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Morphosedimentary features and recent depositional architectural model of the Cantabrian continental margin

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Abstract

Multibeam bathymetry, high (sleeve airguns) and very high resolution (parametric system-TOPAS-) seismic records were used to define the morphosedimentary features and investigate the depositional architecture of the Cantabrian continental margin. The outer shelf (down to 180–245 m water depth) displays an intensively eroded seafloor surface that truncates consolidated ancient folded and fractured deposits. Recent deposits are only locally present as lowstand shelf-margin deposits and a transparent drape with bedforms. The continental slope is affected by sedimentary processes that have combined to create the morphosedimentary features seen today. The upper (down to 2000 m water depth) and lower (down to 3700–4600 m water depth) slopes are mostly subject to different types of slope failures, such as slides, mass-transport deposits (a mix of slumping and mass-flows), and turbidity currents. The upper slope is also subject to the action of bottom currents (the Mediterranean Water — MW) that interact with the Le Danois Bank favouring the reworking of the sediment and the sculpting of a contourite system. The continental rise is a bypass region of debris flows and turbidity currents where a complex channel-lobe transition zone (CLTZ) of the Cap Ferret Fan develops.

The recent architecture depositional model is complex and results from the remaining structural template and the great variability of interconnected sedimentary systems and processes. This margin can be considered as starved due to the great sediment evacuation over a relatively steep entire depositional profile. Sediment is eroded mostly from the Cantabrian and also the Pyrenees mountains (source) and transported by small stream/river mountains to the sea. It bypasses the continental shelf and when sediment arrives at the slope it is transported through a major submarine drainage system (large submarine valleys and mass-movement processes) down to the continental rise and adjacent Biscay Abyssal Plain (sink). Factors controlling this architecture are tectonism and sediment source/dispersal, which are closely interrelated, whereas sea-level changes and oceanography have played a minor role (on a long-term scale).

Keywords: Cantabrian margin; Morphosedimentary features; Mass-movements; Contourite; Cap Ferret Fan; Depositional architecture

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1. Introduction

The Spanish Cantabrian continental margin is located in the Bay of Biscay (or Gulf of Gascony) (Fig. 1A). This bay is a large wedge-shaped re-entrant of the eastern Atlantic Ocean and is bordered by dissimilar continental margins, the Cantabrian or north Iberian margin that trends W–E and marks the boundary of the Iberian plate, and the French or Armorican margin that trends N–S (Fig. 1A and B). The Cantabrian margin was deformed by compression during the Paleocene and Eocene, when the Iberian and European plates converged (Boillot et al., 1987). This motion resulted in the uplift of Pyrenees and the partial closure of the Bay of Biscay (Olivet, 1978; Grimaud et al., 1982; Pérez-Estaún et al., 1995; Pulgar et al., 1996). The Tertiary Alpine orogeny also resulted in a NW–SE oblique convergence between the two plates, the deformation of the Cantabrian margin and the uplift and deformation of the Cantabrian and Pyrenees mountains (Boillot et al., 1979; Alvarez-Marrón et al., 1996; Gallastegui et al., 2002). This tectonic event resulted in the formation of tectonic structures (inverse faults, thrusts and folds) of different scales, types and orientations on the Cantabrian margin (Gallastegui et al., 2002) (Fig. 1B). Seamounts, large WNW–ESE reverse faults, and anticlinal and synclinal structures varying from NNE–SSW to NW–

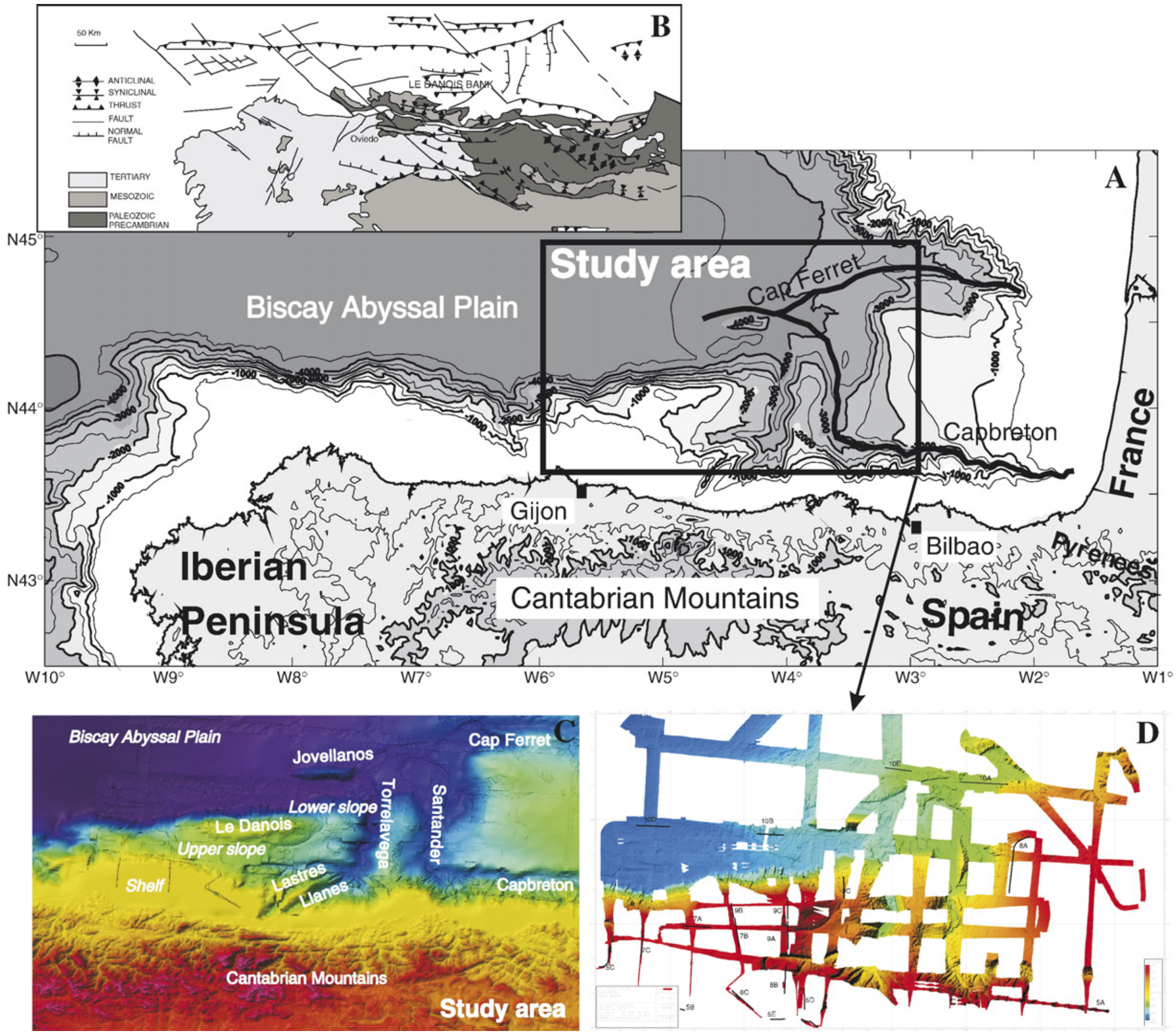

Fig. 1. Maps displaying: A) the location of the study area (from GEBCO Centenary, 2003). The mapping of the Cap Ferret and Capbreton systems are highlighted (from Bourillet et al., 2007); B) structural framework (from LeBorgne and Monel, 1970; Williams, 1973; Laughton et al., 1975); C) shaded mean depth bathymetry with names of principal bathymetric features from GEBCO Centenary and this study; and D) corridors surveyed simultaneously with the multibeam, single-channel airgun and TOPAS seismic systems. Short black lines with numbers plus letters refer to segments of seismic records illustrated in Figs. 5–10.

SE faults are the essential components of the present-day structural disposition of this margin. Although many of those structures have been covered by sediments, they seem to be still recognizable in the present-day morphology (Fig. 1A–C). The sedimentary cover of this margin is relatively thin (0 to 4 s twtt) (Vigneaux, 1974; Derégnaucourt and Boillot, 1982; Thinon et al., 2001; Gallastegui et al., 2002). This cover comprises sediments dating from the Lower Cretaceous to Quaternary, and their distribution is very irregular.

The morphology of the Cantabrian continental margin that reflects the above mentioned structural trends is characterized by a narrow continental shelf which passes abruptly into a continental slope with a variable relief (Boillot et al., 1974; Vigneaux, 1974; Ercilla and Marconi Team, 2006). The slope displays an abrupt transition (approx. 4600 m water depth) to the continental rise in the east and to the Biscay Abyssal Plain in the west. The continental slope is affected by large canyons running down to the continental rise, the location of which is tectonically controlled (Boillot et al., 1974; Belderson and Kenyon, 1976; Cremer, 1981; Kenyon, 1987) (Figs. 1A, C and 2). The morphostructural features and sedimentary history of the Bay of Biscay indicate instability led to the formation of a natural sink for Cenozoic sediments eroded and transported from the surrounding hinterland areas (Vigneaux, 1974). The Quaternary sedimentary regime of this sector of the Iberian margin reflects that it is a glacially influenced margin (Weaver et al., 2000; Zaragosi et al., 2001; Mojtahid et al., 2005). The sediment transfer takes place mainly downslope and the pathways are mainly linear, being represented by canyons and channels (Belderson and Kenyon, 1976; Cremer, 1981, 1982; Kenyon, 1987; Kenyon et al., 1987; Zaragosi et al., 2000; Mulder et al., 2001; Bourillet et al., 2006; Gaudin et al., 2007; Gonthier et al., 2006). The along-slope processes play a minor role and their influence is local. The occurrence of these processes has varied through time due to glacial-eustatic sea-level changes. The downslope processes coming from the Cantabrian and French margins have conditioned the upbuilding of the distal Cap Ferret Fan on the continental rise during the Pliocene–Quaternary

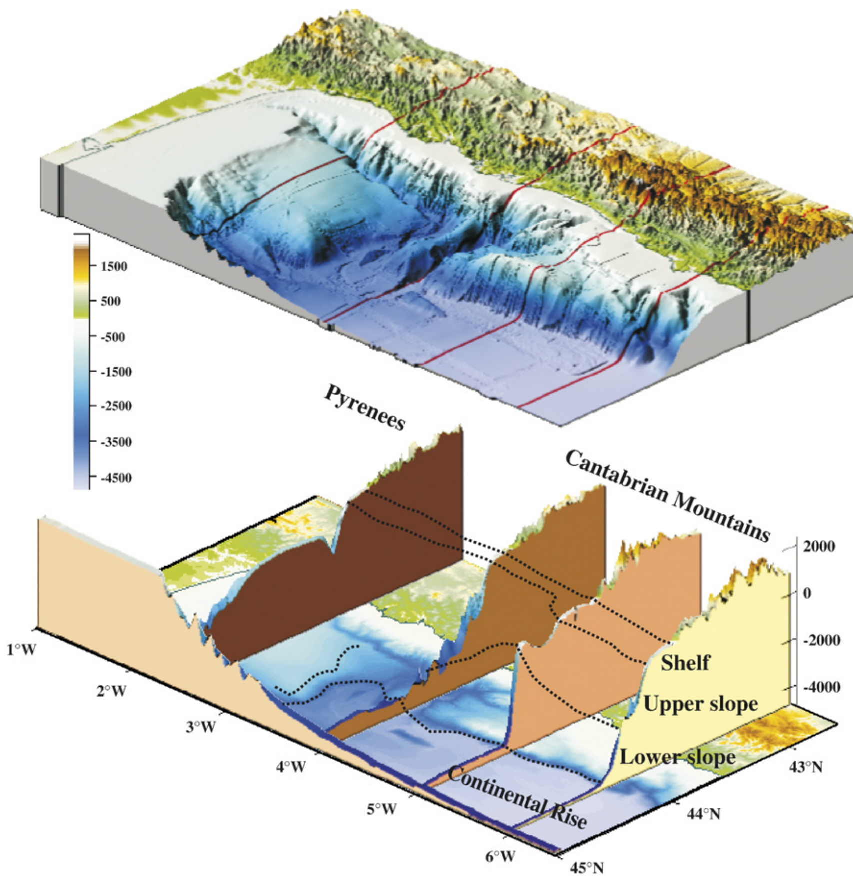

Fig. 2. 3-D block illustrating the topography and bathymetry of the surveyed area (top) with cross-section topographic profiles (bottom). Physiographic provinces are also outlined. Note the roughness and high slope morphological variations of the continental margin.

(Cremer, 1983; Faugères et al., 1998; Gonthier et al., 2006; Gaudin et al., 2007). These studies indicate that the depositional architecture is mainly controlled by sea-level changes, combined with the Coriolis effect, the morphological background and the available sediment supply.

The oceanography model in the Bay of Biscay comprises at least three main water masses. The upper layer is the Eastern North Atlantic Central Water (ENACW), which extends to depths of about 600 m. The intermediate water mass is the Mediterranean Water (MW), which circulates between 600 and ≈1500 m (Iorga and Lozier, 1999). The bottom layer seems result from the mixing of different water masses: the North Atlantic Deep Water (NADW), deeper Antarctic Bottom Water (ABW) and possibly Labrador Sea Water (LSW) (Le Floch, 1969; Botas et al., 1989; Haynes and Barton, 1990; Pingree and Le Cann, 1992; Valencia et al., 2003). The pattern of at least the two upper layers enters the Bay of Biscay and describes eddies that result from the main directions that govern the morphology configuration of the French and Cantabrian margins (Durrie de Madron et al., 1999; Iorga and Lozier, 1999; Gil et al., 2002; Serpette et al., 2006).

Although a large body of sedimentological research exists on the French continental margin, the Cantabrian margin has received far less attention (Vigneaux, 1974; Cremer, 1983; Faugères et al., 1998; Cirac et al., 2001; Le canyon de Capbreton, carte morpho-bathymétrique au 1/50000, 2006). In fact, it represents the least studied Iberian margin from a geological point of view. Our knowledge of morphology, depositional systems and sedimentary processes operating in this area is limited. The main target of the present work is to present the main morphosedimentary features of the Cantabrian continental margin, the sector from Gijón to Bilbao (Fig. 1). A small sector of French continental margin (i.e. the distal continental slope and rise) is also studied (Fig. 1). The analysis of these features will provide insights into recent sedimentary processes and controlling factors. These data will be of particular interest to establish the singularities and complexity of the recent depositional architecture of the margin.

2. Methodology

Multibeam bathymetry and seismic profiles were recovered on board the research vessel *Hesperides* during 2003 (Fig. 1D). The high-resolution bathymetric map was obtained with the Simrad EM-12 S120 multibeam echosounder, which allows simultaneous collection of high resolution seafloor bathymetry and backscatter strength measurements. This system covers a sector of the seafloor approximately three times the water depth at which it is working, uses a frequency of 12 kHz, has an aperture angle of 120°, and provides 81 bathymetry values across the ship track, corrected for the geometric propagation of sound in the stratified water column. The seismic records comprise high and ultra-high resolution single channel profiles that were obtained respectively with airguns and the TOPAS PS 018 (TOpographic PArametric Sonar) system. The airgun records were collected using a 140 cubic inch sleeve gun array, located at a depth of 3.5 m, with a shot frequency of 8 s. The airguns were fired with four Hamworthy air compressors, producing a 140-bar firing pressure. The receptor system was a SIG streamer with a 150 m long active section, comprising three independent channels with 40 hydrophones each, having an optimum working depth of 1.5 m. The penetration of the acoustic signal is about 1.5 s (twtt). The TOPAS PS 018 system is a hull-mounted seabed and subbottom echosounder based on the parametric acoustic array, which operates using non-linear acoustic properties of the water (Dybedal and Boe, 1994). The system uses the interference between two transmitters with primary frequencies of 15 and 18 kHz, to obtain a wave with a variable secondary frequency between 0.5 and 5 kHz (parametric effect). The penetration of the acoustic signal achieved with the TOPAS system varies between 0 and 200 ms at full oceanic depths.

3. Physiography

The Cantabrian continental shelf extends down to 180–245 m water depth and morphologically its edge is a sharp break, displaying a sinuous pathway in plan view (Figs. 1C and 2). The studied shelf, which is the narrowest shelf sector in the Cantabrian margin (Fig. 1A), has a variable width of between 4 and 17 km, tending to increase toward the west. The outer shelf is characterized by a practically flat-lying surface (gradients <0.5°).

The Cantabrian continental slope extends down to 4600 m water depth and has a width that increases toward the east from 3.3 to 5.8 km. The gradients are very variable, ranging from ≈1 to 20° (Figs. 1C, 2 and 3). Based on gradient distribution upper and lower slopes are differentiated. The upper slope is gentler than the lower slope, with gradients of between 1 and 8° (locally to 20°), and extends down to about 2000 m water depth (Figs. 1C, 2 and 3). Likewise, the upper continental slope is characterized by complex seafloor topography (Figs. 1C, 2 and 3). The eastern upper slope sector is characterized by the presence of oblique large valleys that erode practically the whole slope and indent the shelf. The western upper slope sector is an open slope with incision of smaller oblique valleys, and a striking morphological bank named the Le Danois

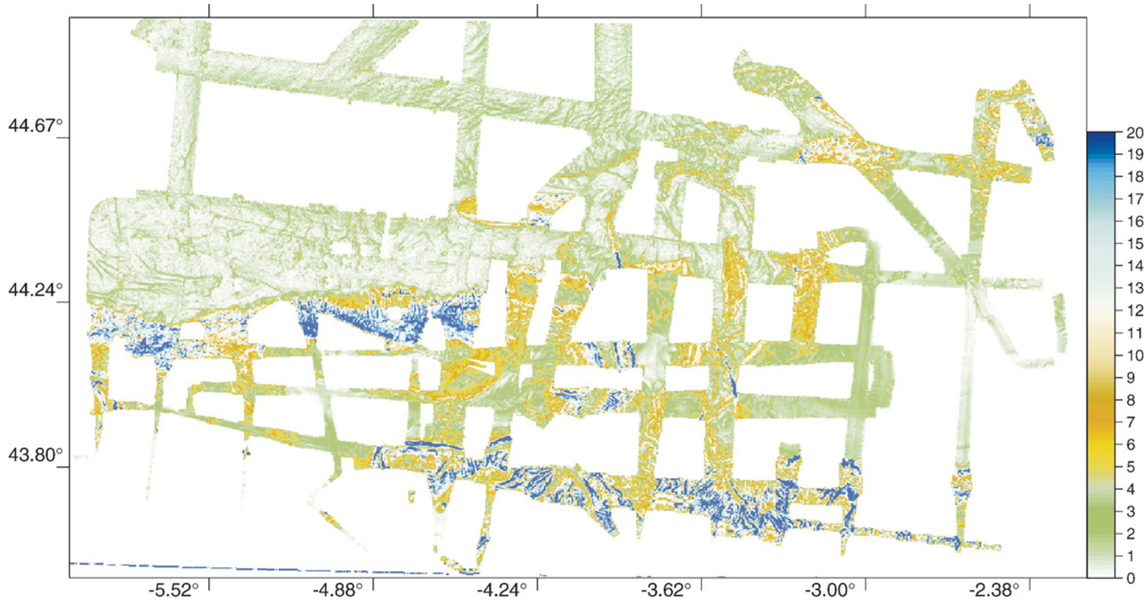

Fig. 3. Map illustrating the gradients of the surveyed area.

Bank. This bank is located in the most distal area of the upper slope and its presence creates an intraslope basin (axis at 990 to 1300 m water depth) paralleling the margin and sloping toward the west. The northern wall joins directly with the steep seafloor of the lower continental slope province. This province is steeper than the upper slope and forms a 2.2 km wide abrupt scarp with gradients always >14° and with the tendency to decrease (≈3°) downslope and eastward (Fig. 3).

Upper and lower subprovinces are also defined for the French continental slope. The upper slope is gentler, with gradients of less than 4°, and extends down to 2000 m water depth (Fig. 3). The surveyed slope is indented by two large valleys parallel to the Cantabrian margin to the north and south. The lower slope is steeper (<8°), forming an abrupt scarp down to 3700 m water depth that is the lateral continuation of that defined on the Cantabrian margin.

The Cantabrian continental slope passes abruptly into the continental rise that is the prolongation of the French Continental rise onlapping the Iberian Continental Margin, and westward connects with the Biscay Abyssal Plain (Fig. 1A). The rise displays a bay shape in plan view and is characterized by the presence of the Jovellanos High (top at <3500 m water depth) (Figs. 1 and 2). The seafloor dips toward the west with gradients of <1° (Fig. 3).

4. Shelf sedimentary features

The Cantabrian outer shelf mostly displays an eroded seafloor surface that is traceable throughout the surveyed area (Figs. 4 and 5). This surface erodes ancient inclined-oblique, subparallel, folded and fractured stratified deposits (Fig. 5A–E). Due to the differential erosion of those subbottom strata, the erosional surface is irregular with isolated morphological highs (Fig. 5A and E), with dimensions of as much as 2 km long and 97 m in relief. Acoustically these highs are defined by prolonged and chaotic facies.

This erosive surface marks respectively the top and bottom of two different recent depositional bodies: a shelf-edge wedge and a drape of transparent sediments (Figs. 4, 5B and C). The shelf-edge wedge is locally identified on the shelf break of the western sector, from about 187 m water depth. It comprises subunits of prograding sediments defined by oblique, seaward-dipping clinoforms that are truncated by that surface. It displays a wedge-shape geometry up to 230 ms thick (Figs. 4 and 5C). This wedge is interpreted as lowstand shelf-margin deposits. The transparent drape underlain by the erosive surface occurs locally at water depths of <80 m in the westernmost sector and is up to 12 m thick (Figs. 4 and 5B). Locally, the transparent sediments display bedforms characterized by asymmetrical sediment waves with the western side steeper than the eastern one. The wave lengths are variable, ranging between 20 and <500 m and the amplitudes are <6 m.

5. Upper slope sedimentary features

Several types of sedimentary features characterize the upper continental slope: 1) canyons, 2) gullies and

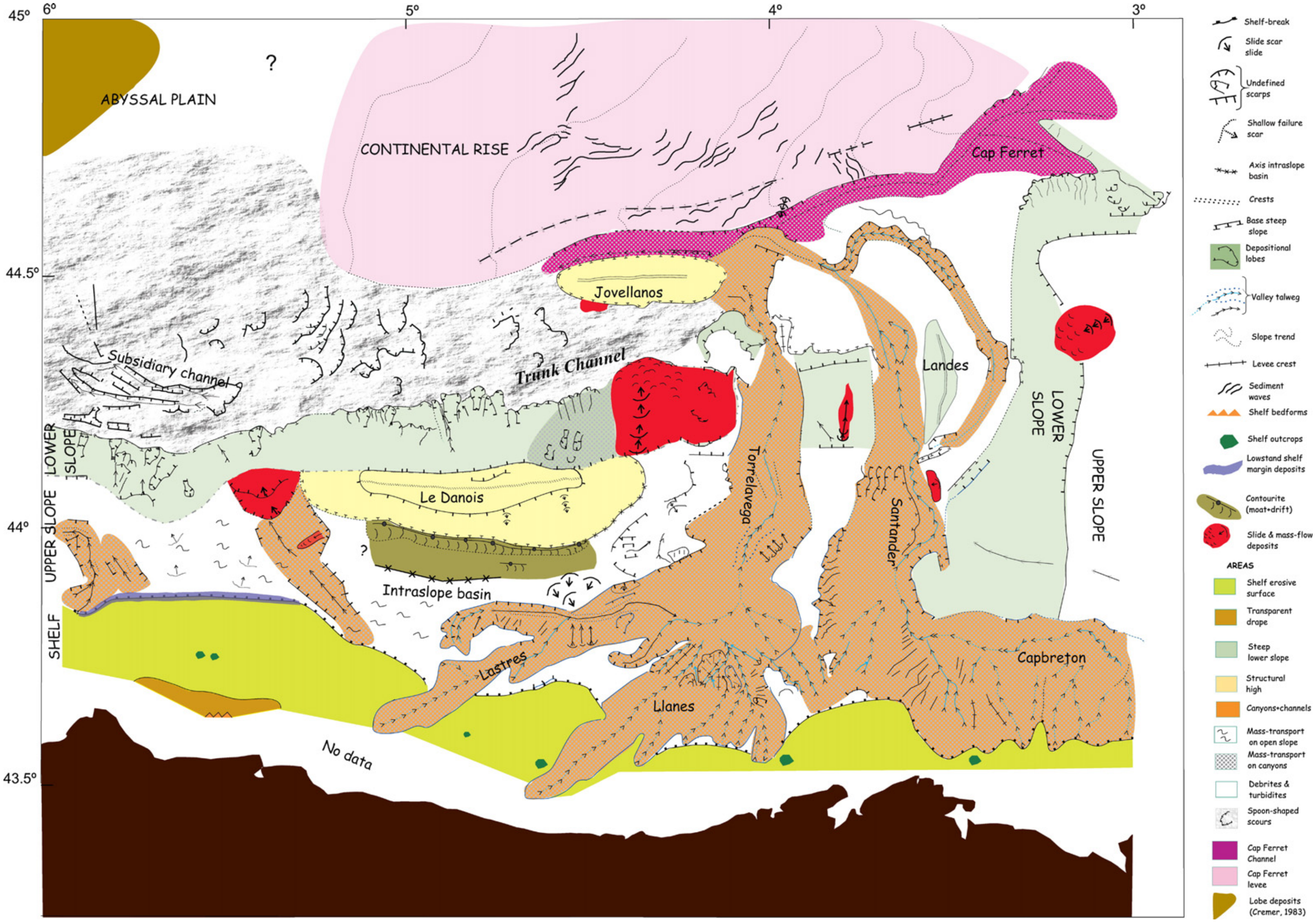

Fig. 4. Map showing the main morphosedimentary features that characterise the present-day seafloor of the Cantabrian continental margin. Names of the principal bathymetric features are also shown.

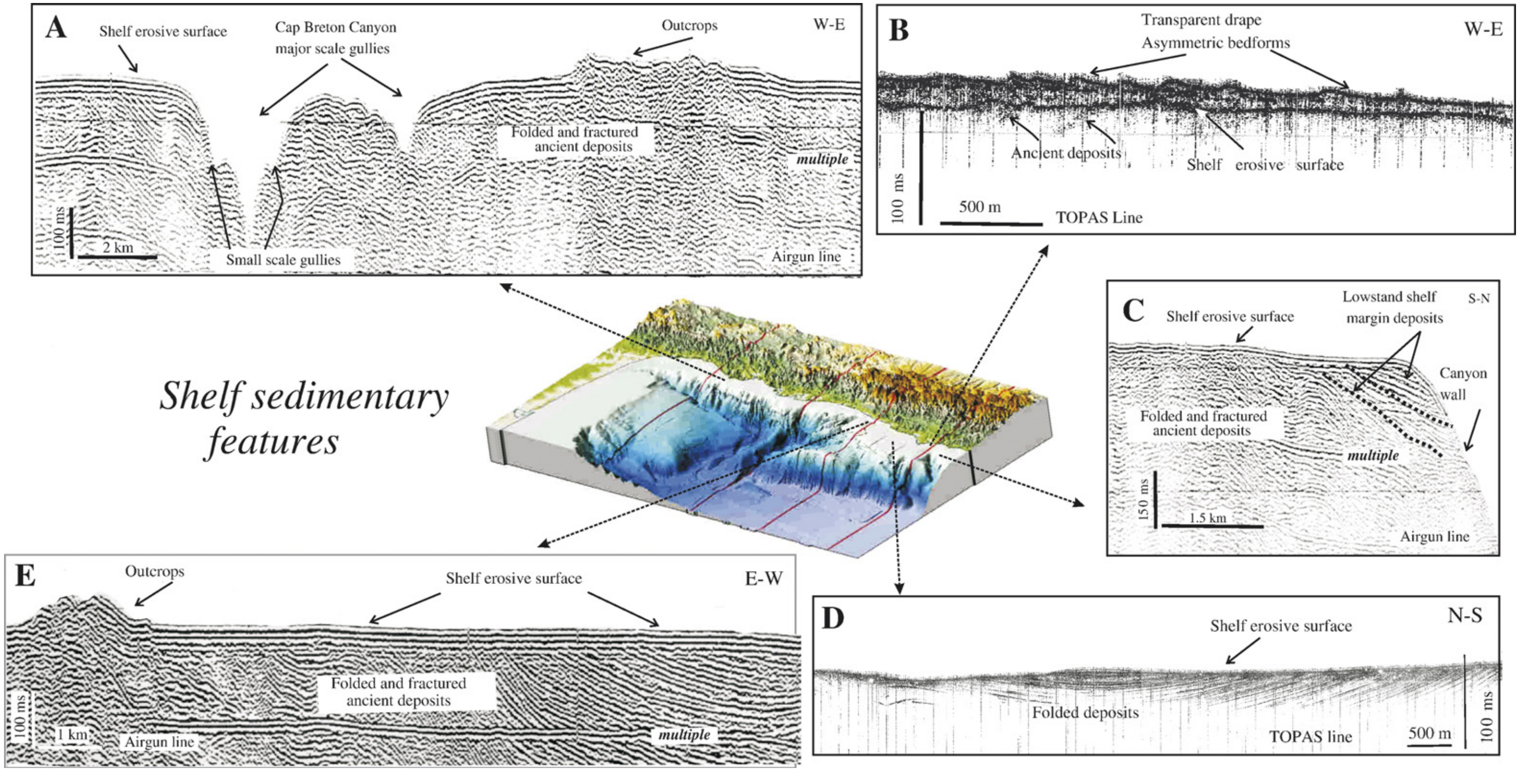

Fig. 5. Segments of airgun and TOPAS seismic profiles illustrating the morphosedimentary features identified on the continental shelf: A) erosive surface that truncates ancient faulted and folded deposits and outcrops. Gullies affecting the southern wall of the Capbreton Canyon and indenting the continental shelf are also displayed; B) a transparent drape with asymmetric waves; C) lowstand shelf-margin deposits; D) and E) erosive surfaces that truncate ancient faulted and folded deposits and outcrops.

rills, 3) mass-movements, 4) contourite deposits, and 5) an erosive outcropping surface (Figs. 4 and 6–9).

5.1. Submarine canyons

Different size-scale canyons indent the continental slope, some of them reaching the continental rise (Fig. 4). Large submarine canyons represent the most prominent features on the continental slope and they are practically eroding its entire eastern sector. Residual interfluves are represented by the Santander Promontory and the Landes High. Using the names from the literature (Boillot et al., 1972), the large canyons are the following: Cap Ferret (up to 20 km wide, few kilometres in relief, Cremer, 1983) and Capbreton (up to 31 km wide, >2.5 km relief) on the French continental margin, and Santander (up to 29.5 km wide, 1 km in relief), Torrelavega (up to 29 km wide, 1.5 km in relief), Lastres (up to 37 km wide, >2 km in relief) and Llanes (up to 15 km wide, >2 km in relief) on the Cantabrian continental margin. In fact, the last four canyons represent only two large submarine canyons, because the Santander Canyon represents the downslope evolution of the Capbreton Canyon, when its pathway changes from W–E to S–N, and the Torrelavega Canyon results from the confluence of two large and complex tributaries, Llanes and Lastres, which indent the shelf for 24 km. The Llanes Canyon has another tributary on the left margin, which displays an arcuate shape in plan view and is 24 km long

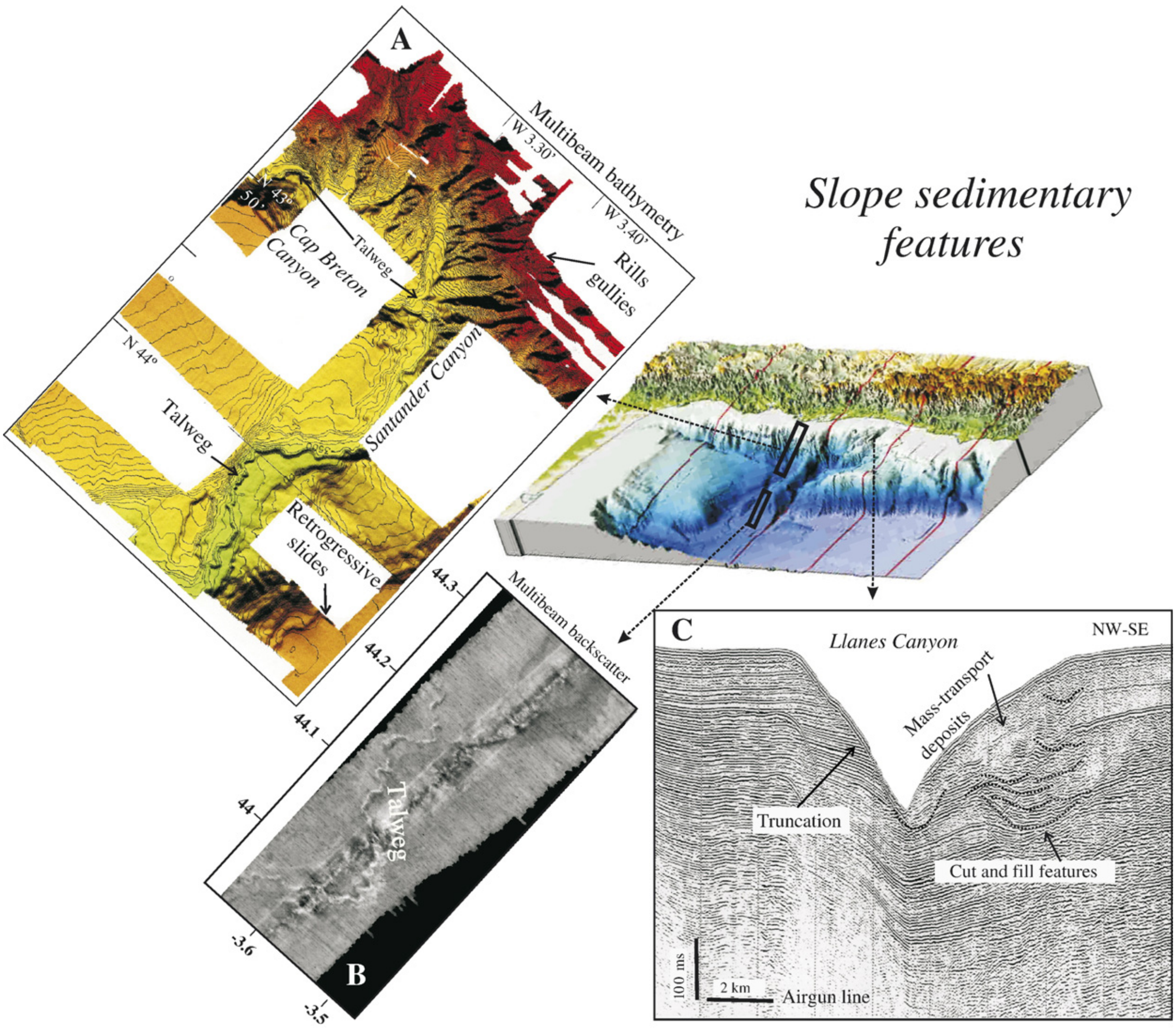

Fig. 6. Segments of multibeam bathymetry (A), backscatter (B), and airgun seismic profile (C) illustrating the morphosedimentary features identified on the continental slope: canyons, gullies, canyon talwegs, and mass-movements (slides and mass-transport deposits).

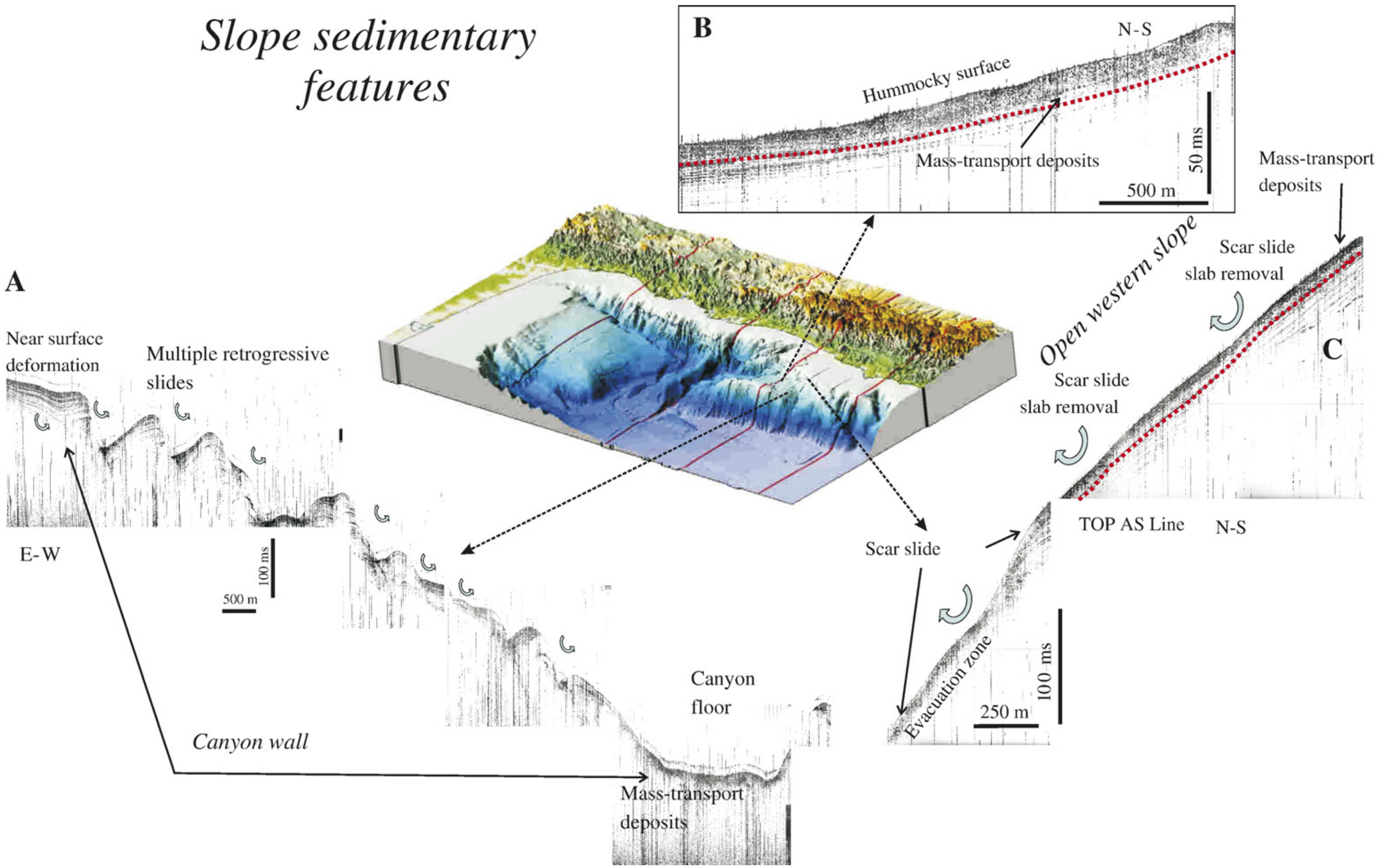

Fig. 7. Segments of TOPAS seismic profiles illustrating the mass-movement deposits identified in the continental slope: A) multiple retrogressive slides on the canyon wall and mass-transport deposits on the canyon floor; B and C) mass-transport deposits on the open continental slope. Here they form a subtabular unit of unstable sediments. For more explanation see the text.

and 8.7 km wide. The right margins of the Capbreton and Lastres Canyons comprise large sectors of the upper continental slope, paralleling its main trend (Fig. 4).

Several common features characterize the large canyons: i) the heads are defined by irregular boundaries with well-developed amphitheatre rims; ii) the walls are asymmetric, one being steeper than the other; iii) well-developed drainage features that form a network of gullies and rills cover much of the less steep walls; and iv) the entrenched axial talwegs display a sinuous pattern in the middle and distal reaches (Figs. 4 and 6). One talweg is identified in all the canyons, except in the Santander Canyon, which displays two (Figs. 4, 6A and B). The talweg of this canyon bifurcates from about 3700 m water depth, and both branches surround the Landes High, remaining as a residual interfluve within the canyon course (Fig. 4). The eastern talweg displays a semicircular pathway and defines a U-shaped cross-section up to 5.5 km wide and 300 m in relief; this talweg seems to be abandoned because it does not display erosion and downcutting, suggesting area of deposition. The western talweg displays a V-shape in cross-section and represents the current entrenched talweg.

Apart from these larger canyons, relative smaller-scale canyons (< 15 km wide and < 1 km in relief) are identified on the western Cantabrian and French upper continental slopes (Fig. 4). On the Cantabrian margin, they display a different direction to that of the large canyons, being oriented NW–SE. Subbottom profilers show that these canyons incise into the sedimentary succession and locally reach the acoustic basement; in fact, truncations of reflections against the canyon walls are observed suggesting their erosive character (Figs. 5A, C and 6C). The canyon floor deposits are characterized by packages of chaotic, hyperbolic and transparent facies with cut-and-fill features indicating that talwegs have been eroded and filled over time (Figs. 6C and 7A).

5.2. Gullies and rills

Dense networks of gullies and rills mostly affect the large canyon walls, which resemble a badland topography (Figs. 4, 6A and B). These networks are better developed on the left margin of the Capbreton, the Santander and Torrelavega Canyons, and the right margin of the Lastres Canyon. Gullies have different scales, from tens of metres to several kilometres long, and are separated by narrow and sharp ridges. Smaller gullies and rills act as tributaries of the larger ones, which coalesce at different water depths and extend into the canyon floor. They are acoustically defined by hyperbolic, chaotic and prolonged facies that define a rough, high-reflectivity seafloor surface.

5.3. Mass-movement deposits

In this study the term mass-movement is defined as the movement of sediment driven by gravity and involves different types of instabilities, from slides to gravity currents (Hampton et al., 1996; Locat and Lee, 2000). Mass-movement deposits in the form of slides and mass-transport deposits characterize the near-surface sediments on the canyons, open slope, and walls of the Le Danois Bank (Figs. 4, 7, 8A, C, 9B and C). Their dimensions are variable, with sediment thickness ranging from tens to hundreds of metres, vertical displacements in the main body of the slides ranging from tens to hundreds of metres, and runout distances (i.e. horizontal displacement) of up to hundreds of metres.

(i) Slides are common on the borders of the canyons walls (Figs. 4, 6A, 7A, 8B and C). Also, isolated slides are identified on the western Cantabrian and French open slope (Figs. 4 and 8A). Slides are easy recognizable as slightly to highly deformed, back-rotated, stratified and chaotic masses resting at the base of a steep scarp (i.e. the slide scar) that displays an arcuate shape in plan view (Figs. 4 and 7A). Slides tend to be rotational and are usually associated, forming multiple slides. The head of the smaller-scale slides is a main scar, whereas the larger slides seem to be composed of multiple rotational scars that display an amphitheatre-like failure surface. In some slides located on the open slope, the area with back-rotated stratified deposits (depletion area) evolves downslope to a depositional area where chaotic deposits with a rugged seafloor are identified (Fig. 8A). This means that sediment sliding has resulted in deformation and disruption of the slide material (Masson et al., 1993). Then, these slides would represent slides and associated mass-flows deposits.

(ii) The most widespread type of mass-movement is mass-transport deposit, defined as deposit that cannot be associated with a defined type of mass-movement because they probably results from complex events involving elements of slumping and mass-flows (Figs. 4, 6C, 7B, C and 8B). This type of mass-movement deposits characterizes mostly the canyon walls and floors, and open slope. In the canyons they appear as incoherent stratified, chaotic, transparent and hyperbolic facies forming an irregular and undulating seafloor surface (Figs. 6C, 7A, 8B and C). On the open slope they form a subtabular unit (< 10 m thick) of unconsolidated sediments defined by contorted,

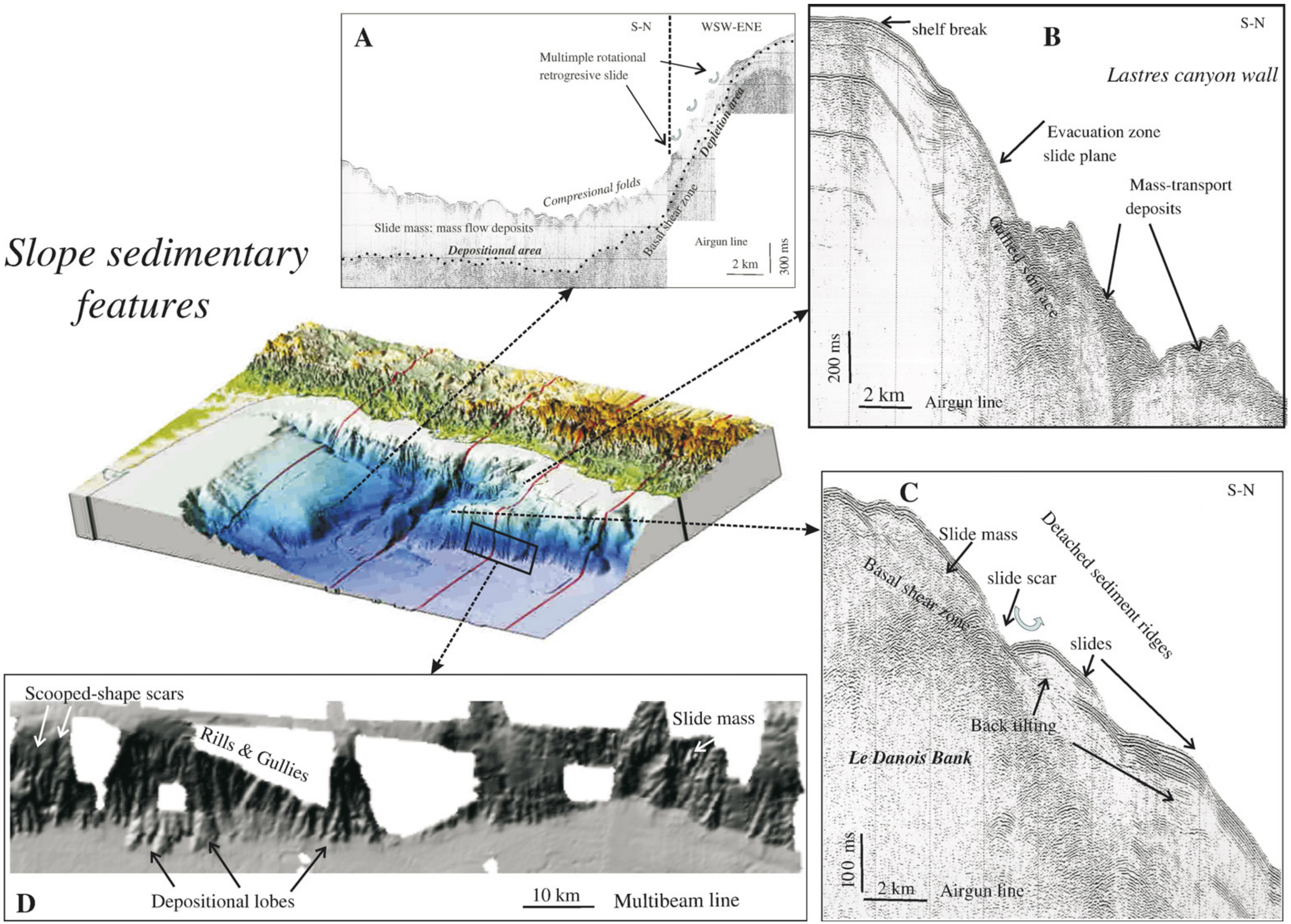

Fig. 8. A to C) Segments of airgun seismic profiles illustrating morphosedimentary features: (A) slides associated with mass-flows deposits on the upper and lower open continental slope; (B) mass-transport deposits on the upper continental slope, at the Lastres canyon wall; and C) slides on the wall of the Le Danois Bank. D) Segment of a shaded-mean depth record from multibeam illustrating the morphosedimentary features that characterize the lower continental slope: rills and gullies, scars, and depositional lobes.

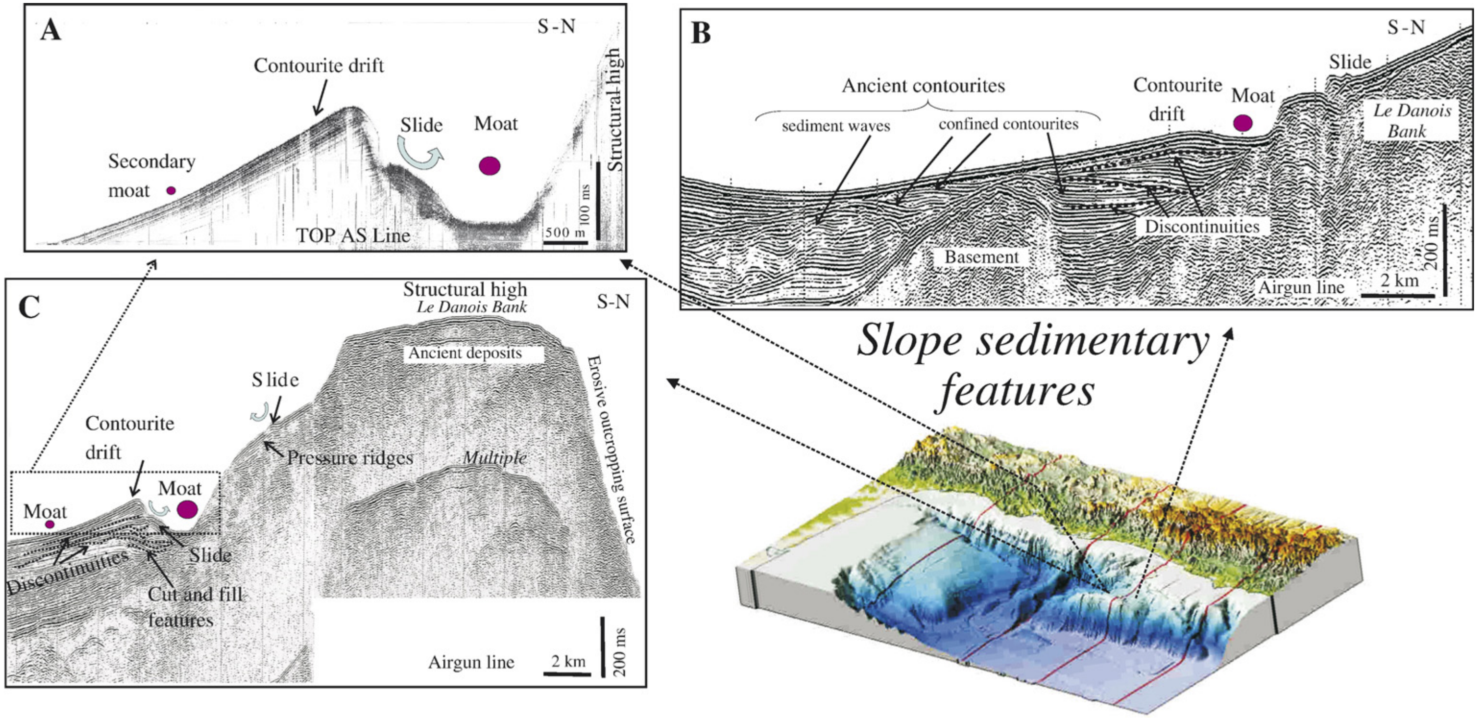

Fig. 9. Segments of TOPAS (A) and airgun seismic profiles (B and C) illustrating the recent and ancient contourite systems formed at the foot of the Le Danois Bank, in the intraslope basin (upper continental slope). The major seismic features (facies, discontinuities) of the recent main moat and drift are displayed. A secondary moat affecting the external face of the main drift, and mass-movement deposits affecting the Le Danois Bank and main moat are indicated (A and C). Note as the near-surface system of contourite deposits overlie ancient and complex systems of contourite deposits (marginal moats, drifts, and sediment waves) associated with the presence of acoustic basement highs (B).

deformed, and discontinuous stratified facies; locally, this unit shows a hummocky seafloor surface (Fig. 7B and C). Internally, major failure planes are not evident, but the seafloor surface shows isolated and smooth surficial erosive scarps (metre-scale relief) resembling shallow failure scars (e.g. shallow bedding plane detachment). The basal surface of this unit of unstable sediments is a horizontal plane that parallels the underlying stratified deposits, and locally overlies unconformably ancient canyon-fill deposits and undefined erosive surfaces.

5.4. Contourites

The near-surface contourite deposits occur at the foot of the southern side of Le Danois Bank, in the intraslope basin, at about 790–1725 m water depth. Morphologically, they are defined by a main elongated drift associated with a moat attached at the foot of the bank (Fig. 9). The elongation trend parallels the bank and is up to 48 km long (Figs. 4 and 9). A smoother secondary drift-moat association are locally identified on the external face of the drift (Fig. 9A and C).

The main moat, which corresponds to the zone of current flows, is about 2.8 km wide and 113 m in relief. The internal seismofacies comprise medium-high amplitude, discontinuous stratified and chaotic facies that onlap U-shaped surfaces of high amplitude displaying numerous cut-and-fill features. These types of deposits are also vertically stacked, showing an upslope migration. The moat floor is defined by a higher reflective surface than the drift. Locally, isolated slumps are identified on the inner walls and channel fill, and are probably associated with failures from the walls and the Le Danois Bank. The main drift is asymmetric, with a short steep flank (113 m in relief) toward the moat, and a smooth and large flank (>5 km wide) that extends toward the intraslope basin axis. Internally, the drift deposits consist of the vertical stacking of prograding stratified sediment packages reaching thicknesses of up to about 200 ms; internal discontinuities are observed, such as downlap and erosive surfaces that are mostly regionally traceable. The direction of progradation of the seismofacies is upslope (Fig. 9).

This near-surface system of contourite deposits overlies ancient and complex systems of contourite deposits (Fig. 9B). These systems comprise marginal moats, drifts, and sediment waves and their distribution and formation are due to the interaction of bottom currents with the acoustic basement highs. The high lateral morphologic variability of the basement paleotopography and the broad spacing between seismic records does not allow their confident regional correlation and thus their mapping. In fact, these subbottom contourite systems have contributed to infill this structural intraslope basin, tending to obliterate and to smooth the acoustic basement irregularities.

5.5. Le Danois Bank outcropping surface

This surface defines a highly rough seafloor mostly on the top of this Bank. It is acoustically defined by high reflectivity with not prolonged and hyperbolic reflections (Fig. 9C). The seismic records display a high-reflectivity surface that erodes fractured and folded subbottom consolidated deposits, as suggested by the truncation of reflections. These seismic features suggest that locally this bank has almost no recent sediment. The rough relief shows different scales varying from a few metres to tens of metres, corresponding to differential erosion.

6. Lower slope sedimentary features

The escarpment face that defines the lower continental slope is mostly characterized by a combination of numerous linear to slightly sinuous and narrow features perpendicular and oblique to the regional slope (Figs. 4 and 8D). These features represent positive and negative relief of tens to hundreds metres, which can be interpreted as sharp ridges separated by scoop-shaped scarps, slide masses, gullies and rills. Some of these features terminate on the face of the escarpment as hanging features and others evolve basinward to slope aprons (at least up to 6 km long, 4 km wide). These aprons form depositional lobes stopping at the boundary between the continental slope and the continental rise, although the large ones are slightly downslope from this boundary (<2 km). The seismic profiles with different degrees of resolution display similar acoustic facies, which are defined by hyperbolic and prolonged facies without acoustic penetration that must be related to steep gradients of that seafloor. Locally, in sectors of the lower continental slope where gradients are smoother, the seafloor displays acoustic penetration, and isolated and multiple slides and mass-transport deposits are identified (Fig. 4). They show similar features (morphology and acoustic facies) to those described for the upper slope, and their facies are defined by deformed and disrupted stratified, chaotic and hyperbolic facies. The surrounding undeformed sediment comprises parallel continuous stratified reflections.

7. Continental rise

This continental rise is complex due to the development of the distal part of the Cap Ferret Fan (Cremer, 1982, 1983; Faugères et al., 1998) (Fig. 4). The new data, in combination with previous published data, give new insights into this part of the fan and indicate that it is formed by a great variety of morphosedimentary features: turbidite channels, spoon-shaped scours, sediment waves, and mass-movements (Figs. 4 and 10).

7.1. Turbidite channels

The turbidite channels consist of (i) canyon talwegs; (ii) the Cap Ferrer Channel; and (iii) a minor channel (Figs. 4 and 10).

(i) The canyon talweg results from the downslope evolution of the entrenched talwegs coming from the Santander and Torrelavega canyons. When they reach the continental rise, they become smaller, branch, and display a sinuous pattern (Fig. 4). The ancient talweg of the Santander Canyon is also present in the continental rise, where it extends down to 4000 m water depth, showing a semicircular pathway running toward the west. The modern talweg displays a NNW–SSE direction that changes toward the west and reaches the Jovellanos High. Around this point, the talweg coalesces with that of the Cap Ferret Channel. The Torrelavega talweg is traceable just before it reached the Jovellanos High.

(ii) The Cap Ferret leveed channel mapped here corresponds to the northern Cap Ferret channel of Faugères et al. (1998) (Fig. 4). Those authors differentiated two main distributary channels in the study area, northern and southern. However, the new data, especially those obtained with the swath bathymetry, show that only one main channel (the northern channel) is present. It results from the confluence of at least three tributaries with NE–SW and E–W directions coming from the French continental margin. The channel reaches the continental rise and shows changes in direction from NE–SW to E–W when it borders the northern flank of the Jovellanos High, to again NE–SW. The channel course is defined by a trough 5.5 km wide and several thousand metres in relief, and locally it is entrenched by a talweg (about 1 km wide and <100 m in relief) when it flanks the Jovellanos High. When the channel goes over the high, the channel trough disappears, and the course opens without showing a clear talweg incision. Acoustically the channel floor is defined by transparent acoustic facies bounded by a highly reflective and irregular surface on the top and an erosive surface that truncates the underlying stratified facies. The facies display tabular, wedge or mounded shapes in transverse and oblique sections. Likewise, chaotic and hyperbolic facies are identified on the channel floor (Fig. 10A).

The Cap Ferret Channel is bordered by a levee on its northern side (Figs. 4 and 10E). It is an asymmetric ridge (at least 120 km long) with the outer face wider (>43 km) than the internal face (≈7 km). The relief is >500 m high, decreasing progressively to disappear at about 4600 m water depth. The internal seismofacies comprise mostly stratified facies, and also chaotic and hyperbolic facies. The crest of the levee is defined by a narrow (7.5 km), flat-lying summit.

(iii) The minor channel refers to the isolated channel identified in the westernmost sector of the surveyed continental rise, which runs parallel to the escarpment of the lower continental slope (Figs. 4 and 10C). Its head is represented by a semicircular scarp (≈8 km wide, tens of metres in relief) with a sinuous boundary that evolves downslope to a linear channel that branches 10 km downslope from the head. Two branches run toward the NW and the third one continues westward, all outside the limits of the study area. This channel would correspond to the southern main distributary channel defined by Faugères et al. (1998). The new data of multibeam bathymetry have allowed it to be outlined with confidence and to be considered as a minor order distributary channel.

7.2. Sediment waves

The sediment waves occur on the northern face of the Cap Ferret levee, where the gradients vary from 0.4 to 0.1° across the wave field. The multibeam bathymetry shows that the crests of these waves are sinuous with bifurcations and roughly parallel to the regional slope (Figs. 4 and 10E). Though there are no seismic lines that cut perpendicularly to the crestlines, the morphological measurements made on waves indicate that their dimensions are variable, with a WH (wave height) of 1–25 m, and a WL (wave length) of 534–2600 m. They are asymmetric and generally the steeper and shorter flank faces upslope. The stratigraphy of the sediment waves is mainly defined by parallel to subparallel stratified facies. Lateral thinning and thickening of individual layers is observed, with individual layers thinning on the downslope flank leading to their pinch-

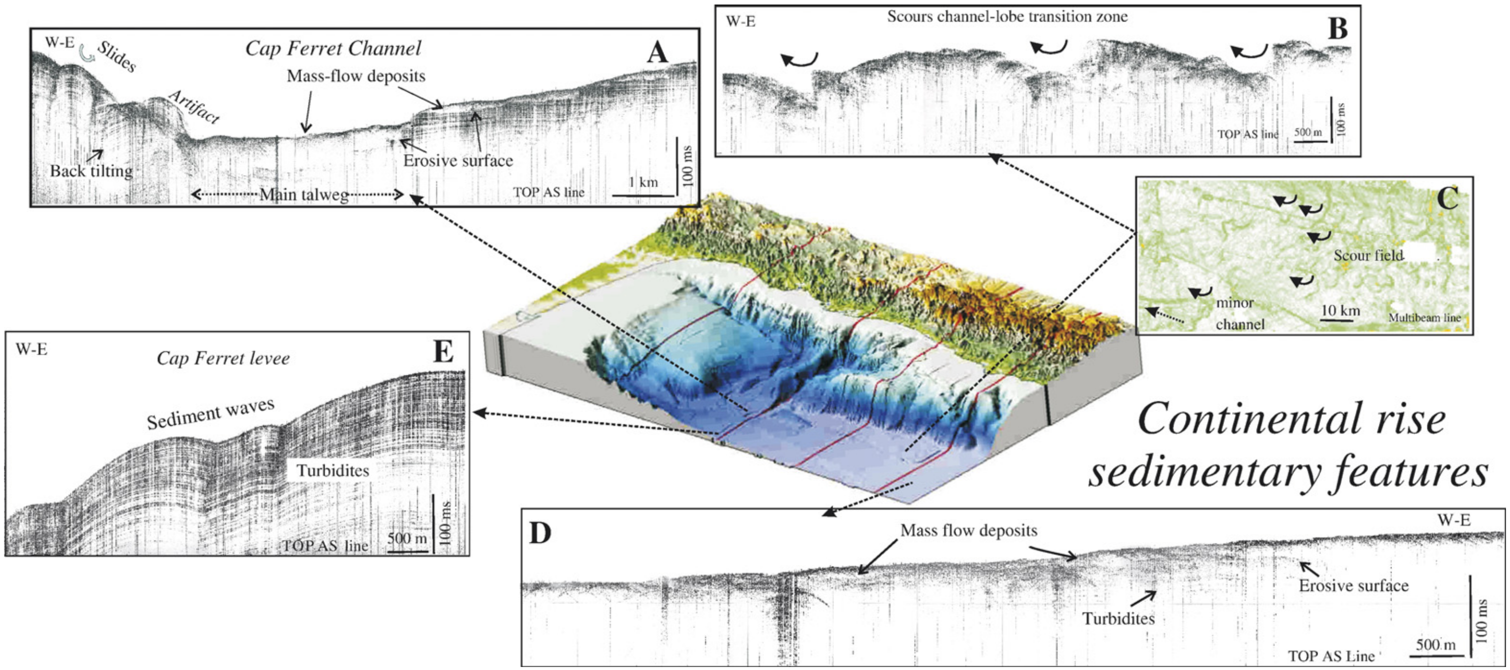

Fig. 10. Segments of TOPAS seismic profiles and colour gradient record from multibeam (see Fig. 3) illustrating the main morphosedimentary features identified on the continental rise: A) Cap Ferret Channel affected by mass-flow deposits and slides; B) scours developed on the CLTZ; C) scours and minor channel on the CLTZ; D) debrites and turbidites that floored the continental rise; and E) turbidite sediment waves on the external face of the Cap Ferret levee.

out. This results in an upslope migration, although some vertical aggradation is also observed.

7.3. Spoon-shaped scours

These scours occur just past the Jovellanos High, downslope from the confluence zone of the Cap Ferret, Torrelavega and Santander talweg incisions (Figs. 4, 10B and C). The scour area extends about 107 km in length. The scours are about 5 km wide, 20 m in relief, and up to 15 km long. They have the tendency to coalesce, creating large areas of erosion. In cross-sections, they have an asymmetric V profile, with the steeper and shorter side facing downslope. The seafloor of the scours is irregular and truncates the near-surface stratified and transparent deposits, indicating what seems to be an area of intense erosion. Acoustically this seafloor is mostly defined by hyperbolic echoes of high reflectivity.

7.4. Mass-movement deposits

Mass-movement deposits occur on the southern face of the Cap Ferret levee, where slides and mass-flows are the most representative types. Their occurrence leads to the presence of scarps and disrupted and contorted sediments forming an irregular seafloor. They extend downward from the upper part of the face and reach the channel floor (Figs. 4, 10A and D).

Mass-movement deposits also characterize the continental rise deposits, and comprise mass-flow deposits and sheet-like turbidites. The mass-flow deposits look like debris flow deposits and consist of lens-or wedge-shaped masses with an internal acoustic transparency and seafloor tangent hyperbolas and prolonged echoes in the surface (Fig. 10D). It is not always possible to identify the individual lenses or wedges, but when it is their upper surfaces display mostly a convex-upward morphology and their lower boundaries are horizontal, whereas others show a V-shaped depression at their base. Individual bodies range from tens to hundreds of metres in length, and are tens of milliseconds in thickness. Their upper surface laps onto the underlying sediments that comprise similar bodies and/or sheet-like turbidites.

The sheet-like turbidites are characterized by discontinuous and continuous stratified reflections of high acoustic amplitude (Fig. 10D). The continuous ones are characterized by individual reflectors of high-medium amplitude and high lateral continuity. The discontinuous ones comprise individual discontinuous reflections of low to high acoustic amplitude that show traces of paralleling reflections.

8. Discussion: Sedimentary processes

8.1. On the continental shelf: Intense erosion

Erosion seems to be the dominant sedimentary process on the Cantabrian continental margin, which is why there is no recent sedimentation, at least on the outer shelf. Several morphological, seismic and sedimentological evidences support this interpretation:

1) The shelf break is sharp. It does not display the typical ramp shape in cross-sections and bulges in plan view that tend to be indicative of prograding sediments making up the recent sedimentary architecture of other continental shelves of Iberian margin (Farran et al., 1992; Ercilla et al., 1994a,b; Chiocci et al., 1997; Hernández-Molina et al., 2002; among others) (Figs. 2, 4 and 5C).
2) The seismic profiles show outcropping folded and fractured deposits (Fig. 5A, C, E and D). The surficial sediment map obtained from the literature indicates that the outcropping material is Cretaceous and Miocene in age (Vigneaux, 1974).
3) Only one wedge-shaped body with prograding sediments is identified, and its location is limited to the shelf break (Fig. 5C).

We propose that the interplay of the narrowness of the continental shelf with the Pliocene–Quaternary sea-level changes have favoured the absence and/or preservation of recent shelf sediments. This interplay has been also proposed in other continental shelves of the Iberian margin (Farran et al., 1992; Ercilla et al., 1994a,b; Chiocci et al., 1997; Hernández-Molina et al., 2002; among others). The narrowness of the shelf favoured that most of the hinterland sedimentary discharge deposited on the continental slope during sea-level falls and lowstand stages. The multiple Plio-Quaternary shoreline regressions exposed successively and repeatedly the continental shelf, favouring incision of streams, nearshore erosive processes during the sea-level migrations across the shelf, and subaerial erosive processes during shelf exposure. In this scenario, the lowstand shelf-margin deposits represent the residual regressive deposits formed during the late Pleistocene lowstand stages.

The combination of these erosive processes produced a widespread truncated and high-reflectivity surface. The outcropping of different stratigraphic units, and consequently of materials with different hardnesses or degrees of consolidation, favoured local differences in the rate of seafloor erosion and therefore the presence of isolated morphological highs (Figs. 4, 5A and E). This erosive nature of the seafloor is only interrupted in the westernmost sector of the inner shelf, where transparent modern sediments with wave morphology are identified (Fig. 5B). Their acoustic nature indicates that they represent modern shelf sediments deposited from settling of particle suspensions coming from short-river discharges and/or hinterland erosion. Their wave morphology suggests seabed rework related to hydrodynamic processes (e.g. coastal/shelf currents) that control the modern sediment redistribution.

8.2. On the continental slope: Predominant slope failure and oceanographic imprint

Sedimentary processes occurring on the surveyed area of the continental slope are associated mostly with slope failures and oceanographic bottom currents. These processes have sculpted the main morphosedimentary features of the upper and lower slope.

8.2.1. Slope failure

The continental slope of the Bay of Biscay is an area of intense slope failures. Three main regions of slope can be characterized based on the variability and distribution of types of mass-movement: (i) submarine canyons and (ii) upper and (iii) lower open slopes.

(i) The failure styles in the submarine canyons include slide and mass-transport (Figs. 4, 6–8, and 11). The large and small-scale canyons appear to have resulted from retrogressive failures, which seem to begin on the upper margins of the canyon walls, where multiple and individual slide failures are recognized. The slide scar orientations toward the canyon, their arcuate shape in plan view, and the less upward translational displacement of the multiple slides all suggest their retrogressive displacement. Their occurrence seems to be associated with the steep slope gradients of the canyon walls. The evacuation of material and/or undercutting that occur there lead to the loss of downslope support and shear strength of the immediately upslope sediment, which increase the likelihood of sliding. Similar observations have been reported in detailed studies in the Capbreton Canyon (Gonthier et al., 2006) and in other areas (Klaucke and Cochonat, 1999; Casas et al., 2003; Mosher et al., 2004).
These slides will have moved through the walls down to the canyon floor, evolving to mass-transport processes and turbidity currents (Fig. 11). The mass-transport processes lead to the depositing of sediment on both the walls and floors, with no indication of an internal structure and a very rugged surface (Figs. 4, 7A, 8B, C and 11). The passing turbidity currents form a well-defined talweg that in the middle and distal reaches looks like a sinuous channel (Figs. 4, 6A and B).

(ii) The failure styles on the open slope are mostly different, although locally slides are also identified (Figs. 4, 7B, C, 8A and 11). The failure style involves short movements because these masses do not appear to have been transported over significant distances; in fact, their acoustic features seem to show evidence of initiation of movements of the material. They are slightly deformed and disrupted and are also locally affected by surficial failure events that have exhumed material and whose presences suggest the occurrence of areas of slab removal. The triggering mechanisms is unknown but tentatively we can consider several factors (or even interplay among them), such as the lower boundary acting as weak layer that fails downslope, seismicity (Engdahl and Villaseñor, 2002), oversteepening, and faulting and deformation of the buried sediments on which they are resting (locally they cover canyons-fill deposits). More high- and very high-resolution acoustic data, especially multibeam data, are necessary to a better characterization and understanding of these masses.

(iii) Finally, the steep lower continental slope, including the northern wall of the Le Danois Bank, are also affected by failures, although the styles and types of deposits are different to those of the upper slope (Figs. 4 and 8D). The geomorphology and acoustic facies observations suggest that this steep slope resembles a scarp affected by mass-wasting processes, and that the products of this erosion are deposited down to the slope break as low-relief bodies (Figs. 8D and 11). These deposits must have formed an apron slope system (Stow and Mayall, 2000) in which slides, mass-flows and short turbidity currents eroded the seafloor forming rill and gully topography, scoop-shaped scars, slide masses and depositional lobes. The erosion activity of this mass-wasting seems to be greater in those sectors where the seafloor gradients are higher (>20°). Here, recently deposited sediment would be prone to failure, sliding and transport downslope. The lack of acoustic penetration observed in this sector could be related to the occurrence of this type of

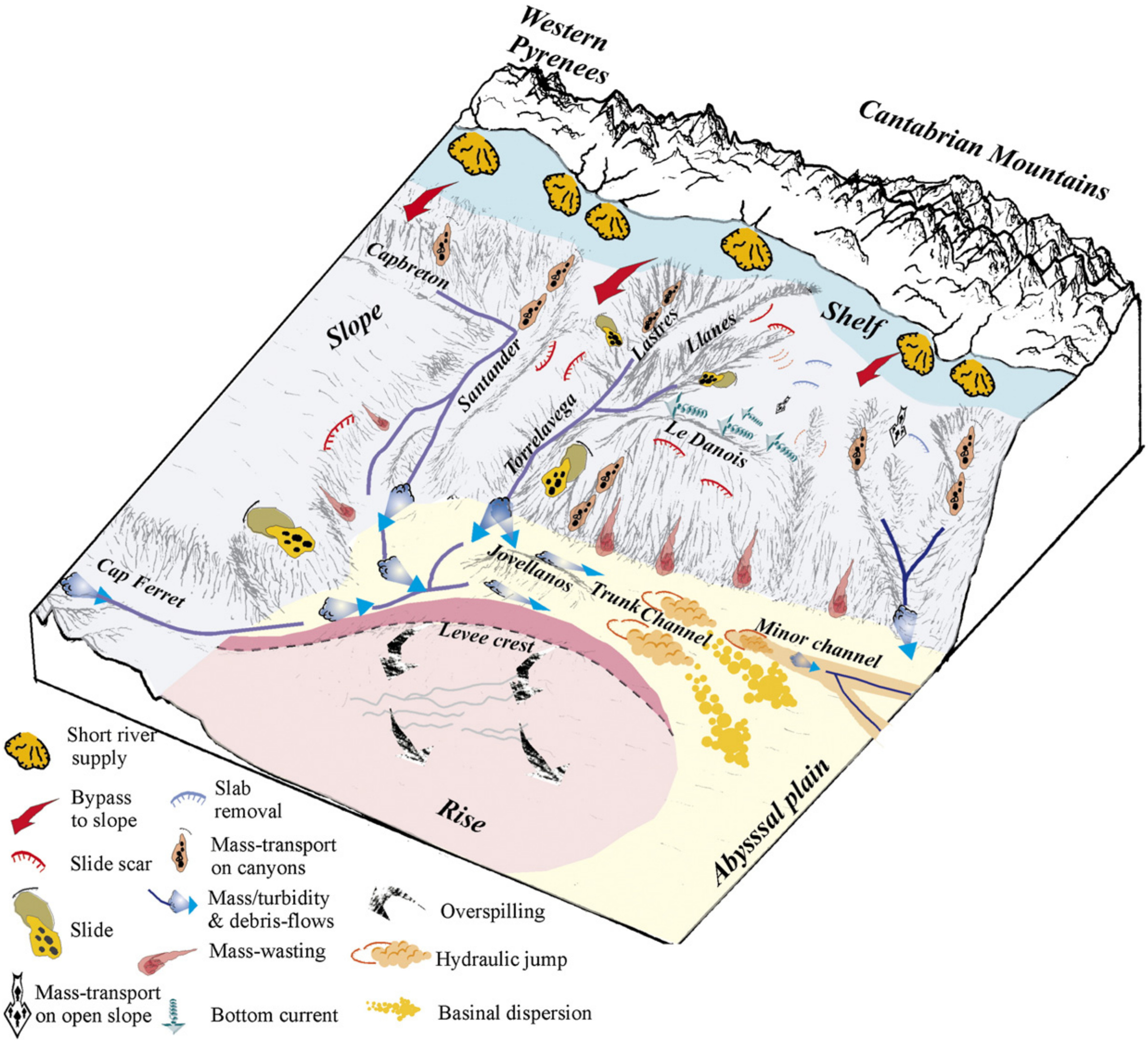

Fig. 11. Sketch of the recent sedimentary processes that characterize to the Cantabrian continental margin. This sketch has been produced based on the main recent morphoseismic features defined in the shelf, upper and lower slope, and rise. Names of the principal bathymetric features are also shown.

sedimentary processes, although the fact that the high slope gradients affect the acquisition and performance of the seismic systems must also be considered. As the gradients decrease eastward (to 3°), the acoustic penetration increases, the areas affected by the erosion activity of mass-wasting processes decrease, and the outline of their resulting near-surface deposits improves significantly. In this case, slides and mass-transport deposits predominate.

8.2.2. Bottom current activity

The continental slope also displays the oceanographic imprint in its morphology. The action of bottom currents has favoured the development of a contourite depositional system at the foot of the Le Danois Bank (southern side) (Figs. 4, 9 and 11). Its action has led to the formation of a moat paralleling the trend of the bank, and an adjacent contourite drift on its southern side. This bottom current is associated with the MW that flows between 600 and ≈1500 m water depth (Iorga and Lozier, 1999).

Based on the morphology of this contourite system, the drift can be classified as an elongated-mounded, separated drift (Faugères et al., 1999). The development of this type of body is the result of interaction between the MW and the local topography. Specifically, its development is conditioned by the Le Danois Bank that acts as an obstacle and creates an elongated intraslope basin bounded laterally by canyons for the passing MW. Its presence forces the MW to accelerate while crossing the intraslope basin down to water depths of about 1725 m, and reaching velocities that are enough to erode and transport the seafloor sediment. Once the MW flows away from the limit of the bank, erosion on the moat and drift deposition are not observed (Fig. 4). The origin of a near-surface secondary drift-moat association identified on the external face of the main drift is uncertain, but it could be also related to distortions in the streamlines (Fig. 9A and C).

The stratal pattern indicates that style of growth has not changed over recent time although depositional processes have changed on several occasions, as is suggested by the presence of internal unconformities (downlap and erosive surfaces) that indicate that the activity regime of the MW has varied over time (Fig. 9B and C). Likewise, the fact that the unconformities are traceable through and along the contourite depositional system suggests that MW changes have been of large-scale. It is widely known that recent sedimentary evolution of the Iberian continental margins has been controlled by climatic sea-level changes (Farran and Maldonado, 1990; Ercilla et al., 1994a,b; Chiocci et al., 1997; among others), which have also been considered a controlling factor in the sedimentation on the continental shelf of the Bay of Biscay (Cremer, 1981; Faugères et al., 1999; Zaragosi et al., 2000, among others). These variations in sea-level could have affected the competence of the MW by means of variations in the thickness and characteristics of the MW masses and/or in the sediment supply for bottom-current transport. More detailed stratigraphic analyses and studies of the relationships with the downslope gravitational processes are needed to confirm or improve these hypotheses.

Sedimentary structure displayed by the high-medium resolution seismic profiles show that the role played by bottom currents was more important in ancient times. This is suggested because the near-surface drift-moat depositional system overlies complex systems of contourite deposits formed by marginal moats, drifts, and sediment waves (Fig. 9B). Their growth suggests that the paleocirculation pattern was more complex and affected a larger area of the intraslope basin. The presence of basement highs acted to obstacles to the bottom currents, generating distortions and eddies (vortices) in the streamlines of the impinging bottom flows. These hydrodynamic features play an important role in the distribution and deposition pattern of sediments around morphologic highs (Taylor, 1917; Roden, 1987; Hernández-Molina et al., 2006; Toucanne et al., 2007; among others). As sediment went infilling, covering and obliterating the irregularities of the acoustic basement, the hydrodynamic processes were less complex.

8.3. On the continental rise: Turbidity and debris flow bypass

The mapping of the morphosedimentary features and seismic data show elements related to the distal part of the Cap Ferret Fan (Cremer, 1981, 1982, 1983) (Figs. 4 and 10). The new data show that the elements identified in the study area correspond to a channel-lobe transition zone (CLTZ), so this region can be considered as a bypass region of gravity flows (Fig. 11). This fan has three main singularities (Figs. 4 and 10).

The first singularity is that the tributaries of this system are not only represented by the Cap Ferret leveed Channel; the overall drainage system includes this main channel and also the network of submarine talweg canyons (Capbreton–Santander and Torrelavega) that open into the continental rise as sinuous turbidity channels (Figs. 4 and 11) (Faugères et al., 1998; Bourillet et al., 2006).

The second singularity is that the Cap Ferret Channel has only developed one levee on its right side. The flows running along the Cap Ferret Channel and also those coming from Capbreton–Santander and Llanes–Lastres–Torrelavega canyons, all mixed have the capacity to overflow successively, contributing to the upbuilding of the levee (Fig. 11). The overflowing and spreading of these currents following the maximum regional slope gradient has also favoured the formation of sediment waves on its outside face (Figs. 4, 10E and 11). That is to say, they represent primary depositional features rather than the product of slope failures or other types of post-sedimentary deformation. This is suggested by the upslope migration, their roughly parallel orientation to the regional slope, the presence of crest bifurcation, and their exclusive location on the levee backslope face. The genesis related to the action of bottom currents has also been rejected because most bottom current sediment waves have an oblique crestline orientation with respect to the regional slope, which is not the case here.

The third singularity is that this network of drainage is constrained between the depression created by the single levee of the Cap Ferret Channel and the steep slope of the lower continental slope (Figs. 1, 4 and 11). This depression with this drainage network must act as a “trunk channel” that feeds the region of channel-lobe transition with turbidity currents and also debris flows. This is suggested by the generalized presence of basinal sheet-like turbidites and debris-flow deposits. We think that flows transporting these sediments come mostly (or almost exclusively) through the “trunk channel”, though the lower continental slope and the Le Danois and Jovellanos highs could also be considered as sources of unconfined mass-movements. However, the acoustic imaging of these mass-movement deposits suggests that here gravitational processes (slumps and mass-flows) have a low efficiency in the sediment transport, so they deposit their sediment close to the source areas.

The presence of both debrites and turbidites, and the different types of debris flow deposits defined according to their geometry and lower boundaries, indicates that the type and energy of the passing flows were variable, with a different capacity to erode and/or deposit the sediment charge (Fig. 10D). Likewise, the presence of erosive spoon-shaped scours suggests that the flow expansion region is associated with a hydraulic jump that occurs within the region of the “trunk channel”, immediately beyond the Jovellanos High, where there is a break in gradient from 0.04° to 0.008° (Figs. 4, 10B, C and 11). In other turbidite systems these jumps tend to occur just outside the main channel mouth (Normark and Piper, 1991; Kenyon and Millington, 1996; Kenyon et al., 1995). In our study area, the presence of the Jovellanos High may constrict the passing flows, which would expand where they exceed the limits of this high. The minor channel and amalgamated scours probably represented zones of stronger erosive turbulence than individual scours (Wynn et al., 2002). These flows affected by hydraulic jumps in the CLTZ must deposit downslope, at water depths of at least 4800 m, outside the limits of the study area, where sandy lobe sediments have been defined by Cremer (1981, 1983), Cremer et al. (1999). The plain shape of these features suggests that the direction of flow dispersal is toward the west and northwest, i.e, toward the Biscay Abyssal Plain (Fig. 4).

9. Conclusions: Depositional architectural model

The Cantabrian continental margin shows a complex architectural model that results from the interaction of the major elements that define the morphostructural configuration and physiographic provinces of the bay with the great variability of interconnected sedimentary systems (Figs. 1, 4 and 11). The literature categorizes the Cantabrian continental margin as a deep and steep margin, based on morphological criteria (Grady et al., 2000). Fig. 2 shows how the entire depositional profile from source (the Cantabrian Mountains) to sink (the continental rise and Biscay Abyssal Plain) extends from 3600 m high onland to about 4500 m water depth in a relatively short transverse distance of about 150 km. In other words, there is a drop of about 8.2 km in 150 km (about 5%), and therefore a relatively steep slope. Figs. 2 and 4 also show the roughness and high slope morphological variations of the margin. These variances are related not only to the physiographic/morphological features created by the structural template, but also to the occurrence of a variety of complex depositional systems whose nature, location and geometry have been conditioned by this template.

The major sedimentological elements or keys that characterize the architecture of the proximal Cantabrian continental margin (i.e. shelf and continental slope) are: i) a truncated stratigraphy on the shelf; ii) canyons with a high degree of incision, iii) a great variety of instabilities; and iv) contourites. The truncated shelf indicates a lack of recent sediments because erosion affects Cretaceous and Miocene deposits. This erosion was favoured by the interplay between the sea-level falls ands lowstand stages and relative shelf narrowness. Furthermore, about 65% of the upper slope is being cannibalized by the canyons, whereas 35% of the eastern upper slope is affected by unstable sediment masses, small-scale canyons, and contourites (Figs. 4 and 11). The alongslope action of the MW locally complicates the downslope effect of the mass-movements, and reworks and redistributes the unstable sediment building a contourite system (elongated-mounded separated drift) at the foot of the Le Danois structural bank (Figs. 4, 9 and 11).100% of the lower slope and walls of the Le Danois Bank are also affected by a great variety of mass-wasting processes (slides, mass-flows and turbidity flows) (Figs. 4 and 11).

The architecture of the distal Cantabrian continental margin (i.e. continental rise) is defined by the construction of the CLTZ of the Cap Ferret Fan (Figs. 4 and 11). The large canyons (Santander, Torrelavega, Lastres, and Llanes) and their intense mass-wasting lead to the channelling of sediments coming from hinterland (the Cantabrian Mountains) and shelfal erosion down to the deeper areas (Figs. 4 and 11). Sediments coming from the French margin through the Capbreton and Cap Ferret canyons also reach the continental rise, developing a complex distal fan in which morphosedimentary (the levee, turbidite channels, sediment waves, debris-flow deposits, distal sheet-like turbidites) and morpho-tectonic features (the Jovellanos High) interact. This study emphasizes that mass-movement also plays an important role in shaping the distal part of this continental margin.

The truncated shelf stratigraphy and the remaining structural template suggest that from a sedimentological point of view the Cantabrian continental margin can be considered as a starved margin. We think that the starved character is not related to a low sediment input, but to its great evacuation through an important drainage system formed by large submarine valleys and instabilities processes. On a long time scale the denudation and erosion of the Cantabrian Mountains western Pyrenees mountains since their formation during the Tertiary orogeny must have contributed large volumes of sediment. This sediment will have been transported by small mountain streams/rivers to the sea. Milliman and Sivistky (1992) give good examples of the behaviour of streams of this type and their great capacity to transport large volume of sediment. The high gradients of the erosional topographic landscape evolve and join the high gradients of the continental margin seafloor. The steepness of the Cantabrian continental margin will have favoured the evacuation of this sediment reaching the sea through the large canyons and it will have been slowly transported by the instability processes toward the gentle continental rise (Figs. 2, 4 and 11). Locally, this transversal dispersal has been interrupted by a longitudinal sediment dispersal in the intraslope basin, when the MW interacts with Le Danois Bank. The continental rise forms the depositional area (i.e. sink) of the Cantabrian and western Pyrenees mountains (i.e. the sources) with the building of a fan, but is also a bypass area of debrites and turbidites towards the Biscay Abyssal Plain. The westward steepness ($<0.3°$ down to $<0.008°$) of its seafloor will have favoured the transverse dispersal pattern of the deposited sediments and the bypass of the flows.

The above-mentioned key characteristics of the stratigraphic architecture show that its main controlling factors are tectonism and sediment source/dispersal, whereas sea-level changes and oceanography have played a minor role (on a long-term scale). Tectonism and sediment sources, both onland and submarine, are closely interrelated in this study case. Tectonic highlights as the Cantabrian Mountains and western Pyrenees are the main sources of sediment fluxes from the north Iberian margin and French margin respectively to the Atlantic Ocean, and mountain streams play an important role in carrying these fluxes. It is widely known that tectonism controls the magnitude, location and evolution of the hinterland drainage systems, and in combination with the climate and local geology, conditions the flux (magnitude and type) to the sea (Frostick and Jones, 2002). However, in this study tectonism would has also been shown to affect the pattern of the submarine drainage systems and several aspects of the architecture, such as the physiographic boundaries, the regional submarine steep slope gradients, the presence of structural highs and intraslope basins, the large canyon locations as well as their enlargement and asymmetric profiles (left and right canyon walls canyons are steeper and have a more irregular seafloor), and the triggering of instabilities (related to seismicity).

The sea-level changes would have controlled shelf deposition or erosion, canyon enlargement or incision and occurrence of instabilities. The latter two occurred particularly during sea-level fall and lowstand stages when larger volumes of sediments are delivered to the deeper areas (Cremer, 1981; Faugères et al., 1998). The oceanography, in the form of coastal/shelf currents and alongslope currents (specifically the MW), has been shown in this study to be a factor controlling the local redistribution of the previously deposited sediment and the reshaping of the seafloor of the continental shelf and slope.

The above-mentioned recent (geologically) sediment dispersal and mixing would be important for a better understanding of the older sedimentary record and paleoclimate reconstructions of the region, both onland and continental margin, and also for paleoceanographic reconstructions. Likewise, the results obtained in this study from the definition and analysis of the morpho-sedimentary features is of great interest from an applied geology point of view. There are a great variety of information about seafloor gradients, abrupt breaks of slope, types of seafloor instabilities, oceanography, sediment pathways, seamounts, types of seafloor and subbottom material (consolidated, semi-consolidated, unconsolidated), that can be widely used in environmental studies and geological assessment.

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