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Geomorphological and sedimentary processes of the glacially influenced northwestern Iberian continental margin and abyssal plains

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Abstract

The offshore region of northwestern Iberia offers an opportunity to study the impacts of along-slope processes on the morphology of a glacially influenced continental margin, which has traditionally been conceptually characterised by predominant down-slope sedimentary processes. High-resolution multibeam bathymetry, acoustic backscatter and ultrahigh-resolution seismic reflection profile data are integrated and analysed to describe the present-day and recent geomorphological features and to interpret their associated sedimentary processes. Seventeen large-scale seafloor morphologies and sixteen individual echo types, interpreted as structural features (escarpments, marginal platforms and related fluid escape structures) and depositional and erosional bedforms developed either by the influence of bottom currents (moats, abraded surfaces, sediment waves, contourite drifts and ridges) or by gravitational features (gullies, canyons, slides, channel-levee complexes and submarine fans), are identified for the first time in the study area (spanning ~90,000 km^2 and water depths of 300 mto 5 km). Different types of slope failures and turbidity currents are mainly observed on the upper and lower slopes and along submarine canyons and deep-sea channels. The middle slope morphologies are mostly determined by the actions of bottom currents (North Atlantic Central Water, Mediterranean Outflow Water, Labrador Sea Water and North Atlantic Deep Water), which thereby define the margin morphologies and favour the reworking and deposition of sediments. The abyssal plains (Biscay and Iberian) are characterised by pelagic deposits and channel-lobe systems (the Cantabrian and Charcot), although several contourite features are also observed at the foot of the slope due to the influence of the deepest water masses (i.e., the North Atlantic Deep Water and Lower Deep Water). This work shows that the study area is the result of Mesozoic to present-day tectonics (e.g. the marginal platforms and structural highs). Therefore, tectonism constitutes a long-term controlling factor, whereas the climate, sediment supply and bottom currents play key roles in the recent short-term architecture and dynamics. Moreover, the recent predominant along-slope sedimentary processes observed in the studied northwestern Iberian Margin represent snapshots of the progressive stages and mixed deep-water system developments of the marginal platforms on passive margins and may provide information for a predictive model of the evolution of other similar margins.

Keywords: morphological features; along-slope and down-slope processes; neotectonic; northwestern Iberia

1. INTRODUCTION

Continental margins are built up by several sedimentary processes driven by plate tectonic evolution and environmental changes (Einsele, 2000; Pickering and Hiscott, 2016). The dominant sedimentary processes mainly originate from the combined action of down-slope movements that are mainly driven by gravity, and along-slope sedimentary processes that are forced by bottom currents (e.g., Faugères *et al.,* 1999; Weaver *et al.,* 2000; Stow *et al.,* 2002; Rebesco and Camerlenghi, 2008). Understanding how these processes build continental margins provides new insights into the origins of different morphologies and their relative importance in the evolution of passive margins.

In locations where down-slope processes are dominant, continental slope successions comprise turbidites, debrites, and submarine landslides (Weaver *et al.,* 2000; Pickering and Hiscott, 2016). Where along-slope processes are dominant, a contourite depositional system (CDS) or contourite sedimentary system, comprising both depositional (mainly "drifts") and erosional features (e.g., moats, channels, and furrows), is generated (Stow *et al.,* 2002; Hernández-Molina *et al.,* 2003, 2011; Rebesco, 2005). Although the dominant process regime on the continental slope can have temporal and spatial variations, there are many examples of continental margins, especially those described between 26 °N and 56 °N in the northeastern Atlantic, that have been considered to be predominantly built up by down-slope sedimentary processes and were then defined as "glacially influenced margins" (e.g., Weaver *et al.,* 2000; Wynn et al., 2000; Benetti, 2006, among many others). This type of margin comprises mainly linear pathways of canyons and channels (e.g., Kenyon *et al.,* 1978; Crémer, 1983; Faugères *et al.,* 1998; Zaragosi *et al.,* 2000; Mulder *et al.,* 2001; Bourillet *et al.,* 2006; Gonthier *et al.,* 2006; Gaudin *et al.,* 2007). On these margins, along-slope processes have been considered to play a minor role, except in the Gulf of Cádiz and at the southern Portuguese margins (Stow *et al.,* 2002; Alves *et al.,* 2003; Hernández-Molina *et al.,* 2006a, 2016a, b; García *et al.,* 2009; Roque et al., 2012, among others).

The northwestern Iberian continental margin is located within the eastern sector of the central North Atlantic (Fig. 1A), an area included within the classification of a "glacially influenced margin" (Weaver *et al.,* 2000; Zaragosi *et al.,* 2001a; Mojtahid *et al.,* 2005). Geomorphological studies have characterised the area by both their down-slope and morphostructural features, such as the numerous submarine canyons, large marginal platforms (Ortegal, Pardo Bazán and Castro) and several structural highs (Maestro *et al.,* 2015). In proximal areas, such as the Galicia Bank to the south (Ercilla *et al.,* 2008a; Llave *et al.,* 2008) and the Cantabrian Margin to the east (Ercilla *et al.,* 2008b; Iglesias, 2009), previous geomorphological studies have also considered the predominance of those morphologies related to tectonics and down-slope sedimentary processes. The major goal of this study is to reveal the impacts of both along-slope and down-slope oriented sediment transport on the northwestern Iberian Margin, establishing the importance of the dynamic oceanographic settings and assessing the impacts of their interactions on reshaping the inherited structures such as marginal platforms and structural highs. A novel and detailed description of the submarine morphological features is presented for a better understanding of the associated sedimentary processes along the continental margin and the abyssal plains off northwestern Iberia.

2. GEOLOGICAL AND OCEANOGRAPHIC SETTINGS

2.1. Geological setting

The northwestern Iberian continental margin comprises the Galicia continental margin and the westernmost sector of the Cantabrian Margin (Fig. 1A). The rift structures, characterised by horsts and grabens bounded by N-S, NE-SW, E-W and NW-SE faults, control the present-day morphology (Montadert *et al.,* 1979; Groupe Galice, 1979; Boillot *et al.,* 1979; Maestro *et al.,* 2017) (Fig. 2). These faults have developed during the geodynamic evolution of the margin from the late-Variscan period until the present day. From the Upper Miocene until the present day, those faults with NE-SW direction have been reverse faults, the NW-SE have been normal faults and the N-S and E-W have been left-lateral and right-lateral strike-slip faults, respectively (González-Casado and Giner, 2000; De Vicente *et al.,* 2004; Martín-González *et al.,* 2010). The Galicia Bank is one of the most important structural highs in the Galicia margin and creates the intraslope basin called the Galicia inner basin (Boillot *et al.,* 1975; Vanney *et al.,* 1979). Other distinct morphostructural features in the northwestern Iberia margin are the Ortegal, Pardo Bazán and Castro Marginal Platforms and the Charcot, Coruña and Finisterre Highs (Maestro *et al.,* 2015) (Fig. 2).

This area is considered to be a starved non-volcanic passive margin with only a thin sedimentary cover. The Mesozoic to Neogene sedimentary cover of the northwestern Iberian Margin is approximately 1,300 m thick (Groupe Cybere, 1984; Vigneaux, 1974; Derégnaucourt and Boillot, 1982; Thinon *et al.,* 2001; Gallastegui *et al.,* 2002). The recent sedimentary units (Plio-Quaternary) show a very irregular distribution overlying the Mesozoic-Neogene sedimentary succession. This unit consists of alternating deposits of silt and clay laminas with interbedded coarse sediments. These sediments mainly include turbidites, debrites, contourites, and pelagites/hemipelagites (Vanney *et al.,* 1979; Boillot *et al.,* 1987; Comas and Maldonado 1988; Alonso *et al.,* 2008; Ercilla *et al.,* 2006, 2008a). The low sediment thickness is mainly due to two reasons: a) the redistribution of sediments by longshore bottom currents and b) the shortness of the rivers of the study area as well as their steep water courses, reflecting their low sediment supply (Jané *et al.,* 2010). Only 4.2% of the overall catchment area of the Iberian Peninsula drains to the north coast, between the Galicia-Asturias border and the French border (Uriarte *et al.,* 2004).

2.2. Oceanographic setting

In the study area, most of the water masses are of North Atlantic origin (Pollard *et al.,* 1996; González-Pola, 2006) and are described below from shallowest to deepest (Fig. 1B).

a) The Eastern North Atlantic Central Water (ENACW) extends down to depths of 400-600 m and flows towards the southwest (Ambar and Fiúza, 1994; Fiúza *et al.,* 1998; Pérez *et al.,* 2001; González-Pola*,* 2006). This water mass generally flows at a velocity of 1 cm/s, although it can occasionally reach velocities of 10 cm/s (Pingree and Le Cann, 1990).

b) The Mediterranean Outflow Water (MOW) flows along the middle slope of the Portuguese margin towards the Galicia Margin and the Bay of Biscay and extends to depths of approximately 1,500 m. This water mass has two distinct cores, centred at depths of 800 and nearly 1,200 m (Ambar and Howe, 1979; Mazé *et al.,* 1997; Iorga and Lozier, 1999; Ambar *et al.,* 2002; Slater, 2003; González-Pola*,* 2006), one of which flows to the west of the Galicia Bank plateau and then continues northward, while the other flows eastwards along the Cantabrian Margin slope. On its southwestern slope, the MOW exhibits high speeds and variabilities at 1100 m depth (with a mean of 18 cm/s and peaks of more than 40 cm/s, Ruiz Villarreal *et al.,* 2006). Moreover, several observations of the meddies (eddies from MOW) along the Galician margin have been published (Fiúza *et al.,* 1998; Paillet *et al.,* 1999*,* 2002; Zhang *et al.,* 2016).

c) The deep-water masses, i.e., those below a 1,500 m water depth (wd), consist of the southward-flowing North Atlantic Deep Water (NADW), flowing between 1,500 and 3,000 m wd, below the northward-flowing Lower Deep Water (LDW) (Van Aken, 2000). The NADW flows below the LSW from the Labrador Sea eastwards towards the Bay of Biscay (Pingree and Le Cann, 1990) and reaches the Galicia margin. This water mass may exhibit a north-westward return flow over the Celtic continental slope (Paillet *et al.,* 1998), and its core, initially defined by Saunders (1986), is located in this margin, between approximately 2,500-3,000 m wd. On the Galicia margin, the LDW is characterised by a near-bottom northward-directed flow at approximately 4,000 m wd

(Paillet and Mercier, 1997; Van Aken, 2000). A cyclonic recirculation cell over the Biscay Abyssal Plain has been identified as having a characteristic poleward velocity near the continental margin of 1.2 (± 1.0) cm/s (Dickson *et al.,* 1985; Paillet and Mercier, 1997).

Internal tides and waves have been locally reported along the slopes of the Bay of Biscay as being due to a combination of favourable water mass stratification, steep topography and strong barotropic tidal currents (Pingree and Le Cann, 1989, 1990; Fiúza *et al.,* 1998; Apel, 2002; Jackson, 2004; Varela *et al.,* 2005; García-Lafuente *et al.,* 2006; Krahmann *et al.,* 2008; Prieto *et al.,* 2013; Zhang *et al.,* 2016).

3. DATA AND METHODOLOGY

The study area is located between the latitudes of 44°57' N - 43°10' N and the longitudes of 13°50' W - 05°29' W, extending across an area of approx. 90,000 km^2 at water depths of 300-5,000 m (Fig. 1A). This work has been conducted in the framework of the 'Scientific Research Programme of the Economic Exclusive Zone of Spain', which is coordinated and directed by the Defence Ministry of Spain. During the oceanographic cruises conducted aboard the R/V Hespérides in 2003 and from 2006 to 2009, bathymetry and reflectivity data as well as ultrahigh-resolution seismic profiles were acquired.

A high-resolution bathymetric map was obtained using the Simrad EM-12 S120 multibeam echosounder, which allows for the simultaneous collection of high-resolution seafloor bathymetry and backscatter strength measurements. This system covers a sector of the seafloor that is approximately three times the water depth in which it operates. The seismic records comprise ultrahigh-resolution single-channel profiles that were obtained with a TOPAS (TOpographic PArametric Sonar) PS 018 system. This system is a hull-mounted seabed and sub-bottom echosounder that is based on a parametric acoustic array and that operates using the nonlinear acoustic properties of the water (Dybedal and Boe, 1994). The penetration of the acoustic signal achieved with the TOPAS system varies from between 0 and 200 ms (twtt) at full oceanic depths.

The data analysis includes: (1) the classification and cartography of the main morphologies, (2) echo-character/backscatter analyses and mapping, and (3) a correlation between the bathymetry, superficial acoustic facies and acoustic backscatter to interpret and discuss the possible sedimentary processes and their shaping of the seafloor. The nomenclature for the echo-character analysis was based on the classic guidelines established by Damuth (1980) and Pratson and Line (1989) but was adapted for the acoustic response of the study area. High-resolution bathymetry and backscatter data analyses have been very useful for the marine research community as they reflect the many studies undertaken for the characterisation of surficial morphologies, sedimentary composition and regional deep-sea environments (Damuth, 1978; Damuth *et al.,* 1988; Pratson and Laine, 1989; Jackson and Briggs, 1992; Hernández-Molina, 1993; Hughes Clarke *et al.,* 1996; Pudsey and Howe, 1998; Wynn *et al.,* 2000; Lee *et al.,* 2002, among others). However, to avoid interpretation errors based on these indirect methods, the information should be complemented with sedimentological data from surface samples (ground truths), near-surface stratigraphy and, if possible, information of near-bottom currents, benthic organism reworking, temperature and salinity (Damuth, 1980; Mc Clennen, 1989; Pratson and Laine, 1989). The scarcity of these types of data in our study area has been compensated for via the correlation of our results with the published results from other works on the sedimentological and sedimentary processes in other nearby areas (e.g., the Armorican system, Zaragosi *et al.,* 2000, 2001a, b, 2006; the southwestern Galicia Bank, Ercilla *et al.,* 2008a, 2011; Hernández-Molina *et al*., 2008; the Cantabrian continental margin, Crémer, 1983; Ercilla *et al.,* 2008b; Iglesias, 2009; along the southern Iberian Peninsula margin, Gràcia *et al.,* 2003; Terrinha *et al.,* 2003) and in similar systems, such as those located in northwestern Africa (Wynn *et al.,* 2002; Talling *et al.,* 2007).

The nomenclature for the general morphological features and classification criteria is based on Emery (1980), Weaver *et al.* (2000) and Posamentier *et al.* (2000). For more specific morphologies, such as those related to the along-slope sedimentary processes, the classifications for the contourite depositional features (*drifts*) proposed by Faugères *et al.* (1999), Rebesco and Camerlengui (2008) and García *et al*. (2009) for contourite erosive features have been used. The mounded, elongated and separated drifts have been referred as *separated* drifts. Those deposits that show the intercalations of along- and down-slope and/or hemipelagic/pelagic sedimentary processes have been called *mixed systems*. In addition, those bathymetric elevations atop the marginal platforms between submarine canyons, within which sedimentary waves do not show the same wavy expressions as on the seafloor, have been called *relict sediment waves.* The morphological nomenclature related to the down-slope sedimentary processes is based on the works of Mutti and Normark (1987), Carter (1988), Alonso and Ercilla (2000), Einsele (2000), Mayall and Steward (2000), and Posamentier and Kolla (2003), among others. The nomenclature for the echo-character analysis was based on the classic guidelines established by Damuth (1975, 1978, 1980), Damuth and Hayes (1977), Mullins *et al.* (1979), Mc Clennen (1989), and Pratson and Laine (1989).

4. MAIN MORPHOSEDIMENTARY FEATURES

On the continental slopes and abyssal plains of the study area, numerous morphological features have been identified based on their seafloor expressions, echo and backscatter characteristics (Figs. 3, 4), as summarised in Tables 1 and 2.

4.1. Physiographic provinces

The northwestern Iberian margins are generally characterised by narrow shelves (approx. 30 km wide) with slopes that extend down to 5,000 m wd and widths that range from between 22-45 km and increase eastwards. Their gradients are highly variable and range from 1° to 12° (Figs. 3A, B).

Westwards of 9 °W, the average width of the continental slope is 35 km and extends down to 5,000 m wd. This zone shows an average gradient of 6° and is crossed by three main submarine canyons that are, from west to east, the Lage, A Coruña and El Ferrol canyons. Additionally, three marginal platforms, namely, the Ortegal, Pardo Bazán and Castro platforms, are located between 200-2,400 m wd (Fig. 3A, B).

Eastwards of 9 °W, the continental slope extends down to 4,800 m wd and is narrower and steeper (being 22 km wide with a gradient of 12°). This zone is characterised by numerous submarine canyons, the most significant of which are the San Jorge, La Frouseira and Avilés canyons (Figs. 3A, B).

The Galicia and Cantabrian continental slopes abruptly pass into the Biscay and Iberian abyssal plains (Figs. 3A, B), which extend down to 5,000 and 5,300 m wd, respectively, and are characterised by the E-W Charcot High to the north and the A Coruña and Finisterre highs to the west, which show a NE-SW trend. A deep passage, the Theta Gap, connects these two abyssal plains (Figs. 3A, B). The Biscay Abyssal Plain, which is characterised by a gentle relief with a 0.03° gradient towards the SW, extends down to 5,100 m wd near the Theta Gap but is found to reach approximately 4,900 m wd near the Cantabrian Margin. The Iberian Abyssal Plain shows a gradient of 0.05° towards the southwest (Figs. 3A, B).

4.2. Morphologies related to tectonics

Four main morphologies related to tectonic have been described: (1) *marginal platforms,* (2) *structural highs, (3) scarps, and* (4) *fluid escape-related features* (Fig. 3C). The main morphological features, such as the lengths, widths, directions, gradients and depths are summarised in Table 1. The echo types are shown in Fig. 4, and the acoustic and reflectivity characteristics are summarised in Table 2.

- *Marginal platforms* have considerable spatial extents (approximately 1600 km^2), relatively gentle slopes (0.2° to 2.5°) and are characterised as having Echo-Type 3A in its distal parts. These include the Ortegal, Pardo Bazán and Castro platforms (Fig. 5A).

- *Structural highs.* The main structural highs are a) the Ordoño and Fernando Highs of the northern Galicia Bank zone, with up to 650 m of vertical relief, which are delimited by several NNW-SSE and NE-SW scarps (Figs. 5A-C); and b) those located on the abyssal plain comprising the E-W trending Charcot High, which is located at 3,200 m wd, and the predominantly NNW-SSE trending A Coruña and Finisterre highs, which are found at approximately 4,200-4,300 m wd. These three highs are characterized by reliefs varying from 650 to 1,800 m and by Echo-Type 3A.

- *Scarps.* On the Ortegal and Pardo Bazán Marginal platforms, there are several scarps with slopes of 14-27° and 150-700 m reliefs (Fig. 5C). These scarps are acoustically characterised by Echo-Type 3A.

- *Fluid escape-related features* are located mainly in the Ortegal Marginal Platform and are characterised by Echo-Type 1G. These features have been observed as having dome-shaped cross-sections with heights of 1 m and diameters of 150 m (Fig. 5D). Other positive relief features with circular and/or elliptical shapes that correspond to coralline mounds with heights of 3 m and diameters of 150 m are shown (Fig. 5E). In addition, almost 340 pockmarks (collapse craters) up to 16 m deep with 30-450 m diameters have been identified (Figs. 5D, E).

4.3. Morphologies related to bottom currents

Five main depositional contourite features have been observed in the study area (Figs. 3, 6A): (a) *plastered drifts,* (b) *mounded elongated and separated drifts*, (c) *mixed systems*, (d) *relict sediment waves* and (e) *sediment waves*. Two erosive contourite features comprising (f) *moats* and (g) *abraded surfaces* have also been identified. The main morphological features, such as length, width, direction, gradient and depth are summarised in Table 1. The echo types are shown in Fig. 4 and the acoustical and reflectivity characteristics are summarised in Table 2.

- *Plastered drifts.* From south to north, several upslope-prograding plastered drifts (Echo-Type 1C), with thicknesses ranging from between 20 to 80 ms (twtt), have been mapped as follows, (a) along the flanks of structural highs (northern zone of the Galicia Bank) at 2,600 m wd (Fig. 6B), (b) on the Pardo Bazán Marginal Platform at 1,200-1,700 m wd, (c) at the head of the A Coruña Canyon at 400-500 m wd, and (d) in nearby canyons, such as to the north of the El Ferrol Canyon (1,000-1,200 m wd), south of the A Coruña Canyon (1,200 m wd), and around the Lage Canyon (down to 2,500 m wd).

- *Mounded, elongated and separated drifts.* From south to north, several separated drifts have been described as being characterised by Echo-Type 1C and showing average thicknesses of 40 ms (twtt). They have been identified at the following locations: (a) to the southwest of the Fernando High at 2,700 m wd, (b) to the west of the Pardo Bazán Marginal Platform at 1,600 m wd, (c) to the northeast of the Pardo Bazán Marginal Platform at 1,200-1,400 m wd, (d) to the northwest of the Ortegal Marginal Platform at 600-800 m wd, (Fig. 6C) and (e) to the north of the Galicia Bank and Castro Marginal Platform at 5,000 m wd in the Biscay Abyssal Plain (Fig. 6D).

- *Mixed systems.* The whole Castro Marginal Platform is a zone comprising mixed systems that are approximately 50 ms (twtt) thick and are found over several parts of the structural highs. Acoustically, these deposits are characterised by well-stratified facies interbedded with transparent and chaotic layers (Fig. 6E), corresponding to Echo-Type 1B.

- *Relict sediment waves.* The western distal parts of the Pardo Bazán and Castro marginal platforms are characterised by sediment waves 2 km long and 15-25 m high that do not show the same morphological expression. These deposits have been classified as Echo-Type 1H (Fig. 6F).

- *Sediment waves.* These are observed only at the head of the El Ferrol Canyon and are characterised by N-S alignments, heights of 5 m, lengths of 200 m, wavelengths of 400-600 m and Echo-Type 4C. These waves are asymmetric with a steeper (3°) eastern side (Figs. 6G, H).

- *Moats*. Several moats have been described as associated with the previously reported separated drifts. They are characterised by seismic reflections truncated by the depression walls with generally symmetric V-shaped cross-sections (Fig. 6C). They are identified as follows: (a) south of the Fernando High, at 2,700 m wd with a thickness of 50 m; (b) in the southwestern and northeastern zones of the Pardo Bazán Marginal Platform, at 1,800 and 1,500 m wd, respectively, with incisions that range from between 4 and 15 m deep; (c) in the Ortegal Marginal Platform, at the heads of the A Coruña and El Ferrol canyons, located at 450-800 m and showing incisions that are 5-20 m deep (Fig. 6C); and (d) in the Biscay Abyssal Plain, where they are characterised by 10 m deep incisions (Fig. 6D).

- *Abraded surfaces*. An extensive area characterised by an erosional surface is located to the southwest of the Ortegal Marginal Platform with a NE-SW trend. The surface defines a very high reflectivity subhorizontal plain, described as characterized by Echo-Type 1A or Echo-Type 1F (Figs. 6C, I). Also, small sectors in the shallowest part of the Ortegal Marginal Platform are described by Echo-Type 1F as abraded surfaces.

4.4. Morphologies related to gravitational processes

- Four main depositional gravitational features have been observed in the study area, including (a) *submarine slides* and (b) *debris-flow deposits,* both of which are included as mass-transport deposits in Table 1, as well as (c) *submarine fans* and (d) *levees*. In addition, three erosive gravitational features have been identified, including (e) *canyons,* (f) *submarine channels* and (g) *gullies* (Fig. 7A). The main morphological features are summarised in Table 1. The echo types are shown in Fig. 4, and the acoustic and reflectivity characteristics are summarised in Table 2.

- *Slides* are common at the borders of the canyons walls, and several isolated slides have been identified along the steepest zones of the continental slope, such as the northern zone of the Galicia Bank (17°) and within the transition of the Ortegal to Pardo Bazán marginal platforms (5°). These slides are characterised by slightly to highly deformed, back-rotated, stratified and chaotic masses resting at the base of a steep scarp (Fig. 7B) as well as by Echo-Type 3B. The heads of the larger slides display scars on the seafloor or show a rugged seafloor when many slides coalesce.

- *Debris-flow deposits.* Extensions of debris-flow deposits of up to 200 km^2 have developed along the lower continental slopes in the distal parts of the El Ferrol and A Coruña canyons at 4,800-4,900 m wd (Fig. 7C). Moreover, on the flanks of the Charcot High, these morphologies are generally 5-16 km long, 3-12 km wide and associated with steep slopes (Fig. 7D). These deposits are characterised by Echo-Type 1D. Also, another mass-transport deposit has been identified in the shallowest sector of the Ortegal Marginal Platform and is characterised by Echo-Type 2A.

- *Submarine fans.* Several submarine fans have been described at the termination of the main submarine canyons located on the Cantabrian Margin and to the north of the Inner Basin (Fig. 7A). These fans are described from east to west as follows: a) the first group comprises the three fans (i, ii and iii in Fig. 7A) that cover the most extensive span of the study area (approx. 300 km long and 70 km wide) and show a dominantly E-W orientation as well as a SE-NW trend with fingers-like shapes in their distal regions; b) the second group comprises three fans located perpendicular to the Cantabrian and Galicia margins that are approximately 5-45 km wide and 29 to 80 km long (iv to vi in Fig. 7A). Acoustically, these fans are mainly characterised by Echo-Type 1B, but fan iii in Fig. 7A is also characterized by Echo-Type 3B.

- *Channel-levees.* A group of channel-levees is described in the Biscay Abyssal Plain between the Ortegal Spur and the Charcot High and is called the Charcot Mid-Oceanic Channel System (Fig. 7E). Two more levees are observed along the right margin of the Ortegal Channel. These levees form part of a second mid-oceanic channel system called the Cantabrian Mid-Oceanic

Channel System (Fig. 7F). These levees are approximately 5-18 m thick and are characterised by Echo-Type 1B.

- *Submarine canyons.* Numerous submarine canyons cross the continental slope of the study area, displaying very steep walls and U- or V-shaped cross-sections with high degrees of incision. The main canyons, described from west to east, are as follows (Fig. 8A): (a) Lage Canyon, which begins in the Castro Marginal Platform (2,200 m wd) (Fig. 8B); (b) A Coruña Canyon, which begins in the Ortegal Marginal Platform (500 m wd) (Fig. 8B); (c) El Ferrol Canyon, which begins in the Ortegal Marginal Platform (500 m wd) (Fig. 8B); (d) San Jorge Canyon, which is located to the west of the Ortegal Spur (500 m wd) (Fig. 8C); and (e) La Frouseira Canyon, which begins at a 900 m wd (Fig. 8C).

Numerous minor canyons to the east at 1,200-1,500 m wd have been described as being primarily characterised by perpendicular and rectilinear trajectories and are U- and V-shaped with 200 m deep incisions. Note that there are several of these minor canyons located in the northern sector of the Ortegal Marginal Platform and to the east of the La Frouseira Canyon that change their orientations from S-N to SW-NE in the distal areas (Fig. 8A). These erosive features are characterised by Echo-Type 3A.

- *Submarine channels*. The channels comprising the Charcot Mid-Oceanic Channel System are characterised by three main channels that are approximately 2-10 m deep: the Biscay, Hespérides and Charcot channels, with several distributaries that are approximately 3-14 km wide, 100 km long, 3-10 m deep and have a NE-SW trend (Figs. 8A, F, E, G). However, the mid-oceanic channels of the Cantabrian System comprise two main channels (the Southern and Ortegal channels) that are 20 to 15 m deep (Fig. 8A). These channels are mainly characterised by Echo-Type 1L but are also characterised by Echo-Type 4B in the proximal zones of the Biscay Channel and by Echo-Type 1E in some parts of the Charcot System and extensive zones of the Ortegal and Interplains Channels. All of these submarine channels converge and are constrained through the Theta Gap, where the interplain channel is formed (Figs. 8A, H, I). This channel adapts its flow to the A Coruña and Finisterre highs and is characterised by a V-shaped cross-sectional profile that is 200 m deep.

- *Gullies.* Several V-shaped gullies that are approximately 30-70 m deep have been observed in the distal parts of the Pardo Bazán and Castro marginal platforms at 2,200-2,700 m wd and in the northern part of the Galicia Bank at 3500 m wd, although these are 25 m deep (Figs. 8A, D).

5. INTERPRETATION OF THE RESULTS AND INSIGHTS INTO CONTINENTAL MARGIN SEDIMENTARY PROCESSES

5.1. Geomorphology and links with morphostructures and sedimentary processes

The integration and comparison of the results provides some practical applications for indirect near-surface and seafloor interpretations. Even though occasionally smooth or subdued bathymetric reliefs characterise the study area, especially in the abyssal plains (Figs. 3A, B), backscatter maps help to better differentiate the heterogeneities and diversities of the seafloor deposits (Fig. 4B). The characteristics and regional distributions of the morphological features (Fig. 3C and Table 1) and echo types (Figs. 4A, 9 and Table 2) show that the seafloor in the study area is highly variable and complex.

The continental slope is predominantly characterised by highly reflective erosional features that result in *Echo-Types 1A, 1F, 1H and 3A*. The areas characterised by *Echo-Types 1A and 1F* are located along an extended SW-NE surface of the Ortegal Marginal Platform and of the Pardo Bazán Marginal Platform. The near-surface sediments obtained in this area have been studied and found to consist of clean, coarse sands and silty sands comprising surrounded and well-sorted quartz and glauconite grains as well as abundant bioclastic fragments (Alejo *et al.,* 2012). This is evidence of high-energy environments and evolving erosion. The area characterised by *Echo-Type 3A* is located along submarine canyons, on the steep marginal platform edges and on structural highs and could be associated with the outcropping of sedimentary rocks or consolidated sediments derived from both erosion and/or tectonics. The area characterised by *Echo-Type 1H* is observed on the lower continental slope and shows similar characteristics to that of *Echo-Type 1C* but is superficially eroded. This pattern can be interpreted as contourite drifts comprising sediment waves that have recently been partially reshaped or eroded. On the other hand, the depositional features mainly located at the heads of A Coruña and El Ferrol canyons (*Echo-Type 4C*), between the Ortegal and Pardo Bazán marginal platforms and on the flanks of the structural highs (*Echo-Type 1C*), represent sediment waves and widespread contourite drifts.

Likewise, the area characterised by *Echo-Type 3B* in submarine canyons could be associated with slides and those characterised by *Echo-Type 2A* in the shallowest zones of the Ortegal Platform are possibly associated with mass-transport deposits from depositional gravitational processes. The areas characterised by *Echo-Type 3C*, recorded on the floors of several channels of *Echo-Type 1B*, are observed on the Castro Marginal Platform. *Echo-Type 4A* is observed in the proximal zones of structural highs and could be associated with the interplay of turbidites or contourite sedimentary processes. Finally, a sector characterised by *Echo-Type 1G* is locally observed in a distal sector of the Ortegal Marginal Platform and is related to fluid escape processes, making this process very characteristic of zones where a continuous supply of fluid flows toward the surface from below (Hovland and Judd, 1988).

These results indicate that gravitational processes are predominant on the abyssal plains. The depositional gravitational features are mainly described as the levees (*Echo-Type 1B*) along several deep-sea channels and as the debrites at the base of several structural highs (*Echo-Type 1D*). Deposits from recent hemipelagic/pelagic sedimentation (*Echo-Type 1E*) infilling several areas of the deep-sea channels suggest the inactivity of those channels. In addition, despite sediment waves being a common feature of many turbidite systems found in areas crossed by unconfined turbidity currents, the observed sediment waves on several levees and submarine lobes (*Echo-Type 4B*) as well as the undulating deposits on proximal zones of the structural highs (*Echo-Type 4A*) cannot be definitively attributed to either turbidity or contour current influence. There is no clear evidence to identify a specific sedimentary process, so we considered that the origins of these deposits and sediment waves can be influenced by both down- and along-slope.

The erosive gravitational processes are represented by several deep-sea channels (*Echo-Type 1I*), especially those located along the westernmost part of the study area (i.e., Hespérides, Charcot and Biscay channels). Another erosive feature of the gravitational processes or the tectonic-related basement outcrops is described the steep structural highs (*Echo-Type 3A*).

5.2. Consideration of tectonic processes

The main morphostructural features of the northwestern Iberian Margin (marginal platforms, scarps and structural highs, Fig. 5 and Table 2) are controlled by several basement structural highs and depressions as well as asymmetric ridges produced by extensional rotated blocks, which are the result of the complex geodynamic evolution of this area that spans the Mesozoic to the present. Currently, it is possible to observe the recent rejuvenation of the escarpments via the reactivation of the NW-SE to N-S and NW-SE normal faults, the tilting of the recent sedimentary sequences above the structural highs, the development of gentle folds related to basement horst and grabens, the sudden changes in the lateral thicknesses of the sedimentary units, the development of growth faults affecting the sedimentary deposits, and the development of sedimentary wedges at the feet of escarpments related to the erosional processes of the fault scarps or sedimentary instabilities (Vázquez *et al.,* 2008). The fault reactivation is evidenced by low to moderate seismic activity that is mainly distributed along the NE-SW and NW-SE fractures (Giner *et al.,* 1999; López-Fernández *et al.,* 2002).

Morphological features generated by fluid escape processes in the Ortegal Marginal are observed to be aligned in two directions, NE-SW and NW-SE (Jané *et al.,* 2010). These directions are parallel to the orientations of the local fractures and are coincident with the locations of the master basement faults. In the same way, the strikes of the maximum axes of the elongated pockmarks are NW-SE to N-S, NE-SW and ESE-WNW, which are also parallel to the main tectonic structures. Moreover, the presence of mound-type deposits with conical or elongated morphologies on the surrounding seabed close to the pockmarks suggest violent eruptions that were sufficiently intense to instantaneously lift huge sedimentary ejecta volumes and were probably related to earthquakes (Clifton *et al.*, 1971; Hasiotis *et al.,* 1996; Tsunogai *et al.,* 1998; Nikonov, 2002; Hieke, 2004; Kusçu *et al.,* 2008; Lomtev and Gurinov, 2009; Vologina *et al.,* 2012; Fischer *et al.,* 2013). It has been demonstrated that earthquakes may suddenly increase fluid emission rates when the magnitude of the seismic event is greater than or equal to a 5 on the Richter scale. This is consistent with the calculations of the maximum magnitudes carried out by Martín-González *et al*. (2010) from a fault analysis of the northwestern sector of the Iberian Peninsula, which reported earthquake magnitudes between 6.1 to 6.8 Mw.

On the Biscay Abyssal Plain, the two large morphostructural features described, namely, the Charcot and A Coruña Highs, are related to the uplift of the oceanic crust spanning the Alpine Orogeny to the present day (Medialdea *et al.,* 2009) and follow an orientation established by a cortical anisotropy. The oceanic crust typically displays a tectonic spreading fabric parallel to the spreading ridge at which the crust was generated (Lonsdale, 1977; Laughton and Searle, 1979). The extension in this sector led to the formation of the Bay of Biscay with an E-W direction and the North Atlantic Ocean with a NE-SW direction. Thus, the Charcot High, which exhibits an E-W orientation, and the A Coruña High, which shows a NE-SW trend, are the result of the reactivation and uplift of the oceanic crust under the Cenozoic stress field favouring tectonic spreading. The deformation and progressive uplift of the Galicia continental margin produces the tilting of the Biscay Abyssal Plain, increasing the seafloor slope towards the north and northwest by approximately 2.5° on average.

Moreover, the orientations of the submarine canyons coincide with the main structural trends defined in the northwestern sector of the Iberian Peninsula (Arthaud and Matte, 1975; De Vicente and Vegas, 2009; Maestro *et al.,* 2017). The Lage, A Coruña and El Ferrol canyons in the Galician margin have NE-SW, NW-SE and EW orientations (Fig. 8B), and the San Jorge and Frouseria canyons in the Cantabrian Margin have predominantly N-S to NNE-SSW and NE-SW orientations (Fig. 8C). The easternmost part of the study area includes the Avilés Canyon, which is related to the offshore continuation of the Ventaniella Fault, has a N137°E orientation and was identified from early bathymetric studies of the Biscay Margin (Boillot *et al.,* 1979; Derégnaucourt and Boillot, 1982).

The presence of steep slopes that commonly exceed 30° in the study of the continental slope of the northern part of the Galicia Margin is caused by tectonic processes that occurred during the Alpine Orogeny, leading to the uplift of the Galicia and Cantabria margins due to the subduction of the Biscay oceanic crust under the Iberian continental crust (Gallastegui, 2000; Gallastegui *et al.,* 2002). Some studies have shown that these uplift processes are still active, as seen via those emerged areas with episodic elevations of coastal terraces (Flor, 1983; Mary, 1983; Alvarez-Marrón *et al.,* 2008) and by the presence of reverse faults in the Quaternary materials located on the coastal terraces (Gutierrez-Claverol *et al.,* 2006).

5.3 Down-slope sedimentary processes

Several submarine canyons, turbidites, slides and debrites are locally distributed on the upper and lower slopes (Fig. 7A and Table 1). They represent the products of both erosional and depositional gravitational sedimentary processes, but most of these features are also caused by tectonics (see section 5.2). This is the case for the main submarine canyons in this study, which are often deeply incised. Many of these canyons are obliquely aligned with the slope and are isolated from areas with fluvial input. Thus, their morphologies are related to their underlying basement topography and faulting. Likewise, the occurrence of slope failures seems to be largely associated with the steep slope gradients of the canyon walls and the tectonic activity that can trigger seismic events. There are numerous studies that relate the mass-transport processes with well-known earthquakes (Sultan *et al.,* 2004; Biscontin and Pestana, 2006; Shanmugam, 2006; Mulder, 2011; Argnani *et al.,* 2012; Dugan, 2012; Lindhorst *et al.,* 2012; Vargas *et al.,* 2012).

The abyssal plains are characterised by the presence of two deep-sea channels systems that are the products of gravitational sedimentary processes. For the first time, this study reveals the courses and morphologies of two independent mid-oceanic channel systems in the Biscay Abyssal Plain: the *Cantabrian and Charcot turbidite systems* (Fig. 10A). The origins of these systems seem to be associated with the distal parts of the Cap Ferret (Figs. 10B, C) and the Armorican deep-sea fans (Fig. 11A), respectively. These systems can extend over long distances, which may be due to an increase in the slope gradient along the abyssal plain that sustains the energies of turbidity currents, as was observed by other authors in different regions (Laughton, 1960; Carter, 1988). Moreover, another factor in their development could be the same as that observed in other similar systems, which is associated with landslide-generated sediment gravity flows that are capable of spreading over extensive abyssal plains and submarine fans (Piper and Normark, 1982; Weaver *et al.,* 1992; Wynn *et al.,* 2002, 2010; Skene and Piper, 2003, 2006; Talling *et al.,* 2007; Hunt *et al.*, 2011), which are often low-energy and non-erosive environments (Weaver and Thomson, 1993; Weaver, 1994).

- The *Cantabrian Turbidite System*, comprising several channels and lobate bodies beyond the ends of these channels (*Lobes-i to iii* in Fig. 10B), shows similar planform sizes and features to those described by Prélat *et al.* (2010). The similarities of the study Cantabrian System to other systems described in the literature (Deptuck *et al.,* 2008; Prélat *et al.,* 2009) suggest that this system constitutes a nice example of compensational stacking. The depositional architecture of a basin floor fan is determined in large part by flow discharge, sand-to-mud ratio, slope length, slope gradient, and seafloor rugosity (Posamentier and Kola, 2003; Deptuck *et al.,* 2008; Prélat *et al.,* 2009, 2010). Thus, depositional elements can change based on location and through time as environmental parameters change (Prélat *et al.,* 2010). For lobes where backscatter data have been collected along with cores, a relationship was proposed between the low (light) backscatter intensity and the presence of coarse-grained deposits (Unterseh *et al.,* 1998; Zaragosi *et al.,* 2000; Kenyon *et al.,* 2002). Therefore, taking this premise into consideration and given the observed backscatter and geometry in the studied lobes (Figs. 3, 4, 9), we suggest that Lobe-i is the most reflective and homogeneous and may have originated in a channel that propagates into the basin from the complex system of the Avilés Canyon (Fig. 10B). As this lobe is very similar to frontal lobes described in other areas (e.g., Posamentier and Kolla, 2003; Morris *et al.,* 2014; Ortiz-Karpf *et al.,* 2015) and seems to be dominated by deposits from high density turbidity currents and other high concentration flows. Its connection with the channel is covered by the development of two more lobes: Lobe-ii, the southernmost lobe in the system, is superimposed on some parts of the higher-backscatter Lobe-i and exhibits adaptations of its morphology to the previous Lobe-i (Fig. 10B); and Lobe-iii, which developed in the northern sector of Lobe-i, also adjusted its distribution depending on the previous lobes. These two lobes comprise many elongated finger-like or finger bodies spanning across the lobes (Fig. 10B). These features are commonly attributed to flow transformations from turbidity currents to strongly density stratified flows (e.g., Klaucke *et al.,* 2004; Talling *et al.,* 2010; Groenenberg *et al.,* 2010; Kane *et al.,* 2017; Spychala *et al.,* 2017). Lobe-iii also has sediment waves on its surface that can be migrated upslope and are roughly parallel to the regional slope (Fig. 10B). These waves seem to represent primary depositional features rather than being the product of slope failures or other types of post-sedimentary deformation. Similar bedforms located in the proximal areas of the submarine fan systems and channel-lobe transitions have been described and interpreted as sediment wave fields formed by unconfined turbidity currents (Wynn *et al.,* 2002). These features have been observed in the overall Cantabrian drainage system, comprising lobes and channels corresponding to a channel-lobe transition zone from the Cap Ferret system, which could be considered as a bypass-dominated area following the classification by Stevenson *et al.* (2015). The study system could is mainly connected to the Cap Ferret system (Crémer, 1983; Ercilla *et al.,* 2008b; Iglesias, 2009) and the Avilés Canyon area (Gómez-Ballesteros *et al.,* 2013).

- In the *Charcot Turbidite System*, prominent deep-sea channels parallel to the bathymetry that comprises numerous distributaries and several levees have been described (Figs. 7A, 8A and Table 1). Primarily based on backscatter and seismic profile data, this system is characterised by a low sinuosity (Fig. 9) and seems to be the oceanic continuation of the large Armorican Fan system (Fig. 11A) that is the result of sediment-laden turbidity currents that have eroded and deposited sediment several hundreds of kilometres basinward. The large extension of the Charcot System can be explained following the results of studies of other high-latitude regions where the Coriolis forces has been observed to influence the gravity currents within these submarine channels due to the very large channel-length scales (Wells and Cossu, 2013). There are numerous factors that can control the developments and sinuosities of submarine channels, such as the slope gradients, flow interactions with the seafloor topography, the calibre of sediment the channel is transporting and eroding into, and the channel maturity (e.g., Clark and Pickering, 1996; Kane *et al.,* 2008; Peakall *et al.,* 2012, among others). However, channel sinuosity is also affected by other factors, such as tectonic controls and sediment supply (e.g., Cronin, 1995; Clark and Cartwright, 2011; Babonneau *et al.,* 2002), and several authors have also suggested that channel sinuosity increases with time, with meander cut-offs forming during this process (e.g., Deptuck *et al.,* 2003; Gee *et al.,* 2007; Wynn *et al.,* 2007; Babonneau *et al.,* 2010; Maier *et al.,* 2013) or being linked to the Coriolis Force (e.g., Peakall *et al.,* 2012; Wells and Cossu, 2013). The Charcot System shares several affinities with the Equatorial Atlantic Mid-marine channel (Baraza *et al.,* 1997), and the Northwest Atlantic Mid-Ocean Channel (Klaucke *et al.,* 1997) as well as with the more recently identified and cored Agadir system (Wynn *et al.,* 2002; Talling *et al.,* 2007; Masson *et al.,* 2011; Stevenson *et al.,* 2014) and Tanzania channel system (Bourget *et al.,* 2008). The examples recently described in the literature have had origins of disintegrative submarine landslides, which can generate long run-out sediment gravity flows, or have been linked to the strong structural control of a sediment pathway associated with a massive sediment transfer towards the ocean related to tectonic activity. The presence or absence of levees in the Charcot System could be related to changes in the density stratification of its associated flows, as is discussed in other places, such that if there is a very narrow grain-size range, the construction of levees is unlikely (Kane and Hodgson, 2011). The observed levees can be classified as external levees (outer levees *sensu* Deptuck *et al.,* 2003, 2007; Kane and Hodgson, 2011). Moreover, several levees show sediment waves that are commonly identified in other regions of the modern seabed (e.g., Wynn et al., 2002, 2007; Posamentier and Kolla, 2003), marking constructional crests and/or silt-prone deposits on the outside outer bends of the external levees (e.g., Normark *et al.,* 1993; Migeon *et al.,* 2001; Wynn and Stow, 2002). Pelagic/hemipelagic sedimentation could produce these semi-transparent facie units with uniform thicknesses that mimic the previous morphologies (including the valley axes), indicating that the channels were inactive (e.g., Damuth *et al.,* 1988; Flood *et al.,* 1995; Baraza *et al.,* 1997; Wynn *et al.,* 2007).

5.4 Along-slope sedimentary processes

Several erosional (abraded surfaces and moats) and depositional (mounded and plastered drifts and sediment waves) features have been described as occurring mainly along the continental margin, e.g., the Ortegal, Pardo Bazán and Castro marginal platforms (at 0.4-0.8, 0.9-2.0 and 2.2-2.7 km wd, respectively) (Fig. 12) and to a lesser extent along the Biscay Abyssal Plain at a 5 km wd at the base of the slope (Fig. 6 and Table 1). Their distribution demonstrates the dominant control of the bottom currents on the sedimentary processes since the distribution coincides with the depths presently under the influence of several bottom currents (ENACW-MOW-NADW along the continental slope and LDW along the abyssal plain) and bounded by density contrasts (pycnoclines) (Figs. 1, 12).

The preliminary results confirm the interaction of the impinging MOW from west with the Ortegal Marginal Platform and the generation of a CDS via the sediment samples collected from near the surface of the drifts containing fine sands to muddy sandy (Hernández-Molina *et al.,* 2009a). The Ortegal Spur forms an obstacle to the MOW as the MOW flows around Cabo Ortegal and into the Bay of Biscay (Fig. 1), causing isopycnal doming and locally enhancing the flow velocity (Hernández-Molina *et al.,* 2011). The influence of the contemporary MOW reaches up to 600 m and down to 1500 m wd (Fig. 12) and can be locally forced higher up the slope such that the topography forms an obstacle to the flow. Thus, this MOW-topography interaction can explain many of the identified erosional and depositional features on the Pardo Bazán Marginal Platform as being influenced by the lower part of the MOW (Fig. 12). In general, the interaction of the contour current with the steep erosional surfaces likely causes highly focused flows within the moats running along their bases, inducing high bottom-current velocities (McCave, 1982) and erosion along the upslope walls. On the other flank of the moats, the flow velocity is reduced, inducing deposition on the separated mounded drifts and on the mounded side of the confined drifts. However, the plastered drifts located on the Pardo Bazán Marginal Platform (Fig. 12) follow the typical contourite accumulation scenario proposed by Faugères *et al.* (1999) and Rebesco (2005) for their development, consisting of a broad, non-focused current on a gentle slope at low current velocities. The drifts located at the base of the Fernando and Ordoño highs, which are influenced by the NADW, are evidence of the effects of obstacles on an impinging flow (Fig. 13). As has been described by other authors for different water masses, the water flow in the northern hemisphere seems to accelerate to the left of a seamount (looking downstream) and decelerate to the right (Roberts *et al.,* 1974; Gould *et al.,* 1981; Hernández-Molina *et al.,* 2006b). This standard behaviour in bottom currents supports the development of moats/mounded drifts on the left flanks of the Fernando and Ordoño highs and plastered drifts located on the right flank and/or around structural highs (Fig. 13). Moreover, the broad erosional and abraded surfaces have lower average slope angles and likely indicate the presence of less confined tabular bottom currents (Rebesco *et al.,* 2014).

While this conceptual model of the water mass interactions can explain many of the along-slope oriented features, it does not explain the presence of the sediment waves in Ferrol and A Coruña submarine canyons. A potential mechanism for these features is the spatial and temporal displacement of the pycnocline at the ENACW-MOW interface (Fig. 12) due to motions like meddies, internal waves and internal baroclinic tides (Cacchione *et al.,* 2002; Lamb, 2014). The interactions of these processes with the margin topography can induce strong bottom currents capable of eroding and redistributing sediments (e.g., Hernández-Molina *et al.,* 2011; Pomar *et al.,* 2012; Preu *et al.,* 2013; Shanmugam, 2013; Hanebuth *et al.,* 2015). The oceanographic measurements acquired on the Galician upper slope indicate large cross-slope-oriented baroclinic bottom currents of up to 19.4 cm/s (García-Lafuente *et al.,* 2006) and efficient internal tide generation on the Galician middle slope (Balmforth and Young, 2001; Zhang *et al.,* 2008; Quaresma and Pichon, 2013; Lamb, 2014). This type of interaction of the seafloor with the filaments of water masses forced to flow upslope could develop these kinds of sedimentary waves, as has been reported for other slopes (e.g., Van Rooij *et al.,* 2003, 2010; Iglesias, 2009).

On the other hand, those relict drifts and sediment waves described at 2,400-2,700 m wd (Table 1) are formed by water masses strong enough to develop contourites and sediment waves. Although the present depth of the AABW flow is below 3,500 m (Fig. 1), it is believed that this current was enhanced (Sarnthein *et al.,* 1982; Duplessy *et al.,* 1988; Maslin *et al.,* 1995; Zahn *et al.,* 1997; Elliot *et al.,* 2002) and shoaled at ~2,500 m (Keigwin, 2004) during the past, especially during the glacial periods. Several studies carried out along the Atlantic margin have discussed the variations in depth of the AABW in the deep Atlantic basin at subtropical Iberian latitudes during the glacial/stadial periods (Sarnthein *et al.,* 2001; Curry and Oppo, 2005; Voelker *et al.,* 2010; Friedrich *et al.,* 2014; Rodriguez-Tovar *et al.,* 2015; Howe *et al.,* 2016) was well as the importance of its influence on developing contourite features (Roque *et al.,* 2015).

Finally, the distal parts of several submarine canyons, e.g., the very noteworthy features to the east of La Frouseira Canyon (Fig. 4A) and the turbidite fans situated at the base of the slope (i.e., turbidite fan *iv* in Fig. 7A), show a change in their direction from S-N to SW-NE, which is interpreted as a consequence of the interplay of the S-N trending gravitational influence through the canyon with the W-S LDW circulation (Fig. 1).

6. DISCUSSION: ARCHITECTURAL SEDIMENTARY CHANGES AND EVOLUTION

6.1 Significance of the along-slope sedimentary processes in changing the conceptual glacially influenced margin model and its comparison with other glacially influenced margins

When considering all described bottom-current products, especially those described for the Ortegal, Pardo Bazán, and Castro marginal platforms (Figs. 5A, B and Table 1), the first noticeable aspect is the relationship between the positions of the water masses (Fig. 1B) and the developments of both depositional and erosive contourite features (Fig. 3C). These features are characteristics of *contourite terraces,* which are formed by the interplay between margin physiography and local current regimes. Marginal platforms or *marginal plateaus* are defined in the submarine morphology as "flat (subhorizontal) but deep (deeper than the shelf break) domains within the continental slope" (Mercier de Lépinay *et al.,* 2016). These features occur on all passive margins, occupying areas of more than 18,000,000 km^2 and comprising 5.11 % of the oceans (Harris *et al.,* 2014). The polyphase tectonic evolution, subsidence evolution and the sedimentary settings controlled by deep currents make the marginal plateaus a target for furthering our understanding of the continental margin and hydrocarbon exploration. Our study reflects that the bottom currents have overemphasized the tectonic processes responsible for the initial development of the marginal platforms and structural highs (Figs. 5, 12). In this new scenario, the Ortegal, Pardo Bazán and Castro marginal platforms, where both erosional and depositional contourite features are described (Fig. 12B) and where the water masses show remarkable density contrasts (Fig. 12C), can be considered to constitute large *contourite terraces* (hereafter named the *Ortegal, Pardo Bazán and Castro terraces*) (Fig. 14). Therefore, the study area constitutes an excellent example for the study of the control of inherited structures and the influence of the topography of marginal plateaus on the local and global circulations of intermediate and deep oceanic waters. Based on the correlations of these morphologies and the ocean regimes, we propose that terrace genesis is strongly connected to the turbulent current patterns typical of water mass interfaces. Furthermore, this energetic pattern might be enforced by internal tides and internal waves, which are known to be generated along strong density gradients typical of water mass interfaces and which have tremendous effects on sediment dynamics, resulting in erosion and resuspension (Dickson and McCave, 1986; van Raaphorst *et al.,* 2001; McCave, 2001; Cacchione *et al.,* 2002; Hosegood and van Haren, 2003). Several contourite terraces have been defined at other continental margins at different latitudes, with the difference with respect to our study area being related to the absence of a structural control on the terrace formation (e.g., Gulf of Cádiz, Hernández-Molina *et al.,* 2016a; Argentine margin, Hernández-Molina *et al*., 2009b; Gruetzner *et al.,* 2012; Preu *et al.,* 2013; the Uruguayan margin, Hernández-Molina *et al.,* 2016c; Alboran Sea, Ercilla *et al.,* 2016).

This contribution proposes that although there are similarities with respect to the previous conceptual "glacially influenced margin" related to the development of numerous submarine canyons and turbidity currents that deliver sediment to abyssal plains (e.g., Kenyon *et al.,* 1978; Lebreiro *et al.,* 1997; Wynn *et al.,* 2000), there is a remarkable difference in the interplay of the down- and along-slope processes, including the presence of 1) three marginal platforms on the continental slope dominated by along-slope processes evolving into contourite terraces and 2) down-slope processes that are only minimally active on the upper slope but are dominant in the lower slope and abyssal plain regions (Fig. 14). These are two major and peculiar characteristics that suggest another perspective of the study area wherein the contour currents rework and/or redistribute the gravity deposits.

6.2. Recent changes in the architectural sedimentary evolution

Down-slope and along-slope sediment transports are the dominant processes during the evolution of continental margins and have major impacts on the shapes of these margins (Stow and Faugères, 1998; Faugères *et al.,* 1999; Stow *et al.,* 2002). Previous studies of glacially influenced margins have suggested that during full-glacial periods, sediment delivery onto the slope was mainly achieved by down-slope mass-wasting processes, while along-slope processes that deposited contourites dominated during interglacial times when the bottom currents were generally stronger and on the abyssal plains (Weaver *et al.,* 2000). In the study area, we propose that the contourite processes were dominant over the middle slope, mainly caused by the MOW circulation and associated with the enhancement of this current during the glacial cycles (Cacho *et al.,* 2000; Schönfeld and Zahn, 2000; Llave *et al.,* 2006, 2010, 2011; Voelker *et al.,* 2006; Hernández-Molina *et al.,* 2011, 2016a; Toucanne *et al.,* 2007, 2012; Rogerson *et al.,* 2012). However, the down-slope processes, which are mainly focused on the upper and lower slopes, are also considered to be more active in the study area during regressive and lowstand stages (Zaragosi *et al.,* 2001a and b; Toucanne *et al.,* 2012) but are dissipated by along-slope processes on the middle slope where the along-slope processes are dominant. This scenario could explain the absence of extensive turbidity systems off the contourite terraces (Fig. 14), and nevertheless they only develop to the east and west of the terraces and associated to the Cap Ferret and Armorican turbidity systems, respectively. Therefore, watermasses circulating in the study area show another example within modern oceans of their importance in re-suspending and advecting seafloor sediments or pirate sediments from other sedimentary processes (e.g., gravity flows),

The contourite terraces may have being controlled by the following key factors, starting with a) the local morphology of the margin: inherited geological features conditioned the study area as having pelagic platforms located on its middle/upper slopes. These structures produced changes in the regional slope trends, providing the best areas for local water mass interactions with the seabed. The next factor is b) sediment supply: superficial samples of the drifts are mainly characterised as biogenic sandy contourites (Hernández-Molina *et al.,* 2009a; Alejo *et al.,* 2012). However, a wide variety of sediment inputs in CDS generation could also be considered. Contour currents can redistribute gravity supplied sediments or simply rework gravity deposits and transport any sedimentary drift bodies downward. Additionally, a greater direct sediment supply from the shelf and hinterland sources should be expected during the regressive and lowstand periods. The third factor is c) oceanographic changes: a vertical variability of the contourite features is observed, including erosive features close to the interface depths, plastered drifts between the interface depths and the upslope progradation of the mounded drifts and sediment waves, suggesting a vertical upward/downward migration or expansion, which observed most clearly at the depths of the MOW. Glacioeustatic changes could have facilitated the absence of the sedimentary imprints of the studied contourite terraces. Palaeoceanographic models of the MOW and its interfaces in the Western Mediterranean Sea and the Gulf of Cádiz assume that intermediate and deep Mediterranean water masses strengthened and sank to approximately 600-700 m deeper than its modern counterpart during the glacial periods of the Quaternary (Cacho *et al.,* 2000; Schönfeld and Zahn, 2000; Llave *et al.,* 2006, 2010, 2011; Voelker *et al.,* 2006; Hernández-Molina *et al.,* 2011, 2016a; Toucanne *et al.,* 2007, 2012; Rogerson *et al.,* 2012). In the study area, this deepening reflects a shift of the upper interface to below 1,100 m wd and of the lower interface down to 2,200 m wd (Sánchez-González, 2013). Our sedimentary model suggests that during colder periods, the deeper ENACW/MOW and MOW/LSW pycnoclines influenced the distal sector of the Ortegal terrace, the upper part and distal sector of the Pardo Bazán terrace and the upper part of the Castro terrace, mainly by developing erosive features (Fig. 12B) that could have masked the development of depositional features, including those that originated from gravity sedimentary processes. Those sectors located between the pycnoclines were more favourable for depositional features, which could be relict or even have been eroded by successive variations of the interface depths. It is possible that the interplay between the along- and downs-slope processes is less evident along the Castro Marginal Platform as a result of the smaller sensitivities to local changes in the LSW compared to those in the MOW, which would lead to alternating periods of dominant along- and down-slope sedimentary processes as well as the generation of the described mixed systems.

On the other hand, the Iberian Abyssal Plain is mainly characterised by two turbidite systems shaping the seafloor, which are the main contributors to both the outbuilding of the distal continental margin and basin infilling (Fig. 10). The Charcot System records multiple phases of incision and several pelagic/hemipelagic sediment infills that are evidence of intervals of active and inactive channel-levee systems (Figs. 7E, F, 8E-I). This fact has sometimes been related to local or regional changes in sediment supply rates or has been considered as being relative to variations of the sea-level. The systems that are connected to the Armorican and Celtic systems in the north (Fig. 11A) are assumed to have increased activity when increased sediment delivery is produced during lowstand sea levels (Zaragosi *et al.,* 2001a, b; Toucanne *et al.,* 2012). In contrast, one can expect that the complete burial and abandonment of a large and long-persistent deep-sea channel could be a consequence of first-order tectonic processes. Our study proposed that there is an evolution in this development/abandonment of several channels and distributaries that is mainly associated with the continental margin deformation and consequent tilting with a progressively westward increased gradient of the abyssal plain during the Pleistocene. The confinement by the structural highs of the flow along with the glacioeustatic changes and influences on the sediment supply are especially important in the submarine landside and the turbidity current activity during the Quaternary (Auffret *et al.,* 2002). The progressive changes in the recent evolution of the system can be synthetized as follows: (a) the first stage consists of an erosive phase when the Charcot, Biscay and Hespérides channels were incised into the seafloor following the topography of the Charcot High and were intensified by the constricted conditions between the Charcot High and the Ortegal Spur (Fig. 11B); (b) the second stage, marking an intensification of the turbidity currents, is observed along the Hespérides channel, which progrades towards the Charcot High, and the development of additional tributaries and levees is observed (Fig. 11C); (c) The third and final stage, consisting of the inactivity of the tributaries and the predominant intensification of the Hespérides channel, is then observed. In this final stage, an extensive levee also develops along the Hespérides channel to the south of the Charcot High (Fig. 11D).

The Biscay Abyssal Plain regionally slopes in a southward direction and (in the area close to the A Coruña High) its deepest section favours the convection of all of these channel/levee systems through the Theta Gap (Fig. 8A). This connection narrows to approximately 5 km wide between the Biscay Abyssal Plain (average water depth of 5,100 m) and the Iberian Abyssal Plain (approximately 5,300 m deep) and could have acted as a deep-ocean overflow between oceanic basins of different depths (Legg *et al.,* 2009). Active erosion occurs approximately 15 km upslope of the narrowing between the structural highs and creates initial incisions of up to 200 m and later incisions of approximately 30 m at points further along the current's course (Figs. 8H, I and Table 1). The straightening of the LDW water mass (Fig. 1) due to this constriction and a topographic barrier could be responsible for an overflow of the water mass generation that favours the excavation of the interplain channel. A change in sedimentation in the more distal part of the interplain channel system would then occur, and turbidites would progressively be replaced by the pelagic/hemipelagic deposits caused by the switch-off of turbidity flow activity (Fig. 8I).

These sedimentary modes and their recent evolution comprising the interplays of the structural and along- and down-slope sedimentary processes require further investigation (i.e., regarding their stratigraphy and sedimentary characterisation) since they have important implications for regional and global climate dynamics, morphostructural evolution and hydrocarbon reservoirs. Thus, the interplay of down-slope and along-slope processes represents a critical and little known topic in the study of deep-marine sedimentation (e.g., Hernández-Molina *et al.,* 2006, 2009b; Rebesco *et al.,* 2008; Mulder *et al.,* 2008; Mutti *et al.,* 2009; Marches *et al.,* 2010; Talling *et al.,* 2012; Brackenridge *et al.,* 2013; Stow *et al.,* 2013).

7. CONCLUSIONS

A comprehensive sedimentary evolution of the recent depositional processes operating along the northwestern Iberian Margin and its adjacent abyssal plains is proposed herein. Our evolutionary and conceptual model provides new perspectives of the interplays between down- and along-slope sedimentary processes in shaping this glacially influenced margin and the important role of bottom currents in obscuring the tectonic process signatures in this area.

Down-slope processes are dominant on the upper and lower slope and within the abyssal plain regions but have minimal impact on the middle slope, which is strongly influenced by along-slope processes. These processes show minimal concurrent interactions.

Therefore, this study provides a new perspective of the early continental margin model based on two main and peculiar characteristics. A) The northwestern Iberian continental slope is affected by down-slope gravitational processes (mass-transport and turbidity) that mainly occur within canyons. However, the dominance of contourite features (contourite drifts, sediment waves, moats and abraded surfaces), described mainly along the inherited marginal platforms, is evidence of the influence of the intermediate bottom currents and their importance in shaping the seafloor and the evolution of contourite terraces. B) The abyssal plains are dominated by pelagic/hemipelagic deposits as well as by debris flows and turbidity currents where two complex channel-lobe systems develop (i.e., the Cap Ferret and Armorican turbidite systems). Nevertheless, in this abyssal plain down-slope scenario, several contourite features are also observed at the foot of the continental slope as a result of the influence of the deepest water masses.

This recent and/or present-day sedimentary stacking pattern and the sediment dynamics in the study area are the result of both the structural framework and the variability of sedimentary systems and processes influenced by glacioeustatic changes. Tectonic processes are considered to be the controlling factors over the long -term, while sediment supply and climatic conditions have critical influences on the present-day configuration of the area at the basin scale, having played major roles over the short -term by influencing the variabilities of different sedimentary processes. Note that the tectonic processes have mainly conditioned the inherited marginal platforms as well as the structural highs, which have then influenced the interactions with the bottom currents, even modifying the signatures of down-slope activity. In the abyssal plains, tectonics processes have also controlled the westward migration of the channels/levee systems by tilting the continental margin. In addition, the lateral and vertical shifts of the water masses influence the depth, and their interfaces have left imprints on the reshaping and evolution of the recent sedimentary architecture of the continental slope, which was conditioned by the climatic variations during the Pleistocene.

Future work in this area should aim to provide a better understanding of the formation, timing and evolution of the morphostructural and morphosedimentary features of this region and to better constrain the interactions between tectonic, gravitational and bottom-current processes as well as sediment supply and climate variations.

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Figure Captions:

Figure 1. A) Digital bathymetric model of the study area. B) Regional circulation of the main water masses (updated and modified from Hernández-Molina *et al.,* 2011).

Figure 2. Geological and tectonic setting of the northwestern Iberian continental margin and the adjacent abyssal domains, modified from Rodriguez-Fernández *et al*. (2014). The bathymetric map was derived from satellite and ship track data (Smith and Sandwell, 1997).

Figure 3. A) Digital bathymetric model of the study area and the locations of some main physiographic and morphosedimentary elements: (1) Ortegal Marginal Platform, (2) Pardo Bazán Marginal Platform, (3) Castro Marginal Platform, (4) Avilés Canyon, (5) La Frouseira Canyon, (6) San Jorge Canyon, (7) El Ferrol Canyon, (8) A Coruña Canyon, (9) Lage Canyon, (10) Inner Basin, (11) Fernando High, (12) Ordoño High, (13) Finisterre High, (14) A Coruña High, (15) Charcot High, (16) Theta Gap, (17) Biscay Abyssal Plain, (18) Iberian Abyssal Plain. B) Gradient map. C) Morphological map.

Figure 4. A) Echo-character map and locations of some main physiographic elements (see the legend of the main physiographic and morphosedimentary elements in Fig. 3A). Legend of the different echo-type descriptions in Table II. B) Backscatter map.

Figure 5. A) Digital bathymetric model of the study area and locations of some main physiographic and morphosedimentary elements (see the legend of the main physiographic elements in Fig. 3A). B) and C) Bathymetric profiles. TOPAS (D-I) and digital bathymetric examples (D'-I') of fluid escape-related features. See text for detailed descriptions.

Figure 6. A) Digital bathymetric model of the study area and the locations of some main physiographic and morphosedimentary elements (see the legend of the main physiographic elements in Fig. 3A). B-I) TOPAS examples of the main contourite features. Depositional contourite features comprising plastered drifts (B), separated drifts (C and D) and sediment waves (G and H). Erosive contourite features are represented by moats (C and D), abraded surfaces (I) and the erosion of relict sediment waves (F). Mixed drifts occur where alternations of contourite and turbidite features are shown (E).

Figure 7. A) Digital bathymetric model of the study area and the locations of some main physiographic and morphosedimentary elements (see the legend of the main physiographic elements in Fig. 3A). B-F) TOPAS examples of the main depositional gravitational features. Depositional gravitational features comprise slides (B), debrites (C and D) and levees (E and F). Also, note that several erosive features are represented by the turbidite channels (E and F).

Figure 8. A) Digital bathymetric model of the study area and the locations of some main physiographic and morphosedimentary elements (see the legend of the main physiographic elements in Fig. 3A). B) and C) Digital bathymetric model of the main studied submarine canyons. D-I) TOPAS examples of the main erosional gravitational features, such as submarine canyons (B and C), gullies (D) and mid-oceanic channels (E to I).

Figure 9. Main morphologies interpreted via backscatter analyses.

Figure 10. A) Digital bathymetric model of the study area and the locations of some of the main physiographic and morphosedimentary elements (see the legend of the main physiographic elements in Fig. 3A). B) Down-slope sedimentary processes described in this study. C) Correlation of this study within the Cantabrian Margin and Abyssal Plain interpretation by Iglesias (2009).

Figure 11. A) Locations of the Celtic and Armorican turbidity systems related to the development of the Charcot Mid-Oceanic Channel. B-D) Evolution of the Charcot Mid-Oceanic Channel in the western part of the Biscay Abyssal Plain.

Figure 12. Vertical distribution of the water masses flowing in the eastern part of the study area in the digital terrain model (DTM). B) Seismic profile crossing the terraces (line position in panel A), where the different water masses and their interfaces are indicated for the present day, and the theoretical position of the MOW is indicated during glacial stages (in black) (Sánchez-González, 2013). C) Water mass percentages in the area adjacent to the contourite terraces (from Sánchez González, 2013).

Figure 13. A) Digital terrain model (DTM) of the northern part of the Galicia Bank showing the NADW bottom interaction that triggers the development of contourite deposits related to structural highs. Examples of high-resolution seismic profiles showing mounded, elongated and separated drifts in the western flank of the Ordoño (B) and Fernando (C) highs and D) a plastered drift on the western flank of the Ordoño High.

Figure 14. Sketch of the conceptual sedimentary model proposed in this study. The main tectonic, along- and down-slope sedimentary processes and the principal depositional/erosional products generated by these processes are shown.

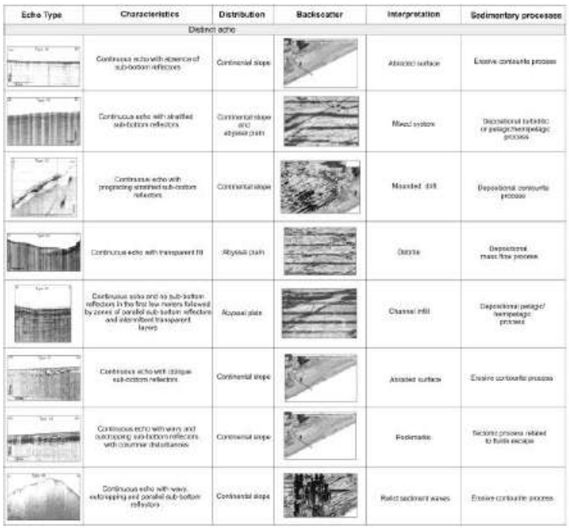
Table 2. Main morphological features identified in the study area based on their geneses.

Table 2. Characteristics of the main differentiated echo-character types and subtypes. * Length and width measured only within the study area. ** Gradient of the surface where a feature is developed. *** Gradient of the steepest flank.

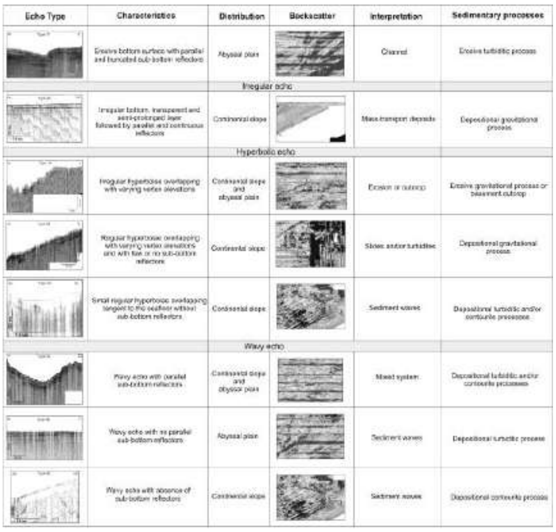
MORPHOLOGICAL FEATURES

	Morphology	Name	Lenght (km)	Width (km)	Direction	Gradient (º)	Depth (m)
STRUCTURAL FEATURE	Structural highs	Ordoño	11,5*	18,6*	NW-SE	16-30	2000
		Fernando	17,8	4,7-0,7	NW-SE	23-30	2200
		Charcot	324*	44*	E-W	8-17	3200
		A Coruña	87*	96*	NNE-SSW	8-18	4200
		Finisterre	75*	20-30*	NNE-SSW	3-17	4300
	Scarps		5-20	0,5-2	NW-SE, NE-SW, NNW-SSE	14-27	600-2700
	Marginal platforms	Ortegal	160	22	NE-SW	0,4	200-800
		Pardo Bazán	80	25	NE-SW	2,5	900-2000
		Castro	32	17	NE-SW	1,5	2200-2700
	Fluid escapes-related features		0,03-0,45	0,03-0,45	NNW-SSE, NW-SE, NE-SW	-	200-800
DEPOSITIONAL FEATURE	Plastered drifts		7-55	10-20	NE-SW, NW-SE, E-W	0,5-0,8**	1000-2600
	Mounded elongated and separated drifts		10-15	2-5	NE-SW, NW-SE	2,2-4,6**	500-4500
	Mixed deposits		32	17	NE-SW	0,8-1,1**	2200-2700
	Relict sediment waves		20-30	7-8	NE-SW	2-4	2400-2700
	Sediments waves		0,2	2	E-W	3*** 1,7**	600-650
	Mass transport deposits		5-16	3-12	NE-SW, E-W	5-17**	4000-4200
	Submarine fans		30-300	5-70	NE-SW, NW-SE, N-S	0,6-2,2 0,03**	4600-4900
	Levees		35-150	4-13	NE-SW, E-W	0,2-0,8*** 0,04**	4800
EROSIVE FEATURE	Moats		5-15	0,5-2	NE-SW, NW-SE	1-5	500-4500
	Abraded surface		90	15	NE-SW	1-2	300-650
	Canyons	Lage	80	5-20	NE-SW, E-W	11-17	2200-4800
		A Coruña	72	4-6	NE-SW, NW-SE	4-9	500-4800
		El Ferrol	64	2-3	E-W, NW-SE	4-12	500-4800
		San Jorge	35	2-3	N-S, NE-SW	11	500-4500
		La Frouseira	26	1,5-4	NE-SW, NNE-SSW	10	900-4700
	Gullies		5-12	1,5	NW-SE	2,8	2200-3500
	Submarine channels						
	Cantabrian System	Southern	90	2-8,5	E-W	0,1	4700-4800
		Ortegal	306	1-7	NE-SW, E-W	0,03	4900-5100
	Charcot System	Charcot	242	2-12,5	NE-SW, E-W	0,02	4900-5000
		Vizcaya	170	3-17,5	NE-SW, E-W	0,02	4900
		Hespérides	358	3-12	NE-SW, E-W	0,04	4900-5100
	Interplains Channel		97	2,2-5	ENE-WSW, NW-SE, NE-SW	0,10	5000-5300

Table I



Echo Type	Characteristics	Distribution	Backscatter	Interpretation	Sedimentary processes
Distinct echo					
	Continuous echo with absence of sub-bottom reflectors	Continental slope		Abraded surface	Erosive contourite process
	Continuous echo with stratified sub-bottom reflectors	Continental slope and abyssal plain		Mixed system	Depositional turbiditic or pelagic/hemipelagic process
	Continuous echo with prograding stratified sub-bottom reflectors	Continental slope		Mounded drift	Depositional contourite process
	Continuous echo with transparent fill	Abyssal plain		Debrite	Depositional mass flow process
	Continuous echo and no sub-bottom reflectors in the first few meters followed by zones of parallel sub-bottom reflectors and intermittent transparent layers	Abyssal plain		Channel infill	Depositional pelagic/ hemipelagic process
	Continuous echo with oblique sub-bottom reflectors	Continental slope		Abraded surface	Erosive contourite process
	Continuous echo with wavy and outcropping sub-bottom reflectors with columnar disturbances	Continental slope		Pockmarks	Tectonic process related to fluids escape
	Continuous echo with wavy, outcropping and parallel sub-bottom reflectors	Continental slope		Relict sediment waves	Erosive contourite process

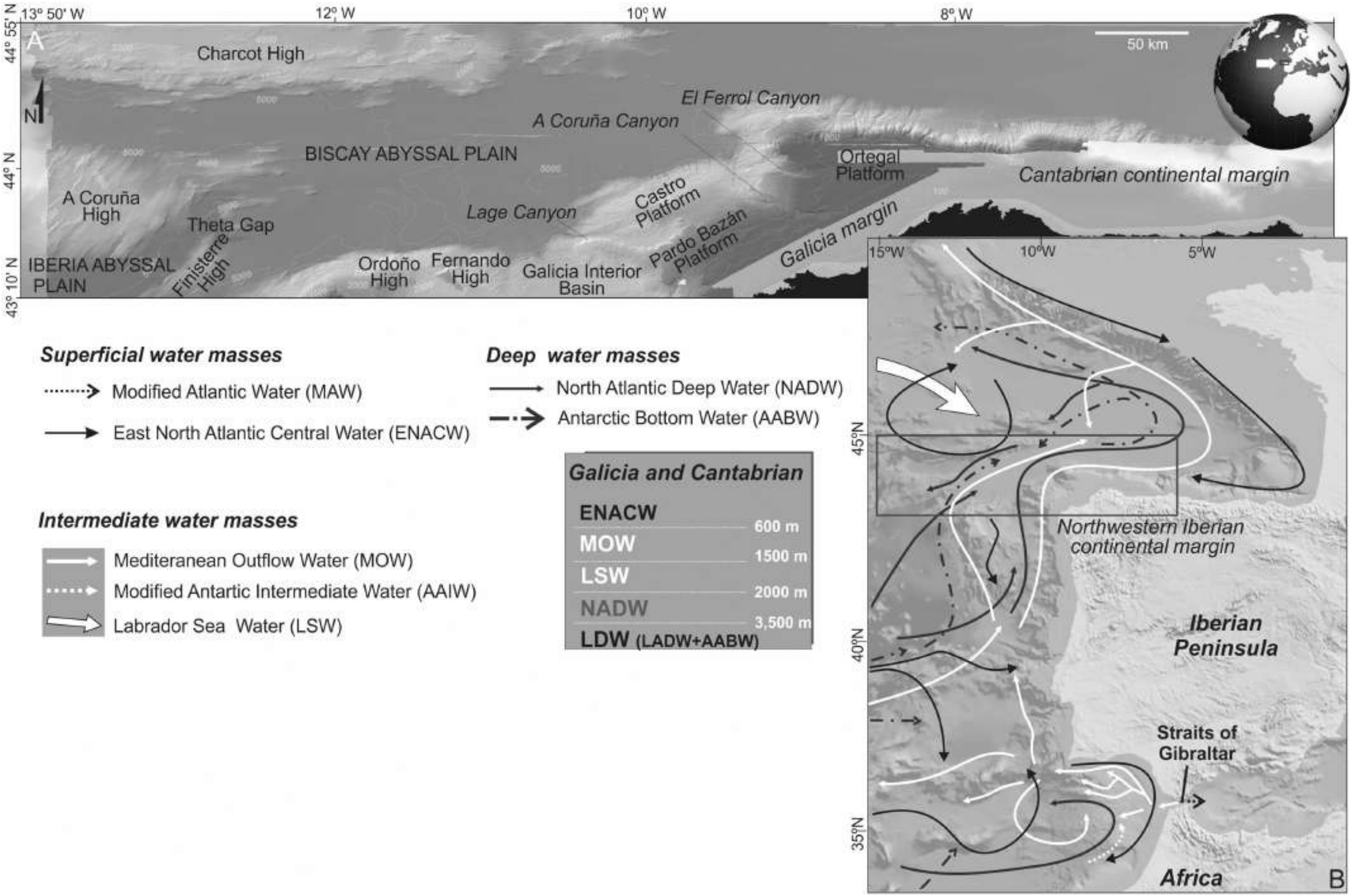


Echo Type	Characteristics	Distribution	Backscatter	Interpretation	Sedimentary processes
	Erosive bottom surface with parallel and truncated sub-bottom reflectors	Abyssal plain		Channel	Erosive turbiditic process
Irregular echo					
	Irregular bottom, transparent and semi-prolonged layer followed by parallel and continuous reflectors	Continental slope		Mass transport deposits	Depositional gravitational process
Hyperbolic echo					
	Irregular hyperbolae overlapping with varying vertex elevations	Continental slope and abyssal plain		Erosion or outcrop	Erosive gravitational process or basement outcrop
	Regular hyperbolae overlapping with varying vertex elevations and with few or no sub-bottom reflectors	Continental slope		Slides and/or turbidites	Depositional gravitational process
	Small regular hyperbolae overlapping tangent to the seafloor without sub-bottom reflectors	Continental slope		Sediment waves	Depositional turbiditic and/or contourite processes
Wavy echo					
	Wavy echo with parallel sub-bottom reflectors	Continental slope and abyssal plain		Mixed system	Depositional turbiditic and/or contourite processes
	Wavy echo with no parallel sub-bottom reflectors	Abyssal plain		Sediment waves	Depositional turbiditic process
	Wavy echo with absence of sub-bottom reflectors	Continental slope		Sediment waves	Depositional contourite process

Table 2

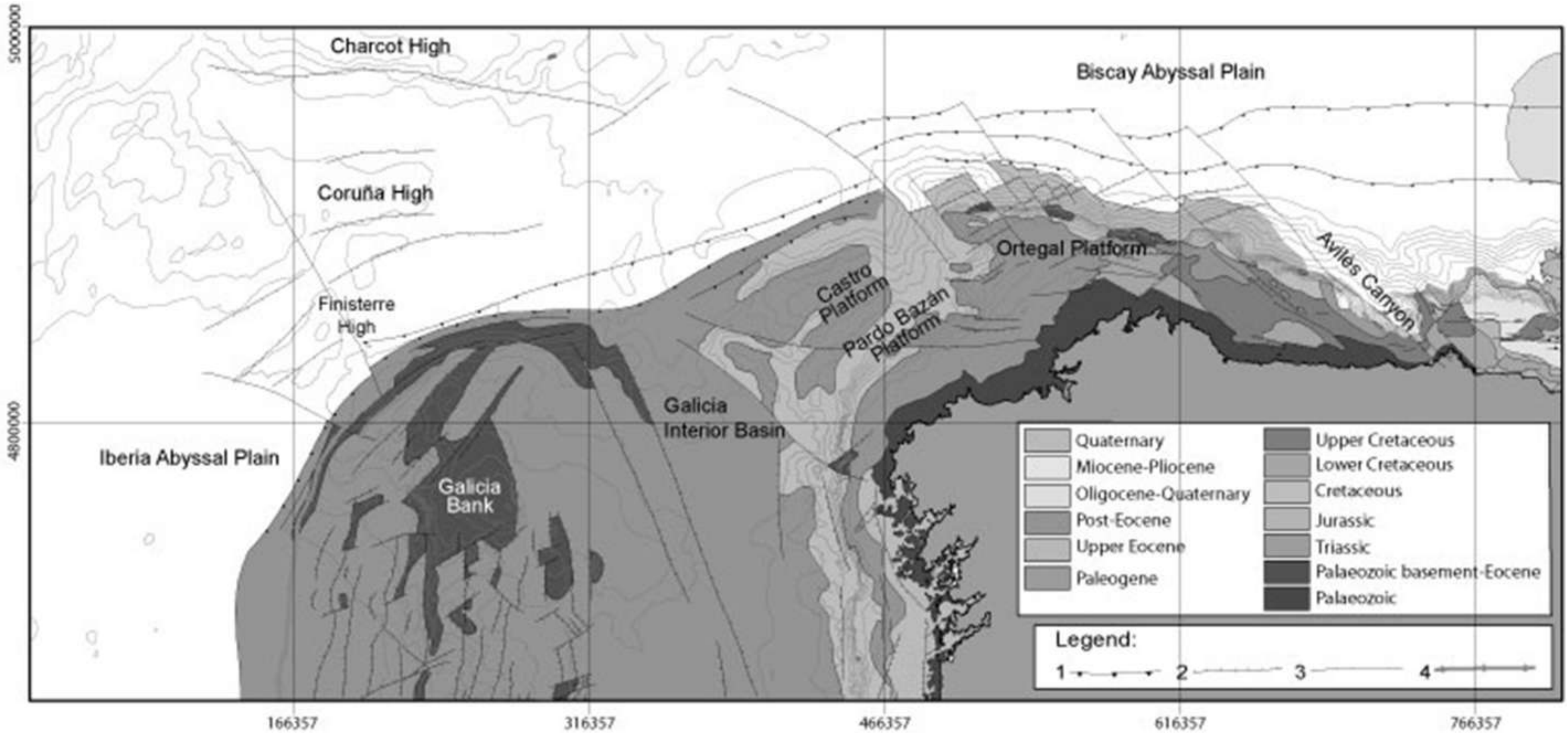
Highlights

- Down-slope sedimentary processes dominate the northwestern Iberia abyssal plains
- The continental slope shows interplay between along-slope and down-slope sedimentary processes
- Tectonic processes conditioned inherited marginal platforms
- Bottom currents re-shaped marginal platforms forming contourite terraces



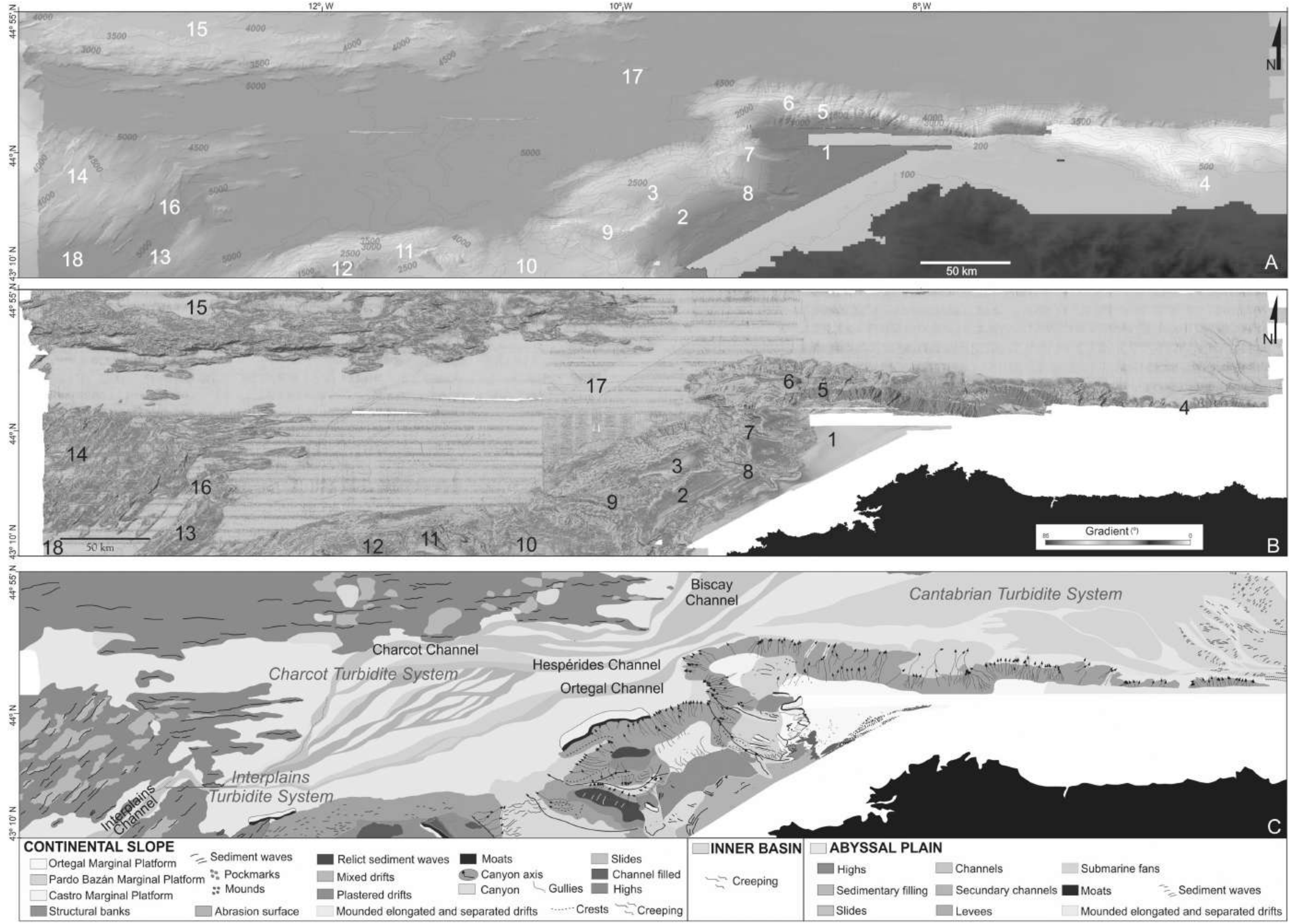
13° 50' W
12° W
10° W
8° W
44° 55' N
44° N
43° 10' N
A
50 km
N
Charcot High
El Ferrol Canyon
A Coruña Canyon
BISCAY ABYSSAL PLAIN
Ortegal Platform
Cantabrian continental margin
A Coruña High
Theta Gap
Lage Canyon
Castro Platform
Pardo Bazán Platform
Galicia margin
IBERIA ABYSSAL PLAIN
Finisterre High
Ordoño High
Fernando High
Galicia Interior Basin
Superficial water masses
Modified Atlantic Water (MAW)
East North Atlantic Central Water (ENACW)
Deep water masses
North Atlantic Deep Water (NADW)
Antarctic Bottom Water (AABW)
Intermediate water masses
Mediteranean Outflow Water (MOW)
Modified Antartic Intermediate Water (AAIW)
Labrador Sea Water (LSW)
Galicia and Cantabrian
ENACW
600 m
MOW
1500 m
LSW
2000 m
NADW
3,500 m
LDW (LADW+AABW)
15°W
10°W
5°W
45°N
40°N
35°N
Northwestern Iberian continental margin
Iberian Peninsula
Straits of Gibraltar
Africa
B

Figure 1



Charcot High
Biscay Abyssal Plain
Coruña High
Ortegal Platform
Avilés Canyon
Castro Platform
Pardo Bazán Platform
Finisterre High
Galicia Interior Basin
Iberia Abyssal Plain
Galicia Bank
5000000
4800000
166357
316357
466357
616357
766357
Quaternary
Miocene-Pliocene
Oligocene-Quaternary
Post-Eocene
Upper Eocene
Paleogene
Upper Cretaceous
Lower Cretaceous
Cretaceous
Jurassic
Triassic
Palaeozoic basement-Eocene
Palaeozoic
Legend:
1
2
3
4

Figure 2



12° W
10° W
8° W
44° 55' N
44° N
43° 10' N
N
50 km
A
B
Gradient (°)
C
Biscay Channel
Cantabrian Turbidite System
Charcot Channel
Hespérides Channel
Charcot Turbidite System
Ortegal Channel
Interplains Turbidite System
Interplains Channel
CONTINENTAL SLOPE
Ortegal Marginal Platform
Pardo Bazán Marginal Platform
Castro Marginal Platform
Structural banks
Sediment waves
Pockmarks
Mounds
Abrasion surface
Relict sediment waves
Mixed drifts
Plastered drifts
Mounded elongated and separated drifts
Moats
Canyon axis
Canyon
Gullies
Crests
Slides
Channel filled
Highs
Creeping
INNER BASIN
Creeping
ABYSSAL PLAIN
Highs
Sedimentary filling
Slides
Channels
Secundary channels
Levees
Submarine fans
Moats
Sediment waves
Mounded elongated and separated drifts

Figure 3

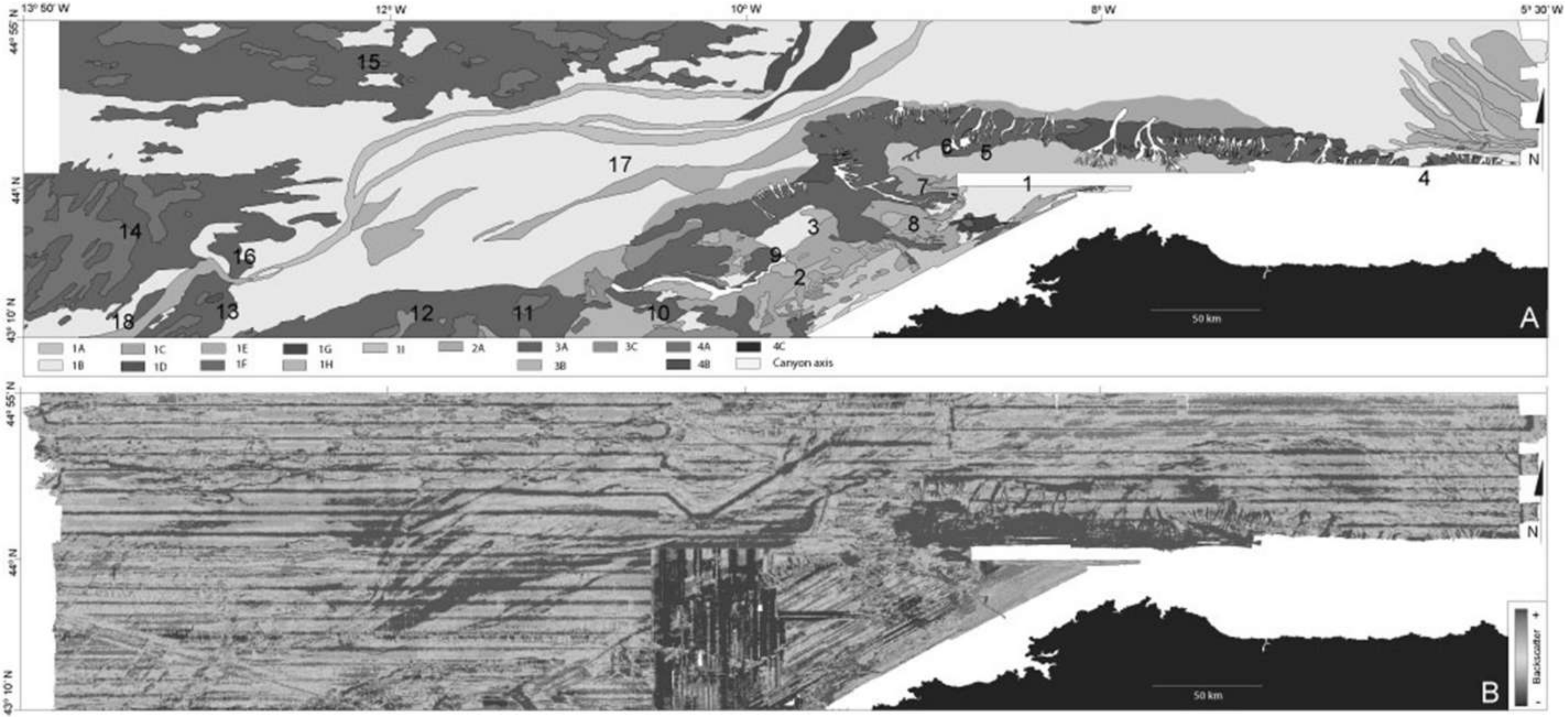

13° 50' W
12° W
10° W
8° W
5° 30' W
44° 55' N
44° N
43° 10' N
15
17
14
16
18
13
12
11
10
9
2
3
8
7
6
5
1
4
N
50 km
A
1A
1B
1C
1D
1E
1F
1G
1H
1I
2A
3A
3B
3C
4A
4B
4C
Canyon axis
N
50 km
Backscatter
+
-
B

Figure 4

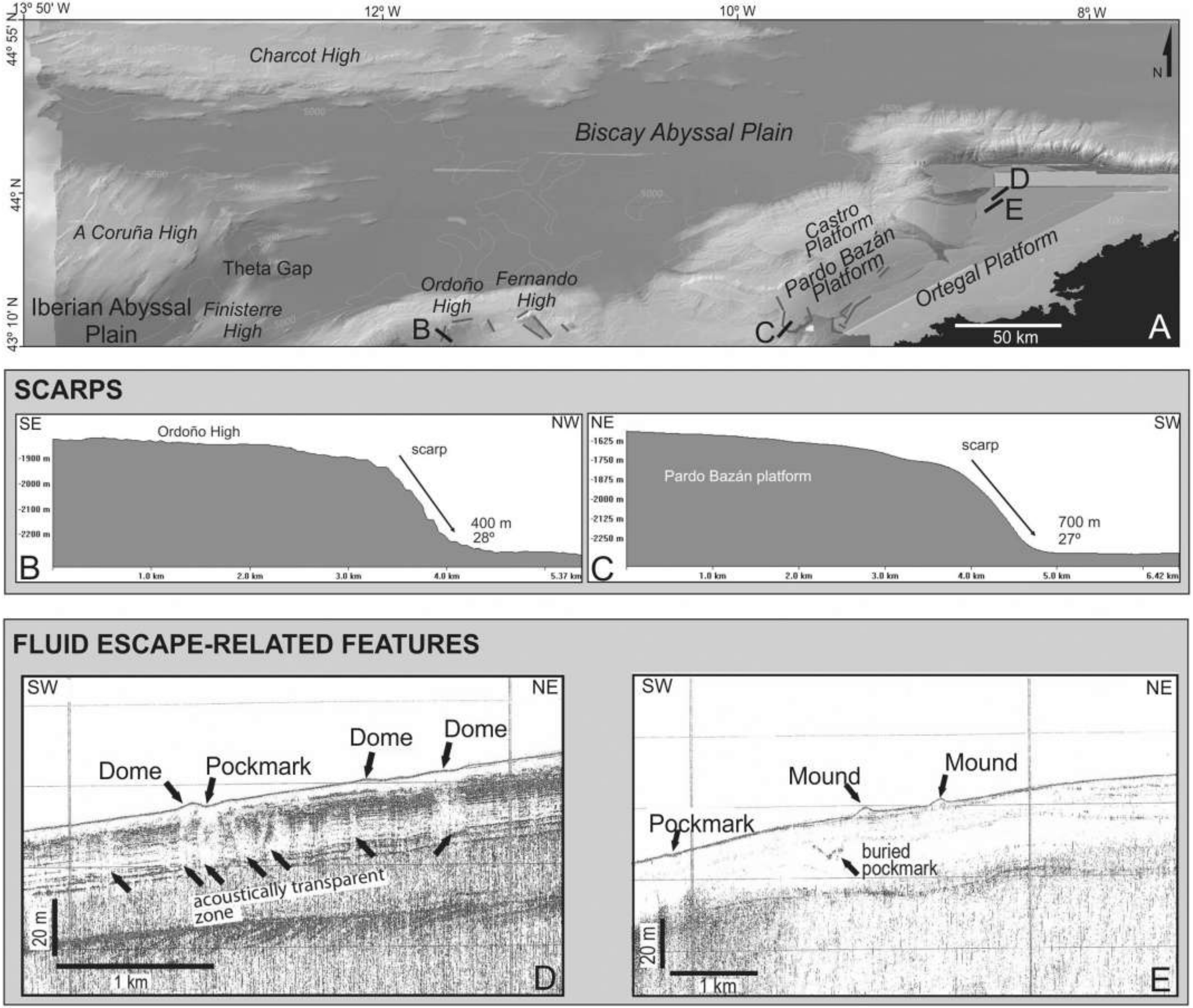

13° 50' W
12° W
10° W
8° W
44° 55' N
44° N
43° 10' N
N
Charcot High
Biscay Abyssal Plain
A Coruña High
Theta Gap
Iberian Abyssal Plain
Finisterre High
Ordoño High
Fernando High
Castro Platform
Pardo Bazán Platform
Ortegal Platform
50 km
A
B
C
D
E
SCARPS
SE
NW
Ordoño High
scarp
400 m
28°
-1900 m
-2000 m
-2100 m
-2200 m
1.0 km
2.0 km
3.0 km
4.0 km
5.37 km
NE
SW
Pardo Bazán platform
scarp
700 m
27°
-1625 m
-1750 m
-1875 m
-2000 m
-2125 m
-2250 m
1.0 km
2.0 km
3.0 km
4.0 km
5.0 km
6.42 km
FLUID ESCAPE-RELATED FEATURES
SW
NE
Dome
Pockmark
Dome
Dome
acoustically transparent zone
20 m
1 km
SW
NE
Pockmark
Mound
Mound
buried pockmark
20 m
1 km

Figure 5

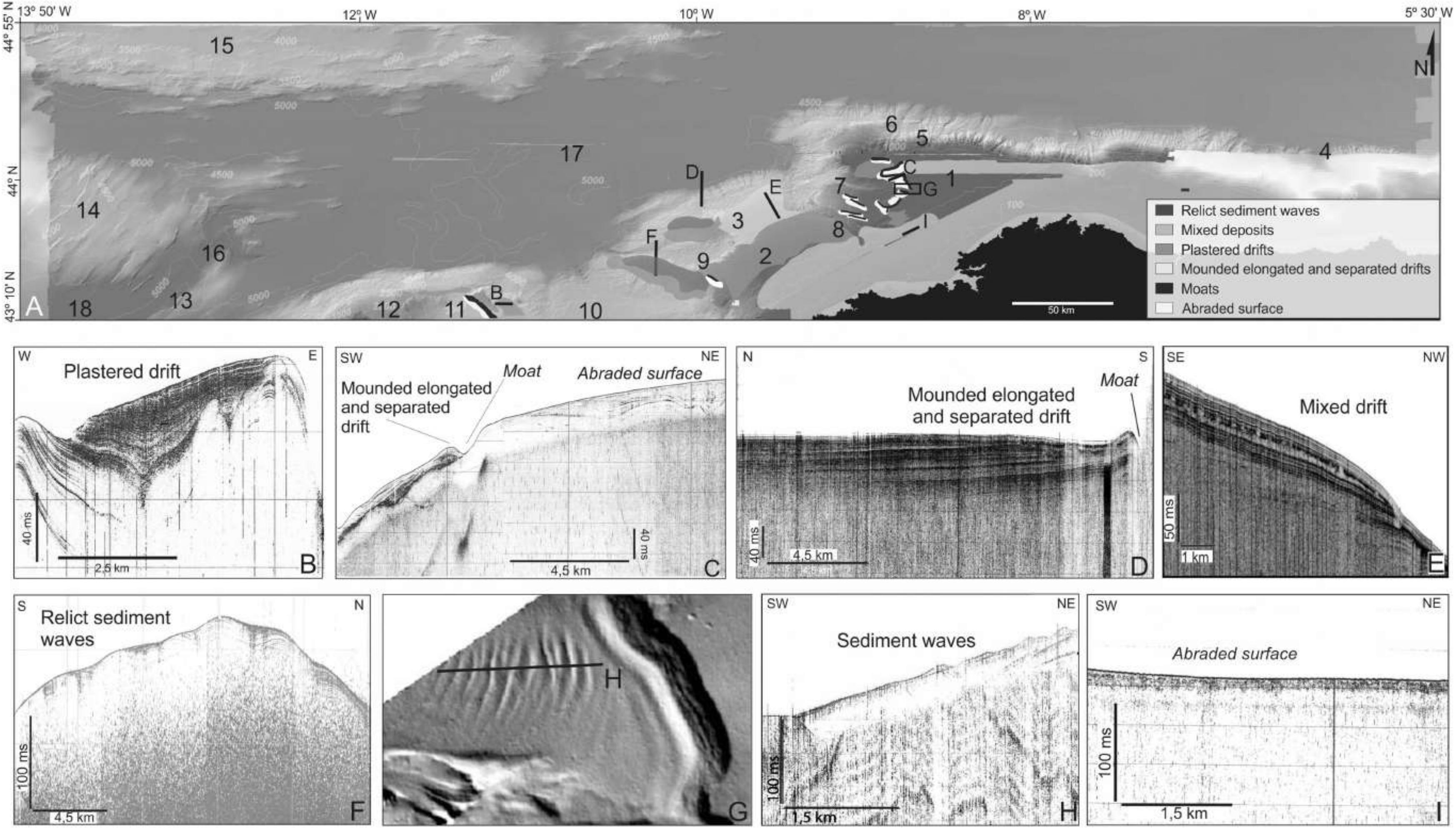
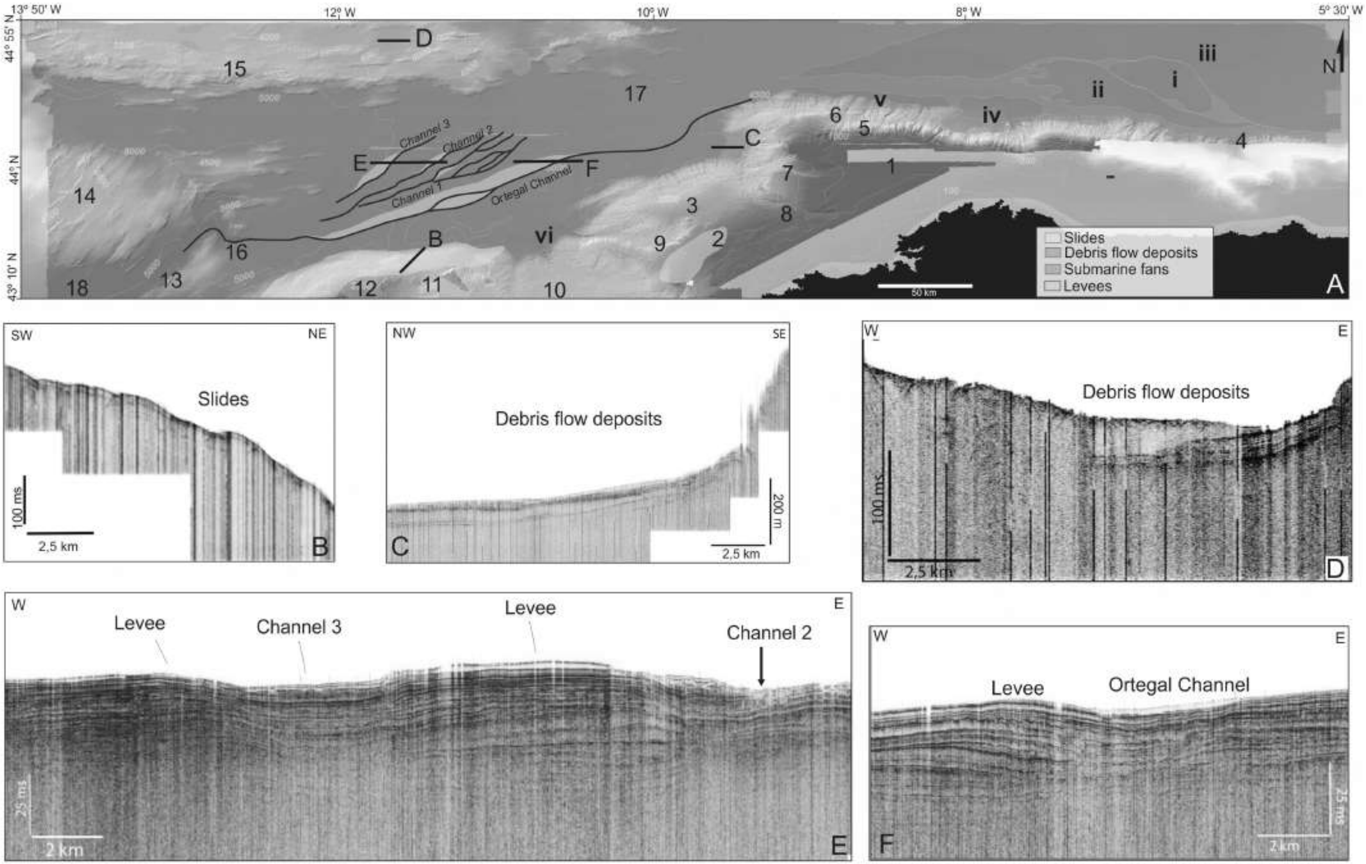
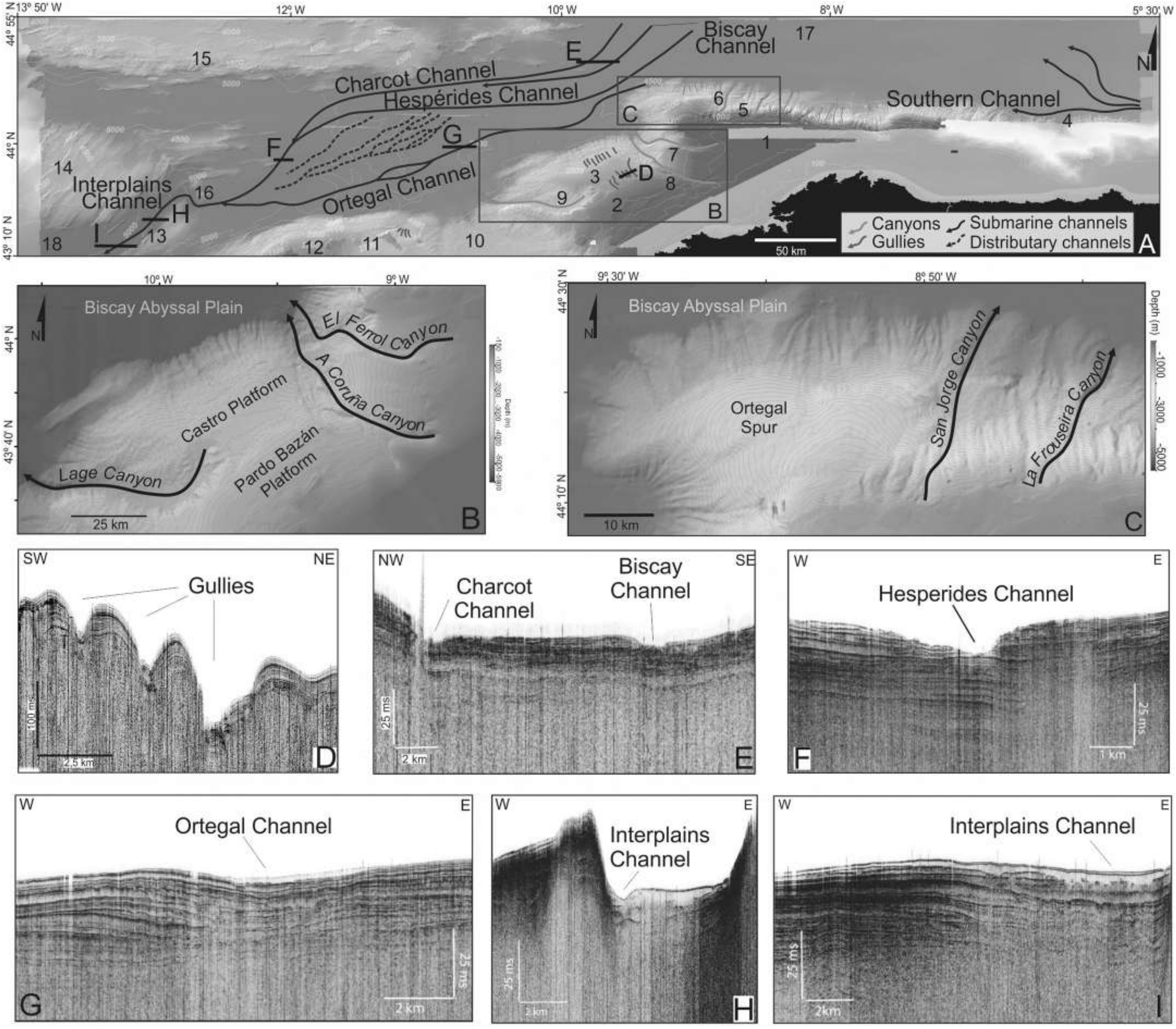

13° 50' W
12° W
10° W
8° W
5° 30' W
44° 55' N
44° N
43° 10' N
N
A
15
17
14
16
13
18
12
11
B
10
D
E
F
3
2
9
6
5
C
G
1
7
8
I
4
50 km
Relict sediment waves
Mixed deposits
Plastered drifts
Mounded elongated and separated drifts
Moats
Abraded surface
W
E
Plastered drift
40 ms
2,5 km
B
SW
NE
Mounded elongated and separated drift
Moat
Abraded surface
40 ms
4,5 km
C
N
S
Mounded elongated and separated drift
Moat
40 ms
4,5 km
D
SE
NW
Mixed drift
50 ms
1 km
E
S
N
Relict sediment waves
100 ms
4,5 km
F
H
G
SW
NE
Sediment waves
100 ms
1,5 km
H
SW
NE
Abraded surface
100 ms
1,5 km
I

Figure 6



13° 50' W
12° W
10° W
8° W
5° 30' W
44° 55' N
44° N
43° 10' N
D
C
E
F
B
Channel 3
Channel 2
Channel 1
Ortegal Channel
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
i
ii
iii
iv
v
vi
N
Slides
Debris flow deposits
Submarine fans
Levees
50 km
A
SW
NE
Slides
100 ms
2,5 km
B
NW
SE
Debris flow deposits
200 m
2,5 km
C
W
E
Debris flow deposits
100 ms
2,5 km
D
W
E
Levee
Channel 3
Levee
Channel 2
25 ms
2 km
E
W
E
Levee
Ortegal Channel
25 ms
2 km
F

Figure 7



Biscay Channel
17
15
E
Charcot Channel
Hespérides Channel
C
6
5
Southern Channel
4
N
F
G
1
7
14
Interplains Channel
3
D
8
16
Ortegal Channel
9
2
B
H
13
18
12
11
10
Canyons
Gullies
Submarine channels
Distributary channels
50 km
A
Biscay Abyssal Plain
El Ferrol Canyon
A Coruña Canyon
Castro Platform
Pardo Bazán Platform
Lage Canyon
25 km
B
Biscay Abyssal Plain
Ortegal Spur
San Jorge Canyon
La Frouseira Canyon
10 km
C
Depth (m)
SW
NE
Gullies
100 ms
2.5 km
D
NW
SE
Charcot Channel
Biscay Channel
25 ms
2 km
E
W
E
Hesperides Channel
25 ms
1 km
F
Ortegal Channel
25 ms
2 km
G
Interplains Channel
H
Interplains Channel
2km
I

Figure 8

Figure 9

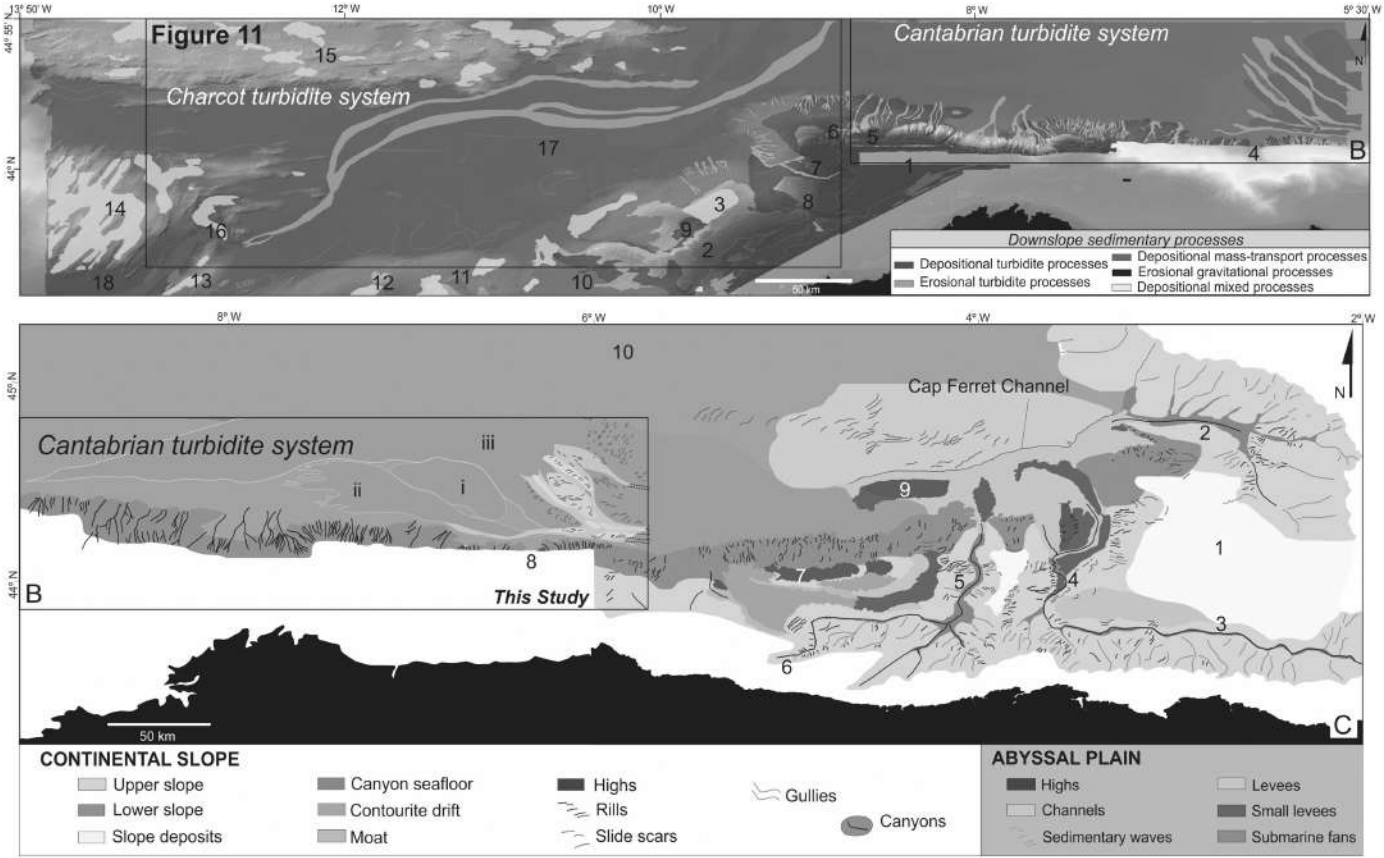


Figure 11
Charcot turbidite system
Cantabrian turbidite system
Downslope sedimentary processes
Depositional turbidite processes
Erosional turbidite processes
Depositional mass-transport processes
Erosional gravitational processes
Depositional mixed processes
50 km
Cap Ferret Channel
Cantabrian turbidite system
This Study
CONTINENTAL SLOPE
Upper slope
Lower slope
Slope deposits
Canyon seafloor
Contourite drift
Moat
Highs
Rills
Slide scars
Gullies
Canyons
ABYSSAL PLAIN
Highs
Channels
Sedimentary waves
Levees
Small levees
Submarine fans

Figure 10

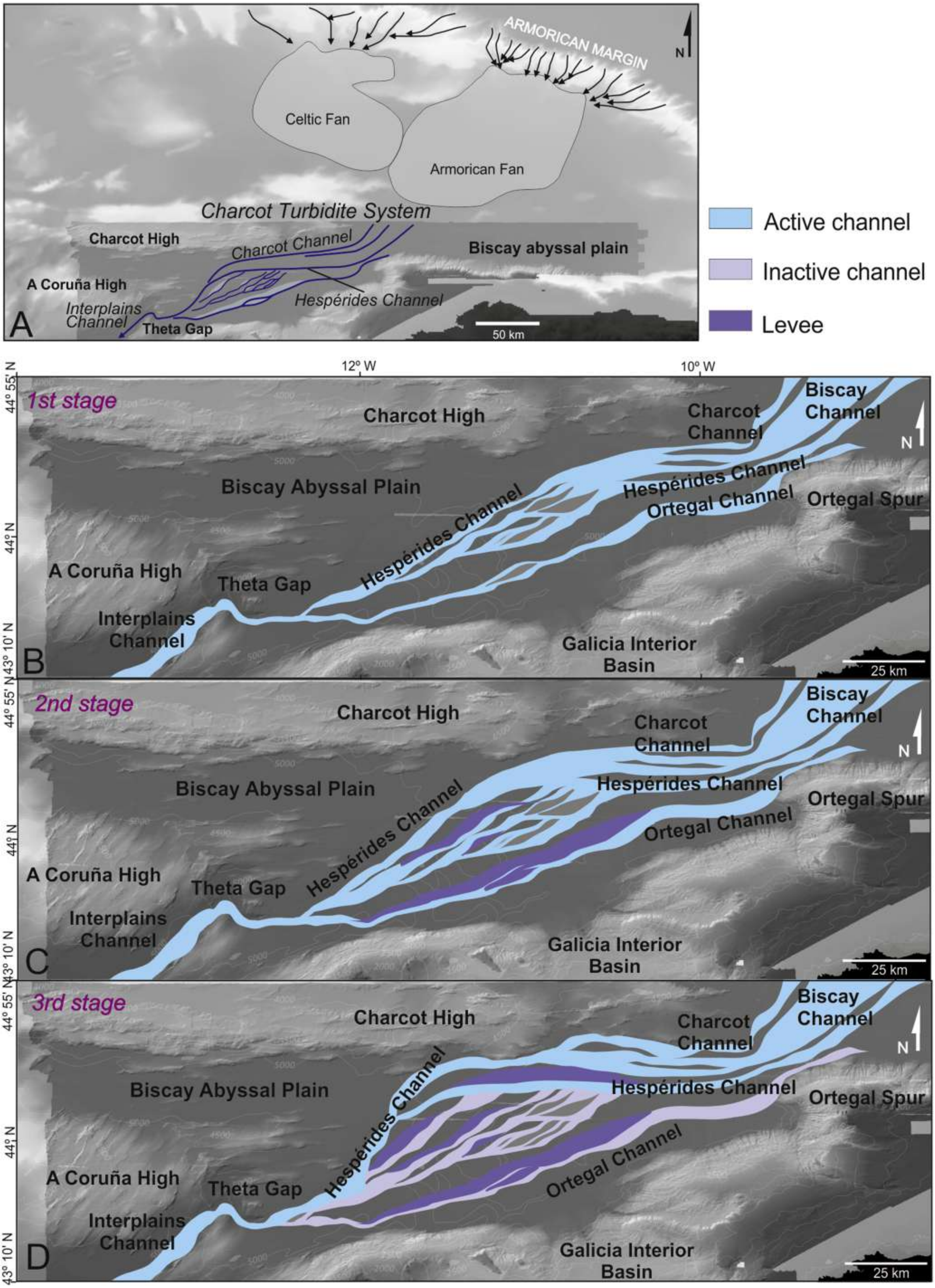

ARMORICAN MARGIN
N
Celtic Fan
Armorican Fan
Charcot Turbidite System
Charcot High
Charcot Channel
Biscay abyssal plain
A Coruña High
Interplains Channel
Hespérides Channel
Theta Gap
50 km
A
Active channel
Inactive channel
Levee
12º W
10º W
44º 55' N
44º N
43º 10' N
1st stage
2nd stage
3rd stage
Biscay Channel
Biscay Abyssal Plain
Ortegal Channel
Ortegal Spur
Galicia Interior Basin
25 km
B
C
D

Figure 11

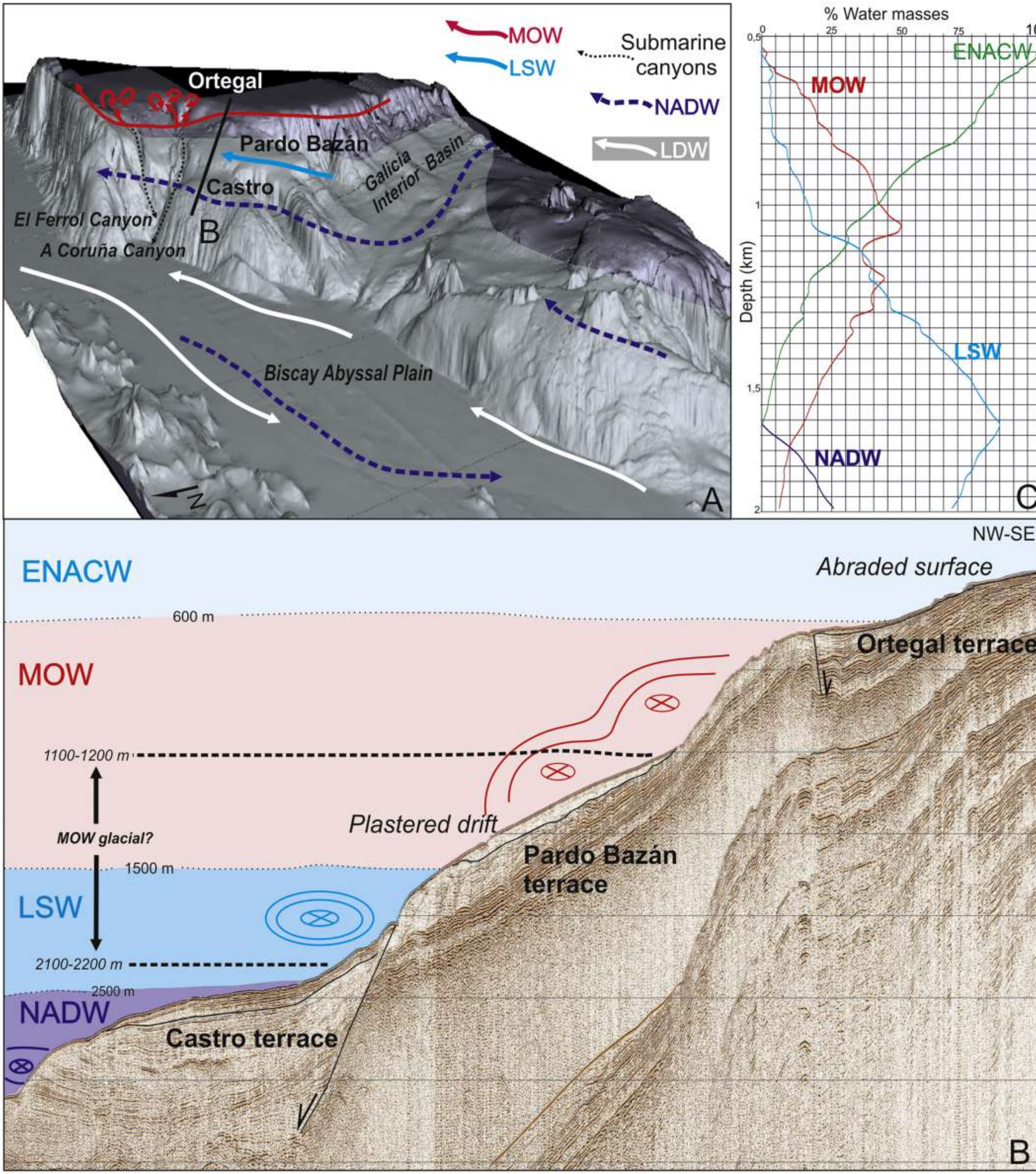

MOW
LSW
NADW
Submarine canyons
LDW
Ortegal
Pardo Bazán
Castro
Galicia Interior Basin
El Ferrol Canyon
A Coruña Canyon
B
Biscay Abyssal Plain
N
A
% Water masses
Depth (km)
ENACW
MOW
LSW
NADW
C
NW-SE
ENACW
Abraded surface
600 m
MOW
Ortegal terrace
1100-1200 m
MOW glacial?
Plastered drift
Pardo Bazán terrace
1500 m
LSW
2100-2200 m
2500 m
NADW
Castro terrace
B

Figure 12

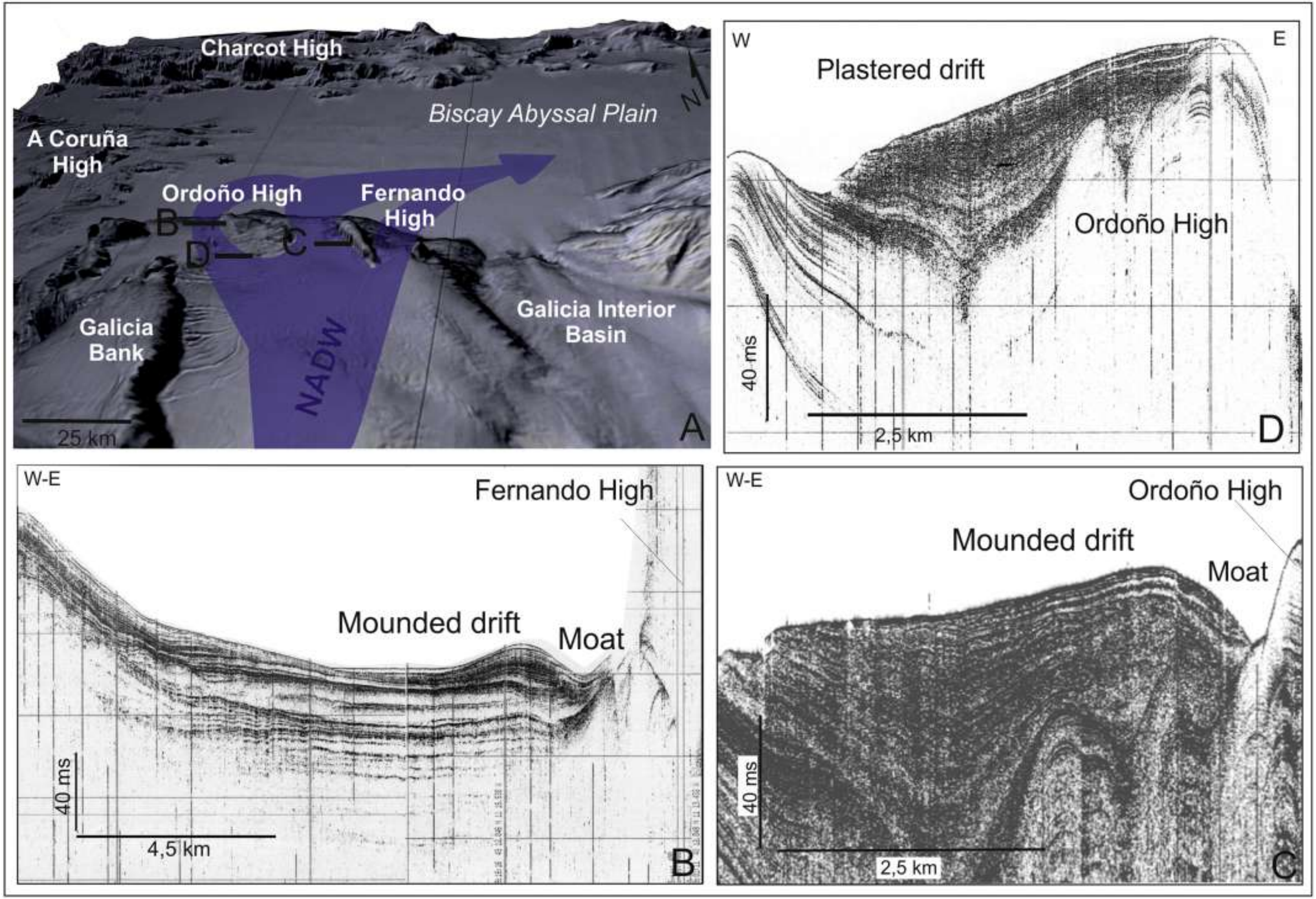

Charcot High
Biscay Abyssal Plain
N
A Coruña High
Ordoño High
Fernando High
B
C
D
Galicia Interior Basin
Galicia Bank
NADW
25 km
A
W
E
Plastered drift
Ordoño High
40 ms
2,5 km
D
W-E
Fernando High
Mounded drift
Moat
40 ms
4,5 km
B
W-E
Ordoño High
Mounded drift
Moat
40 ms
2,5 km
C

Figure 13

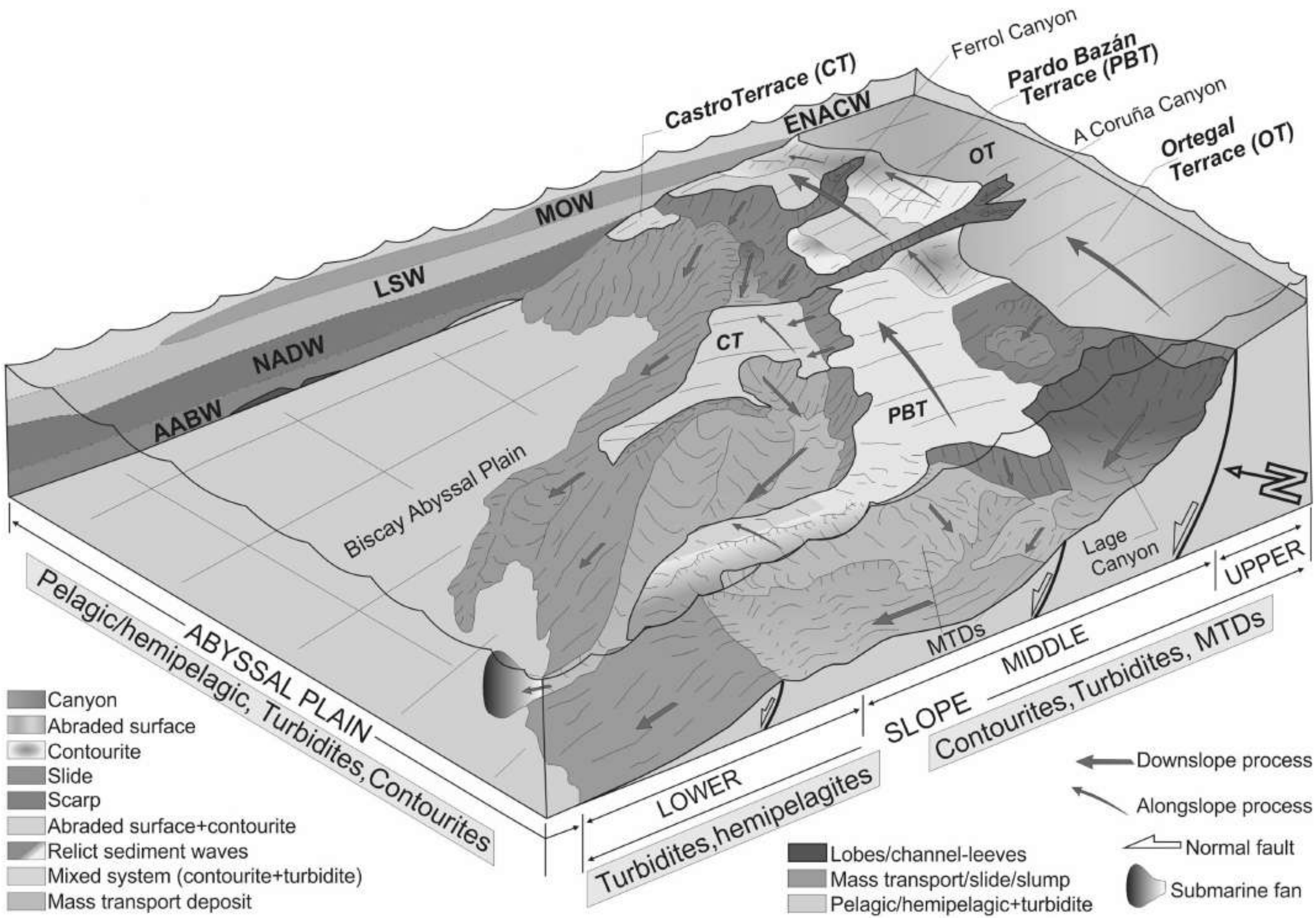

Ferrol Canyon
Pardo Bazán Terrace (PBT)
CastroTerrace (CT)
ENACW
A Coruña Canyon
Ortegal Terrace (OT)
OT
MOW
LSW
NADW
AABW
CT
PBT
Biscay Abyssal Plain
Lage Canyon
MTDs
ABYSSAL PLAIN
Pelagic/hemipelagic, Turbidites, Contourites
LOWER
Turbidites, hemipelagites
SLOPE
MIDDLE
Contourites, Turbidites, MTDs
UPPER
Canyon
Abraded surface
Contourite
Slide
Scarp
Abraded surface+contourite
Relict sediment waves
Mixed system (contourite+turbidite)
Mass transport deposit
Lobes/channel-leeves
Mass transport/slide/slump
Pelagic/hemipelagic+turbidite
Downslope process
Alongslope process
Normal fault
Submarine fan
N

Figure 14