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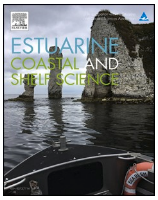

Morphosedimentary characterization of the Capbreton submarine canyon system, Bay of Biscay (Cantabrian Sea)

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ABSTRACT

Various studies have been carried out to the declaration of new marine protected areas for their importance for habitats, according to the Natura 2000 Network. One of these sites is a sector of the Capbreton Submarine Canyon System, located in front of the Basque Country coast, in the Bay of Biscay (North Atlantic). During the Intemares_CapBreton 0619 and 0620 surveys; bathymetric, backscatter, high-resolution parametric data and samples of sediments, rocks and benthic communities from the seabed were acquired. The study was completed by recording video transects with the underwater vehicle ROTV Politolana from the IEO. The processing and analysis of the geophysical information has allowed obtaining a detailed bathymetry grid of 10 × 10 m, from which the first morphosedimentary characterization of the system of tributary canyons to the E-W trending main canyon and its interfluves has been made. One of the main features of this canyon system is the presence of a large pockmark field on adjacent platforms between canyons, located between 500 and 1000 m water depth. Within this field, pockmarks are shown as circular to elliptical depressions, most likely related to gas rich-fluid emissions to the subsurface.

1. Introduction

Submarine canyon systems are very common morphological features that occur on both passive and active continental margins (Harris et al., 2014), acting as preferential sediment transfer pathways and sources from the shelf realm to adjacent deep basins (Puig et al., 2014). Submarine canyons may determine bottom water circulation and so on, remobilizing sediments and affecting communities' productivity being considered as hotspot of benthic biodiversity (De Leo et al., 2010). Anyhow, the canyon influence depends on its shape, dimension and relative position on the continental margin (Shepard, 1972).

Many recent studies on the mapping of submarine canyon seafloor and habitats, using multidisciplinary techniques as high resolution multibeam echosounders and profilers and imagery, have allowed illustrating the seafloor and benthic complexity, and to investigate the formation, interaction and evolution of these environments (Gómez-Ballesteros et al., 2014; Quattrini et al., 2015; van der Beld et al., 2017).

Capbreton Canyon is located in the eastern region of the Cantabrian Sea (in front of the Machichaco Cape) in the Bay of Biscay (North Atlantic), and runs approximately parallel to the coast in an east-west direction (Fig. 1). The southern slope of the canyon is characterized by the presence of several tributary canyons which intersect the slope and running perpendicular to the coast (south–north) (Cirac et al., 2001; Gaudin, 2006). The heads of these canyons are approximately 200 m deep and the canyon axis can exceed 2000 m when they reach the main valley of the Capbreton Canyon depth. This system of canyons covers an extensive area of about 2500 km^2. Using previous available cartographic information, relevant areas were detected for the possible settlement of habitats 1170 and 1180, linked to reefs and submarine structures generated by gas-rich fluids emission (Annex I of the Habitats Directive (EC, 2013)) (Galparsoro et al., 2012, 2015, 2020). Prior analysis of existing datasets revealed that this area was probably eligible for inclusion in the marine Natura 2000network. Therefore, within the scope

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of the LIFE IP INTEMARES project, it was proposed to carry out exhaustive studies only of some of the tributary canyons where, based on previous bathymetry data, a greater presence of rocky bottoms and zones interspersed between the tributary canyons of Capbreton were observed.

Within this context, the main objective of this study was to perform a detailed morphosedimentary characterization of the Capbreton Canyon System (CBCS). For that purpose, new bathymetric, backscatter information and parametric seismic profiles recorded during LIFE IP INTEMARES project have been analyzed. Moreover, sediment samples and underwater videos recovered and recorded during the same project expeditions have also been integrated in this study.

The morphosedimentary characterization is fundamental to increase the knowledge on canyon system functioning in the ecosystems and to study their conservation status and threats. This kind of integrated studies will contribute to the selection and proposal of protected sites to be included in the existing Natura 2000 marine Network.

2. Geological and oceanographic settings

The study area is located between the coordinates 3° 0′ W and 2° 3′ W in longitude and 43° 30′ N and 43° 50′ N in latitude (Fig. 1).

2.1. Geological setting

Capbreton Submarine Canyon is located on the Cantabrian margin, which is classified as a complex passive margin, with a tectonic evolution dating from the Jurassic to present (Pascual et al., 2004; Maestro et al., 2015). This evolution started with the opening of the Bay of Biscay by the oceanic expansion of the North Atlantic (Le Pichon et al., 1971; Sibuet et al., 2004). This movement caused the opening of the Bay of Biscay from W-E, generating oceanic crust. After the Iberian plate became independent, in the Aptian-Albian, an anti-clockwise rotation began, favored by the push of the African plate that caused an oblique NE-SE convergence with Europe at the beginning of the Tertiary period, in the Cenozoic (Maestro et al., 2013). The convergence between the Iberian and the Eurasian plates favored the inversion of the extensional structures to contractional ones (Pulgar et al., 1999), shortening the Cantabrian Margin and creating an abrupt-looking slope that is currently preserved. During Neogene, the network of submarine canyons and tributaries were developed, and the sedimentation that is currently observed in the platforms annexed to the canyon, smoothed the morphology related to tectonics (Gómez-Ballesteros et al., 2014).

The most remarkable geomorphological feature in this area is the Capbreton Canyon. Its head is located immediately next to the shore (Lobo et al., 2015). The Capbreton Canyon forms a 300 km long, meandering submarine valley, reaching depths of up to 3800 m (Brocheray et al., 2014), with an E-W orientation, highly influenced by the tectonic processes that gave rise to the margin (Boillot and Malod, 1988; Cirac et al., 2001). The southern flank of the canyon is dissected by tributary valleys, which are approximately perpendicular to the isobaths of the continental slope. The heads of these tributary canyons are located at the 200 m isobath. There are nine main tributary canyons with lengths from 16 to 34 km, and widths between 2.5 and 5 km (Galparsoro et al., 2020). In this sector, tributaries instead of connecting directly with the main canyon, they do it through terraces (Gaudin, 2006).

2.2. Oceanographic setting

The Capbreton Canyon is influenced by a system of boundary currents (Fig. 1) affecting the eastern region of the North Atlantic (González et al., 2004; Sánchez et al., 2014). Studies on the oceanographic conditions of this area reveal stratification along the water column in water bodies of different density (Montero-Serrano et al., 2013; Llave et al., 2015). Most of these water bodies (Fig. 1) are formed in the North Atlantic or are the result of the interaction of Atlantic water bodies with those formed in the Mediterranean (Pollard et al., 1996). Based on their distribution from surface to bottom, they can be classified as follows:

- Eastern North Atlantic Central Water (ENACW): It extends from 400 to 600 m depths (Ruiz-Villarreal et al., 2006), and is divided in two water bodies. One of them is cooler and with lower salinity, which has a subpolar origin (ENACWsp) (Harvey, 1982), and the other one has a warmer subtropical origin with cyclonic circulation (Fraga et al., 1982; Llave et al., 2015).
- Mediterranean Outflow Water (MOW): It constitutes water of Mediterranean origin that appears between 700 and 1400 m depths. It extends from the Gulf of Cadiz along the western Iberian margin to reach the Cantabrian margin. It is a body of water with high salinity and temperatures around 10 °C, considered abnormally high (Pingree and Le Cann, 1990; Díaz del Río et al., 1998; Iorga et al., 1999).
- Labrador Sea Water (LSW): This water is coming from the south of Ireland, entering from the northwest of the Bay of Biscay, below 1800 m depth. It is characterized by low temperature, below 4 °C, with very low salinity (Van Aken, 2002; Sánchez et al., 2014).

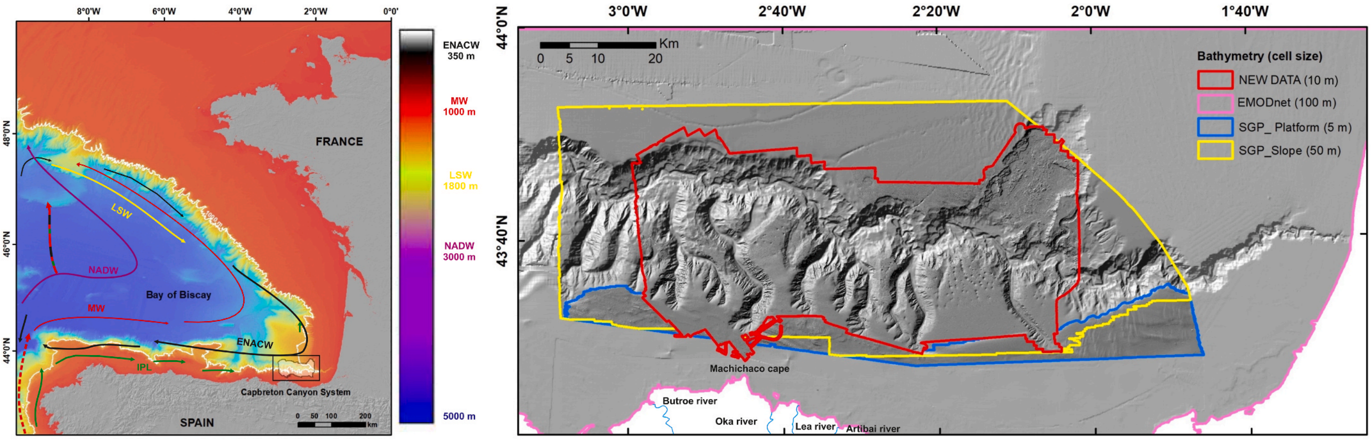


Fig. 1. Study site location within the southeastern region of the Bay of Biscay and multibeam bathymetry available of the study area. Inset: Main hydrographic circulation patterns and mean flow values (numerals in cm s^{-1}) largely from Pingree et al. (1986) and González et al. (2004). Red arrows = Mediterranean Water (MW); Yellow arrows = Labrador Sea Water (LSW); Black arrows = North Atlantic Central Water (ENACW); Purple arrows = North Atlantic Deep Water (NAWD); Green arrows = Iberian Poleward Water (IPL). (Modified from Gómez-Ballesteros et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

- North Atlantic Deep Water (NAWD): It is formed by mixtures of waters of Arctic origin, it presenting up to 3000 m of depth (Pingree and Le Cann, 1990; McCave et al., 2001).

In addition to large-scale currents, the Capbreton Canyon is influenced by local hydrodynamics (Mazières et al., 2014). Two types of currents should be noted at this level: Internal waves generated by the upward and downward movements of water bodies (Pingree et al., 1986), and turbidity currents that transfer particles of various sizes from the continental shelf to deeper areas (Mulder et al., 2012).

3. Material and methods

3.1. Bathymetric and backscatter data

Data recording was carried out between 2019 and 2020 during two oceanographic cruises (Fig. 2) on board the R/V Ramón Margalef owned by the Spanish Institute of Oceanography (IEO-CSIC).

The multibeam echosounder used was a Kongsberg EM-710 transmitting from 40 to 100 kHz, with an acquisition depth from less than 3 m below its transducers and more than 2000 m. The vessel speed was between 5 and 7 kn, to ensure the quality of the information collected and considering an overlap between lines suitable for 100% coverage of the study area. In order to calibrate multibeam echosounder and obtain sound propagation data in the water column, 8 sound velocity profiles of full water column using a AML SV Plus profiler were thrown. A total of 2640 km of navigation were covered, sweeping an area of interest of 2500 km^2 from 72 to more than 2862 m on the lower slope (Fig. 2).

Data acquisition software was SIS (*Seafloor Information System*) v4.3.2. and data processing was undertaken with the software CARIS HIPS and SIPS v11.3, generating CUBE bathymetric grids at 10 to 5 m of resolution for the complete study area and for the intertributary platforms, respectively. This software allows applying data filtering and tide corrections, in that case, using the records of the Bilbao 3 Tide Gauge in Bilbao Port (3.05°W, 43.35°N).

Also, backscatter was processed using the GeoCoder algorithm, resulting into a grid of 10 m of resolution, and a 5 m resolution for specific areas. Finally, the Digital Elevation Model (DEM) was integrated into an ArcGIS Desktop v10.8 project (Fig. 3).

Analyzing the information from the bathymetric data, the ArcGIS spatial analyst tools packages have been used to obtain the hillshade models and other terrain variables such as slope, curvature index, aspect and seabed roughness (Fig. 4).

The bathymetric position index (BPI) from the 10 m resolution DEM was calculated using the Benthic Terrain Modeler (BTM), a module of ArcGIS which provides a supervised seafloor classification (Walbridge et al., 2018).

A hierarchy of canyons was developed using the ArcGIS Hydrology tools. Specifically, a workflow was created with this module using a semi-automatic routine to calculate the flow accumulation and its orientation based on the orientation and slope for each cell defined for the canyon edge track. These data and geomorphological criteria are decisive to obtain most appropriate flow network with a differentiated hierarchy. Thus, it is possible to characterize the importance of each channel according to its contribution to the whole canyon system.

3.2. High-resolution seismic profiles

High-resolution seismic profiles were acquired with a hull-mounted TOPAS PS18 parametric echosounder to obtain information on the shallow structure of the area. This equipment is based on the reflection of seismic waves in the seafloor by an acoustic pulse and emitting simultaneously two close frequencies, between 16 and 20 kHz (Foote et al., 2010). In this way, a unique low frequency pulse is achieved by the difference between both, obtaining wide and penetration in the seafloor. The parametric profiles where lately introduced in the Kingdom IHS Markit software for its visualization and interpretation.

3.3. Surficial sediment samples

A total of 110 sediment samples were mainly recovered using a Smith-McIntyre dredge from the continental shelf to the tributaries and the main canyon, during both oceanographic surveys and further AZTI sediment database (Fig. 2). Granulometric analysis and content of organic matter (OM) has been realized.

The sedimentary characterization compiled has been supported by

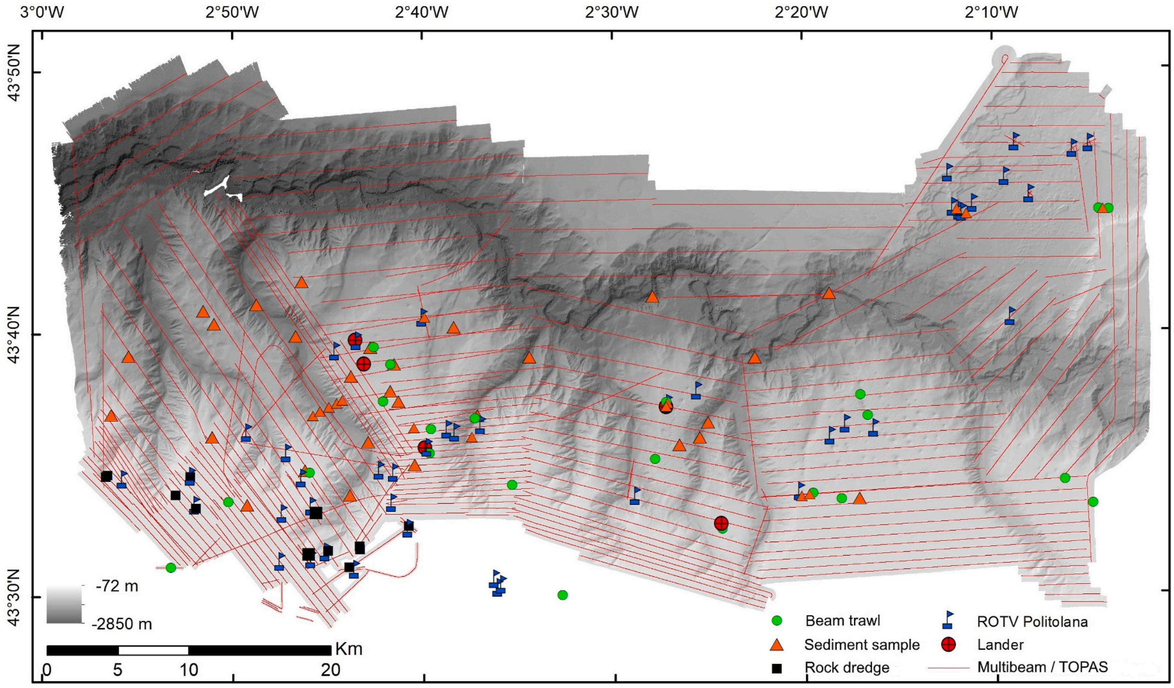


Fig. 2. Location of the sampling station during Intemares_Capbreton 0619 y 0620 surveys.

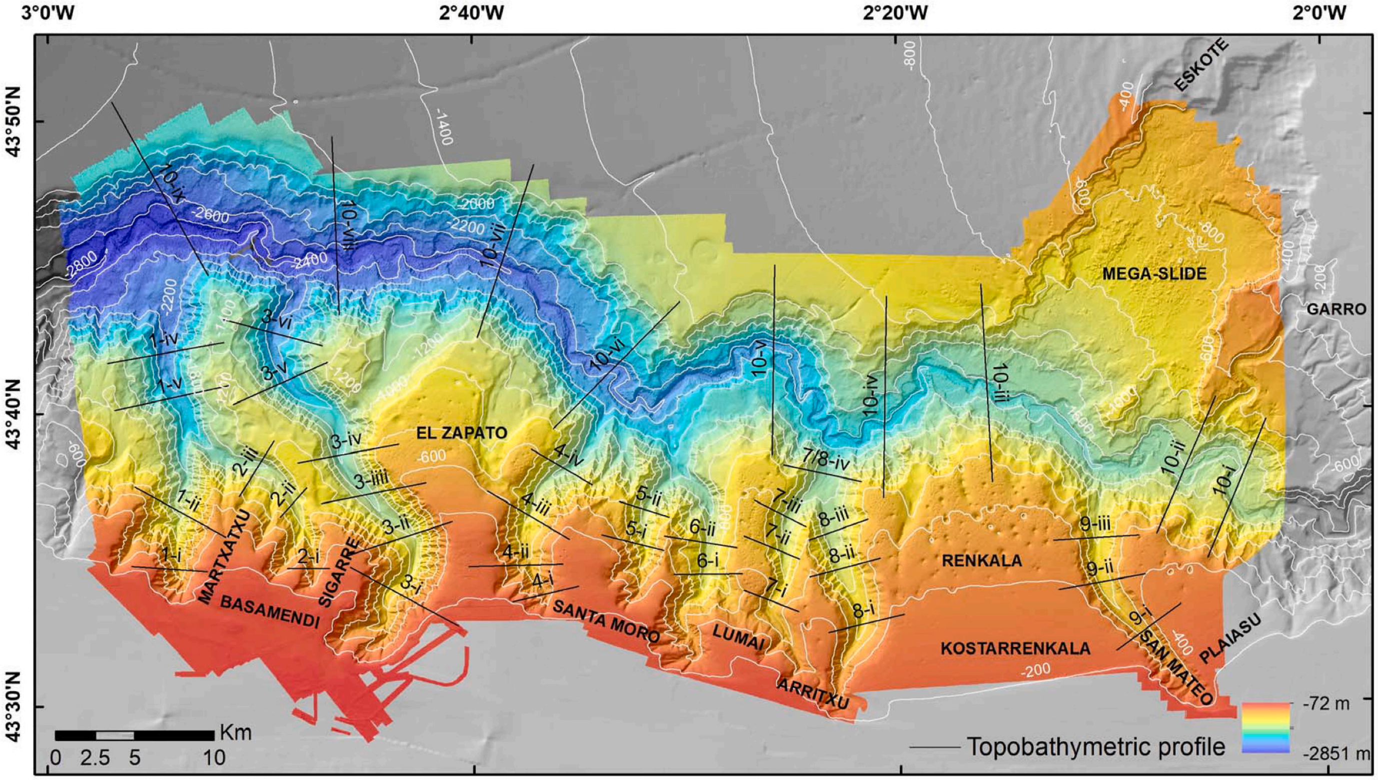


Fig. 3. Digital elevation model (10 m resolution) with location of the bathymetric profiles in Fig. 8 and the main toponyms of the area in Table 1. Areas with no new acquired high-resolution multibeam bathymetry have been completed with EMODnet bathymetry grid (grey colour). The isobaths equidistance is 200 m.

the processed data of backscattering mosaic, integrating grain size data from the surface sediment samples for reflectivity calibration.

3.4. Imagery data

To characterize the seabed facies and identify the species (ground-truthing approach), a total of 40 visual transects were carried out using the Remotely Operated Towed Vehicle (ROTV) Politolana (Sánchez and Rodríguez, 2013) (Fig. 2). This photogrammetric towed vehicle can be operated to a maximum of 2000 m depth. The transects were carried out with the vehicle moving at 0.7 ± 0.1 knots and flying at 1.0–3.5 m from the seafloor, altitudes necessary for the correct lighting of the images. The ROTV is equipped with a high-definition video camera, installed with a forward angle of 45° with respect to the bottom, which records the entire track of the transect. It also has a system of photogrammetry located in zenithal position based on a Nikon Z6 digital camera and four green parallel laser beams that make a still picture in a time-lapse mode each 10 s. The scaling of the zenithal image is very accurate (resolution ~ 1 mm), allowing us to estimate the size and density of species and their coverage on the different substratum types. The accurate location of the vehicle over the bottom is obtained through a USBL (Ultra-Short Base Line) transponder based on a HiPAP 500 Kongsberg system. The configuration provides information for sizing the facies, for estimating the biocenosis densities characterizing distinct habitats, and for associating them with other environmental characteristics.

The visual transects were recorded within the bathymetric range of 91–1190 m. They yielded a total of more than 11,000 valid images for photogrammetric areal quantification of occupied facies and for density estimates of species using the methodology explained in Sánchez et al. (2009). A total of 8.9 Ha were sampled with valid images along transects of 600 m average length.

A lander system (Geodia), designed to obtain high frequency bottom photography and environmental variables, was used for deployment at strategic locations in the area during the last survey. The system consists of a ballasted tripod made of stainless steel equipped with a submarine camera, baits and different sensors (CTD probe and Aquadopp single-point current meter). The structure was deployed and recovered with a main rope with buoyancy elements attached to it. The system was deployed on 6 stations at a range of 267–905 m depth. It was programmed at 1-min intervals taken as 30' burst-sampling periods.

4. Results

Using a DEM with a mesh size of 10 × 10 m for the complete area (Fig. 3 and Table 1) and more detailed resolution, 5 × 5 m, for the intertributary platforms, a geomorphological characterization of the Capbreton Canyon System has been done.

Derivative maps such as slope, curvature, aspect and seabed roughness (Fig. 4), and the information provided by the backscatter mosaics, give an idea of the complexity of the seabed of the area.

The slope gradient ranges between 0 and 50°, being the average slope of 12° (Fig. 4B). The steepest slopes are associated with the incisions of the tributary canyons in a range of 8 to 50°, while the rest of the area barely exceeds 6° of slope.

In general, high backscatter values (Fig. 4F) in the range of 8 to −18 dB correspond to hard substrates such as rocky outcrops and basement substrates as well as zones with very low sedimentary thickness. Low backscatter values correspond to soft materials formed by sands and muds, with values ranging between −18 and −23dB depending on the nature of the sediment. Those low values predominate in the study area, indicating the presence of soft bottoms.

The BPI, on two different scales, has been calculated from the bathymetric data. The broad scale (Fig. 5A) is used to identify large-scale morphological features by choosing an internal and external radius of 20 and 300, respectively; while fine scale BPI (Fig. 5B), with an internal and external radius of 10 and 15, respectively, is used to identify small-scale morphological types. Combining the information from bathymetry, slope and BPIs maps, a dictionary with the representative morphological

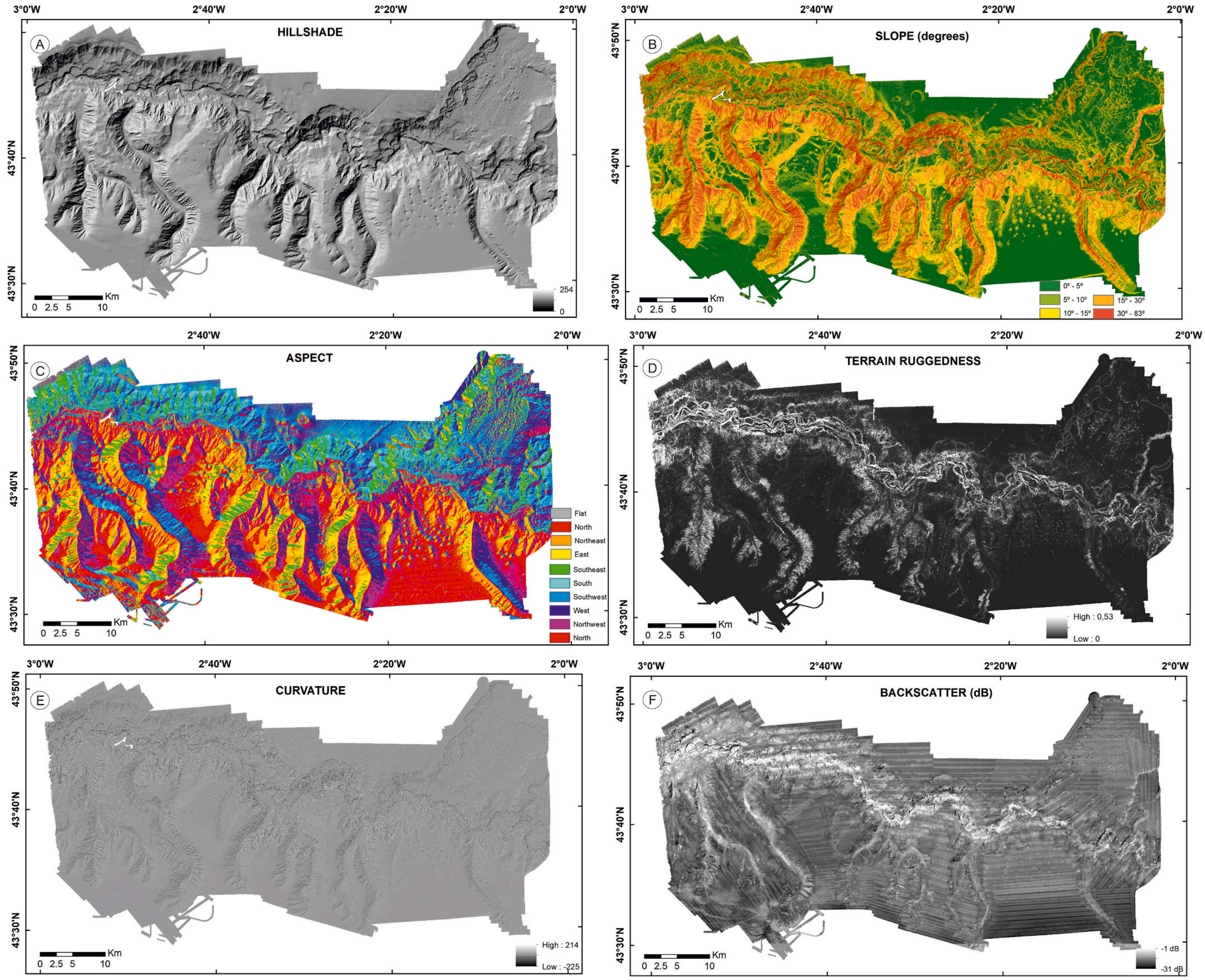


Fig. 4. Derived maps from bathymetry data: Hillshade (A), Slope (B), Aspect (C), Terrain ruggedness (D), Curvature (E) and Backscatter (F).

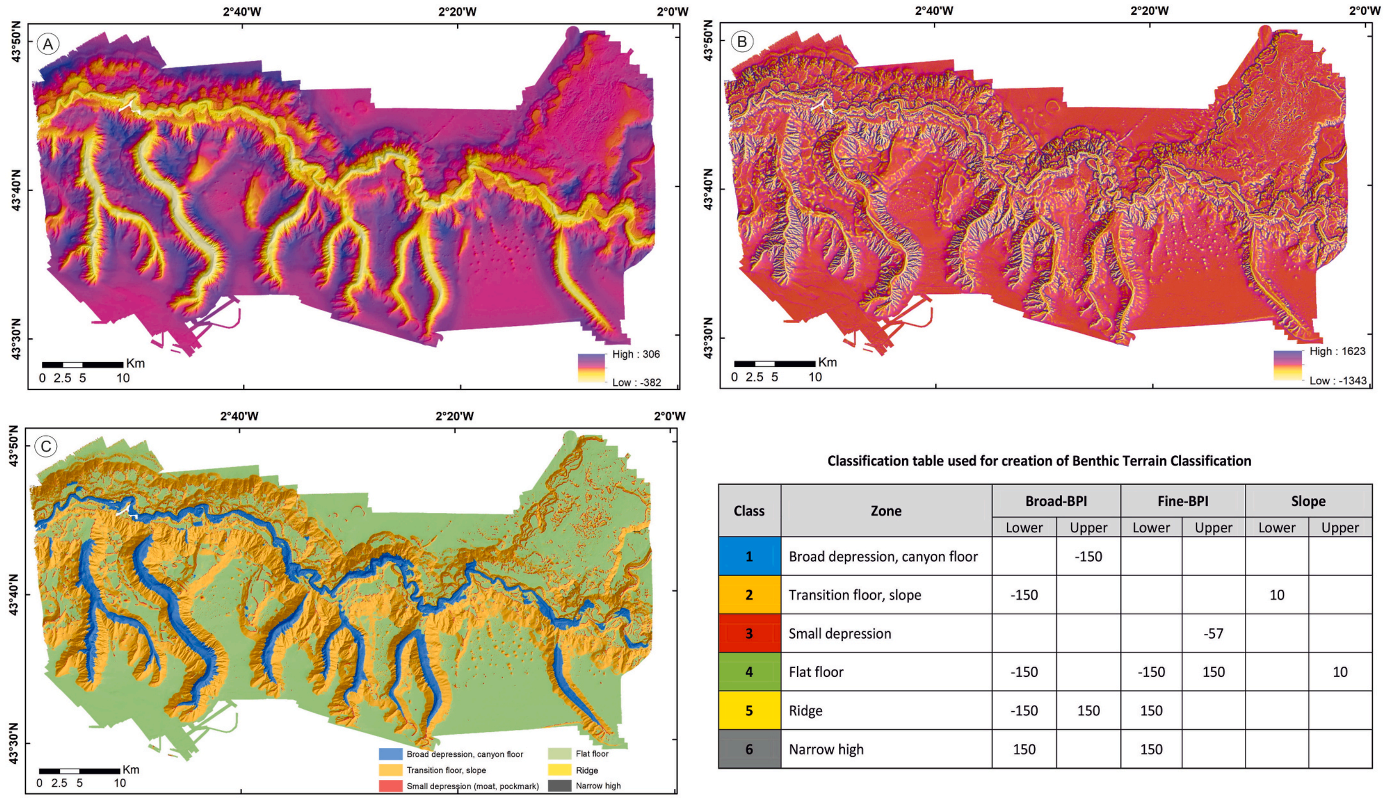
Table 1
Toponymy in the study area.

Morphological elements	Names
Rocky outcrops	Basamendi
Intertributary platforms and pockmarks fields (CBPF)	
	Martxatxu
	Sigarre
	El Zapato
	Santa Moro
	Lumai
	Arritxu
	Renkala
	Plaiasu
Capbreton Canyon System (CBCS)	
Main canyon (CBC)	Capbreton
Tributary canyons (from E to W)	CB-1
	CB-2
	CB-3
	CB-4
	CB-5
	CB-6
	CB-7
	CB-8
	CB-9
Mega-slide (CBMS)	

classes of the study area has been generated. A total of 6 classes have been defined: Broad depression, canyon floor; transition floor, slope; small depression (moat, incision, pockmark); flat floor; ridge and narrow high (Fig. 5C).

From the complete dataset, a granulometric analysis was carried out to study the spatial distribution and variability in the grain size of the soft-bottom, and the percentage of gravel, sand, mud and organic matter in the area (Fig. 6).

The highest percentages of mud are in the most distal part of the Renkala, Arritxu and El Zapato interfluvial platforms and the main canyon axis (Fig. 6). The bottoms of the tributary canyons flanking these platforms also present a high mud percentage, while the content of the sand fraction is very low in these areas. However, it increases in the headwaters of the canyons located on the continental platform, which is characterized by a high sand percentage, especially in the western sector, as opposed to the eastern sector, which has a muddier content. The gravel content is low throughout the area, but an increase of gravel percentage is remarkable on the continental shelf at the eastern edge of the study area. The highest levels of organic matter (>6%) are located in the western sector over the structural high and the mouth of the Basamendi tributary canyon (CB8) which branches into the main canyon (Figs. 3 and 6). This information has been integrated with the data



Classification table used for creation of Benthic Terrain Classification

Class	Zone	Broad-BPI		Fine-BPI		Slope	
		Lower	Upper	Lower	Upper	Lower	Upper
1	Broad depression, canyon floor		-150				
2	Transition floor, slope	-150				10	
3	Small depression				-57		
4	Flat floor	-150		-150	150		10
5	Ridge	-150	150	150			
6	Narrow high	150		150			

Fig. 5. Bathymetric Position Index maps: A) Broad scale and B) Fine scale. C) Morphological-derived classification map and its values in table classification.

collected by direct sampling (dredges and video) to generate a map of the seafloor types (Fig. 7) for the entire study area at a resolution of 10 m, classified in 3 main seafloor types: hard, soft and sedimentary bottom.

Therefore, analyzing the integrated bathymetry and its derivates, backscatter, parametric profiles, sediment samples and imagery dataset, and taking into account the existing literature in the area, a morpho-sedimentary characterization for the area has been interpreted and five priority sub-areas were established within the Capbreton Submarine Canyon System: tributary canyons, main canyon, intertributary platforms, pockmarks fields and a mega-slide. The analysis of the high-resolution seismic profiles acquired (Fig. 2) and their correlation with the surface structure obtained with high-resolution bathymetry is showed in more detail below.

4.1. *The physiography of the capbreton canyon system area*

The continental shelf is narrow and very low dipping, almost flat from 0 to 5° extending to the break shelf at 200 m depth. The continental slope has an average slope of 13°, and its width varies from 13.45 km in the east to 25.3 km in the west (Table 2 and Figs. 8 and 9).

The Capbreton canyon system area is mainly constituted by the south flank of the main canyon and their tributaries systems, which, in turn, are transversal to the main canyon and dissect the slope from south to north. This flank constitutes the continental slope in this area, being characterized by an upper slope with gradients ranging from 2° to 40° with maximum values located just in the tributaries canyons flanks, at the western area. The lower slope locates between 1240–2650 m water depth at the foot of the slope tributaries system canyons, closely matching with the axis of the main canyon. The major morphological features on the continental slope (Table 2) are the deeply incised CBCS, the interfluvial platforms and its associated pockmarks field (CBPF) and a mega-slide (CBMS) (Acronyms in Table 1).

The main morphological features have been identified from the integration of all data collected in the morphosedimentary interpretation map for the study area (Fig. 9), allowing to classify the facies (Fig. 10) in the different domains. The features are described in more detail below for each physiographic unit.

4.2. *Morphology of the Capbreton continental shelf*

The continental shelf is generally narrow, covering an area of 115 km^2. The outer continental shelf width varies from 7 km in the Machichaco Cape to 25 km, in Zarauz, with maximum depths of about 200. In general, the slope is low, almost flat seafloor up to 1°m and without structural highs but one isolated marginal platform. A remarkable feature on the outer continental shelf is the presence of tectonic morphologies and some hard bottom areas.

The shelf break is located at a general depth of about 200 m, with a maximum depth of ~220 m and shows a general E-W trend parallel to the principal axis of the Capbreton Canyon. In this area, the seafloor morphology displays rocky outcrops of different reliefs and morphologies, but 70% of the shelf surface corresponds to areas of low slope, less than 3°, practically horizontal and slightly dipping towards the north, aligned with the tectonic structures of the area described in more detail later. These areas present a scarce cover of fine sediments (Figs. 7and11D) which are not consolidated or correspond to highly eroded base areas, and 3 different types of rocky outcrops have been identified (Fig. 11).

4.2.1. *Massive tectonized rock outcrops*

This type of outcrop has been identified in the western sector of the continental shelf, forming different groups of massive and strongly fractured outcrops. The rocks present a convex and smooth bend in plain view and have reliefs of about 8 m concerning the adjacent seafloor (Fig. 11A).

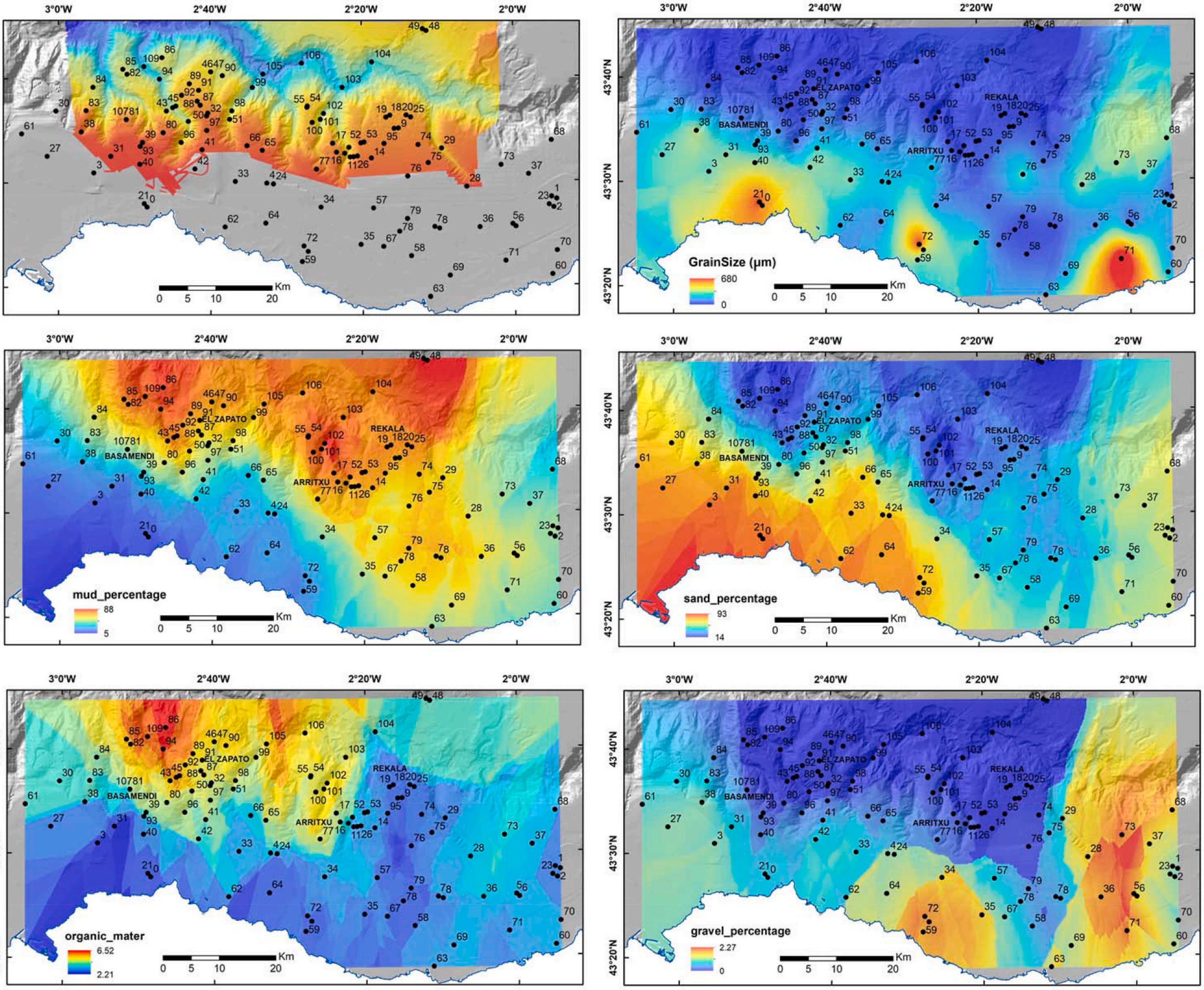


Fig. 6. (A) Sampling location. (B) Spatial distribution and variability in the grain size of the soft-bottom. (C) Spatial distribution and variability in the percentage of mud. (D) Spatial distribution and variability in the percentage of sand. (F) Spatial distribution and variability in the percentage of organic matter. (E) Spatial distribution and variability in the percentage of and gravel.

4.2.2. Folded rock outcrops

Associated with massive tectonized rock outcrops, there is another type of outcrops located in the central part of the continental shelf in the study area. These are characterized by linear folded outcrops with continuous sub-vertical strata. They constitute reliefs of up to15 m on the seabed (Fig. 11B).

4.2.3. Scattered outcrops

Located in the eastern sector of the study area, this type of outcrop has been mapped with a relief of 20 m and isolated on the surface, but possibly corresponding to the highest summits or basement highs (Fig. 11C).

4.3. Morphology of the upper and lower continental slope

The continental slope has been divided in upper and lower regions, covering a total area of ~2300 km^2 (Fig. 9). The upper continental slope occupies the seafloor from the continental shelf break to approximately the 2000 m isobath, with an area of 1950 km^2. The continental slope is cut from S to N by a series of tributary canyons that cross the margin from the shelf to the edge of the Capbreton Canyon. The tributary canyons heads are located at the upper proximal slope, alternating with intertributary platforms where the upper slope reaches its greatest extension. Therefore, the upper proximal slope width is variable from 2000 m in the narrowest area due to the presence of canyon heads (Figs. 3 and 9), located at 450 m depth, to 20,000 m width in the area of the largest marginal platform "El Zapato" (Fig. 3). It is characterized by an abrupt relief and variable slopes in the areas of head canyons, to a sub-horizontal relief in the intertributary platforms. Therefore, the slope varies from sub-horizontal in intertributary platforms to more than 40° in tributary canyons areas (Figs. 4B and 7). The intertributary platforms are mainly characterized by sedimentary thicknesses in which extensive pockmark fields are almost widespread developed (Fig. 9).

The upper distal slope is characterized by higher gradient. It is densely crisscrossed by tributary canyons and gullies (Fig. 9), forming the south Capbreton Canyon's flank, and also limited at the foot of slope by the canyon incision. Along the upper distal slope, we differentiate some sedimentary areas, most of them towards the west, corresponding to different terrace levels.

The lower continental slope in the surveyed region occupies an area

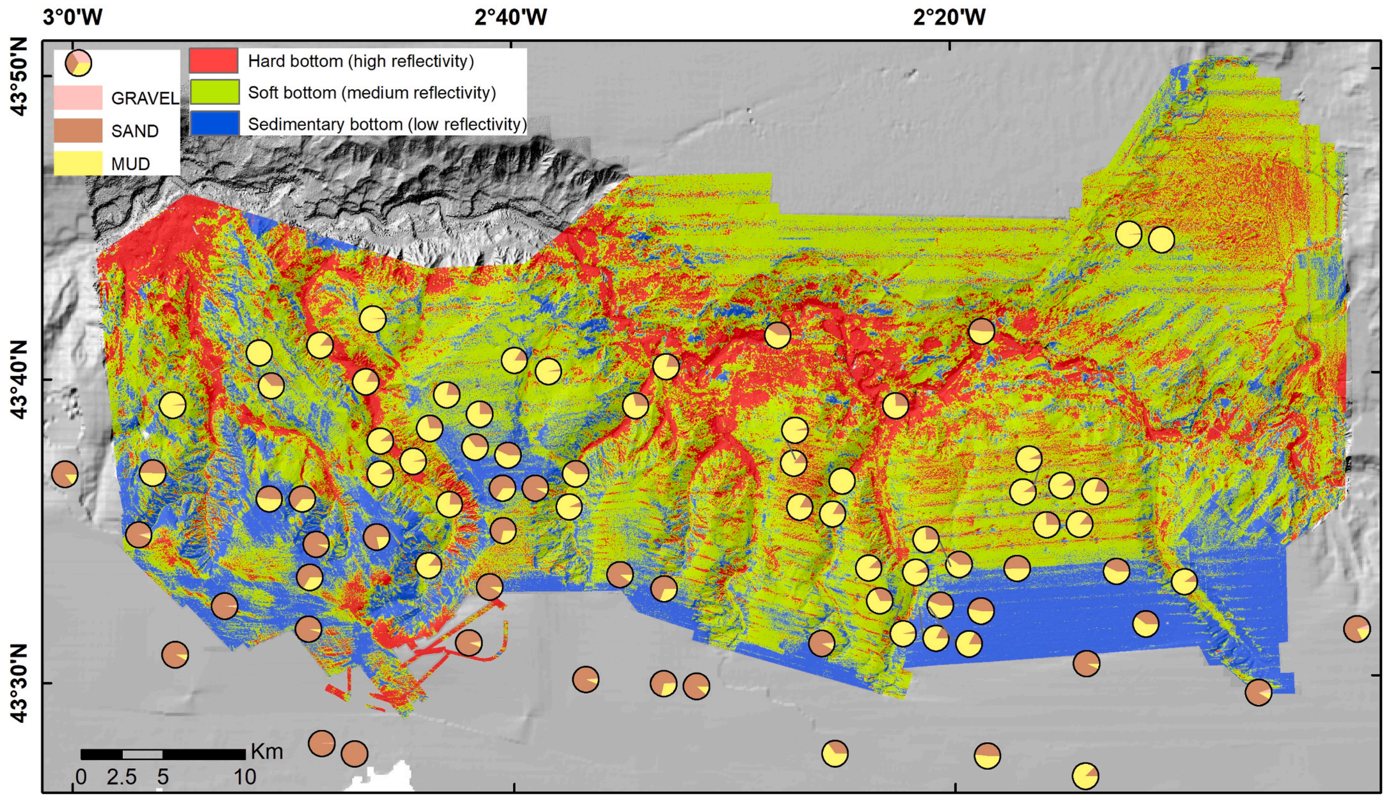


Fig. 7. Seabed substrate characterization from the reflectivity mosaic and the percentage of gravel, sand, and mud in the study area.

Table 2
Summary of the parameters characterizing the physiographic provinces of the Capbreton canyon margin system area, obtained from swath bathymetry dataset (see Fig. 9 for the location and distribution of each physiographic unit).

	Width min-max (km)	Depth range (m)	Average slope (in degrees)
Shelf	7.5–25.5	0–200	0° - 5°
Shelf break	–	200	–
Upper slope	11.5 (E) –24 (W)	1250 (E) - 2400 (W)	15°
Lower slope		1240 (E) –2650 (W)	10°
Base of slope	–	1350 (E)-2850(W)	–
Break	–		–

of ∼350 km^2 with depths ranging from ∼2000 m in the lower part of the upper distal slope, where the main ranging canyon incises, to about 1600 m on the north flank of the main canyon, where it connects with the Biscay Abyssal Plain (Fig. 9).

4.3.1. Morphology of the Capbreton mega-slide (CBMS)

One of the most remarkable structural features in the study area is a mega-slide located at the easternmost part, close to the main canyon head (Fig. 9). The uppermost part of the mega-slide head (Gonthier et al., 2006; Gaudin, 2006; Biscara et al., 2007) lacks of full swath-bathymetry. Consequently, the description of its detailed morphology at the slide inception was done combining our data together with Digital Terrain Model data products derived from the EMODnet Bathymetry portal (http://www.emodnet-bathymetry.eu).

The CBMS shows very thin sedimentary cover that reveals a high reflectivity value due to the basement. The mega-slide is 25 km long and 13 km wide. Its head cuts the continental shelf, the depth of the onset is about 208 m, and its mouth in the main canyon is located at 1500 m depth (Figs. 3 and 9).

The bathymetry resolution obtained on the flanks allows identifying notable differences between both (Fig. 3). The northwest wall is a rectilinear crest with a NE-SW orientation and a length of 23 km. Its edge is characterized by escarpment heads, with horseshoe shapes and has a very steep profile where different terraced levels are observed, with an average gradient of 15° and the top situated at about 60 m. As in the intertributary platforms, from a depth of 400 m onwards, clusters of small pockmarks can be observed, although in this case having smaller size and showing a more disperse distribution. Unlike the northwest wall, the southeast wall of the mega-slide is gullied. Its upper sector looks like an amphitheater-shaped scar, a large erosional scar of arched morphology near the head, which progressively gives way to a 600 m high flank furrowed by short gullies of 400 m averaged length.

Small outcrops or isolates blocks with dimensions of around 12 m and 83 m high, between 625 m and 1250 m deep, have been identified at the base of the mega-slide.

Another relevant morphological element is a high of about 3000 m long and 2800 m wide. This constitutes a structural high located on the SE of the mega-slide in the distal area. This marginal platform is elongated on the NE-SW direction and has a flat top with an area of 1.5 km^2 and height of 350 m.

Additional features as hard outcrops of low relief and NE-SW orientation also appear within this area (Fig. 9).

4.3.2. Capbreton canyon system (CBCS)

This submarine canyon crosses the entire continental slope from the continental shelf to the rise and presents a winding E-W oriented course, according to the tilting of the area. The canyon talweg is about of 300 km long from its head at 200 m water depth, to 3800 m where it reaches the abyssal plain (Figs. 8 and 9) covering an extension of1500 km^2.

The Capbreton main canyon is complex and structurally controlled, with a tributary canyons system that drains into it. The bathymetric transverse profiles (Fig. 8) show differences in depth corresponding to

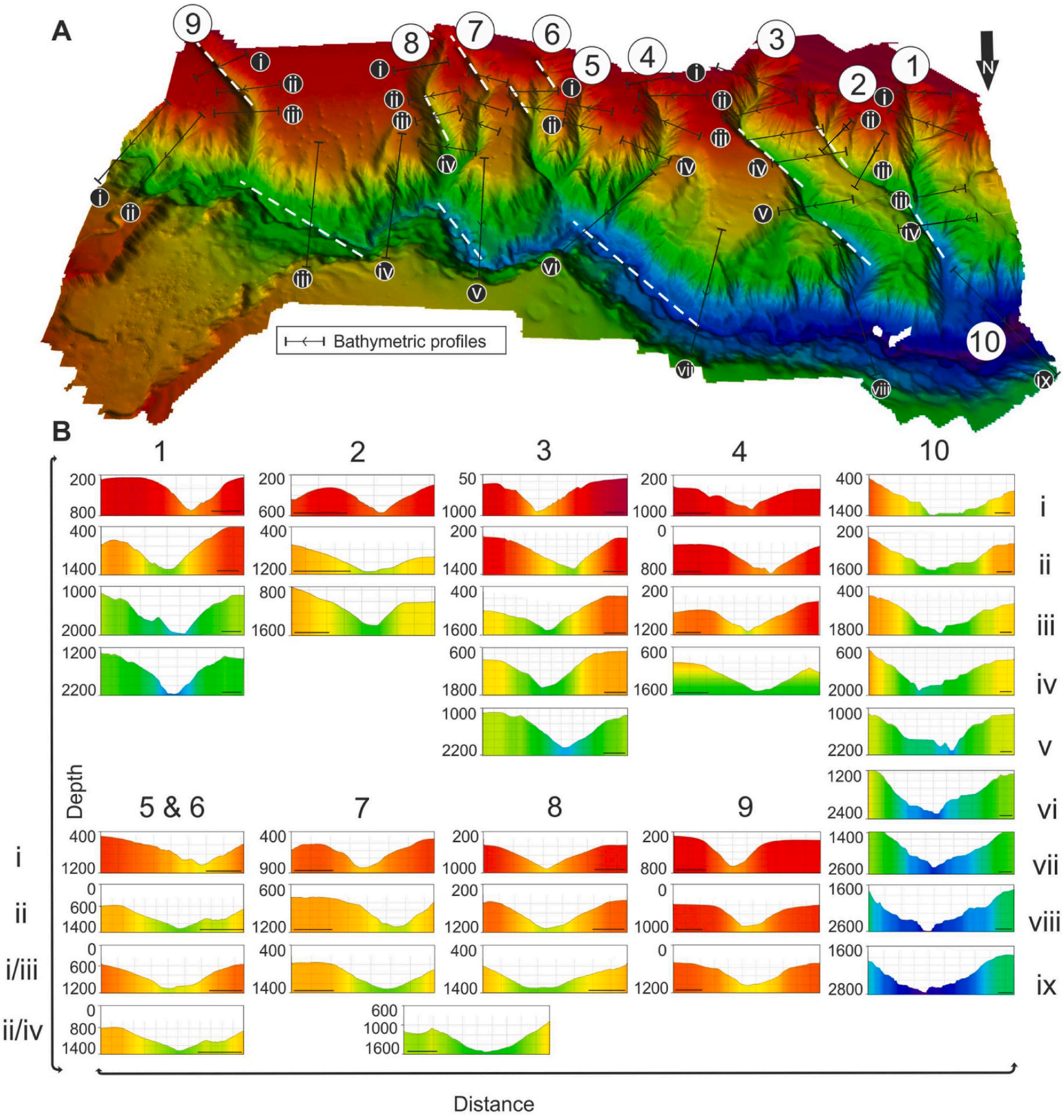


Fig. 8. 3D view of the study area and bathymetric profiles location. In number from 1 to 9 the tributary canyons (Table 1) main canyon with number 10. Dashed lines in white correspond to tectonic direction 110-130° (A). Bathymetric profiles (B).

the incisions of the tributary canyons of the main canyon and the interfluvial platforms, configuring what we have named the CBCS. Based on changes in canyon axial gradients, orientation flanks from slope and aspect maps (Fig. 4), as well as canyon floor width and canyon system main flow (Fig. 12A), the canyons have been classified into three different hierarchical orders: main canyon, tributary canyons, and erosive channels and gullies (Fig. 12B). The flow direction analysis for the whole drainage basin and the flow accumulation analysis indicate that the orientation remains in the same direction as depth increases, and demonstrates the active down-slope flushing from the tributary canyons to the main canyon.

The proximal upper slope is furrowed by a serie of tributary canyons that are wedged between intertributary platforms forming the CBCS. A total of nine tributary canyons have been identified according to their dimensions (Fig. 8). These canyons have well-defined heads, incised at the edge of the platform close to 200 m water depth (Figs. 8, 9 and 12), and run from their headwaters to the foot of the distal upper slope, where they flow into the main canyon, whose axis is embedded in the lower slope at a depth of 2000 m. Their lengths vary from 9.5 km, in the shorter canyons of the central and eastern sector, to 30.5 km in the canyons of the western sector. The steepest slopes recorded (50°) in the study area are located on the flanks of these tributary canyons, mainly NW–SE oriented (N 110°–130°), excepting the central sector, where CB-5, CB-4 and CB-3 canyons present a more marked N–S trend. In cross-sections (Fig. 8), the V-shaped profiles of the canyons can be observed in their heads. Nevertheless, while the canyon course is running, the cross-section morphology evolves to U-shaped until their reach its mouth at foot of the slope. This pattern decreases towards the east, where the canyons have a more extended transverse morphology and a shorter course, flowing into the main canyon at 1500 m depth. On the contrary, the canyons in the western sector are longer (maximum canyon length CB-7, 30.5 km), and discharge at 2625 m depth.

The flanks of the tributary canyons are densely furrowed by channels and gullies, as occur in the distal upper slope. These channels and gullies

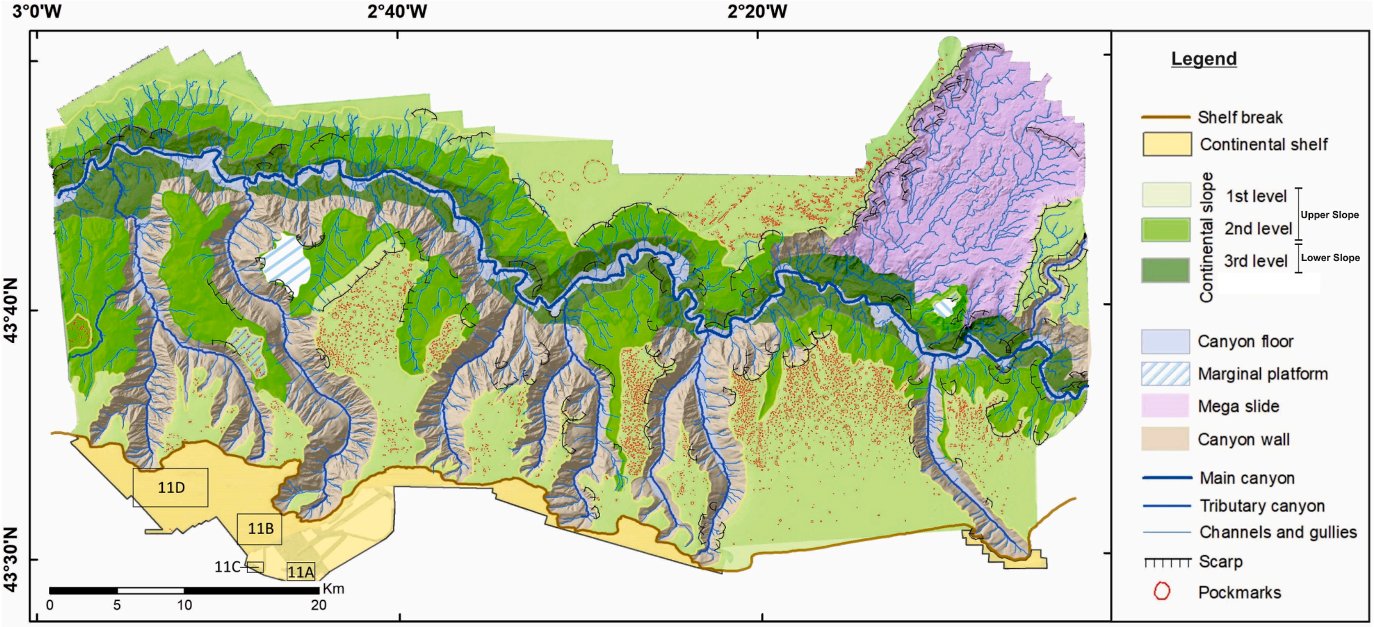


Fig. 9. Geomorphological interpretation map of the Capbreton Canyon system.

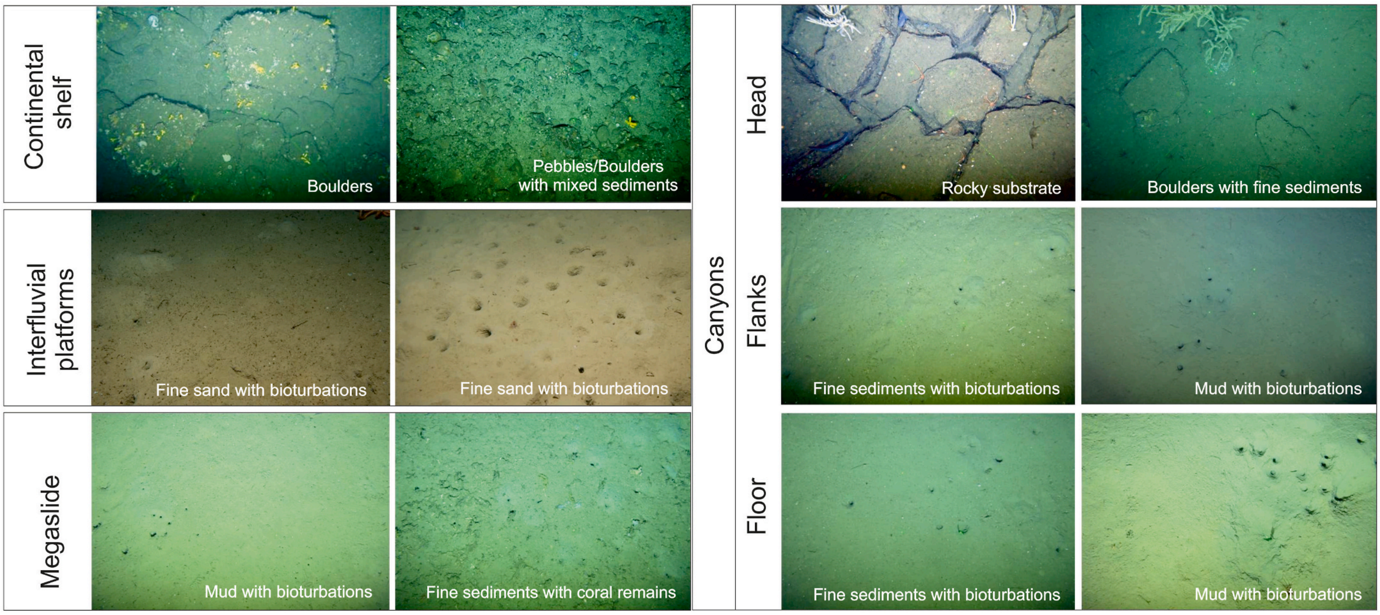


Fig. 10. Photograph of the facies identified in the principal domains of the Capbreton Canyon System, acquired with ROTV Politolana and lander Geodia during Intemares_Capbreton 0619 and 0620 surveys.

net correspond to the third order in the hierarchical CBCS classification (Fig. 12).

The main canyon is embedded in the lower slope following a meandering course and its axis faces this lower slope, changing its transverse morphology from E to W and from V to U-shape bottom, as it approaches to the intersection with the Santander canyon. It has a length of 385 km and an average width of 5 km. The southern flank of the canyon is characterized by a stepper slope than the northern flank. It is also crisscrossed by a dense network of channels and gullies in the same hierarchical order as those on the walls of the tributary canyons. However, this flank, with an average slope of 15°, is less vertical than the flanks of the better developed tributary canyons and with an average slope of 25°.

4.3.3. *Interfluvial platforms*

From west to east, a total of seven platforms have been identified in the study area: Martxatxu, Sigarre, El Zapato, Santa Moro, Lumai, Kostarrenkala and Plaiasu (Fig. 3 and Table 2). Their dimensions are variable from the narrowest, Sigarre platform, 2200 m width, to a maximum of 14,000 m in Kostarrenkala platform. All of them locate in the bathymetric range between 1400 m and 200 m. The walls of these platforms correspond to the flanks of tributary canyons that are furrowed by channels and gullies networks. In the gradient map of the area (Figs. 4B and 13) the northward inclination can be observed. Despite being flat with an average slope of 3°, they present an increasing northern orientation, that is, towards the abyssal platform, following the normal structure of the continental margins.

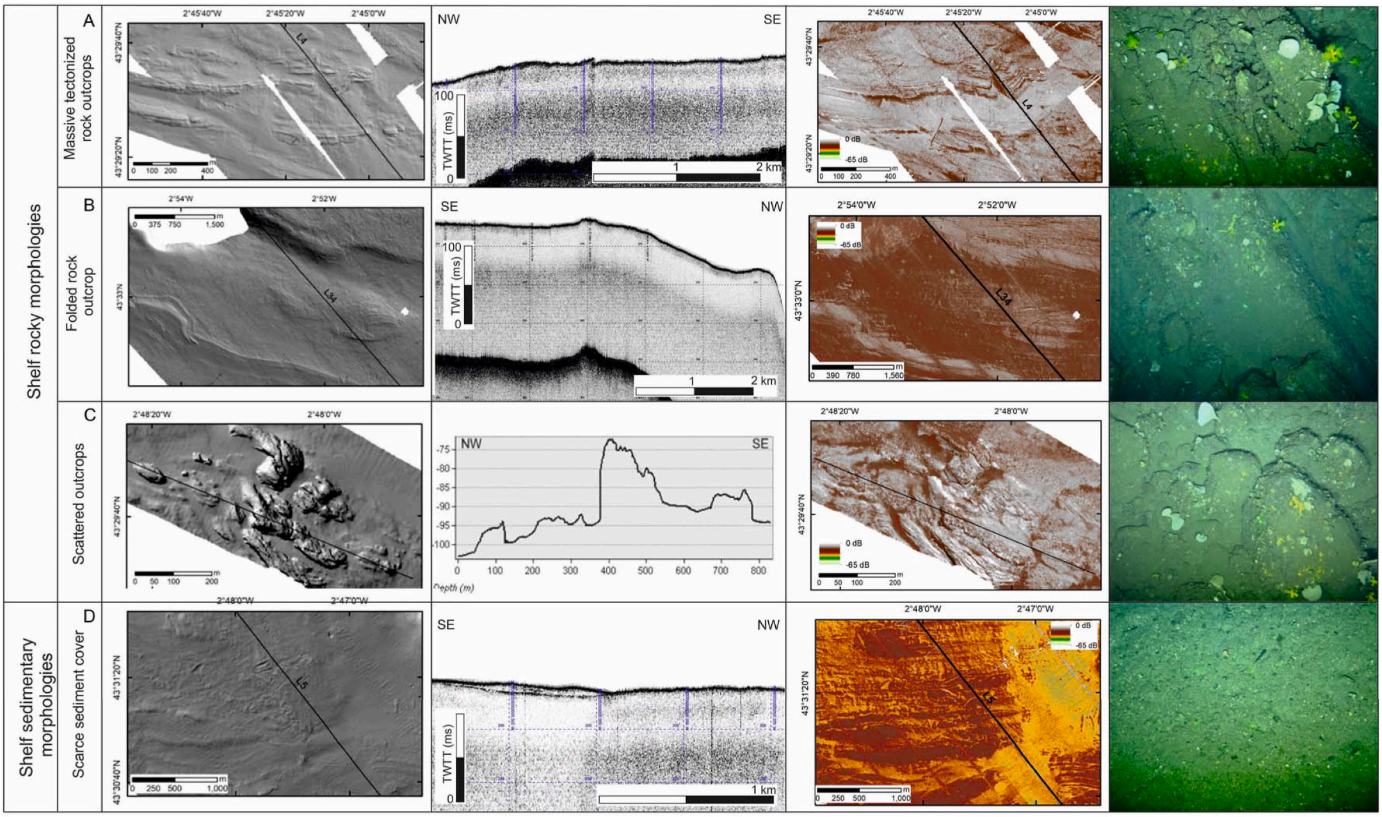


Fig. 11. Sedimentary and rocky morphologies in the continental shelf.

As mentioned in the previous section, the interfluvial platforms are in turn subdivided into three main terrace levels (Fig. 13). The first terrace level in the interfluvial platforms of the south flank, represented in the geomorphological interpretation map (Fig. 9), is the largest and shallowest, located between the depth range of 1200 to 200 m, and with a total extension along the study area of 700 km^2. The second terrace level corresponds to a smaller area of c. a. 350 km^2, and is located in the depth range between 1800 and 600 m. The third terrace level only appears in some very specific locations and mainly in the eastern sector on Lumai and Kostarrenkala-Renkala platforms. At the same time, there is an increase in depth in favor of the main canyon course from E to W.

Sedimentological data, represented in Fig. 7, show that the sediment distribution at the first level terraces has a remarkable change above 400 m depth, where the sediments characteristics change in the organic matter and mud contents. The analysis of the reflectivity values (Fig. 14) shows that this change coincides with a variation in the acoustic properties of the sediment as reflected in the backscatter mosaic. There it can be seen that below 300–400 m depth, in the shallower areas of the proximal upper slope, seabed changes from sedimentary to soft bottom (Figs. 7 and 14).

High-resolution seismic profiles show the sedimentary nature of the materials that cover the seafloor in this area (Fig. 14). A S to N evolution in the sedimentary stacking of the margin, i.e., from the shelf break to the foot of the lower slope (FOS), has been observed (Fig. 14a). The platforms display a seismic profile starting from a sedimentary basin with scarce sedimentary cover in the almost flat (0-3°) areas between the platform break and the proximal upper slope, but with a certain dip to the north. In this area, the reflectivity values are high due to the low thickness of sediments overlying the basement, and the internal structure of the echo-facies is chaotic, semi-transparent and without identification of internal reflectors. However, close to 400 m depth, this configuration changes, related to an increase in the slope (3-6°) and in the sediment thickness due to the sedimentary wedge progradation. This sedimentary accumulation is also evident in the reflectivity values, which reveal lower values corresponding to soft substrates. The internal structure of the plastered echo-facies observed in the seismic profiles corresponds to well-structured facies with well-defined and continuous reflectors (Hernández-Molina et al., 2011). From the 400 m slope onwards, the slope stabilizes again, becoming an almost horizontal platform, with a certain dip towards the north and a very noticeable increase in sediment thickness.

In the distal sector of the first level terraces, the most striking aspect is the abundance of pockmarks as circular or elliptical depressions. They describe different sizes, with diameters ranging from tens to hundreds of meters (70–2920 m, mean 289 m) and variable depths, from a few meters to 80 m (Fig. 9), displayed in a depth range between 400 and 1000 m, with more density in 700 m depth. Pockmarks are usually generated by upward gas-rich fluids emission within the sedimentary deposits to the sub-surface (Dupré et al., 2014; Michel et al., 2017; Galparsoro et al., 2020). These seafloor features have been identified in all the interfluvial platforms of the study area, appearing isolated or forming extensive fields of pockmarks (Fig. 9). The presence of pockmark fields in the distal areas of the platforms is concomitant with an increase in the sedimentary thickness, as can be shown in high-resolution seismic profiles (Fig. 14). Thus, in the areas closer to the coast, where the sedimentary thickness is very low, there is absence of pockmarks. Towards the north, there is an increase in the sedimentary thickness which favors the occurrence of pockmarks. As a result, at the distal area of the platforms, a high number of pockmarks develop, also with larger dimensions, both in depth and in diameter. High-resolution seismic profiles have also evidenced the occurrence of paleo-pockmarks, identified in the underlying substrate and located in the intermediate area of the platforms (Figs. 14 and 15).

There is a remarkable structural high in the study area (Fig. 9) just west of El Zapato. It is an isolated marginal platform on the upper continental slope. It has an approximate area of 6 km^2 and is

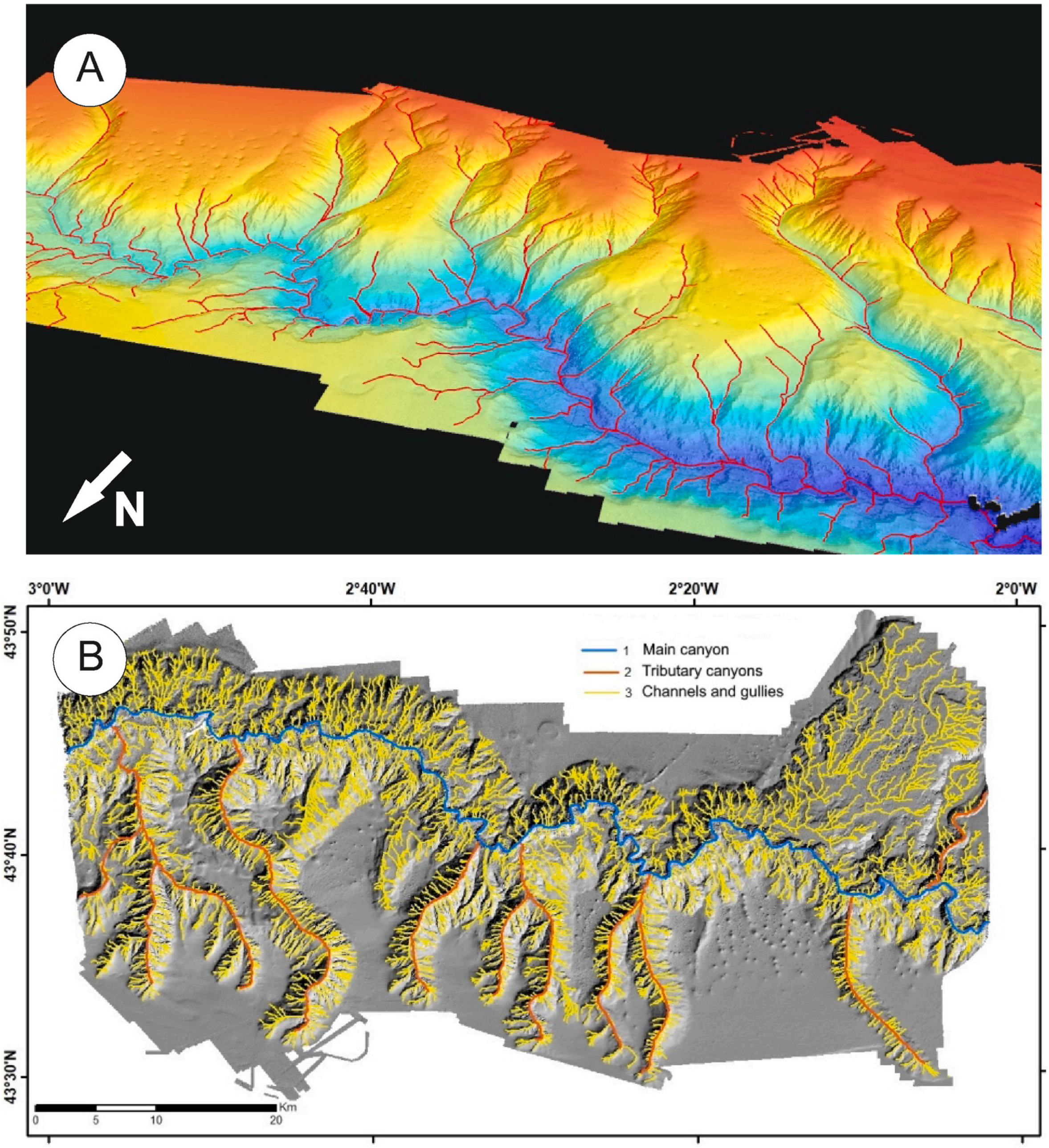


Fig. 12. 3D view of the canyon system with the main flow (A). Hierarchical classification for the CBSC in three orders: main canyon, tributary canyons, and channels and gullies (B).

semicircular-shaped (4 km wide). Its surface and boundaries are irregular, with the top at ~900 m depth.

5. Discussion

The geological processes in the study area and the evolution of the Cantabrian continental margin gave rise to the current configuration of the seabed in the Bay of Biscay. The new data collected and analyzed in the present study has allowed us to advance in the knowledge of the geomorphology and shallow structure of the seabed, as well as the sedimentary processes occurring in the northeastern Cantabrian margin. The block diagram (Fig. 16) shows a geomorphological model of the upper and lower slope, the tributary canyons and their confluence to the main canyon and the morphobathymetric hierarchy of the Capbreton Canyon System (CBCS), as important area for the transport of particles from the continental shelf to the abyssal plain (Van Weering et al., 2002; Palanques et al., 2005; McClain et al., 2010), which directly influences the morphosedimentary dynamics of the canyon.

5.1. *Continental shelf*

The continental shelf presents differences to other areas of the Cantabrian platform such as the Asturian platform, showing an absence of structural highs, except for one isolated marginal platform westwards from El Zapato platform. In the study area, the continental shelf is highly tectonized related to the inherited Hercynian structures and those generated during N–S Cenozoic compression. Evidence of this strong tectonic activity and structural control is its very irregular continental shelf edge, with incoming and outgoing directions oblique to the coastline.

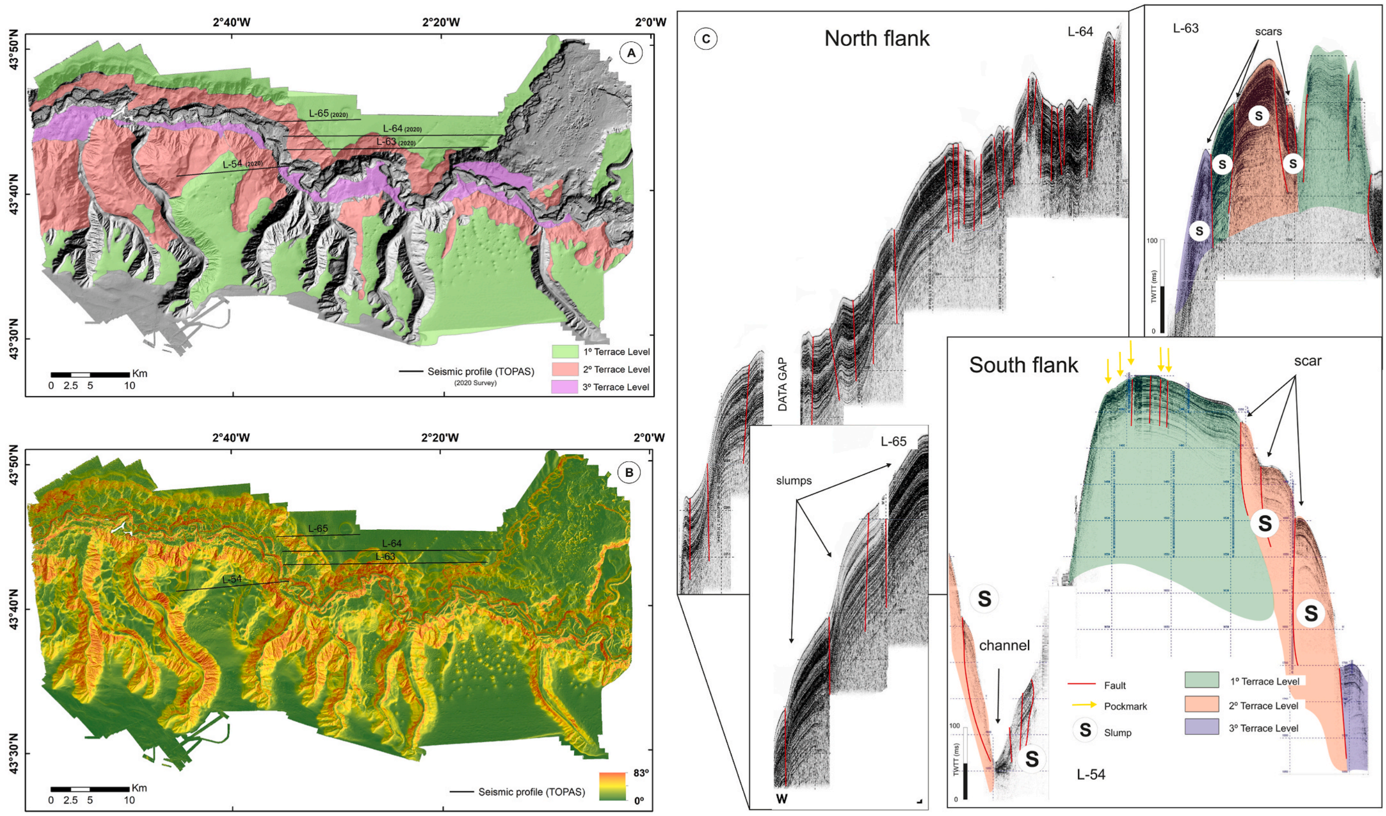


Fig. 13. Correlation between north flank and south flank terraces of the main canyon. A) Three terrace levels at DTM (10 m resolution). B) Slope map in degrees of the study area. C) High resolution seismic profiles (TOPAS) showing different terraces levels, slumps, faults and pockmarks incisions. See location of profiles in A) and B) panels.

Only a narrow strip of the continental shelf has been studied in this work, where folded rock outcrops have been identified and, according to the regional tectonic trends, it may correspond to a sinform/antiform observed in other Cantabrian shelf area (Gómez-Ballesteros et al., 2014), parallel to the main Capbreton Canyon axis NW–SE orientation.

It should be noted that in the sedimentary areas which have been mapped, no sedimentary structures generated by dynamic processes have been observed (Figs. 7 and 9). However, some sedimentary characteristics have been identified in certain areas of the continental shelf (Galparsoro et al., 2010). The scarce sediment cover observed can be interpreted as the result of the action of strong currents on the shelf that cause a little sedimentary cover of the study area, giving place to a starving shelf (Ercilla et al., 2008). The lack of sediments appears to be influenced in the Cantabrian margin by the intense shelf dynamic regime characterized by the seasonal development of opposing shelf currents in the upwelling/downwelling (Lavin et al., 2005), and by a fairly strong semidiurnal tide with barotropic M2 major semi axis of ~5–10 cm/s around the central Cantabrian Sea shelf in the proximity of Peñas Cape (Álvarez-Fanjul et al.,1997). However, the greatest sand content accumulates on the continental shelf in the western sector of the study area, and has its origin in the contributions of terrigenous materials from the mouths of the Butroe, Oka, Lea and Artibai rivers. In contrast, the continental shelf in the eastern most sector has a greater accumulation of muddy fraction and the hydrological network in this area is smaller, limited only to the mouths of the Urolay and Oria rivers. At the eastern limit of the study area, although data are scarce, we interpret the occasional increase in gravel content as a relation to abundant terrigenous material contributions of the Urumea river. Thus, in this part, oceanic dynamics transport longitudinally the coarser materials reaching the foot of the slope located in the first section of the main canyon (Fig. 7).

The rocky outcrops show folded and fractured morphologies, clear evidences of the strong tectonic activity in this area and also identified in other areas of the Cantabrian margin as Avilés Canyon area (Gómez-Ballesteros et al., 2014). Thus, the erosion surface observed reflects the intense erosive processes produced during the sea level migrations across the shelf and subaerial erosive processes during shelf exposure. Erosion seems to be the dominant sedimentary process on the Cantabrian continental margin, that would explain the lack of recent sedimentation, at least on the outer shelf (Ercilla et al., 2008). The presence of tectonic morphologies and some localized hard bottom areas are consistent with a tectonic origin.

The main feature that characterizes the lower continental slope is the Capbreton Canyon axial incision and its stepped north flank. A mega-slide appears in the northeastern area of the lower slope (Biscara et al., 2007), represented by a sub-horizontal abrasion platform characterized by a scarce sedimentary cover and rocky outcrops. This mega-slide has been mentioned previously by Gaudin (2006) and by Biscara et al. (2007), but it is described with more detail in the present study. However, the study area does not include the headwaters, so the lack of high-resolution data of the complete structure and slide scar has not allowed making much progress in the hypothesis of its origin and evolution. In spite of this, from the morphology observed in EMODNET bathymetry it could be interpreted that the upper part of the mega-slide mapped in this work corresponds to superimposed sedimentary lobes originated by massive landslides at its head (Biscara et al., 2007). The base of the mega-slide is furrowed by gullies and channels leading to the main canyon. The erosion on this platform is intense and therefore prevents the accumulation of sedimentary deposits, resulting in an abrasion platform. The superposition of sedimentary lobes from the sediment flows through the gullies network on the eastern flank and the processes of instability and mass movements at the headwaters lead some authors to believe that it is a polyphase slide (Biscara et al., 2007). This would have been controlled by listric faults responsible for the

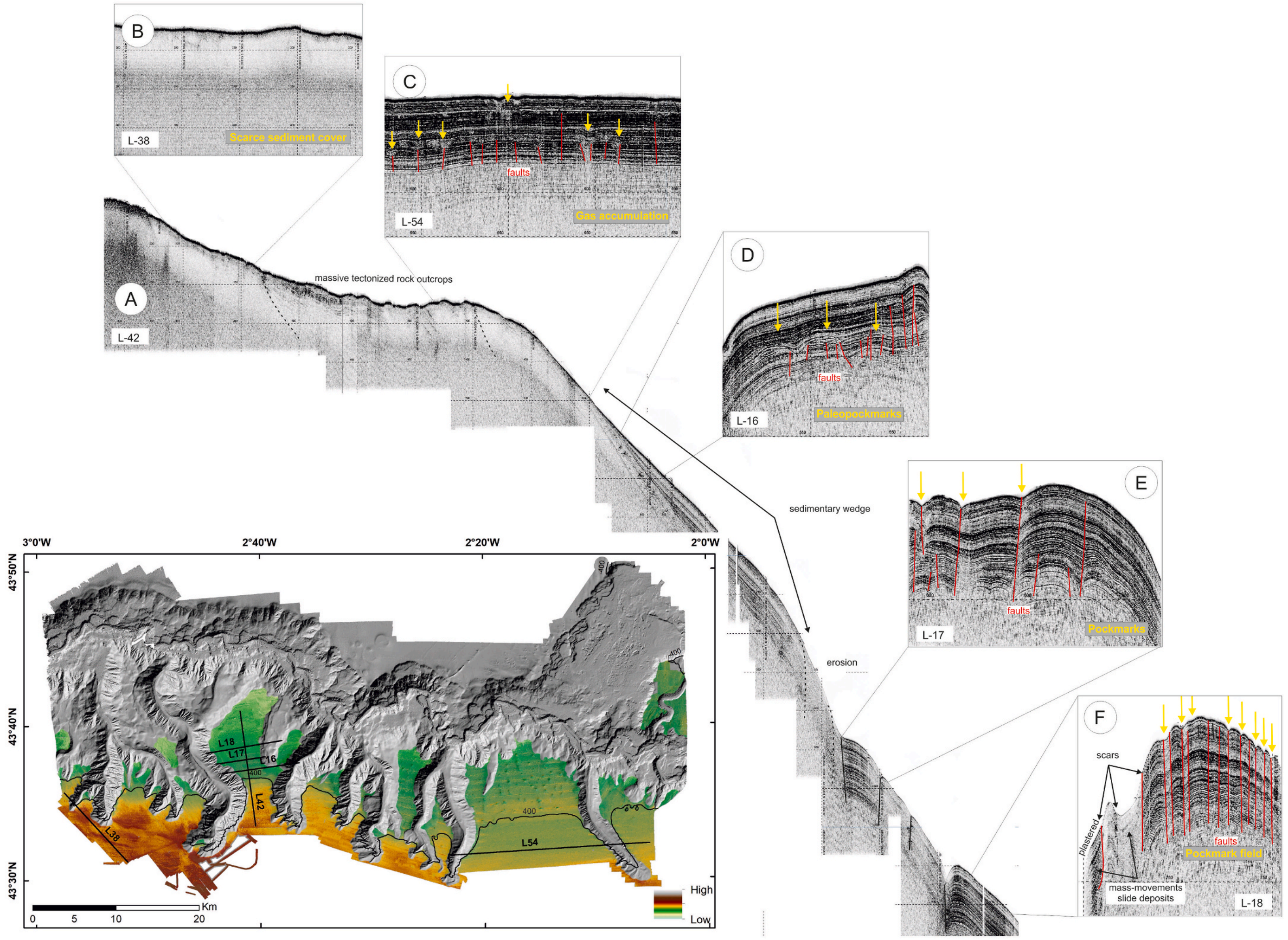


Fig. 14. High resolution seismic profiles (TOPAS) showing different pockmark stages at different ranges of depth in the intertributary platforms. DEM in grey colour scale with backscatter mosaic in colors and seismic profiles location. Profiles L38 and L54 do not cross the L142 but their equivalent scare sediment cover outcrops and positions have been projected in L42 to show an example. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

stepped morphology of its flanks, giving rise to a translational retrogressive landslide. The north wall is a NE-SW rectilinear crest orientation characterized by escarpment heads, with horseshoe shape of erosive origin, and has a very steep profile where different terraced levels are observed.

5.2. *Capbreton canyon system (CBCS)*

The Capbreton Canyon is one of the deepest canyons in the world. This canyon incises the abyssal plain very deeply up to the present coastline and formed in the Basque-Cantabrian margin, an area with a special geological context where tectonic processes have a N 110°–130° trend (Boillot et al., 1971, 1979; Roca et al., 2011; Carola et al., 2013).

The main canyon presents U-shaped cross-section morphology (Cirac et al., 2001; Gaudin et al., 2006; Mazières et al., 2014) and abrupt changes in axis direction, from NW-SE to NE-SW. This suggests a tectonic control of the canyon (Lallemand and Sibuet, 1986; Lastras et al., 2009; Mulder et al., 2004), as has already been observed in other canyon systems of the Cantabrian margin, such as the Aviles canyon system (Gómez-Ballesteros et al., 2014). The present configuration of the southern flank of the Capbreton Canyon the is consequence of gravitational processes and mass-transport movements of the sedimentary flows and deposits of the interfluvial platforms (Fig. 14), which have triggered slides and slumps. However, the absence of slide deposits at the foot of the slope could be due to the remobilization, erosion and transport of the slipped material. By contrary, the northern flank has a softer and stepped relief (Fig. 8), where several terraces can be observed, resulted from the southwards evolution of the Capbreton Canyon talweg. Those terraces were originated by the abandoned meanders of the main canyon during the different stages of erosion and transport.

The canyon is feed on the south margin by several tributary canyons (Fig. 9). Those tributary canyons in the western sector have more pronounced V-shaped cross-sections (Fig. 8) and reach greater lengths and depths at their mouths in the main canyon than the eastern tributary canyons (Fig. 9). This is partly due to the general trend of the area, with an increasing slope to the west and the tilting of the continental shelf to the north. But it is also observed that those canyons of greater lengths and depths present a rectilinear orientation in their axis with NW-SE orientation, which corresponds to the main directions of tectonism in the area (Fig. 9). This evidence points to the fact that the CBCS is strongly structurally controlled (Lallemand and Sibuet, 1986; Mulder et al., 2004), as occurs in others submarine canyons, such as Nazaret Canyon (Lastras et al., 2009). These fracture lineations reach as far as the continental shelf as the headwaters of the San Mateo tributary canyon and are also pronounced in some sections of the main canyon course. The evolution of the tributary canyons, with rectilinear pathway oriented N–S and NW–SE, seems to be tectonic in origin. Incising in favor of the fracture zones, through the planes of weakness, this complex

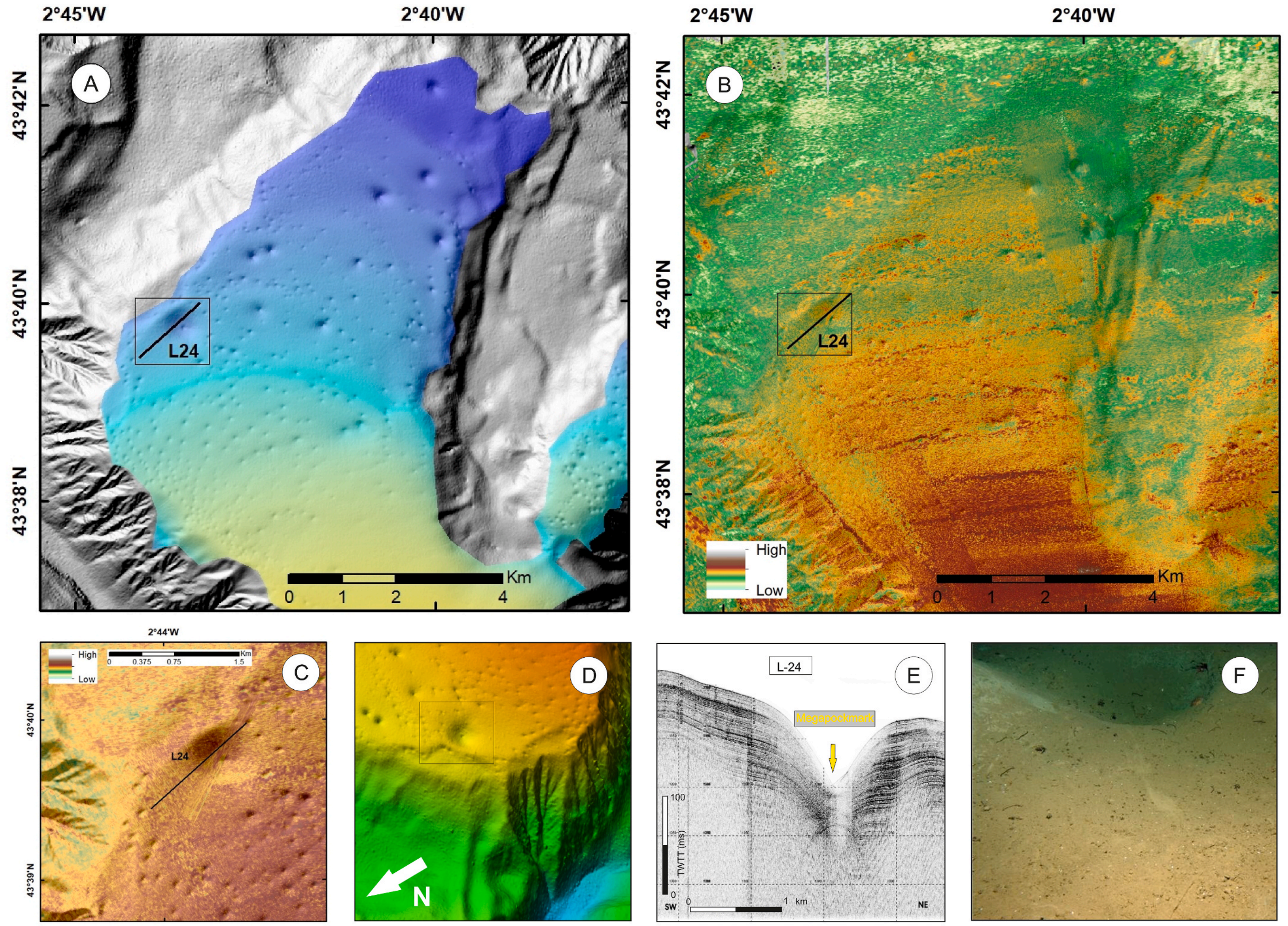


Fig. 15. El Zapato intertributary platform with pockmarks field in DEM (A). Backscatter mosaic (B) and pockmark detail in backscatter over DEM (C) 3D view (D) L-24 high resolution seismic profile (E) and photography inside the pockmark took with lander Geodia.

network of tributary canyons has developed. The conduit of sediments from source (coastal ranges) to sink (abyssal plain) in the northeastern Cantabrian margin is favored by the first- (main canyon) and second-order canyons (tributary canyons), and the dense gully network between them that canalize the flow of matter and energy and balance deeper down-canyon flows (Fig. 12). The main sediments come from the French margin through the main canyon and from the discharge of the rivers at the Basque coast as well as possible along-shelf sedimentary transport.

Another important aspect of the CBCS is the presence of three different terrace levels observed that reveals the tilted geometry to the north of the CBCS. It is conditioned by landslide processes and by the regional tectonics of the area (Tranier, 2002; Mulder et al., 2004). Differences have been observed in the evolution of the different terrace levels between the south and north areas of the main canyon, which coincides with the meandering course of the canyon. On the northern flank of the main canyon, the erosion was stronger, allowing the terraces on the southern flank to evolve. This is clearly evidenced in the central-southern sector, where the course of the canyon is embanked to the north (Fig. 13). However, where the course of the canyon has moved closer to the south, wedging into the southern flank, the terraces on the northern flank have been able to develop, as seen at El Zapato and Sigarre platforms. The third-order terraces show low sedimentary deposits. Possibly, the increased flow accumulation has removed, eroded, and transported the deposits from the upper terrace levels being redistributed by the canyon flow and marine currents.

The southern flank of the canyon is a smoother flank whose present configuration is due to gravitational processes and mass movements of the sedimentary deposits of the interfluvial platforms (Fig. 17), which have triggered slides and slumps. The corresponding deposits associated with these slides are not observed at the foot of slope, as they coincide with the axis of the main canyon and probably have been remobilized, eroded, and transported.

The different terrace levels on the northern flank have been correlated with the terraces mapped on the proximal upper slope (Figs. 9 and 13). The evolution of the tributary canyons of the southern margin of the CBCS is conditioned by erosive and tectonic processes and has led to the development of terraces on that margin. These terraces, which are larger than those observed on the other side of the main canyon, give rise to the interfluvial platforms between the nine tributary canyons. It has been possible to correlate the different terrace levels of the interfluvial platforms on the upper slope with those observed on the northern flank of the main canyon (Fig. 13). The extension and evolution of the terraces are very different on both sides of the canyon, being less developed on the northern flank. The second level terraces can hardly be observed on the northern flank, while on the southern flank of the canyon, linked to the interfluvial platforms, they have developed and spread out annexed to the first order terraces, especially in the central-western sector. The sedimentary distribution has a remarkable change at the first level terraces above 400 m depth in interfluvial platforms. From 400 m depth onwards, the reflectivity decreases due to the increased thickness of the sedimentary cover shown in the high resolution seismic profile

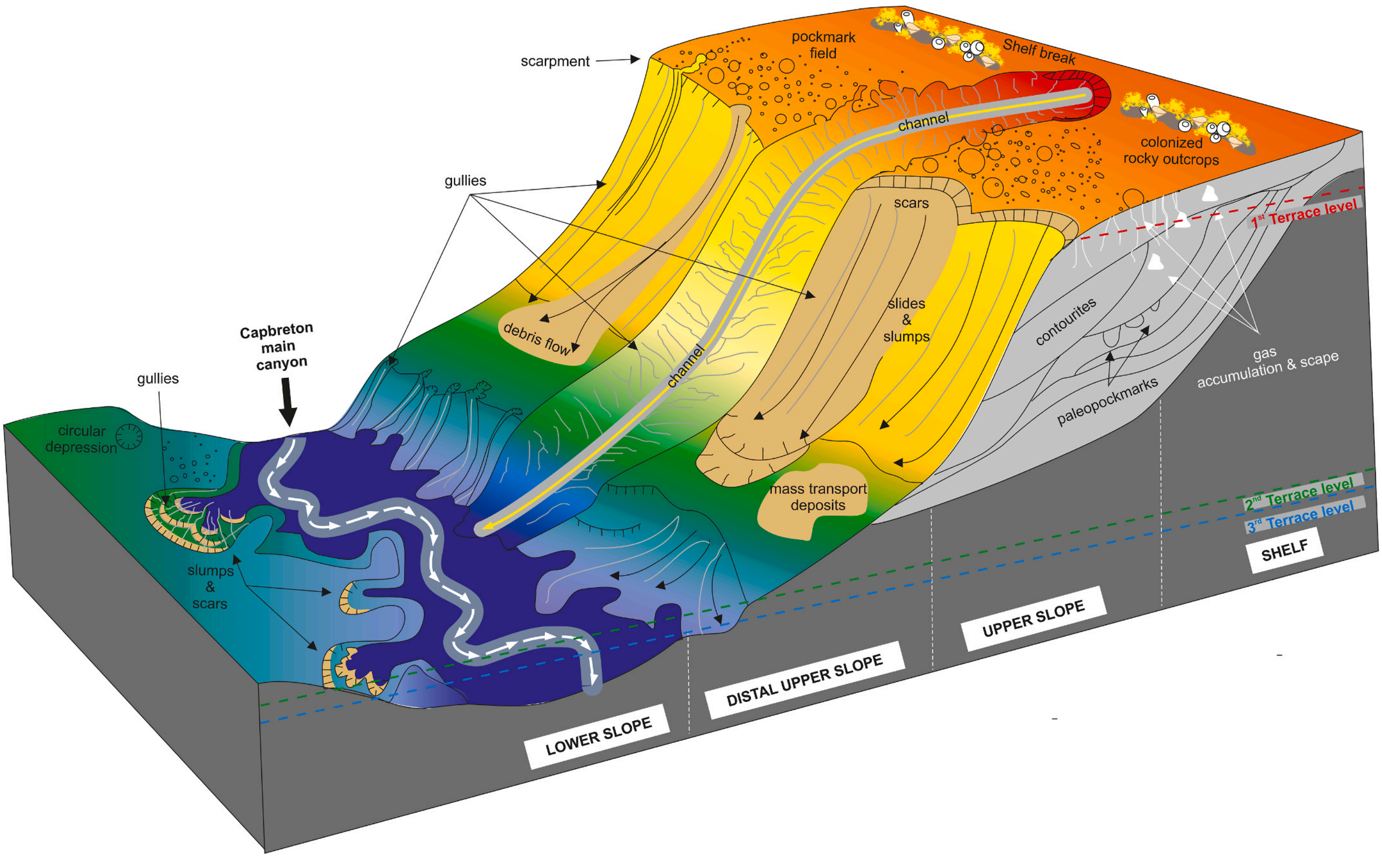


Fig. 16. 3-D diagram model showing the main morphosedimentary and morphotectonic features and related processes in the CBCS.

(Fig. 14B). Its remarkable occurrence is described in Rodríguez et al., 2021.

The crest of the first level terraces is a net boundary, which coincides with the escarpments of numerous slides and slumps originated by gravitational movements. Additionally, these movements are combined with mass-transport processes due to the sedimentary instability of the northward tilted platform and the sedimentary thickness at the ends of these terraces. The outer boundary of the first-level terraces is affected by gravitational slides with recognizable scarps (Figs. 9, 15 and 17). In section, the concave relief of the continental slope in this sector stands out (Fig. 17), and slides are locally affecting the outer limits of the first level terraces (Figs. 9, 13 and 17). They are recognizable due to a rough seafloor, characterized by arcuate and semicircular slide scars associated with deformed sediment. These scars tend to coalesce forming multiple slides, creating large areas of erosion displaying a down slope oriented amphitheater-like failure surface, and sediment masses with a slightly to highly deformed seafloor. Their size is variable, ranging from 10 to 100 km. In some areas where the slope is less steep, the removed sediment forms deposits, e.g.in Lumai platform encompassing an area of 5 km^2, forming the following terrace levels. Conversely, in other areas of the steeper slope, the vertical walls have originated furrowed by a gully network with an irregular distribution less dense than tributary canyons walls. These areas connect directly with the lower slope and main canyon (Figs. 11, 13 and 17).

The second level of terraces is located on the lower slope, which is the level that represents the steepest slope. It is bounded at the top by erosive scars generated as a result of processes triggered by sediment mass movements such as slides, slumps or debris. The base of the second level of terraces is situated at the foot of slope. On the southern flank of the CBCS this terrace level is more developed associated to the inter-tributary platforms, while on the northern flank it is limited to a narrow strip parallel to the meandering course of the main canyon, whose changes in dynamics combined with the mechanisms of gravitational mass movements have resulted in the pronounced arcuate or horseshoe morphology (Tranier, 2002).

The third terrace level corresponds to the deepest bottom in the CBCS, where the axis of the main canyon is embedded, which has formed this last level of almost flat slope with a smooth and eroded morphology and that occasionally presents small lobes or massive accumulations of sediments. The mass-transport processes through the second terrace level gullies and the products of this erosion must be deposited down to the slope break as depositional bodies but just in located areas have been observed (Fig. 9).

The geomorphological features defined as slides and slumps at the head and walls of the tributary canyons reveal a movement that evolved in mass-transport processes and turbidity currents in the main canyon, identified as a mass-wasting system that eroded the seafloor defining an irregular seafloor and gully network drainage. These evidences seem to be the result of retrogressive failures and are also related to the steep slope gradients of the terraces (Gonthier et al., 2006; Ercilla et al., 2008). The mass-transport processes are also evidenced by the erosive scarps, and the strong erosive capability of the turbidity current flowing from the Capbreton turbidite system (Ercilla et al., 2008) that is the responsible of the eroded distal parts of the gullies at the foot of the lower slope in the second level terraces. The absence of sedimentary deposits at the third level terraces, except in the northwest area, as consequence of the mass-transport activity, also supports this interpretation.

Additionally, the marginal isolated platform located at the NW of El Zapato platform, presents a rectilinear east boundary parallel to the NE–SW lineal escarpment of El Zapato, and we can speculate that they were initially the same block. This evidence indicates a tectonic origin and suggest that it is a horst structure limited by normal faults and slightly tilted to the NW (Boillot et al., 1971) as other highs identified in the Cantabrian margin as El Canto Nuevo seamount in the Avilés Canyon

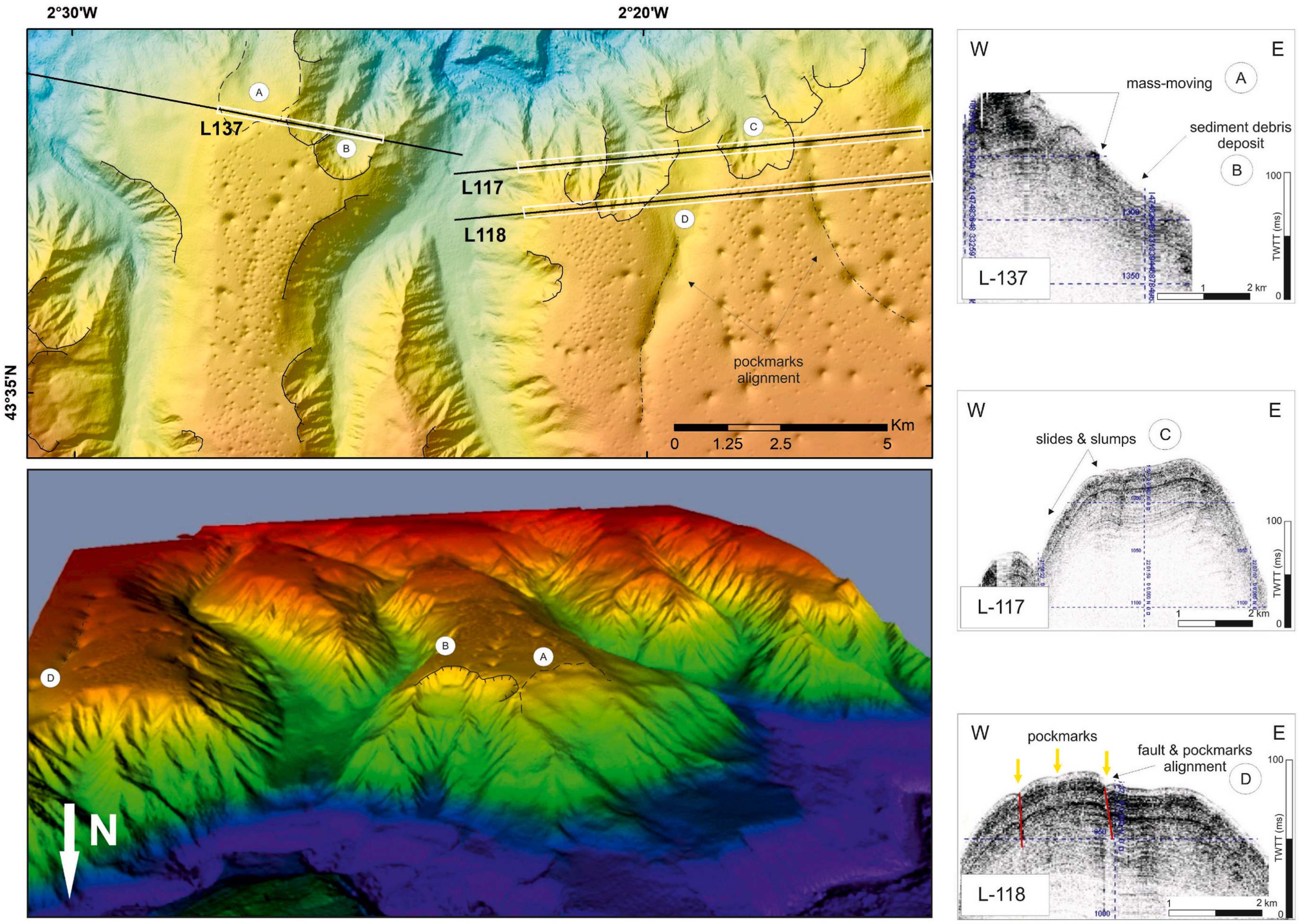


Fig. 17. Mass movements evolution in the study area. Examples for slide, slump and debris flows in the DEM (5 m resolution) and high resolution seismic profiles.

System (Gómez-Ballesteros et al., 2014).

Therefore, the analysis of the morphosedimentary and morphotectonic features and processes at the CBCS indicates that tectonics, processes of sediment supply/re-distribution and transfer and sea-level changes constitute the main factors that would have controlled shelf deposition or erosion, canyon enlargement or incision and occurrence of instabilities in the continental slope within this area.

5.3. *Pockmarks fields*

The analysis of high-resolution seismic profiles, and their correlation with the present bathymetry, has provided relevant information about submarine structures generated by gas-rich fluids emission and especially those related to the pockmark fields within this area. The presence of pockmarks is a phenomenon widespread observed in modern continental shelves all over the world (Hovland and Judd, 1988; Judd and Hovland, 2007). Sediments recovered from these seafloor structures are commonly organic-rich muddy sediments that may favor the generation, further accumulation and lately upward migration of fluids leading to the formation of a pockmark in the sub-surface (Fleischer et al., 2001). The occurrence of vast pockmark fields within the intertributary platforms is in accordance with this assumption. The greatest density of pockmarks largely develops in the most distal part of the interfluvial platforms, where thicker sedimentary layers occur, that is mainly in the Renkala, Arritxu and El Zapato platforms (Figs. 6 and 17). This is agreement with the fact that the development of pockmarks occurs in marine areas of high sedimentation rates, where greater sedimentary thickness develops favoring burial of OM (Judd and Hovland, 2007). In the case of the studied pockmarks, the highest mud and OM contents encountered at their sediments as well as the thicker sedimentary cover at above mentioned Renkala, Arritxuand El Zapato platforms seem to support that these sites constitute potential areas for OM degradation, deep fluid generation, as well as current upward fluid migration throughout these pockmarks. Paleo-pockmarks have been also identified in the underlying substrate and are considered inactive fossil depressions. The occurrence of pockmarks seems to follow the formation of linear incisions observed in the seafloor, originating from fluid migration and leakage in sediment-filled canyons (Gillet et al., 2008). They develop associated with active tectonic processes related to zones of fragility (Iglesias et al., 2010). Alignments of pockmarks and an increasing gradation of their depth were observed, suggesting a possible tectonic control. Connections between these morphologies are also frequent, giving rise to linear incisions leading to the formation of channels, as observed in Renkala platform. In other sites, where pockmarks have been located in the platform edges, the heads or scarps of small landslides have been mapped, suggesting a relationship between pockmarks and areas with unstable slopes, which evolution could be the trigger of an initial stage of head canyon (Fig. 14D). The relationship between these scarps and their associated deposits has been verified in high-resolution seismic profiles (Fig. 14), most likely in areas of low sediment transport and low rates.

5.4. *Vulnerable habitats presence*

The described mega-slide base is a hard substrate that could be susceptible to host corals and sponges that are characteristic of the Red

Natura 2000 1170 habitat. Thus, some individuals of white corals (*Desmophyllum pertusum* and *Madrepora oculata*) were obtained in both campaigns of the years 1987–1988 (Altuna, 1995). During the Intemares_Capbreton 0619 and 0620 cruises, these rocky areas have been intensively sampled with ROTV Politolana with no evidence of the presence of habitat-forming species of the 1170 habitat (Gómez-Ballesteros et al., 2020, 2021a). Due to the geological and geomorphological characteristics of this area, it is deduced that the development of habitat 1170 would not be possible unless the rate of sedimentation is low enough so that the coral will not be buried by mobile unconsolidated sediments. Then, the strong erosion of both marine currents and flows of terrigenous material coming from the land would prevent them from growing.

The morphosedimentary comprehensive characterization and the processes are the base for the characterization of benthic habitats and to develop sedimentary and rocky substrate benthic habitat distribution models. Relevant areas for the settlement of habitat 1170 (Reefs) and 1180 (submarine structures made by leaking gases) of Annex I of the Habitats Directive have been detected in this study, in the hard substrates and in the pockmark fields respectively.

A close connection between the development of cold-water coral reefs and the environmental characteristics has long been hypothesized (Davies et al., 2009; Frederiksen et al., 1992; Freiwald et al., 2004; Freiwald and Roberts, 2005; Hovland, 2008; Roberts et al., 2006, 2009), and evidences supporting this relationship have been rapidly increasing in recent years. Several environmental factors favor coral settlement and growth: hard substrates, strong topographically guided bottom currents, nutrient-rich waters containing labile organic matter and zooplankton (Freiwald et al., 2004), and the depth of the aragonite saturation horizon (Davies et al., 2008). The presence of pinnacles and scarps are preferential sites for this communities and taking into consideration the particular geomorphology of this structural high, the coral reef formations have probably grown above pre-existing rocky outcrops. However, the ground-truthing study in this area does not reveal the presence of live or dead coral colonies (Gómez-Ballesteros et al., 2021a).

Additionally, it is considered that the pockmarks fields could represent particular habitats and host species linked to these emissions, so that they could form habitat 1180 Submarine structures made by leaking gases of Annex I of the Habitat Directive (EC, 2013). Also, as in other underwater canyons in the Atlantic (Mortensen et al., 2005; De Mol et al., 2011; Sánchez et al., 2014), other habitats and species of corals and sponges of high biological value (Habitat 1170; EC, 2013), but whose distribution and conservation status is unknown, are to be expected. Based on the multibeam data and the ROV video imagery, two different cold-water coral reef (CWC) settings were distinguished in the Penmarc'h and Guilvinec Canyons along the Bay of Biscay (De Mol et al., 2011). Also, well developed coral reefs were described on the Aviles canyon system (central Cantabrian Sea area) by Sánchez et al. (2014). In both areas of the Bay of Biscay, the living coral reefs in better condition are concentrated at depths between 700 and 1000 m, indicating their dependence on waters with water density (sigma–theta) of 27.35–27.55 kg m^{-3} as suggested by Dullo et al. (2008). The presence of these environmental characteristics, in the levels between the lower bound of Eastern North Atlantic Central Water (ENACW) and the core of Mediterranean Water (MW), on suitable hard substrate for the settlement of CWC, is very limited in the Capbreton area since the sedimentary bottoms predominate on all the Capbreton canyon flanks.

In addition, the characterization of the bottom communities that will be carried out in next studies, integrating the results of this paper and the biological data obtained in the 2019 and 2020 cruises, will be fundamental to characterize the communities in the hard substrates and pockmark fields, and to determine the presence or absence of the habitat 1170 and 1180 with the data acquired from lander Geodia inside the pockmarks. The morphosedimentary characterization is the base to map the habitat distribution necessary to declare marine protected areas, and to tackle management measures with respect to conservation and protection. It is essential to carry out the analysis of the integration of marine protected areas in the context of the marine spatial planning to reverse the environmental degradation of the seas and facilitate the sustainable use of marine resources under an ecosystem approach (Gómez-Ballesteros et al., 2021b).

6. Conclusions

The present study indicates that the morphology of the northeastern Cantabrian margin is strongly conditioned by tectonics. The well-defined fractured and folded outcrops found in the continental shelf are a clear example of this. Moreover, the complex tectonic and structural framework in this region is also responsible for abrupt changes in the direction of the canyons axis, mainly from N–S to NW–SE of the Capbreton Canyon System (CBCS) and for the intertributary platforms evolution. Tectonics has also affected the seafloor morphology, giving rise to the building of two isolated structural highs (NW of El Zapato interfluvial platforms and SE of CBMS).

The continental shelf shows a flat and uniform slope with a thin unconsolidated sedimentary cover as a consequence of the high hydrodynamic regime affecting the Cantabrian margin, which favors the transport of sediment material along the slope.

The mass-wasting system features identified along the continental slope, especially in the tributary canyons and gully drainage system, have confirmed that mass-movements play an important role in the dynamics and shaping the CBCS in this continental margin.

Another remarkable characteristic of the studied area are the extensive pockmark fields found in the most distal areas of the interfluvial platforms, where the accumulation of rich-organic fine material is higher. The presence of these features is indicative of a frequent occurrence of escape of fluids from the underlaying sediments. The presence of paleo-pockmarks indicates that events of gas/fluid escape also took place in the past. The alignments of the pockmarks indicate that tectonic played an important role in its generation.

Hard substrates have been mainly mapped in the area in the continental shelf and at the base of the mega-slide. They highlight that the basement for structuring species provides three-dimensionality to the substrate and serves as support and protection for other species, enhancing the biodiversity of the environment.

The information and knowledge presented here will be clue to support further works focused on benthic habitats mapping and modeling, with the ultimate aim of identification and map vulnerable marine ecosystems that need the adoption of conservation measures.

CRediT authorship contribution statement

M. Gómez-Ballesteros: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **B. Arrese:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **I.P. Díez:** Visualization, Software, Methodology, Data curation. **I. Galparsoro:** Validation, Resources, Formal analysis, Data curation. **O. Sánchez-Guillamón:** Writing – review & editing, Visualization, Validation, Software, Methodology. **N. Martínez-Carreño:** Validation, Software, Methodology. **M. Sayago:** Validation, Software, Methodology. **C. López-Rodríguez:** Formal analysis, Data curation. **A. Rodríguez:** Visualization, Validation, Investigation, Data curation. **F. Sánchez:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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