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Bottom current processes along the Iberian continental margin

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ABSTRACT

The products of bottom current circulation around the Iberian continental margin are characterised by large erosional and depositional features formed under a variety of geological and oceanographic contexts. The Iberian margins are influenced by several water masses that mainly interact along the upper and middle continental slopes, as well as along the lower slope with the abyssal plains being influenced to a lesser extent. The main depositional features occur along the Ceuta Contourite Depositional System (CDS) within the SW Alboran Sea, in the Gulf of Cadiz (the most studied so far), the western margins of the Portugal/Galician margin, the Ortegal Spur and the Le Danois Bank or "Cachucho". Moreover, erosional contourite features have also been recently indentified, most notably terraces, abraded surfaces, channels, furrows and moats. The majority of these features are formed under the influence of the Mediterranean water masses, especially by the interaction of the Mediterranean Outflow Water (MOW) with the seafloor. The MOW is characterized as relatively warm (13°C) and with a high salinity (~ 36.5), giving it a high density relative to the surrounding water masses, hence constituting an important contribution to the global thermohaline circulation, making it one of the most studied water masses surrounding Iberia. The development of both depositional and erosional contourite features does not only depend on the bottom-current velocity but also on several other important controlling factors, including: 1) local margin morphology affected by recent tectonic activity; 2) multiple sources of sediment supply; 3) water-mass interphases interacting with the seafloor; and 4) glacioeustatic changes, especially during the Quaternary, when the increasing influence of the bottom current has been observed during the cold stages. The main objective of this special volume contribution is to provide a review and description of the regional along-slope processes and their sedimentary impact around the Iberian margin. Despite the numerous examples of bottom current processes recorded, there remains a number of challenges to understanding CDSs around the Iberian margin including: 1) evidencing their important scientific implications (stratigraphy, sedimentology, palaeoceanography and palaeoclimatology); assessing their geological hazard and their economic potential (for mineral and energy resources); and 3) using them to create conceptual models for CDS formation. There is a lack of complete knowledge about the different oceanographic processes that may drive bottom currents, and there is also the need to document the great variety of contourite features (processes and products) and facies models, along with their evolution over time and space. Therefore advances, both in new technologies and integrated studies (Geology, Physical Oceanography and Benthic/planktonic Biology), are anticipated.

Key words: contourites, Iberian continental margin, Mediterranean Outflow Water, sedimentary processes, water-mass circulation.

Procesos sedimentarios por corrientes de fondo a lo largo del margen continental ibérico

RESUMEN

En la evolución reciente de los márgenes continentales ibéricos se han registrado numerosos, y cada vez más frecuentes, ejemplos de procesos sedimentarios generados por la interacción de las corrientes con el fondo. Los productos de la circulación de las corrientes de fondo comprenden tanto rasgos contorníticos erosivos como deposicionales, de dimensiones variables dependiendo de los diferentes contextos geológicos y oceanográficos. En Iberia las masas de agua más relevantes interactúan principalmente a lo largo de los taludes continentales superior y medio y, en menor intensidad también en el talud inferior y llanuras abisales. Estas masas de agua han desarrollado depósitos contorníticos (monticulares separados, laminares, adosados, confinados y asociados a canales),así como rasgos contorníticos de origen erosivo, siendo los más destacables las terrazas, las superficies de abrasión, los canales, los surcos y las fosas contorníticas, en los márgenes del SW del Mar de Alborán, del Golfo de Cádiz (el más estudiado hasta la fecha), de Portugal, de Galicia, de Cabo Ortegal, y del Banco de Le Danois o "Cachucho". Estos rasgos morfológicos se generar mayoritariamente bajo la influencia de las masas de agua Mediterráneas y en concreto por la corriente Mediterránea de salida (MOW). La MOW se caracteriza por ser relativamente caliente (13°) y por su alta salinidad (~36.5 ‰), que le confieren una alta densidad con respecto a las masas de agua circundantes, y considerándose una contribución importante a la circulación termohalina global. Es por ello que es una de las masas de agua, que rodean Iberia, más estudiadas hasta la actualidad. El desarrollo de estos rasgos contorníticos no sólo depende de la velocidad de la corriente, sino además de otros factores de control como: 1) la morfología del margen, afectada por la actividad tectónica reciente, 2) las posibles y múltiples fuentes de aporte de sedimento, 3) la interacción de la interfase entre distintas masas de agua con el fondo marino, y por último, 4) los cambios glacioeustáticos, especialmente relevantes durante el Cuaternario. El objetivo principal de este trabajo es realizar una revisión bibliográfica de los numerosos procesos sedimentarios debidos a la interacción de las corrientes con el fondo a lo largo del margen continental Ibérico que pone de manifiesto que, a pesar de las relevantes implicaciones científicas que tienen estos procesos ya sea en estratigrafía, sedimentología, paleoceanografía, paleoclimatología, riesgos geológicos, como por el gran potencial económico, todavía existe una carencia importante en el conocimiento de los distintos procesos oceanográficos que podrían producir corrientes de fondo; la gran variedad de rasgos contorníticos (procesos y productos); la determinación de un modelo de facies; y la evolución en el tiempo y el espacio de estos rasgos contorníticos. Para solventar estas carencias, las expectativas de avance en este campo y alrededor de Iberia se centrarían, básicamente, en el uso de nuevas tecnologías así como en la integración de estudios multidisciplinares (geología, oceanografía física y biología bentónica/plantónica).

Palabras clave: contornitas, margen continental de Iberia, Corriente Mediterránea de Salida, procesos sedimentarios, circulación masas de agua.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

La interacción de una masa de agua con el fondo marino puede generar tanto rasgos erosivos como deposicionales, desarrollándose de manera individual o constituyendo sistemas deposicionales contorníticos (SDCs) de grandes y variables dimensiones y espesores sedimentarios (Faugères et al., 1999; Stow et al., 2002; Viana and Rebesco, 2007; Hernández-Molina et al., 2008a, b; Rebesco and Camerlenghi, 2008). Durante la última década, el estudio de dichos rasgos contorníticos, ha constituido una de las líneas más activas de investigación dentro de la Geología Marina en el ámbito internacional, tanto por su gran interés científico (estratigráfico, sedimentológico, paleoceanográfico, paleoclimatológico), así como por su relación con procesos de inestabilidad sedimentaria de taludes y por su relación directa con posibles yacimientos minerales *o de hidrocarburos (Pickering et al., 1989; Stow et al., 2002b; Rebesco, 2005; Viana and Rebesco, 2007; Rebesco and Camerlenghi, 2008; Hernández-Molina et al., 2010). Los márgenes continentales Ibéricos han tenido una génesis y evolución geodinámica y sedimentaria muy compleja y desigual, donde la circulación de las masas de agua ha generado importantes y extensos SDCs (Fig. 1), tales como los desarrollados al SO del Mar de Alborán (Ercilla et al., 2002), Golfo de Cádiz (el más estudiado hasta la fecha, Kenyon and Belderson, 1973; Gonthier et al., 1984; Nelson et al., 1999; Llave et al., 2001, 2007, 2011; Stow et al., 2002; Mulder et al., 2003, 2006; Habgood et al., 2003; Hernandez-Molina et al., 2003, 2009a; Hanzquiez et al., 2007; Marches et al., 2007; Roque et al., 2012; Brackenridge et al., 2013, entre otros), margen oeste de Portugal (Alves et al., 2003; Pereira and Alves, 2011), margen de Galicia (Ercilla et al., 2006, 2008, 2009, 2010, 2011), Cabo Ortegal (Hernández-Molina et al., 2009b; Jané et al., 2012; Llave et al., 2013), y el Banco de Le Danois o "Cachucho" (Ercilla et al., 2008b; Iglesias, 2009; Van Rooij et al., 2010) (Fig. 1).*

El objetivo principal de este trabajo es evidenciar los numerosos procesos sedimentarios por corrientes de fondo desarrollados y descritos a lo largo del margen continental Ibérico y el trabajo que queda todavía por hacer. Ya que aunque el conocimiento de estos procesos haya avanzado e implicado una mejora en su definición e identificación, todavía falta mucho para lograr establecer un modelo de facies que caracterice y tipifique este tipo de rasgos morfológicos. Existe todavía una carencia en el conocimiento de los distintos procesos oceanográficos que podrían producir corrientes de fondo; la gran variedad de rasgos contorníticos (procesos y productos); la determinación de un modelo de facies; y la evolución en el tiempo y el espacio de estos rasgos contorníticos, por lo que lo esperable para avanzar en el futuro sería integrar nuevas tecnologías y estudios multidisciplinares (geología, oceanografía física y biología del bentos).

Resultados: Principales rasgos contorníticos a lo largo de Iberia

Los depósitos (o drifts) contorníticos más frecuentes generados por corrientes de fondo a lo largo de Iberia comprenden: drifts elongados y separados, adosados y laminares, y también, aunque en menor medida, se han descrito drifts confinados y asociados a canales (especialmente en la Cuenca de Alborán) (Figs. 2 a 7). Aunque existen varias clasificaciones para los drifts contorníticos, los rasgos erosivos no están aún tan bien estudiados ni clasificados. Alrededor de Iberia este tipo de rasgos contorníticos está representado mayoritariamente por extensas terrazas erosivas o de abrasión, plataformas marginales, canales, fosas y surcos.

Las principales masas de agua responsables de estos rasgos contorníticos, y descritas desde la más superficial a la más profunda, son las siguientes (Fig. 1): A) En la Cuenca Mediterránea: Agua Atlántica (Atlantic Water - AW) o Agua Atlántica Modificada (Modified Atlantic Water - MAW), que circula a 100/200 m de profundidad y hacia el este (Gascard and Richez, 1985); El Agua Intermedia de Levante (Levantine Intermediate Water - LIW), circulando hacia el oeste entre los 200-600 m de profundidad, principalmente a lo largo del margen español, y caracterizada por una alta salinidad y temperatura; y el Agua Mediterránea Profunda (Western Mediterranean Deep Water - WMDW), que también circula hacia el oeste a unos 600 m de profundidad, y llega a alcanzar profundidades entorno los 2000 m, principalmente sobre el talud Marroquí (Parrilla and Kinder, 1987; Millot, 1999). Esta masa de agua se caracteriza por una densidad relativamente alta como consecuencia de su baja temperatura. Recientemente Millot (2009, 2014), en las proximidades del estrecho de Gibraltar, y dentro de la cuenca de Alborán, ha identificado una estructura y dinámica de masas de agua más compleja. B) En el margen del Golfo de Cádiz: Flujo Atlántico entrante (Inflow of the Atlantic Water – AIW) que comprende el Agua Superficial Norartlántica (North Atlantic Superficial Water - NASW), hasta los aprox. 100 m de profundidad, y el Agua Central noratlántica oriental (Eastern North Atlantic Central Water - ENACW), que circula ente los 100 y 700 m de profundidad, con 12-16° C y 34.7-36.25 de salinidad. Estas masas de agua circulan hacia el este para adentrarse en el Mar Mediterráneo a través del Estrecho de Gibraltar. Por debajo circula, desde el Mediterráneao hacia el Golfo de Cádiz a través del Estrecho de Gibraltar, la Masa de Agua Mediterránea de Salida (Mediteranean Outflow Water- MOW), (Lacombe and Lizeray, 1959; Ochoa and Bray, 1991; Baringer and Price, 1999; Nelson et al., 1999) que representa una masa de agua intermedia compuesta por la mezcla de la LIW y en menor medida por la WMDW y caracterizada por su alta salinidad (36.5 ‰) y alta temperatura (13˚C) (Ambar and Howe, 1979; Bryden and Stommel, 1984; Bryden et al., 1994). Esta masa de agua a su paso por el Estrecho de Gibraltar alcanza valores de velocidad entorno los 280 cm/s (Ambar and Howe, 1979; Mulder et al., 2003), circulando dentro del Golfo de Cádiz hacia el NW a lo largo del talud medio (600-1400 m) por encima de la Masa de Agua Noratlántica Profunda (North Atlantic Deep Water - NADW), que se caracteriza por su baja temperatura (3°-8° C) y poca salinidad (34.95-35.2) a profundidades > 1500 m (Lacombe and Lizeray, 1959; Thorpe, 1975; Zenk, 1975; Gardner and Kidd, 1983; Ochoa and Bray, 1991; Baringer and Price, 1999; Ambar et al., 1999; Serra et al., 2005). Por debajo de la NADW, y a > 4000 m circula hacia el norte la Masa de Agua Profunda Inferior (Lower Deep Water - LDW) (van Aken, 2000), que se compone de la Masa de Agua Antártica Profunda (Antarctic Bottom Water - AABW) y de la rama inferior de la Masa de Agua del Labrador (Labrador Sea Water - LSW). Recientemente se ha descrito una quinta masa *de agua, la Modificada Antártica Intermedia (Modified Antarctic Intermediate Water - AAIW), que se caracteriza por una temperatura ~10° C, salinidad ~35.62 y oxígeno disuelto de ~4.16 ml/l (Louarn and Morin, 2011), la cual si bien circula en el mismo rango de profundidades de la MOW, en el talud, localmente se localiza por encima de la MOW (Hernández-Molina et al., 2014). C) Márgenes Gallego y Cantábrico: Corriente de Portugal (Portugal Current - PC) y la Corriente Costera de Portugal (Portugal Coastal Current - PCC) que circulan hacia el sur entre los 0-400 m de profundidad y dominadas por los cambios estacionales (Varela et al., 2005). Por debajo circula la ENACW, hasta unos 600 m; e inmediatamente por debajo se encuentra la MOW, hasta al menos los 1600 m de profundidad. A continuación circula la Masa de Agua Intermedia Profunda (Deep Intermediate Water – DIW) a ~1490-2150 m de profundidad, que es el resultado de la mezcla con la LSW. Por debajo de los 2150 m circula la NADW y más abajo la LDW (>3450 m de profundidad) (Mazé et al., 1997; Varela et al., 2005).*

La mayoría de los drifts y/o SDCs que se han descrito alrededor de Iberia, se desarrollan en el talud continental principalmente bajo la influencia de las diferentes masas de agua Mediterráneas: en el Mar Mediterráneo se localizan en el talud continental medio (en Rosas, al oeste de Cabrera y en Alborán) (Canals, 1985; Lastras et al , 2007; Vandorpe et al., 2011; Ludmann et al., 2012; Ercilla et al., 2012; Juan et al., 2012) y en el talud inferior (Menorca y Alborán (Mauffret, 1979; Velasco et al., 1996; Frigola et al., 2007, 2008; Ercilla et al., 2008, 2009, 2011; Bender et al., 2012; Juan et al., 2012) (Figs. 2 y 3). Estos rasgos contorníticos se deben a la interacción con el fondo del talud inferior y medio de la LIW y WMDW, respectivamente. No obstante, a lo largo del margen Ibérico Atlántico, los principales rasgos contorníticos se encuentran desarrollados en el talud medio, y asociados a la influencia de la MOW. Este es el caso de los SDC del Golfo de Cádiz (Fig. 4) (ej. Madelain, 1970; Kenyon and Belderson, 1973; Gonthier et al., 1984; Nelson et al., 1993, 1999; Llave et al., 2001, 2006, 2007, 2011; Stow et al., 2002; Alves et al., 2003; Habgood et al., 2003; Hernández-Molina et al., 2003, 2006; Mulder et al., 2003, 2006; Hanquiez et al., 2007; Marchès et al., 2007, 2010; García et al., 2009; Roque et al., 2012; Brackenridge et al., 2013), el margen Portugués (Fig. 5) (Mougenot, 1989), el margen de Galicia (Fig. 6) (Ercilla et al., 2008, 2009, 2011; Bender et al., 2012),Cabo Ortegal (Hernández- Molina et al., 2009b; Jané et al., 2012; Alejo et al., 2012; Llave et al., 2013) y Banco de Le Danois (Fig. 7) (Ercilla et al., 2008a, b; Iglesias, 2009; Van Rooij et al., 2010). Son muy pocos los ejemplos de rasgos contorníticos asociados con otras masas de agua a lo largo del margen Ibérico Atlántico, sólo a nivel local, como los descritos a lo largo del talud inferior y ascenso continental portugués (Fig. 5) (Alves et al., 2000, 2003; Badagola, 2008; Roque, comunicación personal, 2013), desarrollados por la ENACW y LDW. En el área del Banco de Galicia se ha demostrado la influencia de las masas de agua LSW, NADW y LDW (Ercilla et al., 2009, 2010).

Generalmente los depósitos contorníticos están compuestos de sedimentos terrígenos y material biogénico, caracterizándose por estar mal seleccionados, e intensamente bioturbados, mostrando más o menos una laminación típica (Stow et al., 2002b; Ercilla et al., 2002). En los últimos años se ha incrementado el estudio y reconocimiento especialmente de los depósitos contorníticos arenosos, descritos principalmente en el Golfo de Cádiz (Hanquiez et al., 2007; Brackenridge et al., 2013; Stow et al., 2013b; Hernández- Molina et al., 2012, 2014), en el margen de Galicia (Bender et al., 2012) y en Cabo Ortegal (Alejo et al., 2012), por su gran interés como potenciales reservas de hidrocarburos y recursos minerales (Stow and Faugùeres, 2008, Viana, 2008, Stow et al., 2011; Brackenridge et al., 2013; Hernández-Molina et al., 2013, 2014; Rebesco et al., 2014).

Discusión

Factores de control

El desarrollo de estos rasgos contorníticos no sólo depende de la velocidad de las masas de agua (Stow et al., 2009), sino también de otros factores importantes de control los cuales incluyen (Fig. 8): (1) Morfología del margen. Las características geológicas heredadas que configuran el fondo y sus irregularidades, facilitan la interacción de las masas de agua de manera local con el fondo marino. El margen continental Ibérico se ve afectado por una actividad tectónica reciente (diapiros, bancos estructurales, dorsales, etc.) que conforman una morfología compleja del margen y la interacción de las masas de agua con estas irregularidades implica: posibilidades de generar múltiples trayectorias, flujos secundarios, pequeños filamentos, ondas internas, turbulencias locales asociadas a remolinos, desbordamientos, flujos helicoidales, upwellings y downwellings. Durante el Plioceno (especialmente tras la apertura del Estrecho de Gibraltar) y el Cuaternario inferior, la tectónica ha representado un factor importante a largo plazo, condicionando, a gran escala, cambios en la estratigrafía, arquitectura sedimentaria y ubicación de diferentes tipos de depósitos o rasgos erosivos (Alves et al., 2003; Hernández-Molina et al., 2003, 2006; Mulder et al., 2003; Llave et al., 2007, 2008, 2011; García et al., 2009; Ercilla et al., 2012, 2013; entre otros); (2) El aporte sedimentario puede depender de una gran variedad de fuentes, y cada una variable en el tiempo. Los procesos transversales al margen como los cañones submarinos, deslizamientos y flujos en masa, pueden aportar grandes cantidades de sedimentos, *así como material biogénico pelágico o hemipelágico o partículas en suspensión de la columna de agua, que pueden ser pirateadas por las corrientes de fondo (ej. Stow et al., 2008; Bender et al., 2012; Mulder et al., 2013); (3) La interacción de las diferentes interfases de masas de agua (picnoclinas) con el fondo marino ha desarrollado diferentes rasgos deposicionales y erosivos. En la actualidad son muchos los estudios que tienen como objeto la detección y caracterización de capas nefeloides intermedias y profundas que a menudo están vinculadas a las interfases entre las masas de agua (McCave, 1986; Dickson and McCave, 1986; Cacchione et al., 2002; Puig et al., 2004; Preu et al., 2013; Ercilla et al., 2014); (4) Los cambios glacioeustáticos influyen de manera importante en la arquitectura sedimentaria del margen y las cuencas (e.j. Grousset et al., 1988; Vergnaud-Grazzini et al., 1989; Nelson et al., 1993; Zahn et al., 1999; Schönfeld and Zahn, 2000; Cacho et al., 2000; Shackleton et al., 2000; Schönfeld et al., 2003; Llave et al., 2006, 2007; Voelker et al., 2006; Frigola et al., 2007, 2008; Lebreiro et al., 2009; Lebreiro, 2010; Voelker and Lebreiro, 2010; Bender et al., 2010, 2012; Gonthier et al., 2010; Mena et al., 2010; Roque et al., 2012; Brackenridge et al., 2013; Hernández-Molina et al., 2013, 2014), especialmente relevante durante el Cuaternario. En un plazo más corto, pueden controlar el patrón de apilamiento y las facies (Shanmugan, 2006, 2012, 2013a, b; Brackenridge et al., 2011, 2013; Mutti and Carminatti, 2012; Gong et al., 2013). Parece más probable que algunas masas de agua alrededor de los márgenes de Iberia, como la WMDW o la LDW, y por tanto la MOW, hayan sido más intensas o hayan circulado a mayores profundidades durante los intervalos fríos (ej. períodos glaciales), periodos en los cuales además se produce un aumento del aporte sedimentario hacia la cuenca (ej. Ercilla et al., 2002, 2013; Hernández-Molina et al., 2002, 2006, 2013, 2014; Stow et al., 2002c; Llave et al., 2006, 2011; Voelker et al., 2006; Rogerson et al., 2006, 2008, 2010, 2012; Toucanne et al., 2007; Frigola et al., 2008, 2010; Van Rooij et al., 2010a; Roque et al., 2012; Juan et al., 2012; Brackenridge et al., 2013). El clima juega un papel importante también en la posición del núcleo de una corriente de fondo, produciendo de esta manera dos efectos diferentes: a) cambios verticales y laterales en el núcleo y/o en la posición de las interfases entre las masas de agua y b) los cambios en la intensidad de los núcleos (Preu et al., 2013).*

Los procesos sedimentarios asociados a la circulación de las masas de agua alrededor de Iberia, son consecuencia de un modelo de circulación muy particular, y caracterizado por el intercambio de masas de agua desde la apertura del Estrecho de Gibraltar durante el Mioceno Superior. Desde entonces, los cambios paleoceanográficos que se han descrito durante la evolución de los sistemas deposicionales del Mar de Alborán, Golfo de Cádiz y Le Danois, han sido coetáneos (Llave et al., 2001, 2006, 2011; Ercilla et al., 2002, 2013; Hernández-Molina et al., 2002, 2006, 2013, 2014; Stow et al., 2002c; Van Rooij et al., 2010; Roque et al., 2012; Brackenridge et al., 2013). A comienzos del Plioceno, hace 4.0-4.2 Ma, los procesos transversales se intercalaban con los procesos longitudinales, siendo estos últimos más débiles (Hernández-Molina et al., 2009c; Llave et al., 2010; Raddatz et al., 2011; Rogerson et al., 2012). No fue hasta comienzos del Cuaternario (2.6 Ma) cuando la hidrodinámica, tal y como la conocemos actualmente, no quedó plenamente definida (Rogerson et al., 2012) y comenzaron a predominar los procesos longitudinales sobre los transversales (Llave et al., 2007; Van Rooij et al., 2010; Roque et al., 2012; Juan et al., 2012; Brackenridge et al., 2013; Stow et al., 2013b; Hernández-Molina et al., 2013, 2014). Una de las principales pruebas de la mayor relevancia de la actividad contornítica, asociado a una intensificación en la circulación de las masas de agua, se produce durante el Cuaternario, coetánea con la Revolución Pleistoceno medio (~ 0.9 Ma) (Llave, 2003; Llave et al., 2007; Van Rooij et al., 2010; Roque et al., 2012; Juan et al., 2012; Hernández-Molina et al., 2014). Se han descrito otros ejemplos de rasgos contorníticos en el ascenso al oeste de Portugal, generados bajo la influencia de las masas de agua más profundas, probablemente por la LDW, la cual desde al menos el Eoceno medio ha interaccionado con el fondo marino (Sawyer et al., 1994; Whitmarsh et al., 1998). Esta actividad de las masas de agua más profundas también viene indicada por la presencia en el registro sedimentario del Eoceno medio hasta el Pleistoceno de campos de ondas de sedimento (Whitmarsh et al., 1998) y por el desarrollo en el ascenso continental de una fosa contornítica y un depósito contornítico a la base del alto estructural de Aveiro (Roque, C. comunicación personal 2013).

Implicaciones

El estudio de los sistemas deposicionales contorníticos es esencial en líneas de investigación como la paleoclimatología y paleoceanografía; así como para el estudio de la estabilidad de taludes y además en el campo de la exploración de hidrocarburos.

Paleoclimatología y paleoceanografía. El registro sedimentario de los depósitos contorníticos es generalmente bastante continuo, lo que proporciona una información de alta resolución temporal y por lo tanto, clave para obtener información sobre la variabilidad de los patrones de circulación oceánica (Fig. 9). A lo largo del margen ibérico los mejores ejemplos contorníticos que constituyen importantes registros de alta resolución temporal se encuentran desarrollados en el Mar Mediterráneo, en concreto al Oeste de la Cuenca de Alborán; en el Golfo de Cádiz y Oeste de Portugal; y en los márgenes Gallego y Cantábrico (Banco de

Galicia, Cabo Ortegal y Banco de Le Danois) (Sawyer et al., 1994; Milkert et al., 1996; Baas et al., 1997; Whitmarsh et al., 1998; Schönfeld and Zahn, 2000; Hall and McCave, 2000; Cacho et al., 2000; Schönfeld et al., 2003; Sierro et al., 2005; Llave et al., 2006; Voelker et al., 2006; Toucanne et al., 2007; Frigola et al., 2007, 2008; Ercilla and Vilas, 2008; Salgueiro et al., 2010; Mena et al., 2010; Abrantes et al., 2012; Bender et al., 2012).

Inestabilidad de taludes. La inestabilidad de los fondos submarinos con cierta pendiente está normalmente relacionada con la distribución, la composición y las propiedades físicas de los depósitos contorníticos. En el margen continental ibérico se han descrito ejemplos de inestabilidad de taludes por circulación de corrientes de contorno al NE de la Península Ibérica, y en el Promontorio Balear (Canals, 1985; Maldonado and Nelson, 1990; Casas et al., 2003a; Urgeles et al., 2006; Lastras et al., 2007). En el Mediterráneo y Golfo de Cádiz se han descrito numerosos deslizamientos submarinos (Gràcia et al., 2003, 2006; Sallarés et al., 2011). En la parte superior del talud del sudeste del Golfo de Cádiz, también se han identificado pockmarks asociados al escape de fluidos (Baraza et al., 1989, 1999; Casas et al., 2003b) y en el margen gallego en la plataforma marginal de Cabo Ortegal (Jane et al., 2010). Tras los estudios geológicos que se realizaron en la zona de hundimiento del Prestige se caracterizaron diferentes tipos de inestabilidades de talud (flujos en masa, corrientes de turbidez y los flujos relacionados), que se podrían relacionar a la actividad tectónica y/o las fuertes pendientes de los altos estructurales del Banco de Galicia (Ercilla and Vilas, 2008). En el margen de Cantabria, se han identificado zonas de inestabilidad del talud en áreas en las que los gradientes de pendiente son elevados (Iglesias, 2009). No obstante, en estas zonas caracterizadas por gradientes de pendientes elevados además se ha observado la influencia e interacción de las masas de agua con el fondo marino.

La exploración de hidrocarburos. Asociados a los rasgos contorníticos erosivos parece frecuente la presencia y desarrollo de extensas capas de arena y arenas limosas, en ocasiones muy bien seleccionadas que podrían constituir potenciales rocas reservorio (Stow and Faugères, 2008; Viana, 2008; Stow et al., 2011, 2013a, b). Además los sedimentos finos interestratificados entre las capas de arena pueden contener un porcentaje importante de materia orgánica (>2%) y representar potenciales rocas madres, así como niveles de sello como consecuencia de su baja permeabilidad y porosidad. Un ejemplo excepcional de rocas reservorio relacionado con depósitos contorníticos es el compuesto por las unidades arenosas del Sistema Deposicional Contornítico del Golfo de Cádiz (Buitrago et al., 2001), localizado en la parte adyacente al Estrecho de Gibraltar. Otros autores han puesto de manifiesto la presencia de arenas contorníticas (interestratificadas con niveles contorníticos de tamaño de grano fino) muy poco conocidas, especialmente en el sector más próximo al Estrecho de Gibraltar (Kenyon and Belderson, 1973; Nelson et al., 1993; Buitrago et al., 2001; Akhmetzhanov et al., 2002; Habgood, 2002; Akhmetzhanov, 2003; Habgood et al., 2003) y en el interior de los canales contorníticos (Nelson et al., 1993, 1999; Hernández-Molina et al., 2006; Stow et al., 2013a), las cuales se consideran de gran interés para la exploración de hidrocarburos (Buitrago et al., 2001; Llave et al., 2005; Akhmetzhanov et al., 2007; Viana et al., 2007; Viana, 2008; Stow et al., 2011; Brackenridge et al., 2011). Recientemente ha tenido lugar la expedición científica 339 a bordo del buque JOIDES Resolution, dentro del Programa Integrado de Perforación Oceánica (Integrated Ocean Drilling Program - IODP) (Hernández-Molina et al., 2013, 2014; Stow et al., 2013c). En esta expedición uno de los descubrimientos más importantes ha sido la recuperación de impresionantes e inesperadas acumulaciones de arenas en los sedimentos contorníticos (algunas con un origen mixto: contornítico y turbidítico). Esto ha puesto de manifiesto la gran intensidad, alta velocidad y larga duración de las corrientes de fondo mediterráneas, así como su interrelación con procesos transversales al margen (turbidíticos) y su gran potencial como recurso energético (Rebesco et al., 2014).

Conclusiones y consideraciones futuras

En los últimos 20 años, los márgenes continentales ibéricos han experimentado un aumento en el estudio de procesos y productos relacionados con la circulación marina profunda. Los productos de estas corrientes de fondo comprenden tanto rasgos erosivos como deposicionales de dimensiones variables, dependiendo de una gran variedad de contextos geológicos y oceanográficos. Los márgenes ibéricos se encuentran bajo la influencia de varias masas de agua que interactúan a lo largo de los taludes continentales superior y medio y, aunque en menor intensidad, también en el talud inferior y llanuras abisales. Los principales rasgos contorníticos definidos alrededor de Iberia se localizan en los siguientes márgenes continentales: SO de Mar de Alborán, Golfo de Cádiz (el más estudiado hasta la fecha), oeste de Portugal Galicia, Cabo Ortegal, y Banco de Le Danois o " Cachucho ", bajo la influencia de las masas de agua mediterráneas, sobre todo por la interacción con el fondo marino de la Masa de Agua Mediterránea de salida (MOW). Como rasgos deposicionales más relevantes destacan el desarrollo de drifts elongados y separados, laminares, adosados y en menor medida los confinados y asociados a canales. Los principales rasgos erosivos comprenden las terrazas, superficies de abrasión, canales, surcos y fosas contorníticas. El desarrollo de estos rasgos no sólo depende de la velocidad o intensidad de la corriente, sino también de otros factores como: 1) Morfología del margen; 2) Aporte sedimentario; 3) Picnoclinas o interfases entre las masas de agua y 4) Cambios glacioeustáticos. A

lo largo de los últimos años, la circulación de las corrientes de fondo y los procesos asociados ha ido adquiriendo más relevancia por su papel en la configuración del fondo marino y en el control de la arquitectura sedimentaria de los márgenes continentales ibéricos. Aún así, existen muchos y diversos procesos oceanográficos que podrían impulsar el desarrollo de las corrientes de fondo, y la mayoría de ellos todavía no se entienden completamente (ver Hernández-Molina et al., este volumen). Por tanto, es necesario documentar y estudiar la gran variedad de rasgos contorníticos existentes en los márgenes ibéricos y así poder elaborar un modelo de facies, determinar su evolución en el tiempo y el espacio, e identificar los diferentes procesos oceanográficos que pueden formar dichos rasgos. Se necesita dedicar especial énfasis en la comprensión del desarrollo de los depósitos arenosos contorníticos, debido a su gran interés económico para su exploración y evaluación como recursos de hidrocarburos. Por tanto lo esperable a considerar en el futuro sería el desarrollo de nuevas tecnologías y la realización de estudios integrados (geología, oceanografía y biología bentónica) con la finalidad de definir y diagnosticar los depósitos relacionados con la circulación de las masas de agua profundas.

Introduction

Deep-marine environments have traditionally been considered as relatively tranquil environments, where water masses flow as slow-moving tabular bodies (< 3cm/s) and are episodically interrupted by down-slope, gravity-driven processes. However, bottom currents can reach higher velocities (> 0.6-1 m/s), especially when they interact with the continental slope, obstacles (seamounts, ridges, hills, mounds, banks, etc.), tectonic disruptions of the seafloor, or when flowing through deep oceanic gateways, straits or confined basins. Such features can lead to the generation of a vigorous turbulent flow, leading to erosion and deposition, even at a regional scale (McCave and Tucholke, 1986; Stow *et al.,* 2009; Hernández-Molina *et al.,* 2011). The general term 'bottom current' is used to denote those semi-permanent currents that are capable of eroding, transporting and depositing sediments at the seafloor (Rebesco and Camerlenghi, 2008; Rebesco *et al.,* 2014). They are the result of both thermohaline circulation (THC) and the major wind-driven circulation pattern of the oceans (Rahmstorf, 2006). These currents are generally persistent processes in nature with a net along-slope flow (following the local bathymetry). They can, however, be extremely variable in direction and velocity (Rebesco and Camerlenghi 2008), hence significantly affecting the seafloor resulting in the formation of pervasive erosional and depositional features. In addition, a number of associated processes are related to the circulation of deep water masses and bottom currents, for example: benthic storms, overflows, interfaces between water masses, vertical eddies, horizontal vortices, tides and internal tides, internal waves and solitons, tsunami-related traction currents and rogue or cyclonic waves (Rebesco *et al.,* 2014; Hernández-Molina *et al.* this issue).

The study of these processes and their products has represented one of the most active lines in marine geological research during the last two decades. The scarce knowledge of contourites has mainly been due to the effort of researchers being focused on recognising turbidites (especially for economic reasons and hydrocarbon exploration), as well as the difficulty of their recognition in both ancient and modern records. Nevertheless, in recent years, a clear and progressive increase in their study has occurred because of the availability of regional scientific data compiled by oceanographic institutions and also through international projects such as the oceanic drilling programmes DSDP (*Deep Sea Drilling Project*), ODP (*Ocean Drilling Program*) and IODP (*Integrated Ocean Drilling Program – International Ocean Discovery Program*). This improvement in contourite knowledge has developed not only because of their great stratigraphic, sedimentological, palaeoceanographic and palaeoclimatological interest, but also because of their close link with sediment instability on slopes and their direct relationship with possible mineral and energy resources (Pickering *et al.*, 1989; Stow *et al.*, 2002b; Rebesco, 2005; Viana and Rebesco, 2007; Rebesco and Camerlenghi, 2008; Hernández-Molina *et al.,* 2010). Recently Rebesco *et al.* (2014) carried out a review regarding the state-of-art understanding and future considerations of deep-water circulation products, which demonstrates the importance of bottom currents in continental margin sedimentation and evolution, and serves as a model for the present study along the Iberian margins.

There is a lack of knowledge about the different oceanographic processes that may drive bottom currents, and there is also the need to document the great variety of contourite processes, features, products and facies models, as well as their evolution over time and space. The main objective of this Special Issue contribution is a regional description of the along-slope processes and their sedimentary impacts or products around the Iberian margin. This review presents the numerous examples of bottom current processes recorded in the sedimentary record of the Iberian margins, confirming their scientific importance. However, the conceptual models associated with these features still need to be proposed. Therefore advances, both in new technologies and integrated studies (Geology, Physical Oceanography and Benthic Biology), are anticipated in this field along the Iberian margin in the future.

Bottom-current depositional and erosional features: contourite depositional systems

The products of bottom-current circulation consist of both erosional and depositional features of variable dimensions (Faugères *et al.,* 1999; Stow *et al.,* 2002; Viana and Rebesco, 2007; Hernández-Molina *et al.,* 2008a, b; Rebesco and Camerlenghi, 2008). As water masses are formed in a variety of geological and oceanographic contexts, they can generate different types and widely varying contourite features (Stow *et al.,* 1986, 2002, 2009, 2013; Ercilla *et al.,* 2009, 2011, 2012; Gao *et al.,* 1998; Faugères *et al.,* 1999; Viana, 2001; Llave *et al.,* 2001, 2011; Maldonado *et al.,* 2003, 2005; Rebesco, 2005; Mulder *et al.,* 2006; Rebesco and Camerlenghi 2008; Hernandez-Molina *et al.,* 2008 a, b, 2009, 2011; among others). The term "contourites" refers to sediments deposited or substantially reworked by the persistent action of bottom currents (e.g. Stow *et al.,* 2002; Rebesco, 2005). This term thus includes a large array of sediments affected to varying degrees by different types of currents (Rebesco *et al.,* 2014). The best-recognised diagnostic contourite features are the depositional features. Thick, extensive sedimentary accumulations are named "contourite drifts" or "drifts". We have adopted the contourite drift classification criteria from Faugères *et al.* (1999) and Rebesco (2005). In practical terms, different drift deposits exhibit a certain degree of overlap. Their gradation suggests that these deposits represent a continuous spectrum of phenomena, rather than discrete categories (Rebesco *et al.,* 2014). The erosional contourite features, mainly consisting of large erosional or abraded terraces, channels, moats, marginal valleys and furrows, are not particularly well analysed or typified (Nelson *et al.,* 1993, 1999; Evans *et al.*, 1998; Stow and Mayall, 2000; Masson, 2001; Llave *et al.,* 2007; Hernandez-Molina *et al.,* 2006, 2008a; Garcia *et al.,* 2009), and they lack a clear genetic relationship with the generating oceanographic processes (Rebesco and Camerlenghi, 2008; Hernández-Molina *et al.,* 2011). Recently Stow *et al.* (2009) proposed a *bedform-velocity matrix*, which is useful for estimating the deep-sea water mass velocities in the formation of the different deposits and/or textural types, or erosional features. This matrix can even be applied to deduce the likely contourite features under a particular water-mass velocity regime. The erosional contourite features are not so well studied nor have they been classified in much detail. Both depositional and erosional features are related to the water-mass velocity from small- (bedform) to large-scale (e.g. Stow *et al.,* 2009). Such features may be found in isolation. More frequently however, a contourite depositional system (CDS) is formed, which is an association of various drifts and related erosional features across an along-slope dominated margin (Hernández-Molina *et al.,* 2003, 2008a, 2009). Similarly, CDSs in different geographic/geologic contexts but formed by the same water mass can be considered as a "contourite depositional complex" (CDC) (Hernández-Molina *et al.,* 2008a). However, it has to be clarified that contourites also occur interbedded with other deep-water facies types, and do not necessarily form individual sedimentary bodies.

The Iberian continental margins are characterised by very complex and varied origins, as well as geodynamic and sedimentary evolution. For several decades, many studies have been conducted on the structure and evolution of these margins (e.g.: Boillot *et al.,* 1972, 1975, 1979, 1987; Derégnaucourt and Boillot, 1982; Comas and Maldonado, 1988; Nelson and Maldonado, 1990; Maldonado and Nelson, 1988, 1999; Maldonado and Comas, 1992; Estrada *et al.,* 1997; Pérez-Belzuz *et al.,* 1997; Pérez-Belzuz, 1999; Maldonado *et al.,* 1999; Vazquez, 2001; Ercilla *et al.,* 2008; Iglesias, 2009, among many others). The circulation of water masses around Iberia is clearly one of the major controlling factors in along-slope sedimentation and shapes the deep seafloor here as they do along many other continental margins (Stow *et al.,* 2009) (Fig. 1). Although there are many scattered bottom-current measurements along the Iberian margin, there is still a major lack of long-term records as well as areas with very few or no measurements at all. The mean recorded velocities are commonly low (5-15 cm/s), but some water masses impinge upon the seafloor with a relatively high velocity, reaching values > 80 cm/s and rarely almost 300 cm/s (for example at the exit of the Strait of Gibraltar) (Mélières *et al.,* 1970; Madelain, 1970; Ambar and Howe, 1979; Iorga and Lozier, 1999; Candela, 2001).

Examples of contourite features along the iberian margin

Around the Iberian margin, several water masses interact along the upper and middle continental slopes and, although lesser in intensity, also on the

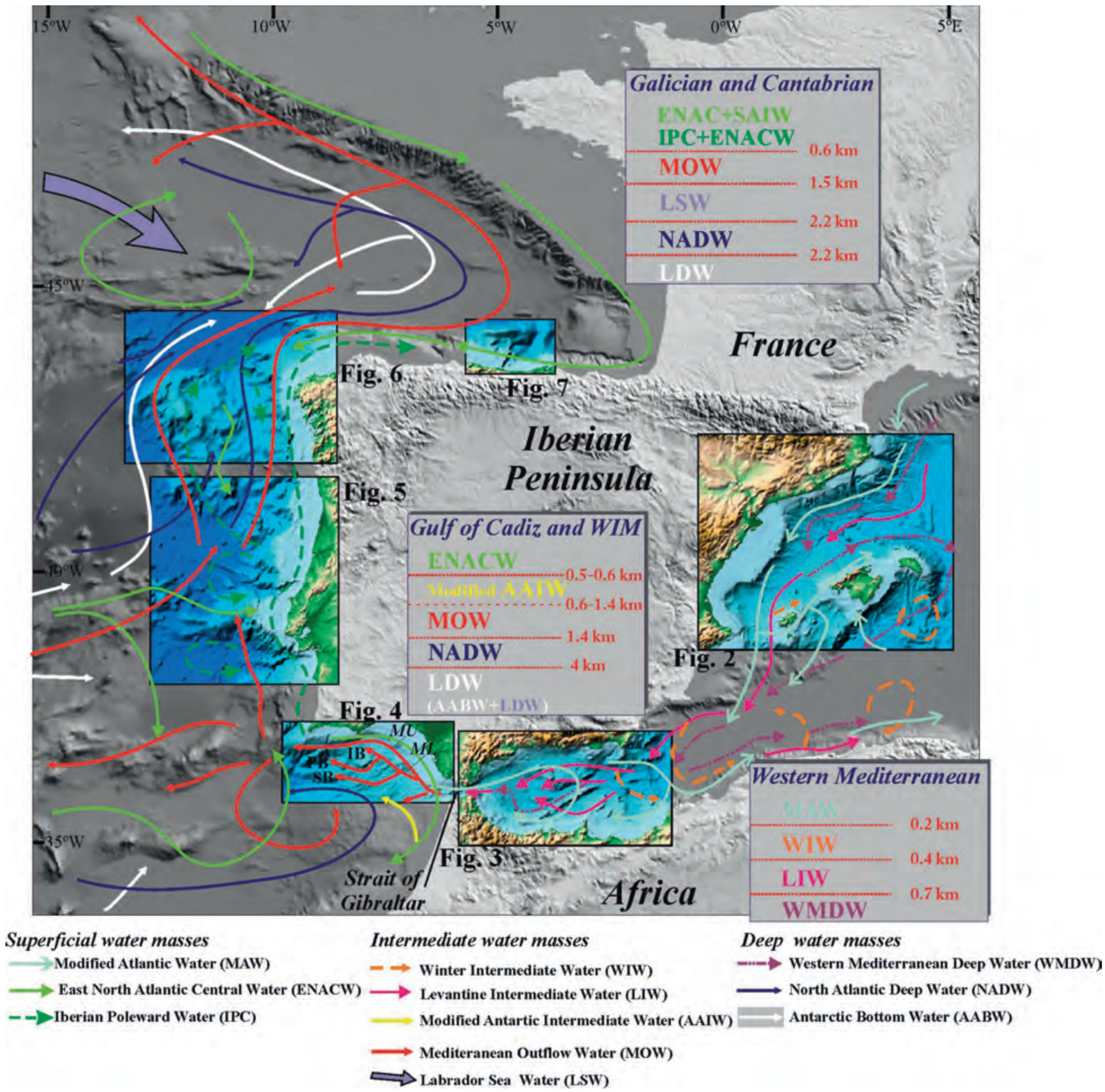

Figure 1. Surficial, intermediate and deep-water circulation around the Iberian Continental Margin. (Modified from Hernández-Molina *et al.*, 2011) and location of the studied areas.
***Figura 1**. Circulación superficial, intermedia y profunda alrededor del Margen Continental de Iberia (Modificado de Hernández-Molina et al., 2001) y localización de las áreas de estudio.*

lower slopes and abyssal plains (Fig. 1). In all of these domains, extensive, complex and often poorly understood contourite features of large dimensions and diverse sediment thickness are developed (Maestro *et al.,* 2013). They occur in a number of different geologic contexts: SW Ceuta CDS within the Alboran Sea (Ercilla *et al.,* 2002), the Gulf of Cadiz (the most studied so far, Kenyon and Belderson, 1973; Gonthier *et al.,* 1984; Nelson *et al.,* 1999; Llave *et al.,* 2001, 2007, 2011; Stow *et al.,* 2002; Mulder *et al.,* 2003, 2006; Habgood *et al.,* 2003; Hernandez-Molina *et al.,* 2003, 2009a; Hanzquiez *et al.,* 2007; Marches *et al.,* 2007; Roque *et al.,* 2012; Brackenridge *et al.,* 2013, among others), the western margin of Portugal (Alves *et al.,* 2003; Pereira and Alves, 2011), the Galician margin (Ercilla *et al.,* 2006, 2008, 2009, 2010, 2011), the Ortegal Spur (Hernández-Molina *et al.,* 2009b; Jané *et al.,* 2012; Llave *et al.,* 2013), and the Le Danois Bank or

"Cachucho" (Ercilla *et al.,* 2008b; Iglesias, 2009; Van Rooij *et al.,* 2010). All these authors have reported the common existence of large muddy drifts as well as erosional contourite features generated by the water masses along the Iberian margin. The most notable erosional elements are the abraded surfaces, channels, furrows and moats, and the recently classified as mixed (erosional and depositional) elements represented by the terraces (Rebesco *et al.,* 2014). The majority of the erosional features have formed under the influence of the Mediterranean Outflow Water (MOW) (Fig. 1) (Nelson *et al.,* 1993, 1999; Llave *et al.,* 2007; Hernandez-Molina *et al.,* 2006, 2008a; Garcia *et al.,* 2009). Moreover, extensive and sometimes very well graded sand layers (or muddy sands) are associated with these erosional features. Their genesis and facies models are still not fully established, despite enormous potential for locating hydrocarbon and mineral resources (Stow and Faugères, 2008; Viana, 2008; Stow *et al.,* 2011; Shanmugan, 2012, 2013a, b). A summary of the main water masses sweeping the Iberian margin are presented as well as those contourite features formed by their action on the seafloor.

The Mediterranean Sea

A. Oceanographic setting. Traditionally, three main water masses are identified in the Alboran Sea (Fig. 1): 1) *Atlantic Water* (AW) or Modified Atlantic Water (MAW*),* which flows eastward at a depth of 100/200 m; 2) *Levantine Intermediate Water* (LIW), which flows westward at depths of between 200-600 m; and 3) *Western Mediterranean Deep Water* (WMDW), which also flows westwards at a water depth of 600 m but also reaches depths of 2,000 m (Parrilla and Kinder, 1987; Millot, 1999). The relatively fresher Atlantic water enters the Mediterranean Sea through the Strait of Gibraltar with a velocity of approximately 1 m/s, where its characteristics change due to climate forcing and mixture with surface waters in the Alboran Sea to form the Modified Atlantic Waters (MAW) (Gascard and Richez, 1985). This Atlantic Jet is usually described as two anticyclonic gyres, one quasi-permanent in the western and another semi-permanent in the eastern Alboran basin. The energy of the Western Atlantic Gyre (WAG) may exert influence down to approximately 500-700 m water depth. Unusually, this gyre disappears in a phenomenon called "WAG Collapse" (Cheney and Doblar, 1982; Heburn and La Violette, 1990; Perkins *et al.,* 1990; Viúdez *et al.,* 1998), caused by the eastward migration of the WAG. This allows the formation of a new western gyre (Viúdez *et al.,* 1998; Vélez-Belchí *et al.,* 2005), or causes true rupture of the WAG in very cold winters, when the AW forms a coastal jet flowing along the African shore (Bormans and Garrett, 1989; Vargas-Yáñez *et al.,* 2002; Periáñez, 2006, 2007; García-Lafuente *et al.,* 2008).

The LIW is characterised by its high salinity and temperature, and forms in the eastern Mediterranean. LIW enters the western Mediterranean through the Sicilian Channel and flows along the Spanish margin and the central part of the Alboran Sea (Fig. 1). The WMDW is characterised by its relatively high density (due to its relatively low temperature). It forms in the Gulf of Lyon during the winters, where it sinks and spreads southwards. In the Alboran Sea, it circulates toward the Strait of Gibraltar with the main core sweeping the Moroccan continental margin and infilling the deep basins (Fig. 1).

A recent study by Millot (2009, 2014) in the Strait of Gibraltar and vicinity in the Alboran Sea proposed a more complex oceanographic structure and considered five Mediterranean water masses that are grouped as light and dense water masses. As such, this author considers two additional water masses: the Winter Intermediate Water (WIW), which is also formed in the Gulf of Lyon and is characterised by a temperature minimum 12.9-13.0 °C at 100-300 m, and the Tyrrhenian Deep Water (TDW), formed by the mixture of eastern deep waters and the different water masses present in the western end of the Sicilian Channel. Based on the findings of Millot (2009, 2014), the present-day circulation consists of an along-slope displacement of the light or intermediate Mediterranean Waters, formed by WIW, LIW plus TDW, circulating along the Spanish slope down to 600 m, and a quite motionless displacement of the dense or deep Mediterranean Waters formed by WMDW plus TDW, flowing along the Moroccan margin and deep basins (Ercilla *et al.,* 2012; Juan *et al.,* 2012). Along this margin, the WMDW mixes with the AW locally forming the Shelf Waters (SW) on the upper slope (Gascard and Richez, 1985) (Fig. 1). The differentiation of the TDW is not an easy task in the Alboran Sea (Ercilla *et al.,* 2012) because it forms a poorly defined core with similar characteristics to that of the overlying LIW and the underlying WMDW. Thus, for convenience, these authors considered it to be within the LIW and the WMDW.

B. Contourite features. To date, the best studied contourites are those developed in the western Mediterranean Sea, located in the Alboran Sea. However, there is also evidence of contourite deposition in other parts of the western Mediterranean margins:

1) Along the NE Catalonian slope (Fig. 2. A), between the Cap de Creus and slightly south of the La Fonera Canyons, prograding upslope drifts have been mapped between 1 200 and 2 300 m water depth (Canals, 1985).
2) In the north of Menorca, on the lower slope at depths down to 2 000 m (Fig. 2. B and C), a broad, low-relief but elongated and separated drift of approximately 150 km in length, 100 m in relief and 25 km wide has been mapped. This drift is defined by prograding stratified facies, locally affected by sediment waves and laterally associated with a contourite moat (200 m relief, 5 km wide) along its seaward margin (Mauffret, 1979; Velasco *et al.*, 1996; Ercilla *et al.,* 2000) (Fig. 2. B and C). The drift is composed of mud and is generated by the southward branch of the WMDW flow, which borders the Valencia Trough from north to south following a cyclonic pattern at depths of 2 000 m (Velasco *et al.,* 1996; Frigola *et al.,* 2007, 2008).
3) To the west of Cabrera Island (southwest Mallorca), at a water depth range of 250-600 m, pronounced elongated mounded shallow water contourites have been characterised within a slope canyon. These deposits are convex-upward oriented, with parallel well-stratified reflections of moderate to

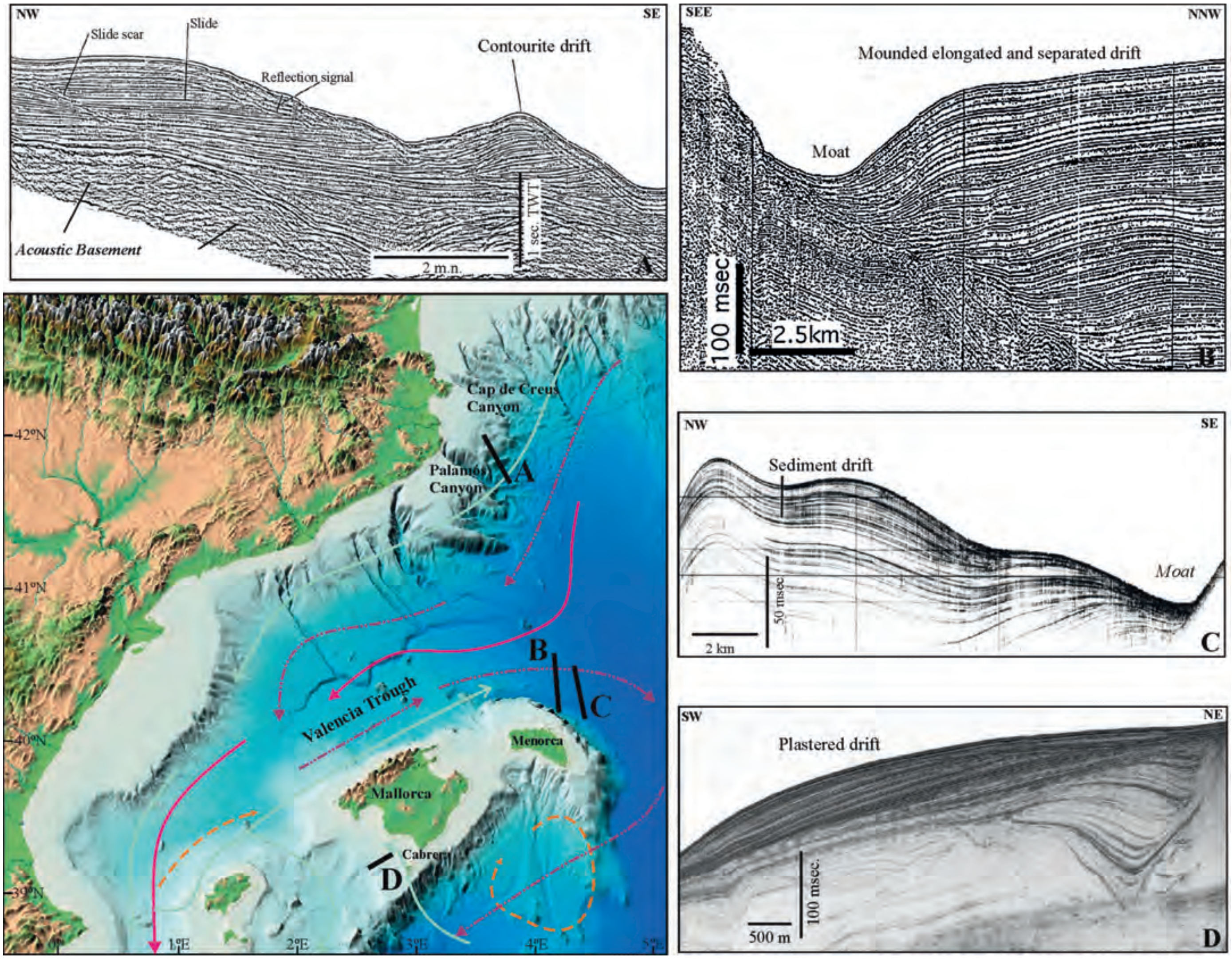

Figure 2. The main examples of contourite features along the Catalonian-Balearic margin (seismic profiles modified from Canals, 1985; Velasco *et al.,* 1996; Vandorpe *et al.,* 2011.

Figura 2. *Ejemplos de los rasgos contorníticos más relevantes estudiados a lo largo del margen Catalono-Balear (perfiles sísmicos modificados de Canals, 1985; Velasco et al., 1996; Vandorpe et al., 2011).*

low amplitude and form overall lens-shaped bodies elongated along the canyon axis. These mounds are flanked by channel-like structures that join upslope near the entrance of the canyon at 250 m. A surficial field of sediment waves has also been produced (Fig. 2. D) (Vandorpe *et al.,* 2011; Lüdmann *et al.,* 2012).

4) Contourites in the Alboran Sea shape large areas of the distal continental margin, and adjacent basins. They comprise a great variety of features, both depositional and erosional, with variable sizes ranging from a few km to several tens of km in length. The depositional features are dominant and are made up of several types of drifts, of both large and small scale. The largest drifts are of the plastered and sheeted type (Fig. 3. A, B, C, D and E). The *plastered drifts* occur along the continental slope of both the Spanish and Moroccan margins, between 235 and 575-1000 m water depth. These drift areas are acoustically defined by upslope onlapping stratified facies, pinching out upslope and downslope (Fig. 3. A, B, C and D). The *sheeted drifts* occur on the central Spanish base of the slope and on the western and southern Alboran sub-basins, from approximately 500 m water depth. They are acoustically characterised by parallel and stratified facies with a sub-tabular geometry that forms a smooth seafloor (Fig. 3. E). Both

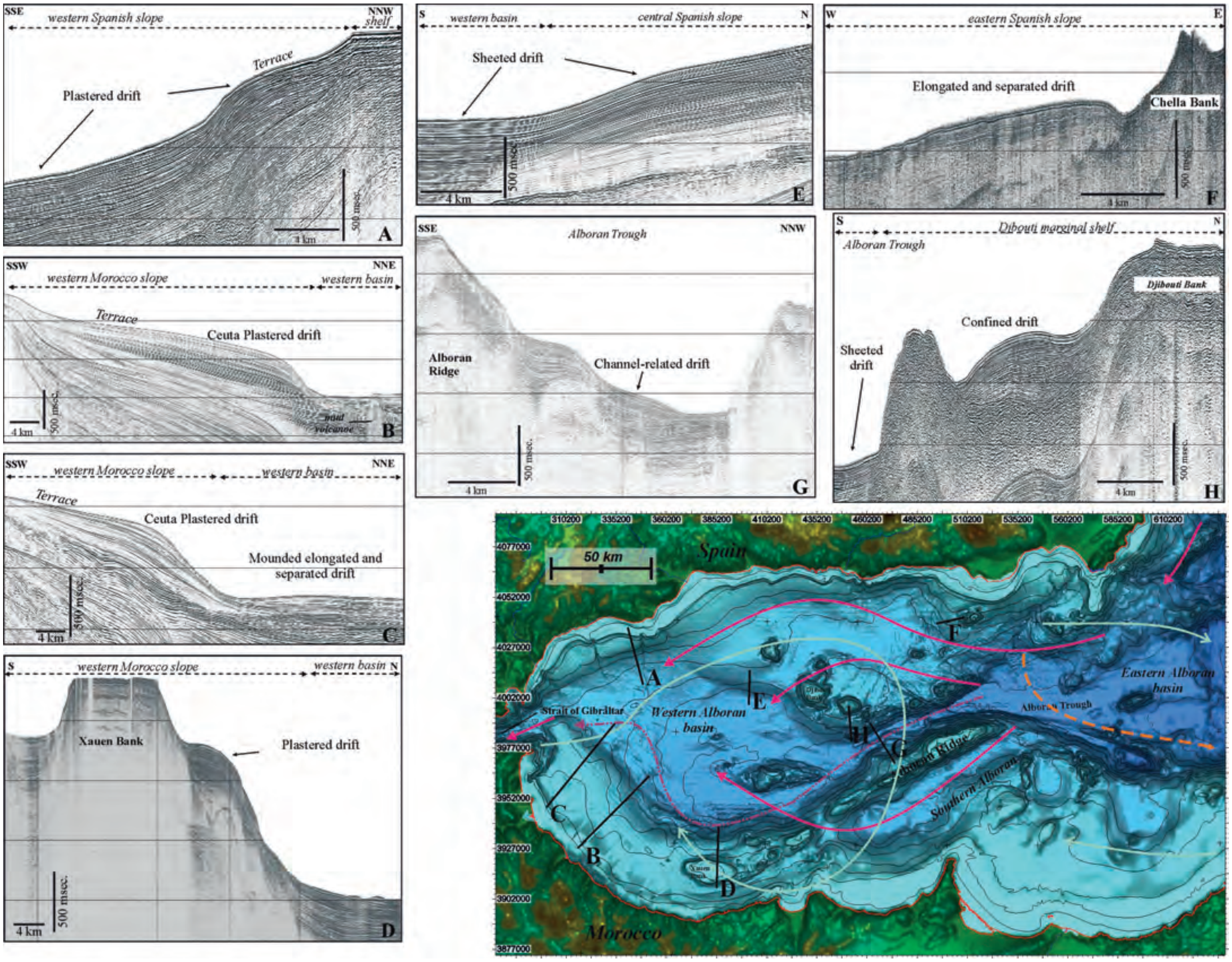

Figure 3. The main examples of contourite features along Alboran Sea continental margin (Seismic profiles modified from Juan *et al.,* 2012, 2013).

Figura 3. *Ejemplos de los rasgos contorníticos más relevantes estudiados a lo largo del margen del Mar de Alborán (perfiles sísmicos modificados de Juan et al., 2012, 2013).*

types of large-scale drift found along the margins and within the basins of the Alboran Sea are formed by the light Mediterranean Waters (WIW+LIW) and dense Mediterranean Waters (WMDW) respectively, which are moving westward. Their action greatly influences sediment distribution and accumulation in the Alboran Sea, with the LIW mainly affecting the slope continental margins and the WMDW affecting the base-of-slope and the sub-basins (Ercilla *et al.,* 2012; Juan *et al.,* 2012).

As far as the small-scale drifts are concerned, in addition to plastered and sheeted drifts, there are also mounded elongated and separated (hereafter referred to as *separated* for simplification) (Fig. 3. C and F), *channel-related* (Fig. 3. G) and mounded *confined* drifts (Fig. 3.H) (Palomino *et al.,* 2010, 2011; Ercilla *et al.,* 2012; Juan *et al.,* 2012). The *plastered* and *sheeted* drifts occur locally on the flanks and tops of seamounts (Fig.3. D and H). The *separated* drifts are locally identified on the westernmost Moroccan upper and lower slope, and at the foot of structural seamounts and diapirs (Fig. 3. F). Acoustically, they are characterised by onlapping stratified facies with internal discontinuities that form a low to high mound geometry. The *channel-related* drifts occur on the floor of the Alboran Trough and the corridor between the Xauen bank and the Moroccan slope and are formed by isolated irregular bodies of stratified facies scattered on the channel floor (Fig. 3. G). The *confined* drifts, locally occurring between structural highs, have a striking mounded morphology internally formed by stratified facies (Fig. 3. H).

The erosional contourite features in the Alboran margin are made up of *moats, terraces, steep surfaces and furrows*. The *terraces* shape the top of the plastered drift on the continental slopes, and are more enhanced in the Moroccan margin (Fig. 3. A, B and C). The terraces are erosional surfaces that correlate seaward to a toplap and concordant surface. The *moats* mostly occur associated to the elongated separated and confined drifts, although some plastered drifts on the walls of the structural highs also display incipient moats where the slope displays topographic changes (Fig. 3. C and F). The *scarps* are narrow, steep erosional surfaces roughly parallel to the margins associated with the landward flanks of the terraces and locally along the base-of-slope. These scarps play a major role in shaping the transition between the physiographic provinces. *Furrows* represent linear features eroding the distal erosional steep scarp in the Moroccan margin, close to the Gibraltar Strait.

The Gulf of Cadiz and west offshore Portugal

A. Oceanographic setting. The present-day hydrodynamic setting of the Gulf of Cadiz is dominated by the water exchange between the Atlantic Ocean and the Mediterranean Sea through the Strait of Gibraltar. This gateway allows the exchange between the warm saline Mediterranean Outflow Water (MOW) towards the Atlantic Ocean, and the overlying Inflow of the Atlantic Water (AIW) towards the Mediterranean Sea (Lacombe and Lizeray, 1959; Ochoa and Bray, 1991; Baringer and Price, 1999; Nelson *et al.,* 1999) (Fig. 1). The MOW represents an intermediate water mass composed of a mixture of waters sourced from the Mediterranean Basin [the Levantine Intermediate Water (LIW) and a small component of the West Mediterranean Deep Water (WMDW)], where the constricted basin with arid climate provides conditions for the formation of warm, saline dense water of 13°C and 36.5 (Ambar and Howe, 1979; Bryden and Stommel, 1984; Bryden *et al.,* 1994). The water mass accelerates through the narrow gateway of the Strait of Gibraltar, locally reaching velocities of up to 300 cm/s (Ambar and Howe, 1979; Mulder *et al.,* 2003) and moves north-westwards along the mid-continental slope of the Gulf of Cadiz under the AIW and above the North Atlantic Deep Water (NADW). The AIW comprises the North Atlantic Superficial Water (NASW), from the surface to a depth approximately 100 m, and the Eastern North Atlantic Central Water (ENACW), which flows between depths of 100 and 700 m, with 12-16° C and 34.7-36.25. In the Gulf of Cadiz, the Modified Antarctic Intermediate Water (AAIW), characterised by a temperature of ~10° C, a salinity of ~35.62 and a dissolved oxygen of ~4.16 ml/l (Louarn and Morin, 2011), has been identified as circulating above the MOW (Hernández-Molina *et al.,* 2014). The underlying NADW is a cold (3°-8° C) and less saline (34.95-35.2) water mass that flows at depths > 1500 m from the Greenland-Norwegian Sea region towards the south (Lacombe and Lizeray, 1959; Thorpe, 1975; Zenk, 1975; Gardner and Kidd, 1983; Ochoa and Bray, 1991; Baringer and Price, 1999; Ambar *et al.,* 1999; Serra *et al.,* 2005). The MOW is restricted to a core approximately 10 km wide as it accelerates through the Strait of Gibraltar and enters the Gulf of Cadiz at depths of 250-300 m with a western trend due to the Coriolis Forces (Ambar and Howe, 1979; Mulder *et al.,* 2003). It deepens westward to approximately 80-100 cm/s at the Cape San Vicente latitude (Cherubin *et al.,* 2000). The MOW current velocity decreases from > 240 cm/s, immediately west of the Camarinal Sill within the Strait of Gibraltar, down to 60-100 cm/s further NW. From there onwards, its volume transport increases by a factor of three to four (Serra *et al.,* 2010; Rogerson *et al.,* 2012). Density-driven descent and mixing with overlying Atlantic waters result in decreasing salinity along the margin from SE to NW (Baringer and Price, 1997). Eventually, the MOW leaves the seabed and reaches a neutral buoyancy at a depth of ~1400 m offshore of Cape San Vicente, where it begins to raft above the NADW. After exiting the Gulf of Cadiz, the MOW displays three principal branches. The main one flows to the north, the second to the west, and the third to the south reaching the Canary Islands, before veering towards the west (Iorga and Lozier, 1999; Slater, 2003). The northern branch flows along the middle slope of the Portuguese Margin, towards the Galicia Margin and the Bay of Biscay (Fig. 1). In the Gulf of Cadiz, the MOW distribution is conditioned by the complex morphology of the continental slope and locally enhanced where neotectonics have created diapiric ridges oblique to the direction of the MOW flow (Fig. 1). These ridges are in part responsible for the splitting of the MOW into numerous distinctive cores (Fig. 1), although vertical layering within the water core has also been proposed as a possible alternative control (Sannino *et al.,* 2007; Millot, 2009; Copard *et al.,* 2011). The main water cores are the Upper Core or Mediterranean Upper Core (MU) and the Lower Core or Mediterranean Lower Core (ML), with each branch demonstrating unique physical oceanographic properties, such as salinity, temperature and average velocity (Madelain, 1970; Zenk, 1975; Ambar and Howe, 1979; Gründlingh, 1981; Börenas *et al.,* 2002; Serra *et al.,* 2005) (Figure 1). The MU flows slope-parallel along southwestern Iberia at depths of 500-800 m with part of its flow captured by the Portimão Canyon at the Algarve margin (Marchès *et al.,* 2007). Overall, the MU is a warmer and less saline water mass (13–14 °C and 35.7–37) compared with the more vigorous highly saline ML (10.5–11.5 °C and 36.5–37.5), which follows a general northwestern trend with a 20-30 cm/s velocity average (Llave *at al.,* 2007) with the major part of the flow concentrated west of 7° W (Madelain, 1970). At 7° W, a filament is detached from the southern part of the ML with a SW direction. At 7° 20′ W, the ML is divided into three distinct branches with a general NW direction: the Southern Branch (SB), the Principal Branch (PB) and the Intermediate Branch (IB). They join at approximately 8° 20′ W and leave the Gulf of Cadiz in the three above mentioned branches (Fig 1). Both the Portimão Canyon and Cape St. Vincent, also act as a source of meddies (Ambar *et al.,* 2002, 2008; Serra *et al.,* 2005; Ambar *et al.,* 2008).

The main water masses flowing northwards along the West Iberia margin at distinct depths are as follows: 1) the Ocean Surface Layer (OSL), which corresponds to a mixture of the ocean mixed layer and thermocline water above 120-200 m (Fiúza *et al.,* 1998); 2) Eastern North Atlantic Central Water (ENACW), which comprises two distinct layers: the upper is the northwards flowing Portugal Coastal Counter current of sub-tropical origin and the lower, of sub-polar origin, prevails up to 30°-35°N (Fiúza *et al.,* 1998); 3) MOW, with two distinct cores centred at 800 m and near 1 200 m in water depth. On the Oporto continental slope, the MOW mixes with the ENACW flowing at a 250 and 540 m water depth; and 4) the deep water masses (below a 2000 m water depth) comprising of the southward-flowing NADW and the northward-flowing Lower Deep Water (LDW) (van Aken, 2000) (Fig. 1).

B. Contourite features. Erosive processes are mainly described within the Strait of Gibraltar, as the bottom-current velocity is high enough to prevent deposition (Kelling and Stanley, 1972; Stanley *et al.,* 1975; Serrano *et al.,* 2005). Despite the amount of surveys that have been conducted, few distinctive contourite features have been identified in this area, apart from several *large depressions* and *large channels* that might be associated with MOW circulation (Esteras *et al.,* 2000), as well as some isolated *contourite drifts* located on the northern continental slope (Fig. 4. A).

After its exit from the Gibraltar Strait, the interaction of the MOW with the middle slope of the Gulf of Cadiz has developed one of the most extensive and complex CDSs ever described around the western Iberian margin (Fig. 4). Many authors have highlighted this interaction and have characterised its erosional and depositional features (e.g.: Madelain, 1970; Kenyon and Belderson, 1973; Gonthier *et al.,* 1984; Nelson *et al.,* 1993, 1999; Llave *et al.,* 2001, 2006, 2007, 2011; Stow *et al.,* 2002; Alves *et al.,* 2003; Habgood *et al.,* 2003; Hernández-Molina *et al.,* 2003, 2006; Mulder *et al*., 2003, 2006; Hanquiez *et al*., 2007; Marchès *et al*., 2007; Roque *et al.,* 2012; Brackenridge *et al.,* 2013). The main depositional features are *sediment wave fields, sediment lobes, mixed drifts, plastered drifts, elongated mounded and separated drifts and sheeted drifts*. The major erosional features are *contourite channels, furrows, marginal valleys* and *moats.* All of them have a specific location along the margin, and their distribution defines five morphosedimentary sectors within the CDS: 1) proximal scours and ribbons; 2) overflow sediment lobes; 3) channels and ridges; 4) a contourite depositional sector; and 5) a submarine canyons sector (Hernández-Molina *et al.,* 2006; Llave *et al.,* 2007; García *et al.,*

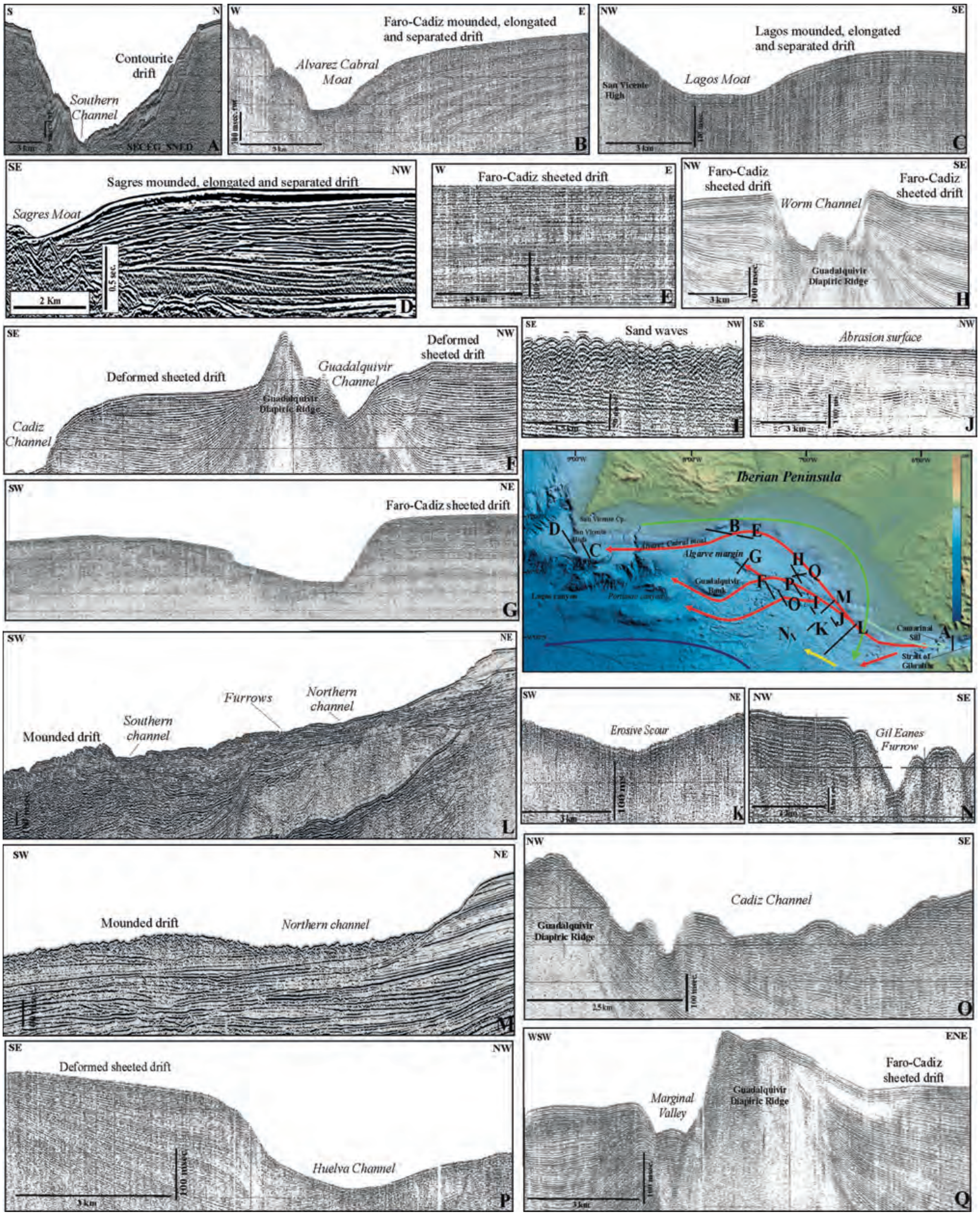

Figure 4. The main examples of contourite features along the Gulf of Cadiz continental margin (seismic profiles modified from Llave et al., 2001; Hernández-Molina *et al.,* 2006, 2014; García *et al.,* 2009; Roque *et al.,* 2012)

***Figura 4.** Ejemplos de los rasgos contorníticos más relevantes estudiados a lo largo del margen continental del Golfo de Cádiz (perfiles sísmicos modificados de Llave et al., 2001; Hernández-Molina et al., 2006, 2014; García et al., 2009; Roque et al., 2012).*

2009). The development of each of these five sectors at any time is related to a systematic deceleration with possible local acceleration of the MOW from its interaction with the irregularities of the seafloor. In general, the drifts are mainly composed of muddy, silty and sandy sediments, with a mixed terrigenous (the dominant component) and biogenic composition (Gonthier *et al.,* 1984; Stow *et al.,* 1986, 2002c). In contrast, within the large contourite channels, sand and gravel are found, as well as many erosional features (Nelson *et al.,* 1993, 1999; Hernández-Molina *et al.,* 2006; Garcia *et al.,* 2009; Stow *et al.,* 2013a). Within the proximal sector close to the Strait of Gibraltar, an exceptionally thick sandy-sheeted drift (~815 m thick) is located, with sand layers that average 12–15 m in thickness (minimum 1.5 m, maximum 40 m) (Buitrago *et al.,* 2001; Llave *et al.,* 2007).

The *mounded elongated and separated* and *sheeted drifts* are dominant between water depths of 500 and 600 m (Fig. 4. B, C, D and E). Four *separated drifts* have been built by the action of the MU at water depths of 500 to 700 along the Algarve margin: the Faro-Albufeira, Lagos, Portimão and Sagres drifts (Fig. 4. B, C and D). The *Faro-Cádiz* and *Albufeira* drifts are the most extensive (approximately 90 km long and 12-20 km wide) and the best developed. They are bound to the upper slope by the Álvarez Cabral moat and display an asymmetric shape with a steeper slope to the north, and a sigmoidal-oblique prograding stacking pattern (Fig. 4. B). These drifts rise 150-200 m above the adjacent moat axis and surrounding deposits, and evolve southwards into the *Faro* and the *Bartolomeu Dias sheeted drifts* where the seafloor has a smooth, almost flat morphology (Fig. 4. E). The *Portimão* and *Lagos drifts* extend from the Portimão Canyon over approximately 50 km and are separated by the Lagos Canyon. They display a smooth mounded morphology and were classified as sheeted drifts (Hernández-Molina *et al.,* 2003; Marchés *et al.,* 2007, 2010). However, Roque *et al.* (2012) showed that the shape of the *Lagos drift* evolves from a *sheeted drift* near the Lagos canyon to a *plastered drift* towards the San Vicente high and finally to a *separated drift* from this high (Fig. 4..C) and the *Sagres drift*, which lies on the transition of the south and west Portuguese margins (Fig. 4. D). *Sheeted drifts*, with an aggrading stacking pattern and gentle morphology, have developed between 600 and 1600 m water depth in the contourite depositional and submarine canyons sectors (Vanney and Mougenot, 1981). They have been deposited over hundreds of kilometres, and are deformed and crossed by diapiric ridges and eroded by large contouritic channels along the channels and ridges sector (Fig. 4. G and H) (García, 2002; Mulder *et al.,* 2002, 2003; Habgood *et al.,* 2003; Hernández-Molina *et al.,* 2003, 2006; Llave, 2003; Llave *et al.,* 2007). Extensive areas of longitudinal *bedforms* (also oriented NW-SE), ripple marks, sand ribbons and sediment waves are especially developed along Sector 1 (Fig. 4. I), proximal scours and ribbons, and Sector 2, overflow sediment lobes (Hernández-Molina *et al.,* 2006; Llave *et al.,* 2007).

Regarding the contourite mixed features, the middle slope of the Gulf of Cadiz is a quite complex area, comprising four relatively flat *terraces* at average depths of 500, 675, 750 and 850 m. Here, the occurrence of diapiric ridges, the Guadalquivir Bank, and numerous isolated diapiric highs has created a composite pattern of erosional features composed of four types of submarine valleys: *moats*, *channels*, *marginal valleys* and *furrows* (García, 2002; Hernández-Molina *et al.,* 2003, 2006; García *et al.,* 2009). The proximal scours and ribbons sector is where the majority of the erosional features are found, between a 500 and 1000 m water depth. Here, an *abrasive surface* (Fig. 4. J), and several NW-SE aligned erosional *scours* (Fig. 4. K) have developed in an extensive area (90 km long and 30 km wide) (Kenyon and Belderson, 1973; Habgood, 2002; Hernández-Molina *et al.,* 2003, 2006). In this sector two main *channels* and *terraces* (Fig. 4. L) have recently been reported along this surface (Hernández-Molina *et al.,* 2012, 2014). The southern channel is large (3-4 km wide) with west-southwest-trending erosion from the Camarinal Sill. It is considered the most significant erosional feature close to the Strait of Gibraltar. The northern channel is infilled close to the Strait and becomes more distinctive towards the northwest, where it joins the Cadiz and Guadalquivir contourite channels (Hernández-Molina *et al.,* 2014). Both channels have an associated mounded drift in the seaward side of the channel and numerous small oblique furrows (Fig. 4. L and M) (Hernández-Molina *et al.,* 2014). In the overflow sedimentary lobe sector, recent studies have interpreted *furrows* as erosional features related to the action of the MOW and are affected by gravity processes (Habgood *et al.,* 2003; Mulder *et al.,* 2003; Hanquiez *et al.,* 2007; García *et al.* 2009). Here, the *Gil Eanes* furrow (Fig. 4. N) is the best developed one, at a water depth of between 900 and 1,200 m. It was first described by Kenyon and Belderson (1973) and recently studied by Habgood *et al.* (2003), Hanquiez *et al.* (2007) and García *et al.* (2009). This furrow is approximately 50 km long, has a width of 0.8-1.7 km with a sinuous trend, and a 90 m vertical incision depth (Fig. 4. N). Up to nine *contourite channels* stand out as the main erosional features in the central area of the Gulf of Cadiz middle slope (Fig. 4. F, G, H, O and P). They have developed at the southern flank of the diapiric ridges and the Guadalquivir Bank. From north to south, the main five-contourite channels are denominated as the *Diego Cao, Huelva*, *Gusano*, *Guadalquivir* and *Cadiz Contourite channels* (Fig. 4. F, G, H, O and P) (García *et al.,* 2009). They have different dimensions, although all of them have a sinuous trend (downslope-trending to along slope-trending zones) (Fig. 3. A). The *Cadiz and Guadalquivir channels* (Fig. 4. F and O) are the largest, being between 1 to 12 km wide, over 100 km long, and incise up to 130 m with the greatest depth generally being reached on the northern flanks (Fig. 4. F and O). *Marginal valleys* are special erosional features identified along the NW sides of the diapiric ridges and isolated diapirs in the channels and ridges sector (Fig. 4. Q). They have a predominantly NE-SW trend, although their pathways are very irregular and locally sinuous. The *marginal valleys* associated with diapiric ridges are up to 28.4 km long, and 5 km wide, whereas those around small or isolated diapirs are shorter and narrower (García *et al.,* 2009). Incision depths reach values of more than 250 m. The *Alvarez Cabral contourite moat* is the main erosional feature defined as a contourite moat in the Gulf of Cadiz (Fig. 4.B), and is associated with the Faro-Cadiz and Albufeira mounded drift (Gonthier *et al.,* 1984; Llave *et al.,* 2001; García, 2002; Stow *et al.,* 2002; Hernández-Molina *et al.,* 2003, 2006; Marchès *et al.,* 2007). It is 80 km long, 3.5-11 km wide, and has been excavated at the base of the upper slope of the Algarve margin, with a WSW trend, parallel to the slope. Following the present-day configuration of these erosional features, García *et al.* (2009) proposed a new and more detailed scheme for the MOW circulation, which combines a) a main along-slope circulation, which is involved in the development of the contourite moat and contourite channels, and b) a secondary down-slope circulation, related to the creation of the marginal valleys and furrows.

SW Portugal is still poorly characterised in terms of contourite deposits, although it will be better described after the acquisition of 958 m of Quaternary sediments at Site U1391 during the IODP Expedition 339 (2012). This CDS is mainly represented by the Sines drift, first identified as a contourite drift by Mougenot (1989) based on its general mounded morphology and wavy acoustic character (Fig. 5. A and B). This drift is an elongated sedimentary body developed along the gentle (~0.5°) N-S trending continental slope of the Alentejo margin between a 500 and 700 m water depth. The Sines drift is dissected by two of the major canyons of the Portuguese margin, the Setúbal canyon to the north and the San Vicente canyon to the south (Fig. 5. A and B). Neves *et al.* (2009) reported evidence of contourite bodies between 2 300 and 3 000 m of water depth, developed at this margin by the MOW. The presence of broad sediment waves has also been revealed in high-resolution seismic reflection data (Alves *et al.,* 2000, 2003),

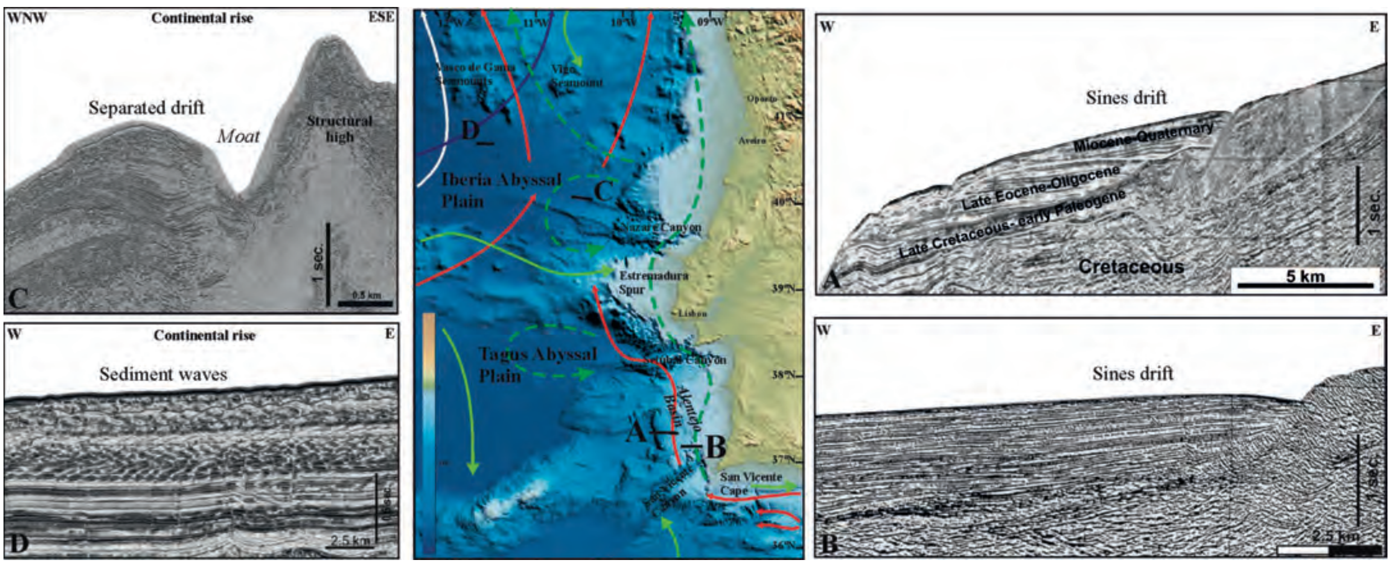

Figure 5. The main examples of contourite features along the Western Iberian continental margin (seismic profiles modified from Alves *et al.,* 2003, 2006; Pereira and Alves, 2011).

Figura 5*. Ejemplos de los rasgos contorníticos más relevantes estudiados a lo largo del margen continental occidental de de Iberia (perfiles sísmicos modificados de Alves et al., 2003, 2006; Pereira and Alves, 2011).*

as well as localised syn-sedimentary deformation, mainly faulting, within the contourite drift package.

Knowledge of CDSs in the eastern Iberia margin is scarce when compared with the well-studied Gulf of Cadiz CDS, and the recently described CDSs in the Galicia Bank region (Ercilla *et al.,* 2009, 2010). However, Hernández-Molina *et al.* (2011) identified potential areas for the development of contourite drifts along the western Iberia margin continental slope based on numeric simulation of bottom-current velocities at a regional scale. The predicted areas along the Portuguese margin where new CDSs could be found include the continental slope, the Extremadura Spur and off Oporto, and the continental rise, off Aveiro. Moreover, the occurrence of contourite features in these zones has been recognised (Alves *et al.,* 2003; Badagola, 2008; Roque, personal communication), locally around structural highs and topographic irregularities associated with the circulation either of the MOW (300-2,000 m water depth) or the Lower Deep Water (>2000 m water depth). In the Extremadura Spur at a water depth of 320 m, Badagola (2008) identified a mounded sedimentary body interpreted as a contourite drift. A new contourite drift has been recently recognised off Aveiro in the continental rise at an approximately 2500 m water depth (Fig. 5. C) (Roque, personal communication). It is approximately 1.5 s TWT thick and 2.5 km wide and consists of a contourite drift separated by a moat from a structural high (Fig. 5. C). The presence of sediment waves deposited by bottom-currents has also been identified in the upper rise within Miocene through Quaternary sediments drilled at ODP Site 1069 (Fig. 5. D) (Whitmarsh *et al.,* 1998).

Galician and Cantabrian margins

A. Oceanographic setting. Along the Galician and Cantabrian continental margins, most of the water masses have a North Atlantic source or result from the interaction between waters formed in the Atlantic with those of Mediterranean origin (Pollard *et al.,* 1996). The modern surface oceanography of the Galician margin is dominated by the southward Portugal Current (PC) and the more coastal Portugal Coastal Current (PCC) (Fig. 1). Seasonality especially dominates the surface circulation in the coastal areas, linked to the upwelling-downwelling regime (Varela *et al.,* 2005). With this configuration, during winter the Iberian Poleward Current (IPC) flows as an enhanced slope current. The upper part of the water column is composed of the Eastern North Atlantic Central Water (ENACW), which extends to depths of approximately 400-600 m in two water-mass types (McCartney and Talley, 1982; Fiúza, 1984; Pollard and Pu, 1985; Ambar and Fiúza, 1994); the colder, less saline subpolar water (ENACWsp) (Harvey, 1982) and the warmer, saltier subtropical ENACW with a cyclonic gyre circulation, displaying an average velocity of 1 cm/s (but peaking higher) (Fraga *et al.,* 1982; González-Pola, 2006). Immediately below, and at least down to a water depth of 1,500-1,600 m, the MOW flows northward (Fig. 1) (Ambar and Howe, 1979; Iorga and Lozier, 1999). This water mass is identified by an increase in water temperature and salinity, with two salinity maxima located at 800 and 1,200 m (forming the upper and the low cores of this water mass, respectively). At approximately 42°N, the Mediterranean flow bifurcates intermittently into two branches (Mazé *et al.,* 1997); one branch flows west of the Galician Bank plateau and the other one moves north along the continental slope of the Iberian Peninsula (Iorga and Lozier, 1999; González-Pola, 2006). Off the coast at Santander, the MOW comprises approximately 11% of its initial properties within the Mediterranean Sea and nearly 40% of the water mass flow in the Gulf of Cadiz (Diaz del Rio *et al.,* 1998). Its velocity has been measured at 8°W and 6°W with minimum values of 2-3 cm/s, indicating that the MOW should theoretically take no longer than 19 months to travel from the Strait of Gibraltar to Santander (Pingree and Le Cann, 1990; Diaz del Rio *et al.,* 1998). The MOW is likely to be influenced first by the Aviles Canyon and later by the Le Danois Bank (with a summit of an approximately 500 m water depth), which may introduce isopycnal doming. Further to the east, in the Santander Promontory, after crossing the Torrelavega Canyon, the MOW displays lower salinity and temperature figures (Valencia *et al.,* 2004; González-Pola, 2006). Below a water depth of 1,500 m, some deep water masses have been identified, including the Deep Intermediate Water (DIW,~1,490-2,150 m water depth), mixed with the Labrador Sea Water (LSW), the North Atlantic Deep Water (NADW, 2,150-3,450 m water depth) and the Lower Deep Water (LDW,>3,450 m water depth) (Fig. 1) (Mazé *et al.,* 1997; Varela *et al.,* 2005). These water masses result from the mixing of different water bodies, depending on the density levels. Thus, at a depth of approximately 1,800 m, a core of LSW moves southwards (Van Aken, 2000, 2002), although hydrographic, dynamical and sedimentary data indicate a northward flow not only of LSW but also of the ENACW and MOW (Gardner and Kidd, 1987; Daniault *et al.,* 1994; Mazé *et al.,* 1997; Fiuza *et al.,* 1998). Below the LSW, and originating from a mixture of southward-flowing water masses formed in the Arctic seas, the NADW flows from the Labrador Sea eastwards towards the Bay of Biscay (Pingree and Le Cann, 1990) and reaches the Galician margin. Its core, initially defined by Saunders (1982), is located in this margin, approximately between 2 500 and 3 000 m (Fig. 1) (Caralp, 1985; Vangriesheim and Khripounoff, 1990; McCartney, 1992; McCave *et al.,* 2001; Gonzalez-Pola, 2006). It has been proposed to have a possible but never found northwestward return flow over the Celtic continental slope (most likely absent because of active mixing) (Paillet *et al.,* 1998). The LDW appears to result mainly from the mixing of the deep Antarctic Bottom Water and the Labrador Deep Water (Le Floch, 1969; Botas *et al.,* 1989; Haynes and Barton, 1990; McCartney, 1992; Pingree and Le Cann, 1990; Van Aken, 2000; Mc Cave *et al.,* 2001; Valencia *et al.,* 2004). It enters into the North Atlantic through Discovery Gap on the western flank of the Madeira-Tore Rise (Haynes and Barton, 1990; McCartney, 1992; Van Aken, 2000) and in the Galicia margin it is characterised by a northward near bottom flow (Paillet and Mercier, 1997; Van Aken, 2000). A cyclonic recirculation cell over the Biscay Abyssal plain has been identified (Fig. 1) with a characteristic poleward velocity near the continental margin of 1.2 (± 1.0) cm/s (Dickson *et al.,* 1985; Paillet and Mercier, 1997).

B. Contourite features. In the Galician continental margin and rise, there are very good examples of depositional (*plastered drift, separated drift, sediment waves*) and erosional (*terraces, moats, furrows*) features from the upper continental slope down to the continental rise (Ercilla *et al.,* 2008, 2009, 2011; Bender *et al.,* 2012). The *plastered drifts* display a low-mound shape, are a few kilometres long, and are tens to a few hundred metres thick They are internally defined by aggradational-progadational, stratified seismic facies of high lateral continuity with reflections of high to very high acoustic amplitude (Fig. 6. A, B and C). The continental slope is dotted by elongated *plastered drifts,* developed: 1) on the northwestern flank (2,100 m water depth); 2) on the northern scarp (1 600 m water depth); and 3)at the base of some structural highs (between 1 500 and 4 980 m deep) on the Galician Bank plateau (Fig. 6.A, and B) (Ercilla *et al.,* 2011), as well as on the distal part of the Ortegal marginal platform, between a water depth of 700 to1,100 m (Figure 6.C) (Jané *et al.,* 2012; Llave *et al.,* 2013). Their occurrence stands out because of their smooth and terraced morphology, morphologically contrasting with the numerous adjacent submarine canyons that incise the seafloor.

The main e*longated and separated drifts* are

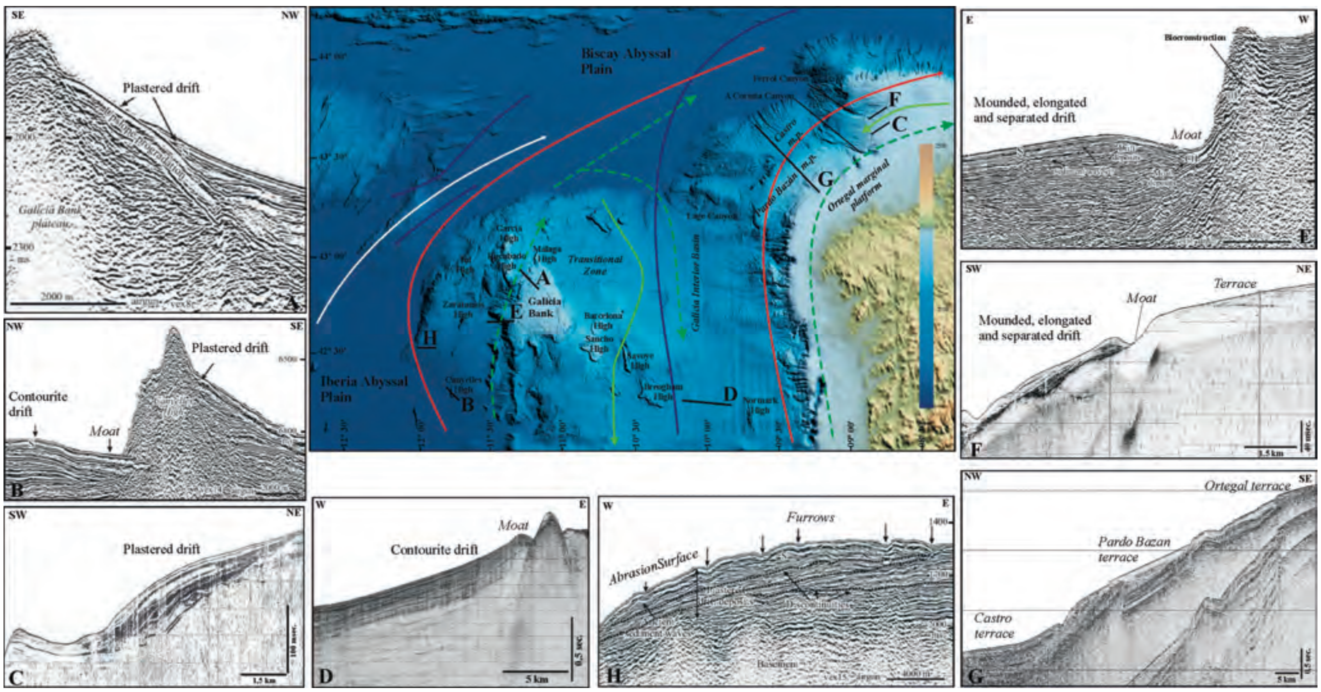

Figure 6. The main examples of contourite features along the Galician continental margin (seismic profiles modified from Ercilla *et al.,* 2011; Llave *et al.,* 2013).

***Figura 6.** Ejemplos de los rasgos contorníticos más relevantes estudiados a lo largo del margen continental de Galicia (perfiles sísmicos modificados de Ercilla et al., 2011; Llave et al., 2013).*

observed in the following locations: 1) on the lower continental slope of the western Galician continental margin, more specifically at the foot and near highs at a water depth of approximately 2 000 m (Fig. 6. D) (Bender *et al.,* 2012). The external face of this drift is affected by *sediment waves;* 2) on the Transitional Zone (1 600 to 2 500 m) (Ercilla *et al.,* 2011); 3) on the Galician Bank plateau (700-800 m water depth) (Fig. 6. B and E), where several moats and associated drifts (15 to <250 m high and 1-5 km wide) occur at its foot and around the numerous highs (Sancho, Rucabado, Málaga, Savoye, Breogham, Normak, Tui, and Zaratamo Highs) (Fig. 6. B). Only the Barcelona, García and Canyelles Highs display an elongated separated drift on one flank, with a local plastered drift on another flank (Ercilla *et al.,* 2008, 2011); and 4) on the Ferrol and A Coruña canyon heads, at water depths of 500 and 700 m, and on the Pardo Bazán marginal platform, at a depth of 1 600 m (Fig. 6. F). They display a monticular shape, 5-22 km long, 2-10 km wide and with an (TWT) average thickness of 50 m (Jané *et al.,* 2012; Llave *et al.,* 2013). Sediment samples collected from the nearby surface of these drifts contain fine to muddy sands (Hernández-Molina *et al.,* 2009b; Llave *et al.,* 2013), as well as planktonic foraminiferal zones as a part of a biogenic sandy contourite facies. This indicates bottom currents of relatively high velocity. Across the lower continental slope of the western Galician continental margin, an *elongated separated drift* has formed at its foot and around the highs (Bender *et al.,* 2012). The external face of several of these drifts is also affected by *sediment waves*.

The *abraded surfaces* are tens of metres in relief, several hundred metres long, and show truncation of reflectors against the erosive seafloor, forming large-scale contourite terraces that are easily recognisable on bathymetric maps. The main abraded surfaces are located along the Ortegal, Pardo Bazán and Castro marginal platforms, at water depths of 200-600 m, 900-1 800 m, and 2 000-3 500 m respectively (Fig. 6. G) (Jane *et al.,* 2012), as well as on structural highs (Fig. 6.H) (Ercilla *et al.,* 2008, 2011). The Ortegal terrace is the most extensive at approximately a length of 150 km, and a width of up to 70 km towards the north and a width approximately 20 km to the south (Llave *et al.,* 2013) where the near-surface sediments are clean coarse sands and silty sands, mostly comprising subrounded and well-sorted quartz and glauconite grains and bioclast fragments. The bioclasts are made up of fragments of foraminifers, gasteropods, bivalves and pteropods (Alejo *et al.,* 2012). The second main contourite erosional feature is represented by *moats* of tens of metres in relief and hundreds of metres wide. They are generally characterised by an asymmetric V-shape section, with a steeper eastern margin (Fig. 6. B, D, E and F) and occur locally at the foot of structural scarps and highs (Fig. 6. B and E). The highs tend to display moats associated with elongated separated drifts around both sides (Ercilla *et al.,* 2011). Several *moats* have also developed on the Ortegal terrace, for example on the Ferrol and A Coruña canyon heads (Fig. 6. F) (Jané *et al.,* 2012; Llave *et al.,* 2013).

Along the Cantabrian margin, the main CDS has been identified on the Le Danois Bank or “Cachucho” (Fig. 7), which is located in an area surrounded by dominant downslope processes (Ercilla *et al*., 2008a, b; Iglesias, 2009; Van Rooij *et al.,* 2010). This CDS comprises both depositional and erosional features, such as *separated drifts*, *plastered drifts*, *moats* and *scours* that have been generated by the MOW circulation and conditioned by seafloor irregularities including two topographic highs; the large Le Danois Bank and the smaller Vizco High (Fig. 7) (Van Rooij *et al.,* 2010). Two *separated drifts* have been identified within the Le Danois CDS: the Gijon and Le Danois Drifts (Fig. 7. A). The *Gijon drift* is located on the upper slope at a water depth of approximately 400-850 m, has a maximum width of approximately 10 km and is approximately 31 km long (Fig. 7. A). The *Le Danois drift* has developed at the foot of the southern side of the Le Danois Bank, in a water depth of between 800 and 1500 to 1 600 m. It is approximately 45 km long, 50 m high and has a variable width, with a maximum of 10 km in the central part of the drift, 3.5 to 4 km in the west and 4.7 km towards the east (Fig. 7. A). Three *plastered drifts* have been identified along the upper southern slope of the Le Danois Bank. They are located on the western edge between 600 and 750 m depth and on the eastern edge at a depth of between 750 m-1 100 m and 1 100-1 550 m (Fig. 7. B). They are all characterised by a mounded relief of approximately 40 m that is 12 to 22 km long and 5.5 to 6 km wide (Van Rooij *et al.,* 2010).

The main erosional features described in the Le Danois CDS are *moats* and *scours*. Two moats have been identified, the Gijón and Le Danois. The *Gijón moat* is the upslope continuation of the Gijón Canyon, has a NW-SE trend, and is approximately 45 km long and 1 to 4 km wide. It starts in a water depth of 1 100 m, shows 400 m incision in the west and disappears to the east (Fig. 7. A). The *Le Danois moat* has a WNW-ESE trend and deepens from a depth of 800 to 1 500 m towards the east. It is approximately 48 km long, has a variable width between 2.8 and 0.8 km, and shows 75-105 m incision (Fig. 7. A). *Scour alignments* are observed over one of the plastered drift with a NE and ENE trend. They are 28-5.5 km in length

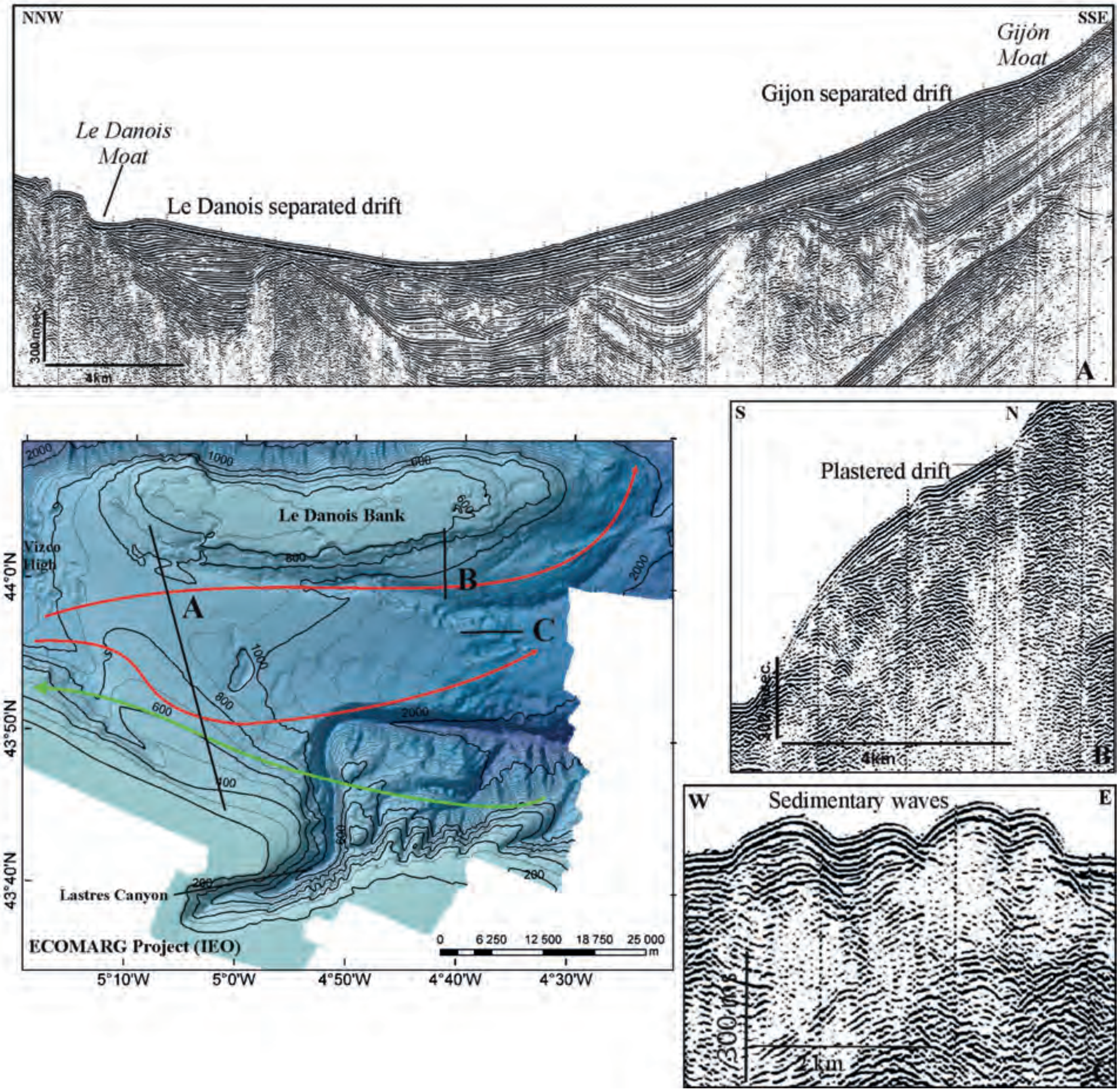

Figure 7. The main examples of contourite features along the Cantabrian continental margin (seismic profiles modified from Van Rooij *et al.,* 2010).
Figura 7. *Ejemplos de los rasgos contorníticos más relevantes estudiados a lo largo del margen continental Cantábrico (perfiles sísmicos modificados de Van Rooij et al., 2010).*

and display a maximal vertical incision of approximately 5m over a width of 1250 m (Van Rooij *et al.,* 2010).

Discussion

Sedimentary processes and controlling factors

The large contourite depositional and erosional features making up the Iberian margin are generated by relatively stable hydrological conditions that lead to long-term bottom water flows. Most of the contourite features are located on the continental slopes. In the Mediterranean Sea, they occur on both the middle slope (the Rosas, western Cabrera and Alboran CDSs) (Canals, 1985; Lastras *et al.,* 2007; Vandorpe *et al.,* 2011; Lüdmann *et al.,* 2012; Ercilla *et al.,* 2012; Juan *et al.,* 2012) and lower slope (Menorca and Alboran CDS) (Mauffret, 1979; Velasco *et al*., 1996; Frigola *et al.,* 2007, 2008; Ercilla *et al.,* 2008, 2009, 2011; Bender *et al.,* 2012; Juan *et al.,* 2012) due to the influence of the LIW and WMDW, respectively (Fig. 1). Along the Atlantic Iberian margin, contourite features are found mostly on the middle continental slope and are associated with the influence of the MOW. This is the case for the CDSs of the Gulf of Cadiz (e.g., Madelain, 1970; Kenyon and Belderson, 1973; Gonthier *et al.,* 1984; Nelson *et al.,* 1993, 1999; Llave *et al.,* 2001, 2006, 2007, 2011; Stow *et al.,* 2002; Alves *et al.,* 2003; Habgood *et al.,* 2003; Hernández-Molina *et al.,* 2003, 2006; Mulder *et al*., 2003, 2006; Hanquiez *et al*., 2007; Marchès *et al*., 2007, 2010; García *et al.,* 2009; Roque *et al.,* 2012; Brackenridge *et al.,* 2013), the Portuguese margin (Mougenot, 1989), the Galician margin (Ercilla *et al.,* 2008, 2009, 2011; Bender *et al.,* 2012), the Ortegal Spur (Hernández-Molina *et al.,* 2009b; Jané *et al.,* 2012; Alejo *et al.,* 2012; Llave *et al.,* 2013) and the Le Danois Bank (Ercilla *et al*., 2008a, b; Iglesias, 2009; Van Rooij *et al.,* 2010) (Fig. 1). To date, very few examples of contourite features have been identified as being associated with other water masses along the Atlantic Iberian margin. Only locally along the Portuguese continental slope and rise (Alves *et al.,* 2000, 2003; Badagola, 2008; Roque, personal communication, 2013) is the influence of the ENACW and LDW sufficient for the local formation of contourites features or sediment waves. In the Galicia Bank area, the influence of the LSW, NADW and LDW has also been demonstrated (Fig. 1) (Ercilla *et al.,* 2009, 2010).

The most prominent contouritic features are the sediment drifts. All the previously described major drifts along the Iberian margin vary in size and type (*plastered, separated, confined and sheeted drifts*). In contrast, the most notable mixed features (represented by *terraces) and erosive (abrasion surfaces, marginal platforms, contourite channels, moats, scours and furrows*) are scarcely described, are still not typified and are without a clear genetic relationship to the involved oceanographic processes (Faugères and Stow, 2008; Rebesco and Camerlenghi, 2008; Hernández-Molina *et al.,* 2011). The Iberian margin contourites have a wide variety of lithologies with different grain sizes (from clay to sand) but are mainly mud rich and intercalated with thinner horizons of fine-grained sands and silt, mostly terrigenous and biogenic. These fines are predominantly poorly sorted, intensively bioturbated and typically display broadly rhythmic bedding trends (Stow *et al.,* 2002b; Ercilla *et al.,* 2002). Sandy contourites have recently been described in the Gulf of Cadiz (Hanquiez *et al.,* 2007; Brackenridge *et al.,* 2013; Stow *et al.,* 2013b; Hernández-Molina *et al.,* 2012, 2014), the Galicia margin (Bender *et al.,* 2012) and the Ortegal Spur (Alejo *et al.,* 2012). Their genesis and facies models still need to be fully established, despite their enormous potential with respect to hydrocarbon reservoirs and mineral resources (Stow and Fauguères, 2008; Viana, 2008; Stow *et al.,* 2011; Brackenridge *et al.,* 2013; Hernández-Molina *et al.,* 2013, 2014).

The classical contourite facies model sequence was initially proposed by Gonthier *et al.* (1984) and Faugères *et al.* (1984) based on research carried out across the Faro Drift on the middle slope of the Gulf of Cadiz. The model comprises two superposed units: a basal coarsening-up unit grading from fine homogeneous mud (clayey fine silt) to mottled coarser silt and finally sandy silt/silty sand, followed by a fining-up unit with an inverse order facies succession. This general model ideally represents an increase from weaker to stronger bottom-current flow followed by a waning to weaker currents again (Stow and Holbrook, 1984; Stow *et al.,* 2002; Huneke and Stow, 2008). Stow and Faugères (2008) extended the model to sandy contourites showing a negatively graded lower subsequence (mud + mottled silt and mud units), a middle sandy silt and an upper positively graded subsequence (mottled silt and mud + mud units) and interpreted most of them as bottom-current-modified turbidites (Faugères and Stow, 1993; Stow *et al.,* 2002; Stow and Faugères, 2008). Mulder *et al.* (2013) have recently concluded that the contourite sequence is not only related to changes in bottom-current velocity and flow competency, but may also be influenced by the sediment supply. They hypothesize that coarse terrigenous particles maybe provided by either increased erosion of mud along the flanks of confined contourite channels and moats, or by the increased sediment supply by rivers and downslope mass transport on the continental shelf and upper slope. Thus, more controlling factors (not only the bottom-current velocity) must be considered when examining the development of both depositional and erosional contourite features including (Fig. 8):

(1) *General margin configuration*: Iberia is a large-scale peninsula, surrounded on all sides by oceans and their associated water masses. As a result, the seafloor is shaped by different water masses that together form a clockwise flow from east to west around the Peninsula. Another typically interesting geomorphological feature for the Iberian margin is represented by the Strait of Gibraltar; an oceanic gateway in which an exchange occurs between the Mediterranean and Atlantic water masses. In addition, north of Iberia, the Bay of Biscay forms a confined morphological control on both the Atlantic and Mediterranean Outflow water masses. The shape and configuration (slope gradient) of the Iberian margin, its laterally variability and its confinement, have influenced the Coriolis Effect and

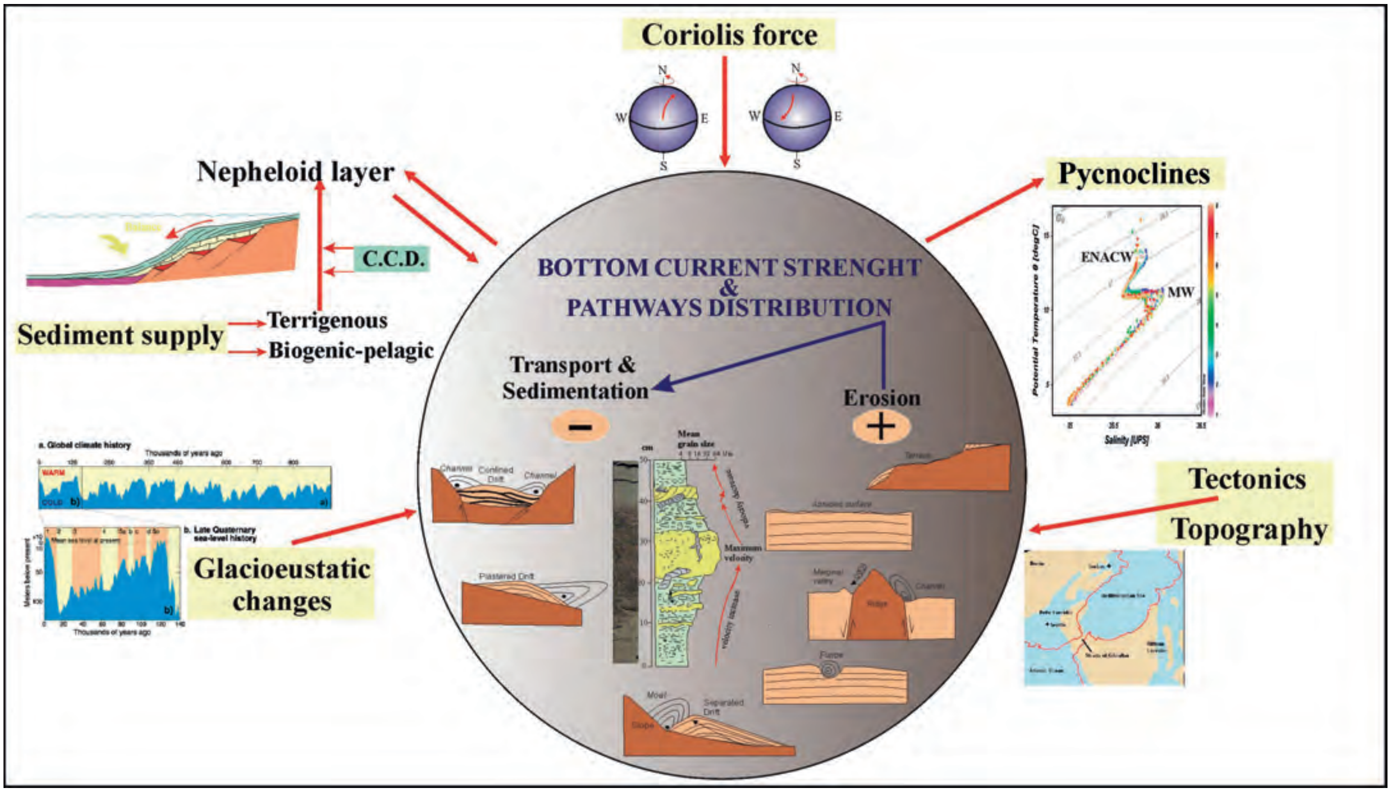

Figure 8. Summary of the main control factors in the contourite sedimentary processes.
Figura 8. *Sumario de los principales factores que controlan los procesos sedimentarios contorníticos.*

hence the variability of bottom current intensities. This is specifically responsible for the large variety of encountered drift types in almost all of the Mediterranean and Atlantic sectors, as well as the great variety of erosive contourite features, mostly associated to the Strait of Gibraltar and across its adjacent margins.

(2) *Local margin morphology:* Both inherited geological features that shape the large-scale morphology of the margin, and various localised slope irregularities facilitate local water-mass interaction with the seabed. The Iberian continental margin has been affected by much recent tectonic activity (diapirs, uplifted fault blocks, banks, ridges, seamounts, etc.), which results in a complex continental slope morphology. The resulting high seafloor stress against the bottom current creates more likelihood of the generation of multiple current pathways and dynamics such as the formation of several different branches of the current, secondary flows, small fluxes (filaments), internal waves, local turbulence associated with eddies, overflows, helicoidal flows, upwelling and downwelling flows. Topographic obstacles are also capable of causing local acceleration and deceleration of the bottom currents. As a result, very complex contourite depositional systems can be generated, as described for many cases in the western Mediterranean, the Gulf of Cadiz and western Iberian margins. During the Pliocene (especially after the opening of the Gibraltar Strait) and lower Quaternary, tectonics represented a long-term factor that controlled drift stratigraphy, architectural changes and the location of large-scale contourite features (Alves *et al.,* 2003; Hernández-Molina *et al.,* 2003, 2006, 2013, 2014; Mulder *et al.,* 2003; Llave *et al.,* 2007, 2008, 2011; García *et al.,* 2009; Ercilla *et al.,* 2012, 2013; amongst others);

(3) *Sediment supply*: A multitude of sources, each with a time-variable aspect, may be responsible for sediment supply. Downslope density currents may deliver sediment from submarine canyons, slides and debris flows. In contrast, settling may occur with either pelagic bioclasts or suspended sediments through the water column from the shelf break. Settling sediments may form pelagic or hemipelagic accumulations where bottom currents are absent (or very sluggish), or they may be pirated by water masses. Sand spill-over may occur from adjacent shelves and the hinterland. In

addition, local and distal erosion caused by water masses must be considered (Stow *et al.,* 2008). Finally, active slope tectonics might trigger more effective down-slope processes, which can partially or completely mask contourite processes (e.g., Bender *et al.,* 2012; Mulder *et al.,* 2013);

(4) *Pronounced density contrasts (pycnoclines)*: The interaction of the interphases between water masses with the seafloor can generate different erosional and depositional contourite features. The detection and characterization of intermediate and deep nepheloid layers (often located at water mass interphases) and benthic boundary layers are currently under investigation and discussion (McCave, 1986; Dickson and McCave, 1986; Cacchione *et al.,* 2002; Puig *et al.,* 2004; Preu *et al.,* 2013; Hernández-Molina *et al.,* 2013; Ercilla *et al.,* 2014);

(5) *Glacioeustatic changes*: Many researchers have stressed the significance of glacioeustatic changes in the formation of large depositional and erosional features on the Iberian margin and basin scales (e.g., Grousset *et al.,* 1988; Vergnaud-Grazzini *et al.,* 1989; Nelson *et al.,* 1993; Zahn *et al.,* 1999; Schönfeld and Zahn, 2000; Cacho *et al.,* 2000; Shackleton *et al.,* 2000; Schönfeld *et al.,* 2003; Llave *et al.,* 2006, 2007; Voelker *et al.,* 2006; Frigola *et al.,* 2007, 2008; Lebreiro *et al.,* 2009; Lebreiro, 2010; Voelker and Lebreiro, 2010; Bender *et al.,* 2010, 2012; Gonthier *et al.,* 2010; Mena *et al.,* 2010; Roque *et al.,* 2012; Brackenridge *et al.,* 2013; Hernández-Molina *et al.,* 2013, 2014). These were especially significant during the Quaternary (Fig. 8). In the shorter term, they control vertical contourite stacking patterns, sequences, and facies. Some authors have also attempted to relate water-mass circulation with eustatic changes and how they modify turbiditic or mass flow deposits (Shanmugan, 2006, 2012, 2013a, b; Brackenridge *et al.,* 2011, 2013; Mutti and Carminatti, 2012; Gong *et al.,* 2013; Lobo *et al.,* 2014).

It appears likely that some water masses around the Iberian margins (the WMDW, MOW or the LDW) are enhanced or flow deeper during cold intervals (i.e., glacial periods) when more sediment is also provided to the basin (e.g., Ercilla *et al.,* 2002, 2013; Hernández-Molina *et al.,* 2002, 2006, 2013, 2014; Stow *et al.,* 2002c; Llave *et al.,* 2006, 2011; Voelker *et al.,* 2006; Rogerson *et al.,* 2006, 2008, 2010, 2012; Toucanne *et al.,* 2007; Frigola *et al.,* 2008, 2010; Van Rooij *et al.,* 2010a; Roque *et al.,* 2012; Juan *et al.,* 2012; Brackenridge *et al.,* 2013). Subsequently, climate can produce two different effects on water masses: 1) vertical and lateral changes in the core and/or interphases between water-mass position and 2) changes in the intensity of the bottom current cores (Preu *et al.,* 2013).

Hence, it seems clear that the local palaeotopography plays an important role in governing the circulation routing of water masses around Iberia and thus affects the type of contouritic deposits found. On the other hand, climate and sea level changes have influenced the sediment types (acoustic facies), stratigraphic patterns and thicknesses. Climate and sea level changes also drive the oceanography and the general behaviour of the water masses. Along-slope sedimentary processes around Iberia are mainly generated by the Mediterranean water masses. Although the opening of the Gibraltar gateway is dated to 5.33 Ma (Bache *et al.,* 2012), the development of contourite features in the Atlantic Ocean did not start until ca. 3.8 Ma when the overflow was sufficiently intense to cause reworking of the continental slope (Hernández-Molina *et al.,* 2014). Since then, the palaeoceanographic changes in water masses in the Alboran Sea, Gulf of Cadiz and Le Danois CDSs have been described and are thought to be coeval (Llave *et al.,* 2001, 2006, 2011; Ercilla *et al.,* 2002, 2013; Hernández-Molina *et al.,* 2002, 2006, 2013, 2014; Stow *et al.,* 2002c; Van Rooij *et al.,* 2010; Roque *et al.,* 2012; Brackenridge *et al.,* 2013). It has recently been assumed that during the glacials, intermediate and deep Mediterranean water masses were enhanced (Cacho *et al.,* 2000, 2006; Sierro *et al.,* 2005; Hernández-Molina *et al.,* 2011; Toucanne *et al.,* 2012), increasing the current strength of the MOW plume after its exit through the Strait of Gibraltar. This led to complex variations in the MOW flow path along the Atlantic Iberian margin (Rogerson *et al.,* 2012). A saltier, denser and enhanced MOW lower branch sank to levels of approximately 700 m deeper than today, impinging the continental slope of the Gulf of Cadiz at depths of approximately 1,600-2,200 m (Schönfeld and Zahn, 2000; Cacho *et al.,* 2000; Rogerson *et al.,* 2005; Llave *et al.,* 2006; Voelker *et al.,* 2006; Toucanne *et al.,* 2007; García *et al.,* 2009). This enhancement of the MOW has been shown to have occurred during Heinrich events, Dansgaard-Oeschger stadials and the Younger Dryas (Sierro *et al.,* 2005; Llave *et al.,* 2006; Voelker *et al.,* 2006). A more vigorous, less dense upper branch of the MOW during the recent highstand period has been highlighted (Stow *et al.,* 2002a; Rogerson *et al.,* 2005; Llave *et al.,* 2006). Sandy contourites are related to the Younger Dryas, Heinrich events (in particular H1 and H2) and stadial Dansgaard-Oeschger events. Fine-grained contourites, however, are related to warm periods such as the Bolling-Allerod and Dansgaard-Oeschger interglacials (Mulder *et al.,* 2002; Hanquiez, 2006; Llave *et al.,* 2006; Voelker *et al.,* 2006; Toucanne *et al.,* 2007; Hernández-Molina *et al.,* 2014).

Pliocene-Quaternary evolution

Since the Lower Pliocene, along-slope processes appear to have progressively smoothed the Messinian palaeotopography which posed a strong morphological control on the water masses (Juan *et al.,* 2012). During this time, down-slope mass transport and debrite deposits developed interbedded with sheeted contourite drifts in the Alboran Sea and the Gulf of Cadiz (Roque *et al.,* 2012; Ercilla *et al.,* 2012; Brackenridge *et al.,* 2013). Major evidence of Mediterranean water-mass circulation has been demonstrated approximately 4.0-4.2 Ma ago (Hernández-Molina *et al.,* 2009c; Llave *et al.,* 2010; Raddatz *et al.,* 2011; Rogerson *et al.,* 2012). At this time, relatively sluggish water masses were influencing the Iberian margins. Locally however, diapirism affected bottom water flow, intensifying it and resulting in the formation of: 1) confined drifts (with the local and regional extent), plastered drifts, sediment waves and channel-infilling drifts along the Alboran Sea (Juan *et al.,* 2012); 2) upslope progradation, sheeted drifts and localised patch drifts of coarser material in the Gulf of Cadiz (Roque *et al.,* 2012; Brackenridge *et al.,* 2013); and 3) confined drifts and sediment waves locally within the Miocene palaeotopography in the Le Danois CDS (Van Rooij *et al.,* 2010). The full establishment of the most recent hydrodynamic situation is thought to have developed at the start of the Quaternary (~2.6 Ma, Rogerson *et al.,* 2012; Hernández-Molina *et al.,* 2013, 2014), being linked to global cooling, which initiated the glacial-interglacial cyclicity of the Pleistocene (e.g., Thunell *et al.,* 1991). It was at this time that a major reorganisation in the margin was initiated, marked by both a major period of repeated water mass intensification and the continuing diapiric movements. These factors were likely to be instrumental in the change to a contourite-dominated system. Despite the domination of ongoing regional along-slope sedimentary processes, the influence of turbidites was still present, for example as observed in the Alboran Sea where relocation of some turbiditic fans is seen. Partial infilling and/or disappearance of some downslope canyons are also seen at this time, while others showed an increase of activity (Juan *et al.,* 2012). These climatic changes started to control the presence and flow intensity of the water masses along with the sedimentary input, as reflected by more mature contourite drifts, including plastered, sheeted, confined and elongated separated drifts in the Alboran Sea (Juan *et al.,* 2012), low-mounded drifts in the Gulf of Cadiz (Llave *et al.,* 2007; Roque *et al.,* 2012; Brackenridge *et al.,* 2013; Stow *et al.,* 2013b), and more pronounced confined drifts in the Le Danois CDS (Van Rooij *et al.,* 2010). One of the main pieces of evidence of increasing contourite activity associated with the enhanced water mass circulation during the Quaternary is coeval with the mid-Pleistocene revolution (~0.9 Ma) because of the switch to a "full glacial" mode with 100 ka cyclicity (Llave, 2003; Llave *et al.,* 2007; Van Rooij *et al.,* 2010; Hernández-Molina *et al.,* 2014). This has led to the development of the basin draping plastered drifts, enhanced terraces and sheeted drifts of the Alboran Sea (Juan *et al.,* 2012). In the Gulf of Cadiz, an important change in the contourite stacking pattern was produced, moving from predominantly sheeted drifts (aggradational) to elongated mounded drifts (progradational and aggradational), as well as more frequent erosional features (Llave *et al.,* 2007; Roque *et al.,* 2012). Within the Le Danois CDS, the formation of upper slope separated drifts, plastered drifts, and associated erosional features was also observed since the Middle Pleistocene (Van Rooij *et al.,* 2010).

The onset of other examples of contourite features generated under the influence of deeper water masses(such as the LWD) are located on the continental rise of the western Iberian margin, where bottom currents have been sweeping the sector in a semi-permanent regime since at least the middle Eocene (Sawyer *et al.,* 1994; Whitmarsh *et al.,* 1998). The sediments consist of a mixture of reworked turbidite and hemipelagic sediments, deposited at the base of the lower continental rise (Milkert *et al.,* 1996). This bottom-current activity is also indicated by the presence of large-scale migrating sediment waves affecting the middle Eocene through to the Pleistocene sedimentary record (Whitmarsh *et al.,* 1998). In addition, the new contourite drift separated from a structural high off Aveiro by a moat in the continental rise indicates enhanced bottom-current activity during the Lower Pliocene (Roque, C. personal communication 2013).

Implications

The study of contourite depositional systems is essential for palaeoclimatology and palaeoceanography, in addition to slope stability and hydrocarbon exploration (Rebesco *et al.*, 2014). These issues are discussed below.

Palaeoclimatology and palaeoceanography. Contouritic deposits generally show continuous and relatively high sediment accumulation rates. They play an important role in high-temporal resolution studies (Rebesco *et al.*, 2014). Therefore, these sedimentary records hold the key to valuable information regarding the variable patterns of ocean circulation, current velocities, oceanographic history and basin interconnectivity. The main examples of this high temporal resolution, registered along the Iberian margin, are located in the Mediterranean Sea (Cacho *et al.,* 2000; Sierro *et al.,* 2005; Frigola *et al.,* 2007, 2008; Abrantes *et al.,* 2012), Gulf of Cadiz and west off Portugal (Figure 9) (Sawyer *et al.,* 1994; Milkert *et al.,* 1996; Baas *et al.,* 1997; Whitmarsh *et al.,* 1998; Schönfeld and Zahn, 2000; Hall and McCave, 2000; Schönfeld *et al.,* 2003; Llave *et al.,* 2006; Voelker *et al.,* 2006; Toucanne *et al.,* 2007; Salgueiro *et al.,* 2010) and the Galicia and Cantabrian margin (Ercilla and Vilas, *2008*; Mena *et al.,* 2010; Bender *et al.,* 2012). These studies provide reconstructions of changes in palaeoceanography and palaeo-current energy and pathways, depending on the climate changes.

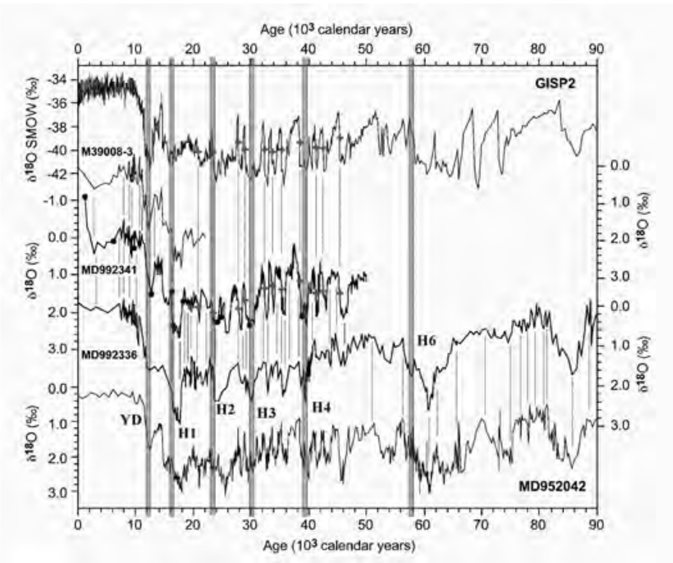

Figure 9. Correlation of data with the parallel-core M39008-3 (Cacho et al., 2001) in the upper part of the MD9923-41 core with the GISP2 ice core $\delta^{18}O$ record in the lower part of the core, where the thin grey lines are the correlations. The thick grey line is H1. The crosses are midpoints of cold/warm transitions which were used for correlating MD9923-41 with GISP2. The dots are ^{14}C-datings and H as defined by IRD scans (Llave et al., 2006).

Figura 9. *Correlación del registro de $\delta^{18}O$ entre los datos del testigo M39008-3 (Cacho et al., 2001) y la parte a techo del testigo MD9923-41 con el testigo de hielo GISP2, donde las líneas grises indican las correlaciones existentes. La línea gruesa gris es el H1. Las cruces son puntos medios de transiciones frio/cálido en las cuales se han basado las correlaciones de MD9923-41 con GISP2. Los puntos son dataciones ^{14}C y H definidas por escáneres IRD (tomado de Llave et al., 2006).*

Slope stability. Submarine slope instability is commonly related to the distribution, composition and physical properties of contourites (Rebesco *et al.,* 2014). In the northeastern Iberian continental margin and in the Balearic Promontory, landslides and debris flows have been described (Canals, 1985; Maldonado and Nelson, 1990; Casas *et al.,* 2003a; Urgeles *et al.,* 2006; Lastras *et al.,* 2007). These widespread examples demonstrate the repeated occurrence of instability, even along margins that are considered as seismically quiet (Lastras *et al.,* 2007). In the western Mediterranean and Gulf of Cadiz, submarine landslides are widespread, especially below 2000 m water depth (Sallarés *et al.,* 2011). In the eastern Alboran Sea, submarine landslides are observed on the flanks of the banks (Gràcia *et al.,* 2006; Martínez-García *et al.,* 2011; Alonso *et al.,* 2014), whereas in the western Alboran Sea (mainly in the Spanish margin), the contourite features are interrupted by the construction of turbidite fans, and by sedimentary instabilities that locally affect the open slope, the Alboran Ridge and morphological highs (Ercilla *et al.,* 2012). In the southeastern upper slope of the Gulf of Cadiz, submarine slumps were mapped from seismic data (Baraza *et al.,* 1989, 1999), which tend to be associated with gassy sediments (Baraza and Ercilla, 1996). The area with free gas is locally affected by gravitational processes in the form of slumps (Baraza *et al.,* 1999). Likewise, slumps occur downslope and westwards of the acoustically turbid zone (Casas *et al.,* 2003b). In the northern sector of the Gulf of Cadiz, submarine landslides are associated with the Marquês de Pombal fault (Gràcia *et al.*, 2003). Geological studies conducted in the Prestige sinking area have characterised different types of instabilities (slides, debris/mud flows, turbidity currents and related flows) (Ercilla and Vilas, 2008), which could be triggered by the tectonic activity and/or the steep slopes of the structural highs suggested by Ercilla *et al.* (2008a, 2011). In the Cantabrian margin, Ercilla *et al.* (2007) and Iglesias (2009) identified zones of instability at the shelf-break, the upper open slope or intra-slope outcrops, i.e., areas where the slope gradients are high, favouring the occurrence of sedimentary instabilities that may evolve to mass-transport processes and turbidity currents. These instabilities described in high slope gradients, are also affected by water-mass interaction with the seafloor.

Hydrocarbon exploration. Coarse-grained contourites deposited by robust flows may represent hydrocarbon reservoirs, whereas fine-grained contourites accumulated by weak bottom currents may provide sealing (and source) rocks (Rebesco *et al.,* 2014). In this case, the occurrence of potentially economically interesting accumulations of sandy contourites is dependent on their vicinity to a sand-rich area prone to being swept by bottom-currents. On the other hand, fine-grained contourites, related to both sealing facies/permeability barriers and source-rock accumulation play an important role in the characterization of deep-water petroleum systems. In the Iberian margin, a large volume of sand transported and re-deposited by persistent and efficient hydrodynamic regimes have been reported in the Gulf of Cadiz (Llave *et al.,* 2005; Habgood *et al.,* 2003; Hernández-Molina *et al.,* 2006; Brackenridge *et al.,* 2013). After the IODP Expedition 339 (Hernández-Molina *et al.,* 2013; Stow *et al.,* 2013a, b), the improved knowledge of sand-rich contourite deposits will have significant implications, both in the establishment of a facies model for sandy contourites (Stow and Faugères, 2008; Viana, 2008) as well as in consideration of their potential as a future deep-water hydrocarbon exploration target (Buitrago *et al.,* 2001; Llave *et al.,* 2005; Akhmetzhanov *et al.,* 2007; Viana *et al.,* 2007; Viana, 2008; Stow *et al.,* 2011; Brackenridge *et al.,* 2011, 2013).

Notwithstanding the noticeable economic significance of contourites, there are still a limited number of scientific publications dealing with this topic. The reasons, according to Viana *et al.* (2007), may be related to the early establishment of gravity-flow accumulation models, volumetric predominance of sandy gravity flow deposits, lack of unequivocal sedimentological criteria and poorly investigated oceanography aspects for contourite identification. The increasing access of academic institutions to high-resolution seafloor imaging techniques and industrial seismic 3D is providing a deeper understanding of the contourite deposits and confirms their role as important constituents of petroleum systems. This new perspective is crucial for understanding the origin and predicting the distribution of deep-water sandstones in future petroleum exploration and production worldwide (Rebesco *et al.,* 2014).

Conclusions and future considerations

For many years, research on contourites was conducted by just a few specialists. It is only in recent years that a larger number of researchers have become involved in this field. This trend is occurring hand in hand with the increased awareness that the effects of bottom-currents and their associated oceanographic processes are very widespread. Such processes occur almost everywhere in the oceans and are crucial in shaping the morphology of the seafloor. Many scientists, even if not specialists in contourites, have to face the issue of sediments affected by bottom currents within their own field of research (Rebesco *et al.,* 2014). This is the case of the Iberian continental margins, where in the last 20 years, numerous examples of water-mass circulation processes and contourites have been recorded. The products of these bottom currents consist of both erosional and depositional features of variable dimensions that are dependent on a variety of geological and oceanographic contexts. The Iberian margins lie under the influence of several water masses interacting along the upper and middle continental slopes and, although lesser in intensity, also along the lower slopes and abyssal plains. In all of these domains, extensive, complex and often poorly understood contourite features of large dimensions and diverse sediment thickness occur in different geologic contexts such as the Ceuta CDS SW Alboran Sea, the Gulf of Cadiz (the most studied so far), the western margin of Portugal, the Galician margin, the Ortegal Spur, and the Le Danois Bank or "Cachucho". Associated erosional and mixed contouritic features that are generated by the water masses along the Iberian margin have only recently been studied in detail, with the most notable features being the abraded surfaces, channels, furrows and moats and terraces, respectively. The majority of these erosional contourite features are formed under the influence of the Mediterranean water masses, most notably the Mediterranean Outflow Water (MOW).

The development of both depositional and erosional contourite features not only depends on the bottom-current velocity but also on several other important controlling factors: 1) regional margin configuration. The Iberian peninsula favours a clockwise flow of the water masses that have shaped the continental margin since the opening of the Strait of Gibraltar; 2) local margin morphology formed by recent tectonic activity (diapirs, uplifted fault blocks, banks, ridges, seamounts, etc.), causes a complex slope morphology and multiple current pathways, including several different branches of the current, secondary flows, small fluxes (filaments), internal waves, local turbulence associated with eddies, overflows, helicoidal flows, upwelling and downwelling flows; 3) sediment supply, which can come from multitude of sources, each with a time-variable aspect (downslope density currents, slides, debris flows, pelagic bioclast, suspended sediments, etc.). Fault activity may trigger additional active down-slope processes, which can partially or completely mask contourite processes; 4) in addition, pronounced density contrasts (pycnoclines) are influential, as the importance of the water-mass interface interaction with the seafloor in generating contourite features has been demonstrated; 5) glacioeustatic changes play an important role in the growth of large depositional and erosional features of the Iberian margin, especially during the Quaternary, when increasing influence of bottom-currents was observed in the sediment types (acoustic facies), stratigraphic patterns and the thicknesses deposited. Indirectly, climate and sea level changes have also driven the oceanography and general behaviour of the water masses. In this sense, it has recently been assumed that during the glacials, intermediate and deep Mediterranean water masses were enhanced.

Although since the 1990s knowledge of contourite features has noticeably increased, work on defining diagnostic criteria in contourite identification and facies models is far from being finished. The role of bottom-current circulation and associated processes in shaping the seafloor and controlling the sedimentary stacking patterns on the Iberian continental margins is becoming clearer, but there are many different oceanographic processes that could drive bottom-currents, and most of them are not fully understood. There is the need to document a large variety of contourite features (processes and products), facies models, their evolution over time and space, and the oceanographic processes that form them. Particular emphasis in understanding sandy contourites is needed because of the economic interest of these deep-water deposits for exploration and evaluation for hydrocarbon resources. Thus, an advance both in new technologies and integrated studies (Geology, Oceanography and Benthic Biology) is anticipated in the future.

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