Coral Patch Smt. over the Horseshoe Abyssal Plain (Martínez-Loriente *et al.,* 2013; 2014).

The Gorringe Bank has been studied for many years, due to the interest in its main size and gravity anomaly (Auzende *et al.,* 1978), alkaline volcanic rocks have been dragged from it but it corresponds to a structural high constituted as both oceanic basement (Féraud *et al.,* 1986) and serpentinized peridotite (Sallarés *et al.,* 2013). It has a long geodynamic history, and it has recently been proposed that it was formed in a Late Jurassic transtensional phase (Jiménez-Munt *et al.,* 2010; Sallarés *et al.,* 2013). On the southern flank of the Ormonde Smt, the oceanic basement gabbros have been intruded by a few doleritic sills (Girardeau *et al.,* 1998a,b; Girardeau *et al.,* 1998b) and covered by younger alkali-basalt lavas (Schärer *et al.,* 2000). The intrusion of these alkaline rocks is related to the Late Cretaceous alkaline magmatism that affected western Iberia (Cornen, 1982; Bernand-Griffith *et al.,* 1997; Miranda *et al.,* 2009), in about 67-65 Ma (Féraud *et al.,* 1986) or 66-60 Ma (Schärer *et al.,* 2000). Volcanic rocks retrieved from the Ormonde Smt., such as alkali basalts, nephelinites, nephelinesyenites, tinguaites, phonolites and monchiquites, are similar to those found onshore on the Monchique and Sines sub-volcanic massifs (Cornen, 1982; Bernand-Griffith *et al.,* 1997), and have been suggested as being part of the Monchique-Ormonde-Madeira hot-spot track (Geldmacher *et al.,* 2006). The Gettysburg Smt. has been interpreted as having formed due to deformation of the serpentinized basement (De Alteriis *et al.,* 2003; Ferranti *et al.,* 2014). Finally, during the Eocene-Miocene compressional phases, the Gorringe Bank was affected by tectonic reverse faulting, overthrusting northwards towards the Tagus Abyssal Plain (Terrinha *et al.,* 2003; 2009) along the deep thrust-fault that bounds its northern flank. Present-day clustering of earthquake epicentres in this feature indicates recent tectonic activity (Borges *et al.,* 2001).

The genesis and formation of the Tore Smt. has been explained by three different hypotheses: i) a giant caldera caused by the collapse of a super volcano into its magma chamber, ii) a meteorite impact crater, and iii) a mixture of tectonic trends (Laughton *et al.,* 1975; Monteiro *et al.,* 1998; Ribeiro, 2002). Alkaline rocks have been dredged along the Tore seamount and related features consist of basalt, trachyte, diorite, granodiorite, and breccias, ranging in age between ~104.4 Ma and ~80.5 Ma (Merle *et al.,* 2006). These volcanic rocks and new data acquired as part of the Portuguese Continental Shelf Extension project show that the morphology of this seamount seems to be due to the conjugation of Late Cretaceous magmatic activity and tectonics (Roque *et al.,* 2009). The Late Cretaceous saw the emplacement of alkaline volcanism along ~E-W to NNE-WSW fractures, clusters of small seamounts with the same orientation, and volcanoes aligned ~E-W to WNW-ESE (Roque *et al.,* 2009). This alignment suggests a channelling and extrusion of the alkaline magmas through deep-faults with this orientation (Merle *et al.,* 2009) that work as a secondary transfer system for the continental break-up, as has been suggested by several authors (Tucholke *et al.,* 2007). These structures were reactivated as thrust-faults during the Cenozoic as a consequence of the Alpine orogenic phases associated with the formation of the Pyrenean and Betic chains. Lastly, Pliocene and Quaternary deformation can be related to the post-Tortonian reorganisation of the Eurasian-African plate boundary (Roque *et al.,* 2009).

### *Recent geological processes*

Several episodes of slope failure and mass movement have been identified on the flanks of the three eastern Iberian margin seamounts studied (Roque *et al.,* 2009; D'Oriano *et al.,* 2010; Lo Iaccono *et al.,* 2012). A major episode of mass movement can be seen on the northern flank of the Ormonde Smt. (Gorringe Bank), evidenced by a large slope scar at a water depth of between 2 900 and 5 100 m. This episode would have originated an avalanche comprising ~80 $km^3$ of material and 35 km runout (Lo Iacono *et al.,* 2012). These authors simulated a near-field tsunami for the volume of displaced sediments, and calculated that a wave more than 15 m high would have been generated, which would have hit the southern Portuguese coast less than 30 minutes after the occurrence of the landslide (Lo Iacono *et al.,* 2012). Numerous amphitheatre scarps and slumps have been identified on the flanks of the Tore Smt. and also within the stratigraphic succession of Tore Basin (Roque *et al.,* 2009). There is also evidence of bottom-current activity, including ripples and scours, observed during ROV dives on the south-eastern flank of the Coral Patch Smt. (Wienberg *et al.,* 2013). Lastly, the summits of the Gorringe Bank were affected by erosive processes related to a sea level fall that favoured terrace formation (Ferranti *et al.,* 2014).

## Seamounts on the Galicia margin

### *Morphology*

Five main seamounts (Porto, Vigo, La Coruña and Finisterre seamounts and Galicia Bank) have been identified in the Galicia matgin (numbers 34 to 38 in Fig. 1), as well as at least thirteen smaller features (Vanney *et al.,* 1979; Ercilla *et al.,* 2006, 2008b, 2011) (Fig. 9A). In this section, only the Galicia Bank (36 in Fig. 1) is described as it is the most relevant seamount due to its size. This bank is located in the distal domain of the western Galician continental margin (north-western Iberian margin), about 200 km from the coast (Fig. 1) and is considered a major structural seamount controlled by two Mesozoic fault families: N-S to NW-SE trending normal faults and NE-SW transfer faults (Boillot *et al.,* 1989; Vázquez *et al.,* 2008a).

The Galician Bank (summit at 605 m water depth) is a plateau-like feature with quasi-rhombohedral geometry (84 km long; 60 km wide) that occupies an area of 2 946 km$^2$ (Fig. 9). The top is a smooth, asymmetric, low-mound surface (1°-2.5° but locally up to 5°). This plateau has sharp boundaries with steep flanks (17-40°). The main morphological and structural features observed on this bank are (Ercilla *et al.,* 2011): erosive furrows, an abraded plain, biogenic mound-shaped features, plastered drifts and sediment waves on its top; gullies on the flanks; and a moat and associated elongated drift at the foot of the flanks (Fig. 9B). The erosive furrows are mainly located at the south-western periphery of the plateau (825-2 100 m water depth) and appear as numerous NNW-SSE linear depressions spaced between 1 200 and 1 600 m apart. They display U- or V-shaped cross-sections (0.5 to 1.5 km wide and a few metres to 10 km long). The abraded plain (<1° to 10°) has been defined on the south-western periphery of the plateau. The plastered drift deposits blanket the wall of the western flank and the crest of the plateau at a water depth of between 768 and 1 400 m. These latter deposits have an E-W trending, step-shaped profile facing westward, and a N-S mound geometry (gradients 0°-2.5°, locally up to 5°). Small (< 7 m relief, hundreds of metres wave length) and large scale sediment waves (55-65 m relief and 1.5 km wave length) affect these plastered deposits. Finally, biogenic mound-shaped feature have been identified on the periphery of the bank top (700 to 1 125 m), which appear as ridges (a few kilometres to 25 km length) with reliefs of up to 200 m, and widths of around 500 m (Ercilla *et al.,* 2011; Somoza *et al.,* 2014). The flanks are characterized by scarps. They have reliefs of between 600 and 2 000 m, are 15 to 50 km in length, with variable orientations (NW-SE, N-S, and NE-SW). Numerous erosive gullies, seen as narrow V-shaped incisions separated by sharp ridges (hundreds of metres wide, ≈1 to < 5 km long, and from a few to tens of metres in relief), affect the flanks. At the foot of the south-eastern flank of the Galicia Bank, a 33-km long moat has been identified that runs parallel to the bank. The moat has an asymmetrical U-shaped cross-section that decreases in width northwards (8.5 to 1.7 km) while increasing in relief (35 to 55 m). Associated to the moat, a mounded and separated elongated drift has been defined (Fig. 9B).

#### *Genetic processes*

The early genesis of the Galicia Bank must be related to the formation of the rifted margin, as evidenced by the Mesozoic normal blocks that constitute the main structures around the bank, as well as by the presence of Cretaceous volcanic rocks and pre-Mesozoic metamorphic and granitic basement. Originally this feature would probably have been a main horst. The exhumation of these geological units and the present regional morphostructure is a result of Mesozoic rifting phases and later Eocene-Miocene compression (Boillot *et al.,* 1989). The bank can be explained as part of a major antiform related to the north-western thrust of the margin corresponding to the subduction of the western end of the Bay of Biscay, in the context of the Pyrenean orogeny (Sibuet *et al.,* 2004). The prevailing morphology corresponds to the interference of the regional uplift and the reactivation of Mesozoic normal faults during Pyrenean tectonics. The Cenozoic reactivation of normal faults affected the relief, particularly the scarps making up the flanks of the Galicia Bank (Vázquez *et al.,* 2008a).

#### *Recent geological processes*

The Galicia Bank is affected by various transport modes: downslope and the more dominant alongslope processes (Ercilla *et al.,* 2011). The downslope processes are mainly represented by turbidity flows and related flows which dominate on the flanks of the bank. These processes are responsible for gully formation. The alongslope processes erode, redistribute and winnow the seafloor sediments of the Galicia Bank plateau, developing erosional (furrow and abraded plain) and depositional (plastered drift and sand wave) features. These features are also present at the foot of the eastern and northern scarps where the influence of bottom currents produces a moat-elongated drift system. The contourite deposits are generated by the MOW (Fig. 2). The contour-current hemipelagic deposits mainly result from the interaction of hemipelagic settling with low-velocity MOW and LSW. There are also several features related to

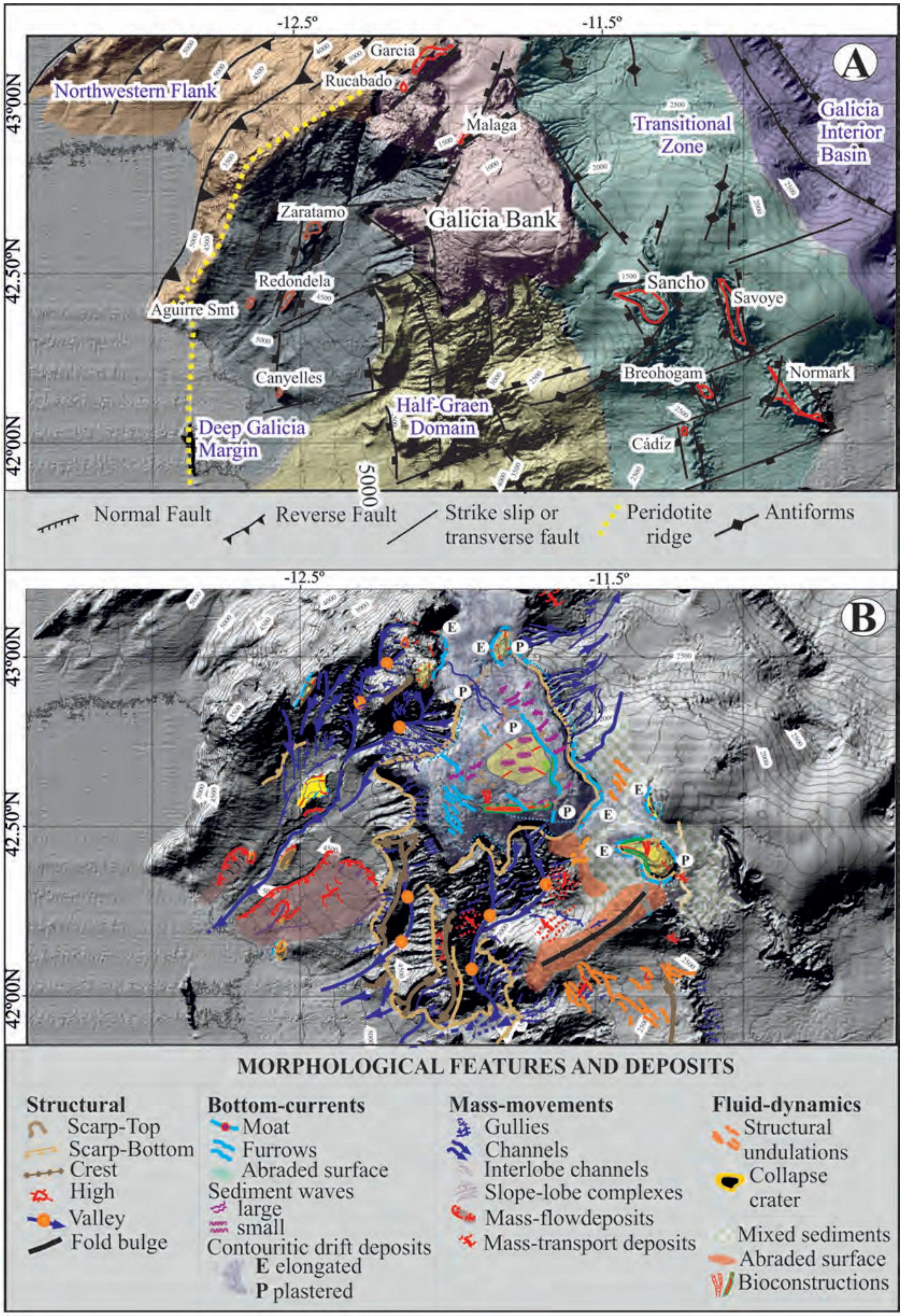


**Figure 9**. The Galicia Bank of the Galician margin (NW-Iberian): (A) Physiographic and tectonic map of the Galicia Bank region, and (B) Geomorphological map showing the main structural, fluid-dynamic, mass-movement, and bottom current features. Fig. 9A has been modified from Vázquez *et al.* (2008) and Fig. 9B from Ercilla *et al.* (2011).

***Figura 9**. Banco de Galicia en el Margen de Galicia (NO-Iberia): (A) Mapa Fisiográfico y Tectónico de la región del Banco de Galicia y (B) Mapa Geomorfológico mostrando los principales rasgos estructurales, de dinámica de fluidos, de movimientos en masa y de corrientes de fondo. La Fig. 9A ha sido modificada de Vázquez et al. (2008) y la Fig. 9B de Ercilla et al. (2011).*

biogenic cold water coral constructions (Ercilla *et al.,* 2011; Cartes *et al.,* 2014; Somoza *et al.,* 2014).

## Seamounts on the Cantabrian margin

### *Morphology*

Eight main seamounts (Vizco High, Le Danois Bank, ECOMARG High, Santander Promontory, Landes, Jovellanos, Charcot and Vizcaya Smt.) have been described on the Cantabrian continental margin and the Bay of Biscay (numbers 39 to 46 in Fig. 1). Here, the Le Danois Bank (40) is described as it constitutes a first order feature of the continental margin physiography and has recently been declared Spain's first 'Marine Protected Area' (Sánchez *et al.,* 2008; 2009) (Fig. 1). The Le Danois Bank, also called "The Cachucho" by local fishermen, was described for the first time in the 1948 book 'Les Profondeurs de la Mer' by the French scientist Edouard Le Danois. It is located 70 km to the north of the Cantabrian continental margin on the Asturian Marginal Plateau (Fig. 10). The positioning of the Le Danois Bank creates an intra-slope basin to the south (Asturian Intra-slope Basin) parallel to the margin and dipping toward the east (from 920 to 2 050 m water depth) (Fig. 10).

The Le Danois Bank (summit at 550 m water depth) is W-E trending, has an elongated shape, and occupies an area of 1,150 km$^2$ (72 km long and 15 km wide) (Table 1). Its top is relatively flat (< 2°). The flanks have moderate slope gradients (16.5° to 18° in the north; about 12° in the south) (Table 1). The main morphological features and deposits recognised on this seamount are (Fig. 10): gullies, slides, slide scars, a turbidite channel, and contourite features. Gullies and slides are observed mainly on the northern flank, whereas slide scars and a wide range of mass-movement deposits are identified along the northern and southern flanks. The Le Danois turbidite channel runs along the south-eastern base of the bank and mouths onto the lower slope as a hanging channel (Van Roij *et al.,* 2010), its associated levee and overbank deposits develop in the intra-slope basin. The group of contourite features comprises plastered drifts, moats, elongated drift and sediment waves (Iglesias 2009; Van Roij *et al.,* 2010). Three plastered drifts have been mapped on the southern wall, one in the west and two in the eastern part. The Le Danois moat runs along the foot of the southern wall and leads into the Le Danois turbidity channel. Associated to this moat, there is an elongated drift developed over the intraslope basin.

### *Genetic processes*

The Le Danois Bank was previously formed as a horst, through rifting and subsidence from the Triassic to Upper Cretaceous), and was later uplifted by means of several northwards thrusts between the northern base of this bank and the continental shelf during the period of compressive deformation from the Paleocene to the Oligocene (Gallastegui *et al.,* 2002). The pre-Mesozoic basement and Mesozoic sedimentary rocks outcrop at the top of the bank forming a monoclinal series dipping toward the south (Boillot *et al.,* 1974; Alvarez-Marrón *et al.,* 1997). Post-tectonic gravitational processes smoothed the relief during the Neogene-Quaternary (Boillot *et al.,* 1974).

### *Recent geological processes*

The uplift of the Le Danois Bank mainly took place during the Tertiary compression, although its current configuration is the result of recent tectonic readjustments. Some of these readjustments were produced by diapirism and subsidence in the Asturian Intraslope Basin which may also have entrapped the sedimentary input coming from the continental shelf (Boillot *et al.,* 1979). Diapirism has also affected the basement highs of the intraslope basin (Leprêtre, 1974; Iglesias, 2009). Biogenic constructions have been observed on this seamount (Sanchez *et al.,* 2008; 2009). The main sedimentary processes affecting this seamount include downslope processes (mainly mass movements) and alongslope processes principally related to the MOW (Fig. 2) (Van Rooij *et al.,* 2010). Mass transport is suggested by the presence of slide scars, gullies, and mass movement deposits on the flanks. Many of these mass-transport deposits evolve into gravity flows favouring the incision of gullies: on the northern wall they can reach the continental rise where they generate depositional lobes, and on the southern wall they are canalised around the bank inside the Le Danois turbidity channel at the foot of the bank (Ercilla *et al.,* 2008a; Iglesias, 2009; Van Rooij *et al.,* 2010) (Fig. 10). The alongslope processes are represented by plastered drifts and moat elongated drifts (Iglesias, 2009; Van Rooij *et al.,* 2010). When the MOW reaches the Asturian Marginal Plateau it is divided into three branches, interacts with the Vizco High and the Le Danois Bank, and is capable of reworking the gravity deposits of the bank and the shallower part of the intra-slope basin to create the moat and associated drifts along the foot of the bank.

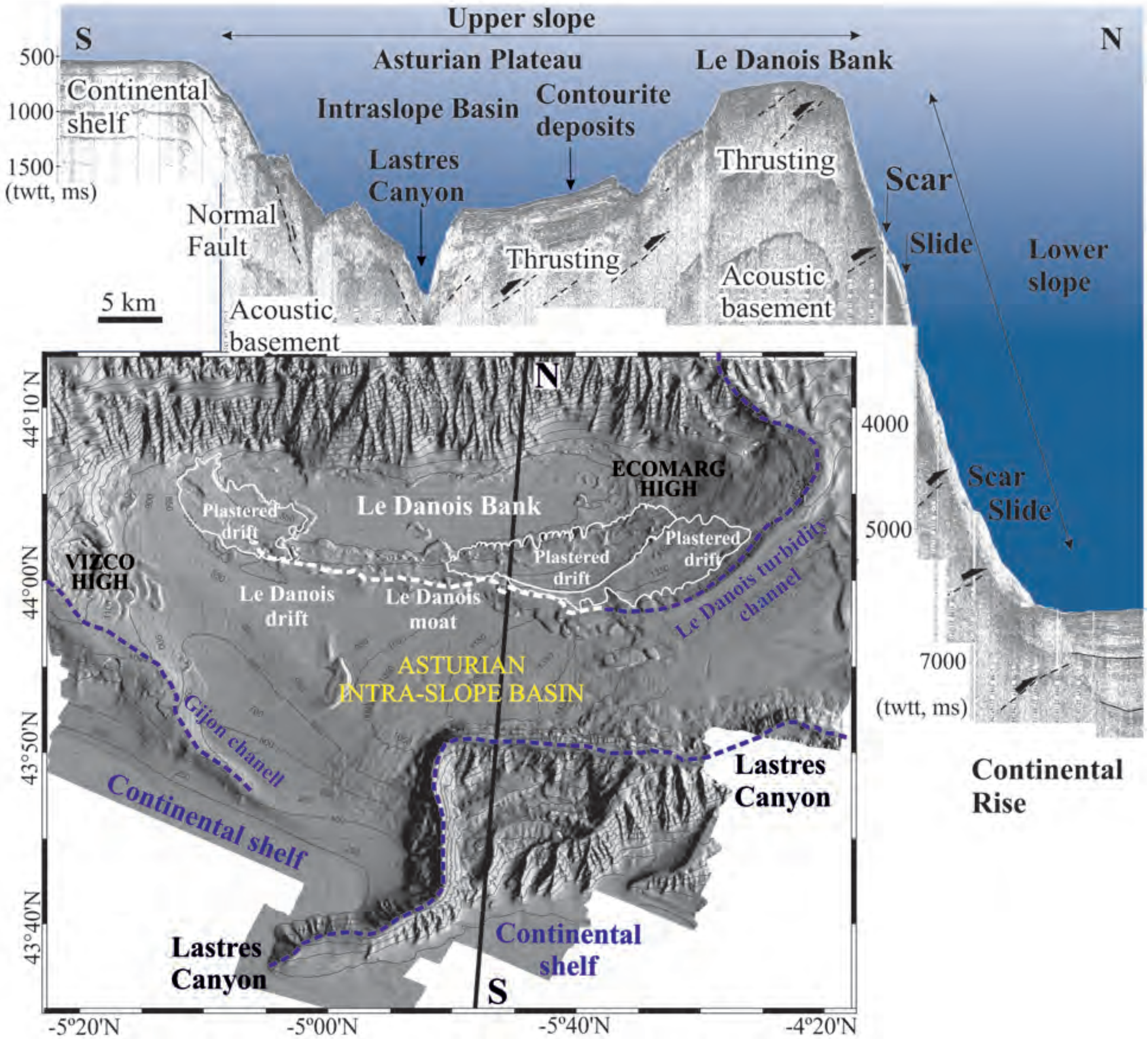


**Figure 10**. The Le Danois Bank of the Cantabrian margin: (A) Seismic profile showing the architectural features and (B) Bathymetric map showing the geomorphological features. Modified from Iglesias, (2009).

***Figura 10**. Banco de Le Danois en el Margen Cantábrico: (A) Perfil sísmico mostrando los rasgos arquitectónicos del margen y (B) Mapa batimétrico mostrando los rasgos geomorfológicos. Modificada de Iglesias, (2009).*

## Remarks on the compilation of Iberian seamounts

The compilation of Iberian seamounts describes the geomorphology of 15 seamounts in the context of the genetic and current morpho-sedimentary process in six sectors around Iberia (Balearic Promontory, Alboran Sea, Gulf of Cadiz, Western Portugal, Galician Margin, and Cantabrian Margin). Other seamounts are also shown in Figure 1 that will be studied in the future. This compilation is not a complete synthesis of all the seamounts around Iberia but an attempt to show that full advantage must be taken of existing geological knowledge to provide an overview of the main areas of seamount distribution.

*On distribution and size.* The majority of the seamounts considered are located in the southern (five seamounts) and eastern (three seamounts) areas of Iberia, with two seamounts from the Gulf of Cadiz, three from the Atlantic oceanic domain (southwest and west of Iberia) and two on the continental margins of north-western and northern Iberia. In the future it is hoped that further knowledge will be gathered on the Atlantic oceanic domain seamounts, which are numerous and varied in the vicinity of the

Horseshoe Abyssal Plain and close to the Tore Smt., and the Bay of Biscay. The seamounts can be divided into two groups based on size: i) those less than 20 km long, basically those studied on the Mediterranean margins; and ii) those longer than 50 km, corresponding to those studied on the Atlantic margins, with the exception of the Guadalquivir Bank. The width of these seamounts ranges between 7.5 and 25 km, apart from the Tore Smt. which exceeds 100 km, and the Galicia Bank, Gorringe Bank and Coral Patch Smt. which are wider than 50 km, probably in all four cases due to their geological complexity. However, it is worth noting that the length/width ratio is, in most cases, between 1 and 2, with the exception of the Alboran Ridge and Portimao and Le Danois banks, probably due to the linear nature of their tectonic origin.

The area occupied by all the seamounts varies greatly and includes the exceptional Tore Smt. (31,000 $km^2$), the Gorringe Bank (14 000 $km^2$) and Coral Patch Smt. (8 400 $km^2$). The remaining highs can be divided into two groups: those with an area greater than 1 000 $km^2$ (Alboran Ridge, Le Danois, Galicia and Portimao banks) and those with an area of 50 to 200 $km^2$ (all the Mediterranean seamounts apart from the Alboran Ridge, and the Guadalquivir Bank). This parameter again points to geological and tectonic complexity as determining factors. There is a general difference between the Mediterranean seamounts (Balearic Promontory and Alboran Sea), which are smaller and distributed in specific clusters, and the Atlantic seamounts (southwest, west, northwest and north Iberia), which are bigger and associated with large crustal elevations of volcanic and/or tectonic origin. The exception is the Alboran Ridge because of its great length and elevation.

*On scientific knowledge*. The Iberian seamounts are first-order morphological elements in the sedimentary evolution of continental margins and the adjacent oceanic domains. These seamounts are numerous and varied, and together they constitute a fair representation of the global diversity of these features. Most of the submarine elevations are structural in origin and their most recent reliefs are related to the different compressive stages that have affected Iberia since the Eocene. Volcanic seamounts are underrepresented in this region, although they are the most common globally. The location, distribution and morphogenetic evolution of the seamounts around Iberia clearly reflects the tectonic evolution, including the geodynamic context where these structures are located (in the case of the most western feature), as well as the consequence of compressive episodes in Iberia since the Eocene. This highlights the importance of tectonic reactivation in the area. A Pliocene-Quaternary reactivation can be observed in the Balearic Promontory (Emile Baudot Smt.), and the Alboran seamounts (especially on the Alboran Ridge), as well as in the Coral Patch Smt., Gorringe Bank, Tore Smt., Guadalquivir Bank and Portimao Bank, where deformation is also related to diapirism. Miocene reactivation, however, is responsible for the latest uplift of the Galicia and Le Danois banks. In this sense, tectonic reactivation of relief is more recent to the south of Iberia as the distance to the active plate boundary between Africa and Eurasia decreases.

The presence of seamounts on continental margins and in ocean basins, both past and present, has favoured the development of a series of sedimentary processes: i) the formation of slope failure and landslide deposits (Gorringe Bank, Alboran Ridge), partly caused by steep slopes due to tectonic reactivation of relief, ii) interference with water mass dynamics generating the bottom currents associated with contourite systems (Djibouti Banks and Galicia Bank) and specific features of regional contourite systems (Guadalquivir Channel associated to the Guadalquivir Bank); iii) specific habitat generation due to the high dynamics associated with seamounts, especially cold-water coral reefs (Coral Patch Smt, Galicia and Le Danois banks); and iv) development of isolated shelves where the summits are located at a water depth of less than 100 m, with erosive terrace levels related to sea level changes and carbonate sedimentation characterised by maërl carpets (Alboran Ridge, Ausiàs March and Emile Baudot seamounts).

*On the next steps for seamount science*. In order to continue making relevant scientific discoveries, it is important to consider the most exciting and significant research topics. Which new approaches and technologies will give the highest return for the investment of research time? As in other fields where complex systems are involved, seamount science depends on the effective integration of multidisciplinary science and research coordination. Although certain special features have received a great deal of attention, many fundamental questions regarding the nature of seamount processes remain unanswered.

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