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Geomorphological evolution of the calcareous coastal cliffs in North Iberia (Asturias and Cantabria regions)

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ABSTRACT

This paper presents an analysis of the main morphologies observed in the coastal cliffs of northern Spain (Asturias and Cantabria regions). The objective of this contribution is to establish a hypothesis on the origin and evolution of this rocky coast, as well as to present a detailed inventory, to characterise quantitatively and qualitatively singular morphologies and to highlight the geological heritage of this protected coast. The evolution process starts with the formation of an ancient coastal planation surface characterised by a flat morphology caused by regional mainly uplift and to relative sea level falls. Afterwards, wave erosion processes would have started eroding the cliff foot and simultaneously, karst activity produced some exokarst morphologies (sinkholes, karren, etc.) through stratification and fracturing network, while the underground drainage systems produced some caves and chasms. In the following step, corresponding to the last glaciation from the paleoclimatic point of view, sea level fall together with a deepening of the fluvial network caused the preservation of the existing caves and chasms and the generation of new ones at a lower level. On the other hand, dissolution processes on limestones created sinkholes in those areas characterised by alternating layers of limestones and marls, generating collapses. When the sea level reached the maximum height during the Holocene a new erosion cycle of the coastal cliffs began. As a consequence, new landforms and processes were produced, like bays, caves fillings, and intrusion of new sediments in small confined estuaries. In these areas, other types of morphologies associated with the last sea level rise can be observed, such as closed beaches, uncommon closed estuaries developed inside a sinkhole, blowholes produced by mixed wave action and widening of prevailing vertical pipes inside the limestones (including the second largest in the world), total or partial sedimentary filling of small confined estuaries, as well as a tombolo deposit. It is important to point out, that some sites described are included in the Spanish Inventory of Sites of Geological Interest (IELIG). Due to the evolution model here proposed, a portion of the coastal sector described are included in the Global Geosites Project.

1. Introduction

Although 80% of the world's coastlines are classified as rocky of the global shoreline, they have not been validated on a global scale (Young and Carilli, 2019) and the karst surface and near-surface outcrops occupy ~15–20% of the Earth's ice-free land surface. (Engel, 2011). In the case of the continental European coastline, Atlantic cliffed and rocky coasts occur along more than one-third (37%) (Gómez-Pujol et al., 2013).

This type of coast have not received as much attention as other sedimentary and biogenic types of coasts. This is probably due to their apparent stability, slower evolution, and lower touristic interest. However, the characteristics and evolution of rocky coasts have been analyzed by several authors (Trenhaile, 1987, 2004; Sunamura, 1992;

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Trenhaile et al., 1998; Naylor et al., 2010; Dasgupta, 2011). The development of cliffs and their associated shore platforms depends on the nature of the bedrock and its structure. Particular factors include the lithology and its bedding, fracture spacing and orientation with respect to the coastline, and the type and intensity of weathering and erosion processes (Del Río and Gracia, 2009; Moura et al., 2011). In the case of calcareous cliffs, their dynamics are mainly determined by storm and wave action, tides, and a combination of gravitational, fluvial, and karst processes (Cvijic, 1918).

A retreating costal cliff with an important karst control, that provides a wide range of processes and landforms such as in the Cantabrian Coast described in this proposal, does not exists in the world.

In some cases, it is possible to observe some examples of processes and features separately, such as the example of retreating coastal cliff in south coast of Great Britain, or in the case of The Twelve Apostles, Victoria, Australia (Hurst et al., 2016; Young and Carilli, 2019); or like other regions, such as Normandy (Etretat), or Ireland (Moher Cliffs), or Dover in England, but the alternation of a but a wider variety of morphologies produced by cliff erosion together with karstic processes and sedimentation processes at the same time does not exist.

The rate of evolution of rocky cliffs is much lower than that of sedimentary coasts. Consequently, the establishment of geomorphological trends on such environments must be based on different morphological indicators of change (often relict forms) to conceive conceptual models of medium–long term evolution (Trenhaile, 1987). Since morphological indicators are not always abundant, and due to the maintenance of broadly similar geological and dynamic conditions over wide zones, such models should be elaborated on at a regional scale to be sufficiently representative (Naylor et al., 2010; Kennedy et al., 2014). According to Trenhaile (2011), the acceleration rates of cliff retreatment could be related to rising sea levels, and to a lesser extent, possible increases in storm frequency, although based on in BruschiRemondo (2019) criteria, undermining produced by marine erosion are favoured by sea level rise and recurrent strong sea storms. Bray and Hooke (1997) estimated cliff recession for England at between 22% and 133% in response to rising sea levels up to 2050.

The number of Iberian Peninsula studies are focused on cliff retreat describing some coastal evolution models based on the features and processes observation is very scares, such as those providing information on cliff behaviour in Algarve (Portugal) by Moura et al. (2006) and Oliveira et al. (2019) and in Spain in the cost of Cádiz (Del Río and Gracia, 2009; Anfuso et al., 2007), Catalonia (Montoya-Montes et al., 2019) or in Galicia (Blanco-Chao et al., 2003; Pérez-Alberti and Gómez-Pazo, 2019). Fewer still are those that present a global and general vision of the functioning of the northern coast of the Iberian Peninsula, considering the different morphologies together with the karstic processes and that, therefore, define the bases for a general evolution coastal model.

This work focuses on the calcareous coastal cliffs of Asturias and Cantabria, which are divided into five sectors (A to E) (Fig. 1). These form a very indented coast that only measures approximately 90 km in a straight line E–W, which in actuality is longer than 540 km when measured in detail (Fig. 1). These cliffs are characterised by a high variety of structures and landforms at different stages of geomorphic evolution and present a high concentration of sites with geological, geomorphological, and tourist interest (Calaforra and Fernández-Cortes, 2006). An understanding of the morphological changes experienced by this zone would provide clues about the genesis and distribution of landscapes and forms. Further, it would help in anticipating future morphological trends considering the different climate sea-level rise scenarios proposed by the IPCC (2019), among other drivers.

These cliff coasts include many outstanding examples of karstic

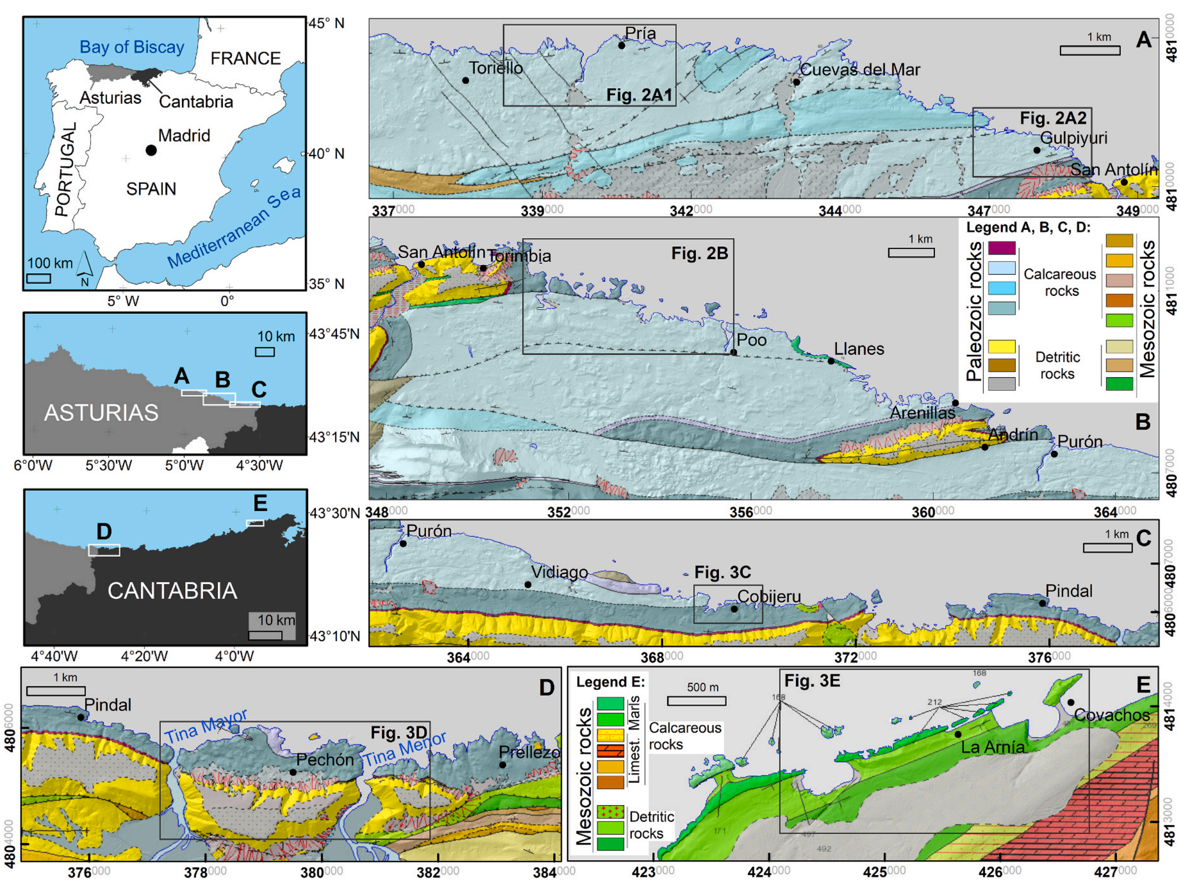

Fig. 1. Location of the study area and geological maps of the sectors analyzed in the present work (IGME, 2016).

morphologies and one of the highest densities of blowholes and singular karstic estuaries and beaches in the world. The high concentration of karstic coastal forms under different evolution stages in a quite restricted space, makes this coast almost unique, with an exceptional geological heritage (Nuche, 2002). There are very few comparable coastlines, where some authors have studied the processes, geomorphologies and evolution trends as Sardinia (De Waele et al., 2009), Algarve -South Portugal- (Moura et al., 2020), or Australia (Bourman et al., 2016), which has the greatest density. All of them are coasts with a great tourist and environmental attraction, however, there are certain morphologies on our coast that stand out for their peculiarity and state of conservation. Some of them are occasionally represented on the aforementioned coasts, but not so profusely.

Previous works on the studied region are focused on highlighting the geological heritage and showing general characteristics of great utility for our study (Domínguez-Cuesta et al., 2019; BruschiRemondo, 2019) or studying recession rates from satellite techniques (Cuervas-Mons et al., 2021). Other more specific publications are those on the study of geomorphic features. Romero (1984), Hoyos Gómez and Herrero Organero (1989) and Flor and Flor-Blanco (2013) presented a description of karst landforms at the foot of the Asturian eastern littoral and revealed their relationship with morphostructural features (mainly microfractures), including a general geomorphological map of some karstic morphologies and some morphostructural schemes in small representative segments. Bruschi (2007) conducted a detailed morphological study of the central Cantabrian coast, while Adrados González (2011) described the nature and genesis of landforms on limestones along the narrow coastal fringe affected by wave action and then reconstructed its evolution at a local scale. Important studies in caves and their deposits have been carried out by several authors (Jiménez-Sánchez et al., 2006; Stoll et al., 2013; Álvarez-Lao, 2014; Álvarez-Lao et al., 2015), while Ballesteros et al. (2017) related the development of a coastal cave with sea-level low stands. However, no regional evolutionary model was proposed for these cliffs, including the combined action of coastal and karst processes. Consequently, this study represents the first work to examine coastal morphodynamics, tectonics and environmental changes on the calcareous cliff coast of the northern Iberian Peninsula of Asturias and Cantabria.

The aims of the study are as follows: i) identify the main morphological units in this coastal environment and compile a detailed inventory; ii) show the macro and microkarstic forms iii) propose a conceptual model of the genesis and evolution of the calcareous cliffs as a response to different evolutionary stages due to changes in fluviokarstic, beach, and estuarine processes triggered by Quaternary uplift and climate and sea level changes; iv) expose within the model the degree of recession of the coast by analysing inherited morphologies; v) apply the model for proposing long-term future trends, and vi) highlight the geological heritage, which in many cases is only known at national and local levels, and a proposal of some geological sites.

Due to the evolution model proposed herein,a coastal sector located in Cantabria has been included in the Global Geosite Project, within the Geological Framework of International Relevance No. 19, corresponding to the "Coasts of the Iberian Peninsula" (Gracia, 2009) because is one of the best places in the world where all the evolutionary morphologies of a receding coastline can be identified in just 4 km. Moreover, it is important to highlight that some of the sites described are included in the Spanish Inventory of Sites of Geological Interest.

2. Regional setting

The Northern coast of Spain, also called the Cantabrian coast, extends linearly East-West for more than 600 km. It is mostly developed on two different rock substrates: prevailing siliceous rock units in the western part (Galicia and western Asturias) and mainly calcareous materials in the eastern part (eastern Asturias, Cantabria and the Basque Country). The segment of the coastline considered in more detail in this work belongs to the second type of substrate, it is 90 km in length and includes some estuaries areas which extend landward up to 1 km. Within the study area, the western part is dominated by the exposure of Upper Carboniferous limestones, mostly fine-grained, but there are also quartz-arenites formations, Ordovician in age (IGME, 2016). In the eastern part, in Cantabria, the rocky part of the coastline is built on Cretaceous and Paleogene limestones and marls (Fig. 1).

The tectonic history of the area is determined by two major orogenies and several rifting episodes. The older compressive event, in the study area Carboniferous in age is the Variscan orogeny, (e.g. Pérez-Estaún et al., 1988), the second compressive event is the Alpine orogeny, formed during the Paleogene (e.g. Teixell et al., 2018). Between both orogenies there are several rifting episodes, different in age, kinematics and extent (e.g. Cadenas et al., 2020). Without going into the detail of the very different circumstances in which these two tectonic events produced structures with the same orientation and similar kinematics, we will first describe the structures that can be observed in the geological map in Fig. 1 extracted from the Geological Map of Spain (GEODE-IGME).

The first four sectors of the coastline studied in detail (Fig. 1) are characterised by a series of thrust sheets formed by bedded, compact Carboniferous limestones (e.g. Bahamonde et al., 2008). Currently, bedding is subvertical and strikes E–W. The thrust sheets in the area are constituted predominantly by Ordovician quartz-arenite formations alternating with Carboniferous thick sequences of limestone. The eastern Asturian coastline trends WNW–ESE/W–E and follows the Variscan structure in the substrate. There are three lithostratigraphic units in the area: Barcaliente Fm, Valdeteja Fm, and Picos de Europa Fm (Fig. 1A–D). Both Barcaliente and Picos de Europa fms are very well-bedded and tend to determine locally the orientation of the cliffs. This pattern is in contrast to the cliffs formed over the Valdeteja Fm, where bedding is much weaker and erosion is mostly controlled by tectonic structures, such as joints or minor faults.

The current orientation of major structures in the study area, such as the Variscan thrusts or some of their associated folds, is E–W, as shown in Fig. 2A, B, 2C, and 3B. Younger major structures associated with the raise of the Cantabrian mountains are also oriented E-W, following the orientation of the plate boundary at that time along the bottom of the continental slope (e.g. Fernández-Viejo et al., 2021).

Given the favourable orientation of some of the Variscan structures to the Alpine N–S compression, several older structures were reactivated during the Alpine convergence (e.g. Alonso et al., 2007). The Alpine overprint can be easily recognised when affecting Mesozoic formations, and there are two examples in the study area where this can be readily observed (Figs. 2C and 3B).

From a geomorphological perspective, cliffs developed in Carboniferous limestones are subvertical and show fresh rocks that are only interrupted by dissolution hollows, caves, and notches. Further, they usually formed without the presence of a basal shore platform. In contrast, cliffs and hillsides developed on Ordovician quartzites have gentler slopes and preserve old periglacial and scree deposits. The culminating relief consists of a great number of flat erosion surfaces, regionally named "*rasas*". These are stepped, forming up to seven levels that are very well preserved along this coast (Flor and Flor-Blanco, 2014; Domínguez-Cuesta et al., 2015). One of these erosional platforms, has a regional extent and continues to the west for most of the length of the Cantabrian coast (López-Fernández et al., 2020).

In more detail, the sedimentary rocks outcropping in Sector E (Fig. 1E) comprise an alternation of leafy marl deposits and silty limestones of Late Cretaceous age (Campanian to Maastrichtian). Gray limestones characterise the end of this period (Latest Maastrichtian), while unfossiliferous brownish dolomites represent the Cretaceous-Paleogene boundary. Small bays and headlands alternate due to strata dipping, wave action, and differential erosion. Generally, headlands and vertical cliffs occur on the resistant Cenomanian limestones, while bays are excavated on the more erodible marl series (Turonian-Santonian).

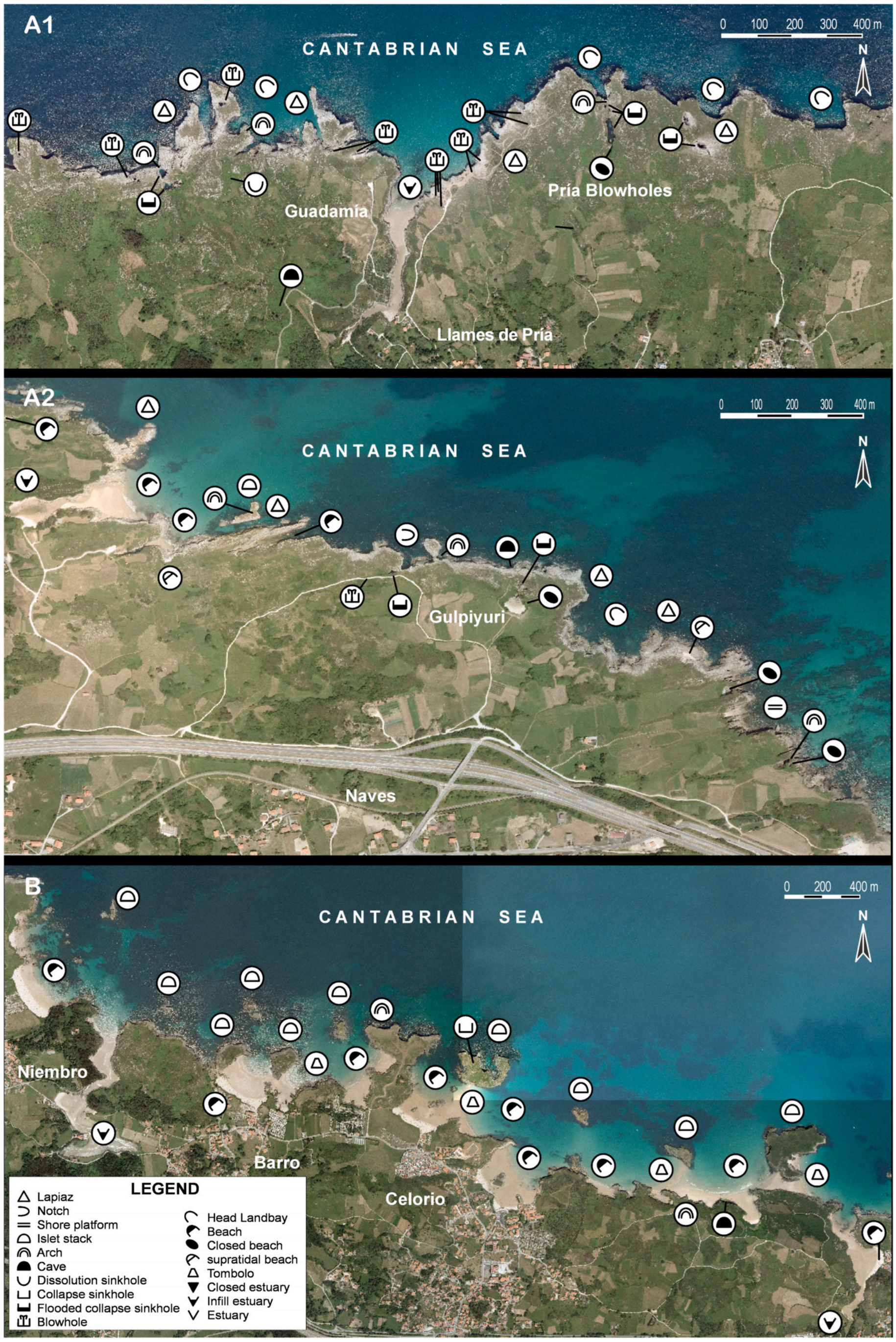

Fig. 2. Landforms mapping. A1) Sector A. Toriello-Pría, A2) Sector A. Gulpiyuri, B) Sector B in Llanes.

Several detached islets bear massive, compact, and resistant Aptian limestones (Bruschi, 2007).

After the Miocene, a complex crustal uplift occurred at the regional scale, which gradually dips 0.08° to the west. Here, the elevation decreases, and the eastern sector is located higher than the western sector, related to an apparent vertical offset of 50 m across the trace of the Ventaniella fault (López-Fernández et al., 2020). The ensuing stabilisation favoured the excavation of continental erosion surfaces and coastal *rasas*, with the lower ones containing mixed continental and marine deposits (Mary, 1983; Flor and Peón, 2004; Flor and Flor-Blanco, 2014).

The climate in the study area is temperate–humid, with a strong Atlantic influence (hot-maritime climatic domain) and frequent storms from the west and north. The water balance is positive except in July and August and sometimes in September (Confedearción hidrográfica del Norte). The mean annual precipitation oscillates between 423 and 507 mm in the zone, with a potential dissolution rate in limestones ranging between 38.1 and 42.6 mm/ka (Romero and Sendín, 1986).

Although winds of the third quadrant prevail, NW and NE components are also important, especially during anticyclonic conditions. The winds vary from SSW to NW during springs and summer time, while dry and cold winds blow from E and NE during springtime and summer, cooling the coastal waters if they persist. Only 15% of the annually recorded wind speed exceeds 18 km/h, although bursts of western winds can reach 160 km/h (Flor and Flor-Blanco, 2013). With regard to wave climate, significant wave heights less than 2.0 m are considered low energetic conditions (55% annual frequency), and peak periods vary between 8 and 12 s. The maximum expected wave storm with a return period of 100 years has a wave height of 8 m, while the maximum

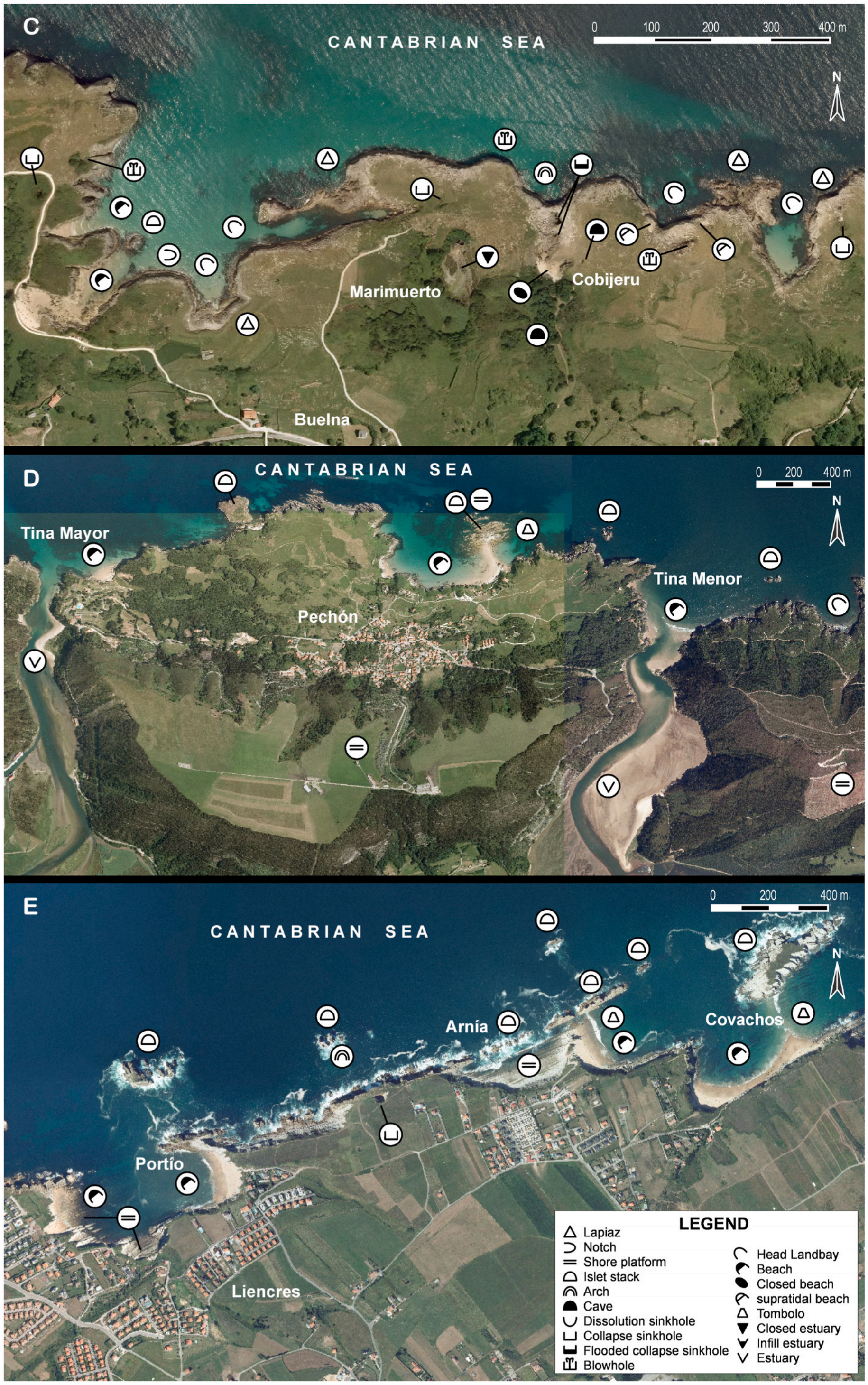

Fig. 3. Landforms mapping. C) Sector C. Cobijero, D) Sector D. Tina Mayor and Tina Menor estuaries, E) Sector E. Costa Quebrada.

recorded wave was 14.40 m (Puertos del Estado web). However, maritime storms caused by winds from the W and the NW may lead to waves over 7 m in height, being more recurrent during this century (Flor--Blanco et al., 2021). These storms show strong seasonality with peaks in winter and significant inter-annual variability (Izaguirre et al., 2011).

The astronomical tides were semidiurnal and mesotidal between 1992 and 2020, with an average tidal range of 2.79 m, a historical maximum value of 5.40 m, and a minimum of 0.18 m (Puertos del Estado web). As a consequence of such dynamic agents, the vertical fringe affected by the water level and seawater spray is quite large, in some cases reaching several hundred meters inland.

3. Methods

The methodology used in this study includes the following: i) a compilation of topographical and geological digital information layers from the Instituto Geológico y Minero de España (IGME) ii) aerial photointerpretation (map viewer of Asturias-SITPA-IDEAS, map viewer of Cantabria-mapas.cantabria Fototeca Digital of the Instituto Geográfico Nacional-IGN, Google Maps), iii) fieldwork consisting of studying the heights of the levels of *rasa*, identification of meso and micro karst forms, characteristics of notches and cave geometry, the particular case of blowholes, beach and estuarine deposits, rockfall megaclasts, etc., iv) creation of a GIS database, and v) a genetic classification of forms and interest areas.

This work has required intensive field survey to collect data in situ: geometries, length, width, *rasa* levels, eustatic sedimentary records, cartography of estuarine sediments, beach deposits as transgressive sands constituting backbeach terraces, etc. In the particular case of the recognition of *rasa* levels, their identification is very dificult where the surface not exceed 30,000 m^2, although LiDAR-based digital terrain model (5 m pixel size), available from the Spanish National Centre of Geographic Information (CNIG). has served to delimit some less obvious surfaces. The heights of each *rasa* level correspond morphologically to the limit between the cliff slope and the old abrasion platform (paleo-shoreline angle), but some cases need a geometric reconstruction. Other mesoforms, such as coves, notches, karren, shore platforms, etc also require to be described in situ.

An inventory of the main morphological units developed in the calcaroeus coastal belt of eastern Asturias and central-western Cantabria (Cantabrian Sea) is carried out. Geometric features, size scales, and formation processes are detailed. These are the basis for establishing the main steps of a preliminary hypothesis of coastline evolution that should be supported in future dating. The use of Google Maps facilitates the exact location, as well as other morphological, karstic and sedimentological peculiarities of large scale along the coastal belt.

The geologic digital information used in this work is from the GEODE Project developed by the Spanish Geological Survey (IGME, 2016), which consists of geological cartography on a 1:50,000 scale (Fig. 1).

The first survey of the study area consisted of aerial photointerpretation using 1:5000 stereopairs and ortophograpgs published by the Asturian and Cantabrian regional governments and CNIG for the recognition of forms and tectonic structures. A database in ArcGIS v. 10.3 was created by digitising the position and the attributes of the different geomorphologic and structural data collected.

The studied coastal area was divided in the GIS into five sectors, following general geological and geomorphological criteria (Figs. 1–3). The most representative examples of coastal marine-karstic geomorphologic landforms were selected for each sector (Fig. 4): old coastal planation surfaces (*rasas*), karren, notches, shore platforms, islets/stacks, arches, caves, sinkholes and uvalas, flat-bottomed depressions, collapse sinkholes, blowholes, headland-bay systems, beaches (exposed, perched and closed), tombolos, and estuaries (infilled, closed estuaries).

For the representation of stratification, faults and diaclases, an exhaustive study of change has been carried out in order to represent the results in the programme Stereonet version 10.1.1.

4. Results

4.1. Landforms inventory

The studied coasts are particularly active where its cliffed and calcareous nature are beaten by sea storms arriving from the NW and N, that are most effective when they occur with spring high tides. Wave reflection and erosive processes produces very intense geomorphological dynamics that are mainly linked to coastal, karstic, fluvial, and gravitational processes, which gives rise to a great number of coastal karren of first-order and second-order (Fig. 5A) and other linked morphologies (such as solution pans) shape the relief on the calcareous surfaces (epikarst), being widely represented along the study area. However, many old morphologies including the fossilized ones are present and are part of the coastal relief.

The most interesting and representative geomorphologic elements are described in the following section as they constitute the basis for

			STUDY AREAS (Length-km / Nr morphologies)				
	LANDFORMS	PROCESSES INVOLVED	TORIELLO-S. ANTOLIN SECTOR A (11.2)	TORIMBIA-ANDRIN SECTOR B (13.8)	PURON-TINA MAYOR SECTOR C (15.3)	PECHON-PRELLEZO SECOTOR D (6.5)	COSTA QUEBRADA SECTOR E (13.0)
1	OLD MARINE ABRASION SURFACE	Coastal	W.R	W.R	W.R	W.R	W.R
2	KARREN	Karstic	W.R	W.R	W.R	W.R	W.R
3	NOTCH	Coastal	W.R	W.R	W.R	W.R	W.R
4	SHORE PLATFORM	Coastal	W.R	W.R	W.R	W.R	W.R
5	ISLET/STACK	Coastal	6	29	15	3	8
6	ARCH	Coastal, Mass movement	4	3	1	-	2
7	CAVE	Karstic	2	6	9	-	-
8	SINKHOLE - UVALA	Karstic, Sedimentation	>50	>50	>50	>20	14
9	SUBSIDENCE HOLE	Karstic, Mass movement	4	11	-	2	-
10	COLLAPSE SINKHOLE FLOODING	Karstic, Coastal, Mass movement	11	6	7	-	1
11	BLOWHOLE	Karstic, Coastal	40	5	-	-	-
12	HEAD LAND-BAY	Coastal, Mass movement	W.R	W.R	W.R	W.R	W.R
13	EXPOSED BEACH	Coastal, Sedimentation	9	18	7	6	5
14	PERCHED BEACH	Coastal, Sedimentation	2	5	6	-	-
15	CLOSED BEACH	Karstic, Coastal, Sedimentation	4	-	1	-	-
16	TOMBOLO	Coastal, Sedimentation	-	7	2	2	1
17	ESTUARY	Coastal, Fluvial, Sedimentation	1	2	1	2	-
18	INFILL ESTUARY	Coastal, Fluvial, Sedimentation	1	1	1	-	-
19	CLOSED ESTUARY	Coastal, Fluvial, Sedimentation	-	-	1	-	-

Karstic Coastal Fluvial Mass movement Sedimentation

W.R = Widely represented

Fig. 4. Different landforms that have been identified in these studied sectors, including lengths (km) and the number of mapped morphologies, many of which are widely represented.

Fig. 5. Morphologies in sectors A, B and C along the eastern Asturian coast. A) *Rasas* (background) and karren surrounded by sand emplaced by blowhole, B) Very narrow hanging shore platform and notch (*rasa* level VIII), C) Pinacles in the foreshore of Toró and karren. Sedimentary terraces developing in the backbeach. D) Sandy small beaches, tómbolos, islets, and the infilled estuary of Niembro in the foreground. E) Cave of Cobijero F) Sinkhole and uvala.

establishing the main steps of coastline evolution (Figs. 2–4).

4.1.1. *Old marine planation surface-Rasas (Figs. 3, 4 and 5A, D)*

This morphology corresponds to an ancient shore platform that was developed when the relative sea level was higher compared to today. These flat staggered surfaces seaward (<3°) have a limited extension of 5 km along the coastal belt forming up to seven levels. In these studied coasts, they are irregularly distributed, generally as isolated flat hills, and preserve scarce overlying deposits, with continental origin. Many levels can be identified in the littoral belt from 285 m (*rasa* I); but within the limestone area near the sea, the oldest (VIII) appears with heights between 61 and 65 m high, and the modern surfaces include levels IX (35 m), X (20 m), which is the most numerous, XI (7 m), and XII (4 m) (Flor and Flor-Blanco, 2014; Domínguez-Cuesta et al., 2015). According to López-Fernández et al. (2020), there is a regional surface approximately 200 km long, and with a medium height of 100–150 m, divided into two zones with small relics of a higher flat surface. This break consiste in an apparent vertical offset of 50 m across the trace of the Ventaniella fault (C Asturias).

Several outcrops of level XI contain eustatic sedimentary records (metric thickness) of gravel and sandy beaches between which rockfall and peat deposits are interspersed (Mary, 1983). Also, eustatic deposits of Oyambre (near eastern Sector C) include associated aeolian sands with a 6 m thickness (Flor and Flor-Blanco, 2014) that were aged since 130 kyr (MIS 5) to 100 kyr (MIS 5c) and 70 kyr for the younger top deposit (Sainz de Murieta et al., 2021). The sandy outcrops located between 4 and 7 m high, not related with *rasa* outcrops, in sector B (Llanes) are comparable to the marine terrace of Bañugues (C Asturias), dated at 2,20 ± 0.23 kyr (Álvarez-Alonso et al., 2020).

Some sectors very close to the sea develop flat surfaces with gentle slopes facing south or counter slopes due to very long-term karst processes (B and C). In this way, a smoothed relief is generated between which numerous dissolution depressions are embedded (Fig. 5A, C).

4.1.2. *Coastal karren*

(Fig. 5A, B, and C) and other linked morphologies (such as solution pans) shape the relief on the calcareous surfaces (epikarst) and are widely represented along the study area as first-order and second-order karren (Allen, 1984). The contribution of salt water spray by the waves, better if wave storms, allows the formation of an outer belt of the cliff with little vegetation that favors the development of these karstic formsIn the beaches of Llanes (Sector B) and Gulpiyuri (Sector C), outstanding few examples of intertidal rock pinnacles (Figs. 3C and 4A), including the conserved field in the foreshore of Toró (Fig. 5C), and fewer flachkarren. Much more abundant are other second-order karren distinguishing kamenitzas or solution basins, which range in width from <1.0 cm to 3.0 m and in depth from 5 cm to 0.9 m, and others at centimeter and decimeter scales are rillenkarren, rinnenkarren, rundkarren as well as channels and grooves. They can be recognised all along the coast of Pría and the eastern estudied belt, in Cuevas del Mar and its western and eastern coastal areas, Arenillas (Fig. 1B) and Cobijeru (Figs. 1C and 3C), and La Silluca (near Cobijeru-Fig. 1) An exceptional outcrop of honeycomb dissolution structures (alveolar weathering) is developed in the beach of Vidiago (Fig. 1).

4.1.3. Shore platforms and notches

Shore platforms and notches are visible in all studied sectors during low tide (reaching no more than 50 m in width), although the rocky outcrops can extend in depth up to almost 1.5 km. Also, the tides play an important role because they control the width of the shore platform and may be partly dependent upon the degree of inheritance (Trenhaile, 2002).

One of the best examples is in sector E, where a well defined shore platform is associated to the embayed beach of Arnía (Figs. 3 and 8D), where it reaches 90 m width and boulders and gravels edge the cliff toe.

However, the notches develop at the cliff foot with a discontinuous distribution, being typical of subvertical cliffs. In some cases, these levels are preserved at different heights, meaning it is possible to identify previous sea levels (Kershaw and Guo, 2001). For their formation, the effect of the wave breaker is combined with chemical weathering although to a lesser degree (Trenhaile, 2015). Many morphologies has been identified first measuring the dimensions of each notch: average width, depth and bottom (Fig. 6).

All notches have an U-shape profile extending between the highest and lowest tidal levels (mesotidal range in our case) and with an apex near mean sea level (Pirazzoli and Evelpidou, 2013). Three types of morphologies have been distinguished: 1) semi-circular with a well-defined abrasion platform (metric) (Figs. 6A), 2) oval with a short step (Figs. 6B), and 3) oval with low depth (Fig. 6C).

Numerous measures have been taken along the coastline with heights varying between 1.5 and 1 m and reaching more than 4 m, correlated with the lower *rasas* XI and XII levels, respectively (Flor and Flor-Blanco, 2014). The best preserved examples corresponding to the beaches of Cuevas del Mar (Sector A) and Las Arenas (Sector D), where notches are preserved at different heights with depths varying from 0.27 to 1 m and heights of up to 1.6 m (Fig. 6). These morphologies can be observed in the intertidal zone, in overhanging levels at about 3–4 m and cliffs exposed to the effects of waves and tides.

Associated with these forms of abrasion, in various areas of sectors A (Fig. 5B), B, C and D there are deposits of gravels and pebbles, mostly of quartzite origin, linked by calcareous cement and coarse sand. These sediments come from the dismantling of the upper rasa and their subsequent remobilisation by waves and tides when they reach the beaches, constituting an example of a previous sea level as their record is preserved at heights of 3 and 4 m.

4.1.4. Islets

Islets correspond to the ancient coastline; hence, they represent an important step in the evolution of this shoreline recession (Fig. 5D 7C, D, F). In the first four sectors, mainly they are well developed in Barcaliente Fm (Carboniferous), are at variable distances of up to 250m from the current coastline. In Sector B is accounting up to 29 (Fig. 4), with promontories in a W–E direction connected to the land by a submerged sand spit that is 45 m wide. These morphologies are less represented in Zone D, and they often evolve to tombolos in both zones, where larger volumes of sand have allowed the formation of numerous small beaches.

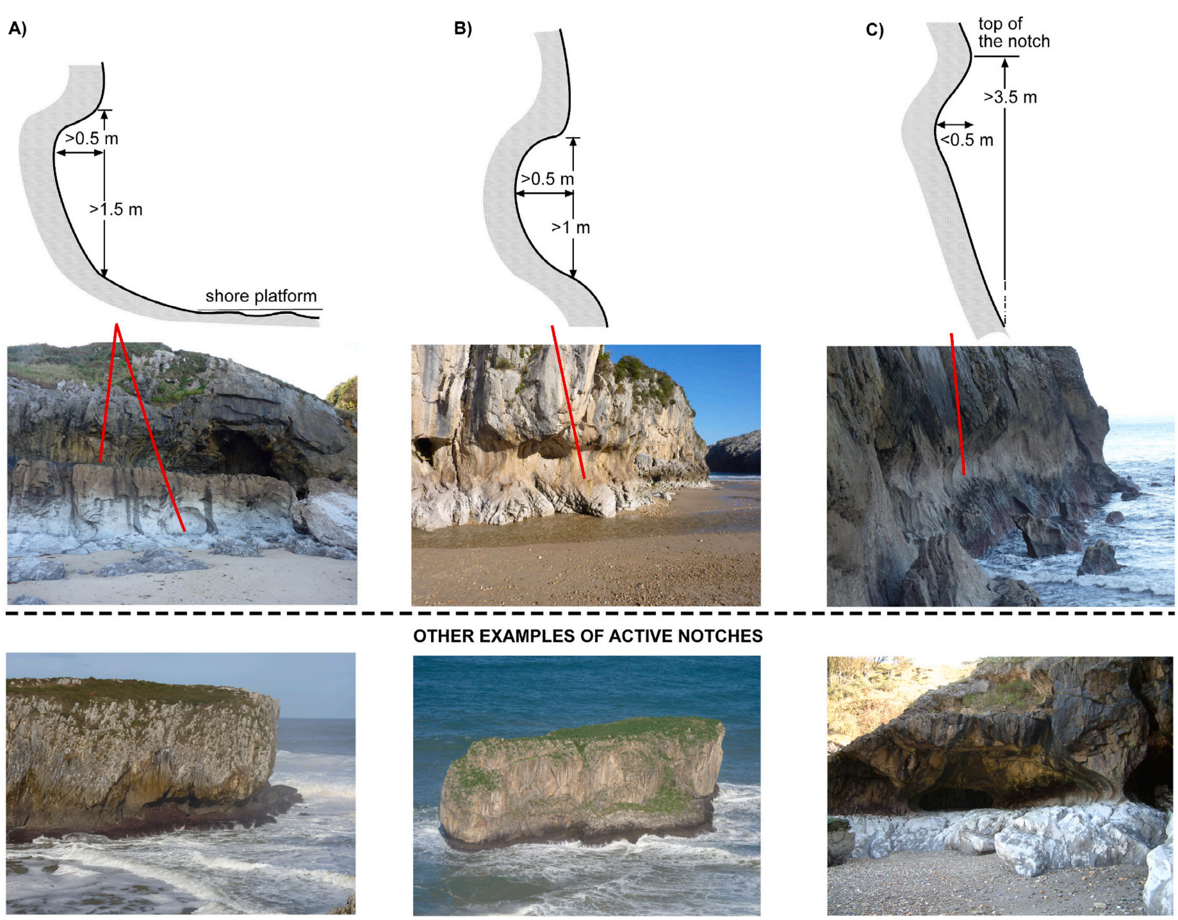

Fig. 6. Transverse profiles of main morphological notches developed in the study coast. A) semi-circular with a well-defined abrasion platform (metric), B) oval with a short step, C) oval with low depth.

Many arched forms due to karstic erosion are preserved.

There are better examples of islets and stacks in Cantabria, standing at a distance of 200 m from the cliff face. In sector E, Covachos and Arnía beaches (Fig. 7C, F) this type of process leads to differential erosion between more resistant limestones (Aptian) to wave action and soft marls.

4.1.5. *Coastal caves*

These dissolutional structures are abundant with a variety of erosional voids as well as those of a constructive nature (Mylroie and Mylroie, 2013). They developed complex galleries, some continuing perpendicular landward, connecting with beaches at different heights and depths. The outer area mainly have a flat surface, generally perched, and a convex shape upward, being the length greater than the height, always metric scale. Other conduits show a cylindrical section, typical of the karstic underground drainage. This underground network is due to the lowering of the base level as a consequence of the cortical uplift and the karst connection between different levels. In some cases, caves are connected to the surface by sinkholes and blowholes. Moreover, some karstic galleries end at a level located within the present tidal range (Fig. 5E).

Previous studies have focused on the distribution of the caves and the filling of the cavities. In the case of the Tito Bustillo Cave (World Heritage Site), located just west of the beginning of Sector A, with 600 m

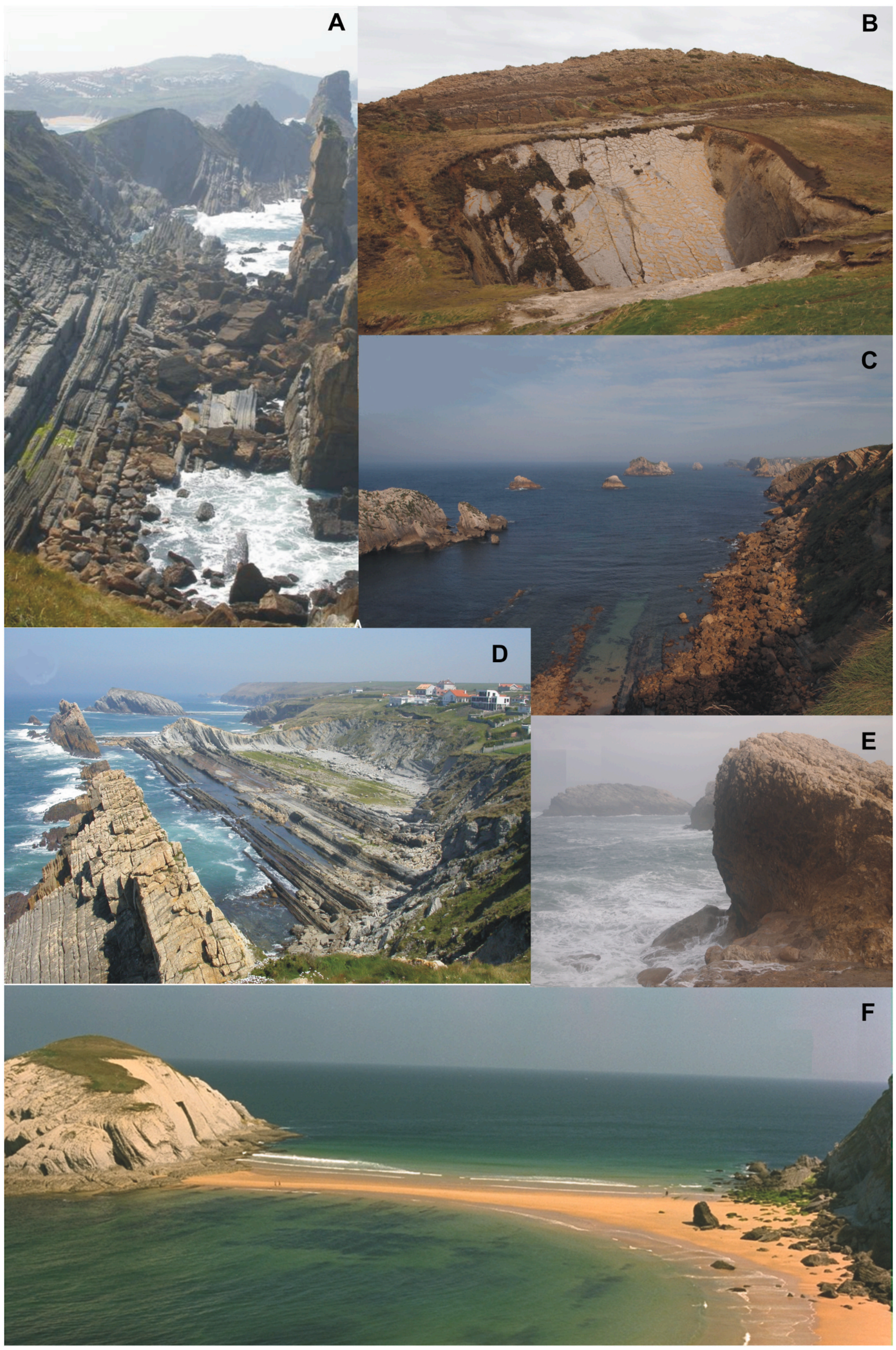

Fig. 7. Morphologies in sector E (Costa Quebrada). A) Headland-bay and stacks where scattered blocks are sedimented, B) Collapse sinkhole flooding, C) Shore platform during hightide and islets. The foot of the cliff contains rockfalls., D) Headland-bay, sediment emptied and shore platform bordered by rockfall deposits (La Arnía), E) Notch and islets, F) Islet with tombolo (Covachos).

long and E-W to ESE-WNW and NW-SE to NNWSSE trending (Jiménez-Sánchez et al., 2004, 2011). On the other hand, in Sector C, Pindal cave is 590 m long with E-W trending (Jiménez-Sánchez et al., 2006).

4.1.6. Sinkholes, uvalas and poljes

Following the criteria of Salomon (2000), three types of surface hollows within karstic closed depressions can be distinguished: sinkholes (metric scale), uvalas (Fig. 5F), and poljes, being the largest and most numerous from hollows to poljes. While sinkholes and poljes are widely accepted terms, the term uvala is more controversial, because could beconsider it the product of the union of different sinkholes or such as coalescence of dolines or multiple dolines (Fig. 5D, F).

The first three sectors (Asturias) are the ones with the greatest quantity (Fig. 4) and with diameters varying from a few metres to tens of metres, being in some cases filled with sandy sediment for agricultural and livestock use.

These morphologies appear along the study area with different evolution stages (Fig. 4) and their bottoms are usually infilled by decalcification silt and clays and the hundreds of existing examples of the first three sectors, were mapped by Adrados González (2011). Some complex depressions in Sector B that are considered uvalas in this work were interpreted as poljes by Romero (1984). On Costa Quebrada (Sector E) they are aligned according to the dissolution and erosion of the marls and represent the first stage of evolution of coastal karstification.

4.1.7. Collapse sinkholes

Collapse sinkholes correspond to ancient blowholes or collapsed dolines with a wide opening surface, which in some cases allows seawater to flow through. In Sectors A and B (Fig. 4), some of these features develop beaches at their base. These forms are also frequent in the Algarve region of South of Portugal (Oliveira et al., 2019) and in Campania, southern Italy (Del Prete et al., 2010), although they hardly develop any beach deposits inside due to sediment scarcity. Solution and collapse sinkholes are common inland of the coastal area, and in some cases their bases are below the present sea level (Figs. 7B and 8A). Once again, the first 3 sectors are the best represented, with the 11 from Pría (Fig. 4) standing out. They are mainly visible in association with the blowhole fields, as they are the stage prior to the formation of these. A series of pits in Pría (Sector A) are worthy of mention, which are developed on a karstic depression located along an NNW–SSE fault and are flooded by sea water (Fig. 8B).

4.1.8. Blowholes

Blowholes are vertical openings in the ground connected to a cave or other opening that is exposed to strong waves, which produce fountains of water escaping upward through a vertical hole. These are vertical pits of karstic origin (Bird, 2011) located on the cliff at some distance from the sea, but can be generated in other rocks as volcanic as in Hawai and

Fig. 8. Morphologies in sectors B, C and D. A) Subsidence sinkhole and beach (Llanes), B) Collapse sinkhole flooded (Pría), C) Blowholes (Arenillas), D) Arch into a beach and caves (Cuevas del Mar), E) Closed beach (Gulpiyuri), D) Closed estuary (Cobijero), unique in scientific bibliography.

Tenerife (Canary Islands-Spain). When waves break on the cliff face, a wide opening surface allows seawater vapour to flow through, similar to a geyser, projecting several meters up like a plume. Despite the fact that in other areas of the Iberian Peninsula, karstic structures associated with the coast, such as the Algarve, are developing, there are very good examples of this process in the Asturias region (45 blowholes), which has one of the highest concentrations in the world and even the most numerous. The most developed are located at Toriello (Fig. 2A1), Pría (Fig. 2A1), Arenillas (Figs. 3C and 8C), and Cobijero (Sectors A, B, and C), associated to *rasa* X. In the case of Pría is a "Natural Monument" and "Site of Geological Interest" (IELIG)".

Field morphometric analysis have been recorded despite the inaccessibility and hazard of the study areas from the sea, improving previous studies of Schülke (1968), Mensching (1965) and Adrados González (2011). Conduits generally have variable diameters between 1 and 5 m, and up, and eroded walls produced by the transport of confined water. Table 1 shows the morphologies and surfaces in plan, the topographic heights, as well as the main directions of development in the two most representative blowhole fields of the whole study area.

On the top, the sections are mainly ovalsubelliptic with metric widths and top heights between 17 m and 40 m, lower in the blowhole field of Arenillas (Table 1) sub-rectilinear outline that extend with ramps of a few tens of meters (<30 m).

Seawater and sand flow through the conduits, hence, it is very common to observe sand deposits with thicknesses of centimetres to decimetres located around the holes (Fig. 5A).

Table 1
Main characteristics of the blowhole fields of Pría (A) from the both sides of the estuary of Guadamía (Sector A. Fig. 2), and Arenillas (B), located in the eastern side of the Purón estuary (Sector B. Fig. 2).

Shape in plant	Surface (m^2)	Top height (m)	Direction
A) Blowhole field of Pría (from W to E)			
subelliptic	25	35	E-W
subtriangular	90	35	NE-SW/NW-SE
irregular	35	40	ENE-WSW
narrow elongated	5	37	NW-SE
irregular	105	30	NE-SW
narrow elongated	15	30	NW-SE
narrow elongated	15	28	NW-SE
subelliptic	80	30	NW-SE
subelliptic	55	20	E-W
subelliptic	435	20	NW-SE
subelliptic	135	20	NW-SE
subelliptic	185	22	ENE-WSW
lenticular	5	17–18	E-W
very narrow lenticular	6.5	18	ENE-WSW
irregular	8	17	N–S?
irregular	3.5	19	ENE-SSW
very narrow irregular	8	17	NNE-SSW
very narrow lenticular	2	17	WNW-ESE
subelliptic	3.5	22	E-W
subelliptic	2.5	22	NE-SW
irregular	7	20	NE-SW/NW-SE
B) Blowhole field of Arenillas (from W to E)			
Shape in plant	Surface (m^2)	Top height (m)	Direction
subelliptic	50	25	NNE-SSW
lenticular	55	26	N–S
subelliptic	180	27	ENE-SSW
subelliptic	115	22	ENE-WSW
narrow subelliptic	110	18	NE-SW
narrow subelliptic	110	18	NE-SW
elongated lenticular	145	22–23	NE-SW
subelliptic	25	25	E-W
subelliptic	125	22	E-W
subelliptic	125	25	ENE-WSW
subelliptic	110	25	E-W
lenticular	15	29	ENE-WSW
lenticular	10	45	E-W

4.1.9. Head land-bays or coves and beaches

Both morphologies are typically developed on the most demarked shoreline concavities, with many of them produced by the marine capture of previous dolines.

In the case of head land-bays do not contain any sand deposits, however, mass movements are common in the back part, favouring the increase of their surface area when the recession of the cliff takes place. In some cases, there are deposits of blocks at the base.

In this case, beaches are developed between two headlands, under the name of embayed beaches. Most are sandy and dissipative developing very narrow backshores with a few to tens of meters. During sustained calm waves low tide terraces are built, vaying from 250 to 400 m when spring low tides happen. They are present along the whole area, especially in Sector B (Fig. 2) and Sector E (Fig. 3).

Other rocky morphologies present in the shoreface of the beaches confined by limestone are the arches which also appear in islets and stacks as the case of Cuevas del Mar in Sector A (Fig. 8D) and Arnía and Covachos in Sector (Fig. 7D).

On the other hand, the beaches have variable dimensions (26 m minimum-685 m maximum), with sandy beaches being more numerous than mixed beaches (sand-gravel-pebbles). Previous studies have indicated that beach deposits are composed of fine siliciclastic sands supplied by rivers Sella and to a lesser extent from the Bedón (Flor and Flor-Blanco, 2013). Also, biogenic carbonates (20–30%) are supplied by coastal organisms that colonize the rocky cliffs of the tidal and peritidal fields (Flor and Flor-Blanco, 2013). Up to 18 examples of beaches have been inventoried in Sector B and less than 10 in the remaining sectors (Fig. 4).

Other small sand deposits formed on rocky bottoms are located in relatively distant areas from sea level as perched deposits, whose sediments are deposited during storm surges, constituting discontinuous sheets or patches and filling some solution basins. Elevated surfaces (such as those previously cited) promote the formation of perched beaches (Richmond et al., 2008).

These morphologies represent the final stages of coastal cliff evolution, as active morpho-sedimentary units.

4.1.10. Closed beaches

Closed beaches are one of the most representative morphologies in the study area, however similar beaches have been studied in Algarve-Portugal (Oliveira et al., 2019), which the most representative is Benagil. According to Schülke (1968), these kind of morphologies have been named "marine dolines or tidal sinkholes", whose first describing study was carried out in Morgat and Corsica (France) and in our zone of study (Asturias-Spain).

Their origin was an ancient collapse sinkhole, maybe between the MIS 4 and 1 (Domínguez-Cuesta et al., 2019), with suvertical walls and close to the shoreline, presently flooded by seawater flowing through cracks in the cliff. Together with seawater, sands are transported inside the depression and create a beach. Gulpiyuri (50m wide and 32m long) in Sector A (Fig. 8E) and Cobijero (40m wide and 38m long) inSector C are quite good examples of closed beaches in the studied area (Sectors A and C). These morphologies are unique to Spain, developing on ancient collapse dolines with an elliptic shape, which have been gradually filled with sand. In general, they are approximately 50 m in length and 30 m in width, and the distance from the present cliff face is approximately 80 m. Waves and sediments flow through horizontal pipes, and even tidal oscillations are detectable. In the case of Cobijero, the deposits are composed of sand and gravel produced by the erosion of deposits located on the marine abrasion surface. By contrast, there is only sand in Gulpiyuri. These morphologies are exceptional and unique for their beauty, which is why they constitute touristic and protected sites.

4.1.11. Tombolos

Tombolos form when islets or stacks close to the cliff act as barriers against wave action, and the disposal of sand or mixed sediments favours the sedimentary connection between them

They appear in Sectors B (Fig. 5D), C, and D in Asturias, and in the Costa Quebrada area of Sector E (Fig. 7F), where beaches present an E–W orientation and are protected by a group of stacks.

4.1.12. *Estuaries*

All estuaries in the study area could be classified as rock bounded, with almost vertical limestone cliffs. According to the sedimentary fill, three different typologies of estuary can be distinguished: Full infilled, closed, and complex.

Full infilled estuarys are represented in Sectors A, B, and C by estuaries main filled with sand (a type already defined by Bird, 2011). This type of morphology is well known in the Mediterranean countries (Salvator, 1869) and has been extensively studied in the Balearic Islands by Roselló (1995), Gómez-Pujol et al. (2013), and Fornós et al. (2019), but introducing the term "cala".

The most interesting examples in the studied coast are in Sectors A and B, which occupied ancient sinkholes.

Marimuerto (Sector C) is an example of a permanently closed estuary, previously mapped by Schülke (1968) and Romero (1984) and and currently has the protection status of "Protected Landscape" and." "Site of Geological Interest" (IELIG). Freshwater provide from a karst spring from the landward karst conduncts, suppliyng quartzite gravel fractions during high rains, and sands are introduced by the tides and waves, allowing the development of typical estuarine forms and sedimentary units (Fig. 8F). The origin of this morphology is very similar to the closed beaches, from ancient sinkholes connected to the sea by a horizontal karstic conduit extending almost 80 m to the sea.

No examples of this type of estuary have been found in the international literature, therefore, and probably this is a unique example in the world, although temporarily open/closed estuaries, named as bar-built intermittently closed estuaries, are common in Australia, USA, Brazil, Uruguay and South Africa (Thorne et al., 2021).

Complex estuaries are those that are currently being filled with sediments but also, during floods, they are the main contributors of sediment to the east thanks to the current drift in the same direction.

In this case, the Niembro estuary could be interpreted as an ancient polje, transformed into an estuary (Fig. 5D, Sector B). Other examples can be found in Sector B, while Tina Menor and Tina Mayor (Fig. 3), in Sector D, are the widest estuaries, and have been studied in detail by Flor-Blanco et al. (2015) and Flor-Blanco et al. (2022. **Under consideration**), respectively, being the main suppliers of sediment to the east, giving rise to the filling of the San Vicente de la Barquera estuary and the whole of the Oyambre Natural Park. Tina Menor is considered as and "Site of Geological Interest" (IELIG). All these estuaries are gradually developing into full infilled estuaries, the process being accelerated by strong storms that push sediment inland.

4.2. *Structure in the studied sections*

In the five sections studied, the regional structures in the rock massif (both bedding and the major cartographic structures) are all oriented parallel to the coastline. However, there are local secondary structures (mostly faults and joints) that exhibit different and contrasting orientations. There are two sets of decametric and hectometric faults that appear in all five sectors studied, although they have variations in frequency (Fig. 9). Faults trending ENE–WSW are present in all sectors, dominating in Pría (Fig. 9A) and Celorio and less represented in Pechón. The other set is formed by faults with a northwesterly trend, which are dominant in Gulpiyuri and common in Pechón. Very similar to the latter set of faults are faults oriented NNW, which are common in Celorio, Cobijeru (Fig. 9C), and Pechón (Fig. 9D), which also controls the orientation of estuaries. The length of these faults is in the range of tens of meters. While their associated offset is often difficult to determine precisely, they do not exceed the scale of meters.

With respect to the various joints measured, there are bigger differences between the sectors studied than with the faults, particularly when the dominant lithostratigraphic formation is the Valdeteja Fm. The lack of consistency in joint orientation between sectors is also seen locally in some sectors, where some areas present numerous joints in one direction and other dominant orientations in other areas. The length of joints is strongly controlled by the presence of the previous fabric in the rock, as they normally do not tend to exceed the thickness of the beds. In this respect, the joints observed in Valdeteja Fms are very long compared to

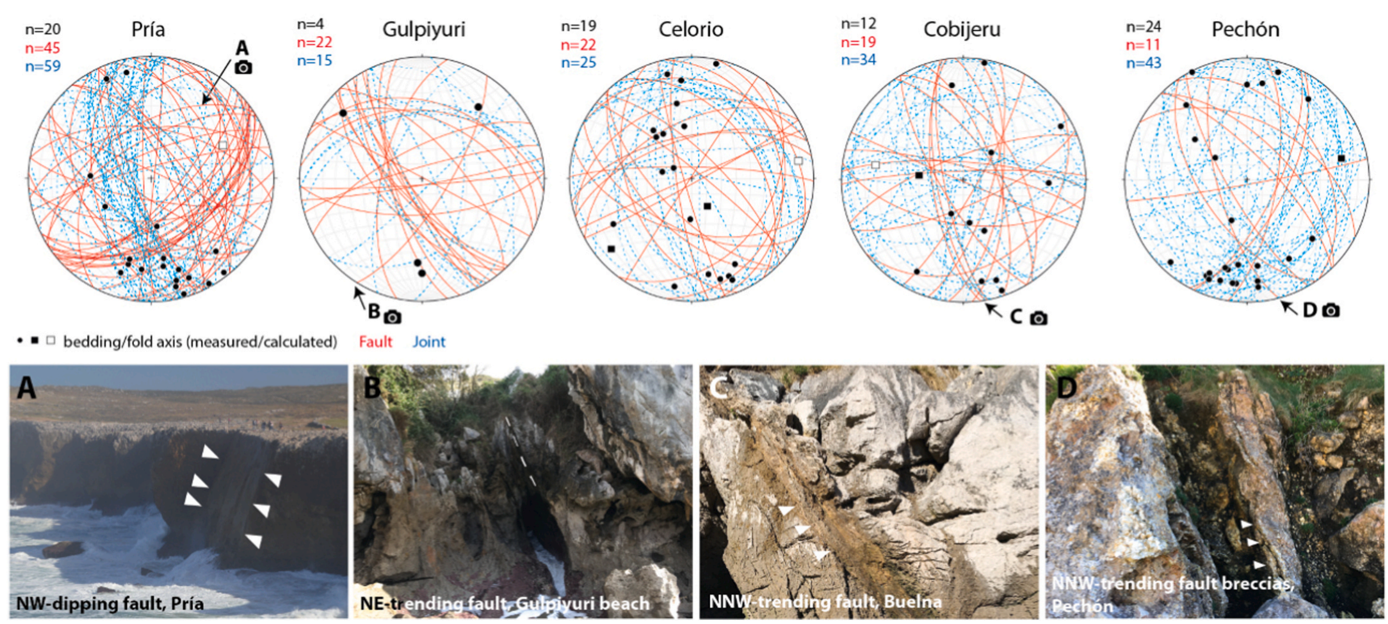

Fig. 9. Tectonic structure may control locally the orientation of the coastline. Red = faults. Blue = diaclases. The upper part of the figure shows stereographic projections of bedding (poles of planes), faults and joints in five locations from Figs. 2 and 3. Below, four images from representative structures observed in the studied areas: a) fault slip surface dipping southeast in Pría; b) NE-trending fracture connecting the Gulpiyuri Beach (onshore) with the coastline; c) NNW-trending fault near Buelna; and d) NNW-trending fault breccias associated with dolines by the coast in Pechón. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

any of the other units studied, where the rocks are massive and poorly bedded.

The case of Sector E is totally different, where the stages of the retreating coastal cliffs are controlled by three different factors: the bedrock and the different responses of more and less resistant rocks to erosion, structure represented by sub-vertical strata and the presence of faults that control the beginning of the erosion process.

All features observing in this sector presented a ENE-WSW direction, parallel to strata and are characterised by a series of vertical faults perpendicular to the strata direction.

Due to those conditions, coastal morphology corresponds to an alternation of coves and inlets, which is generated parallel to the strata direction. Islets are composed by Aptian limestone, more resistant to erosion, and represent an ancient straight coastline, while, the more developed inlets are carved in less resistant lithology, such as Turonian marls and limestones.

5. Discussion

5.1. Conceptual model for coastal evolution

On many calcareous coasts the evolution may be strongly controlled by dissolution processes ss the main triggering factor in coastal evolution (Bruno et al., 2008), but on the Cantabrian coast, in addition to these, the cortical uplift and mechanical wave processes are very important, as well as the role of sea level changes in the configuration of some sedimentary systems.

The varied forms described previously (including their geographical location, nature, and mutual relationships) provide enough data for proposing a conceptual evolutionary model applicable to all the calcareous coastline of the North of Iberia. The evolution would start with the formation of coastal planation surfaces that gently slope seawards, which emerged due to the regional uplift. Consequently, the littoral belt widens and occupies increasingly northern areas, the relief experiences an elevation and the coastline is framed within an cliffed coast. Most planation surfaces (*rasas*) in this and other higher areas have been identified and described previously, and are interpreted as evolutionary stages related to different tectonic uplift pulses since the Miocene and previous times within a broader context in which the Cantabrian Range is built (Mary, 1983; Flor and Flor-Blanco, 2014; Domínguez-Cuesta et al., 2015; López-Fernández et al., 2020).

The most extensive and representative planation levels (VI, VIII, and IX) are located 65, 35, and 20 m above sea level, respectively. Regardless of the origin of such surfaces (related to mixed continental and marine processes), they were rised up along the Pliocene and Pleistocene (Flor and Flor-Blanco, 2014). Erosion processes acting during the generation of surfaces upon Ordovician quartzites produced siliciclastic sediments, which were subsequently deposited on younger, lower surfaces and inside karstic caves.

Generally, the western sectors (A, B, C, and D) are characterised by a high density of fractures and faults oriented ENE–WSW and NW–SE. Northwesterly faults, by analogy with the Ventaniella fault (i.e, López-Fernández et al., 2018), form late in the Alpine convergence cycle as they affect earlier Alpine W–E thrusts. Despite these faults being numerous in the studied sector, they are generally short (commonly tens of meters). Moreover, regardless of their modest size, their relevance to the advance of erosion is being used by meteoric waters to infiltrate and dissolve the limestone massif. As seen in Fig. 7, some of these structures have accompanying joints, which also favours the introduction of meteoric fluids within the otherwise low-permeable fined-grained limestone. From the perspective of weathering, such structures can be regarded as weak lines, promoting the opening of hollows (by wave and tidal action) and karst dissolution. Sedimentation of sands produced beaches inside the coves, sedimentary filling of pipes, and small closed estuaries at a larger scale.

By contrast, Sector E is characterised by a straight shoreline controlled by the strata direction. The alternation of limestones and marls increases the efficiency of marine erosive processes (BruschiRemondo, 2019).

The evolutionary model proposed in the present work is illustrated in Figs. 10 and 11, and is represented by the four following main stages. Each stage represents the carving of a marine abrasion surface over long periods of time that undergoes a relatively rapid uplift that raises this surface. In a subsequent stage, a new erosion surface is generated, reaching a decreasing height.

5.1.1. Stage 1

The evolution could start once the abrasion platform is emerged as

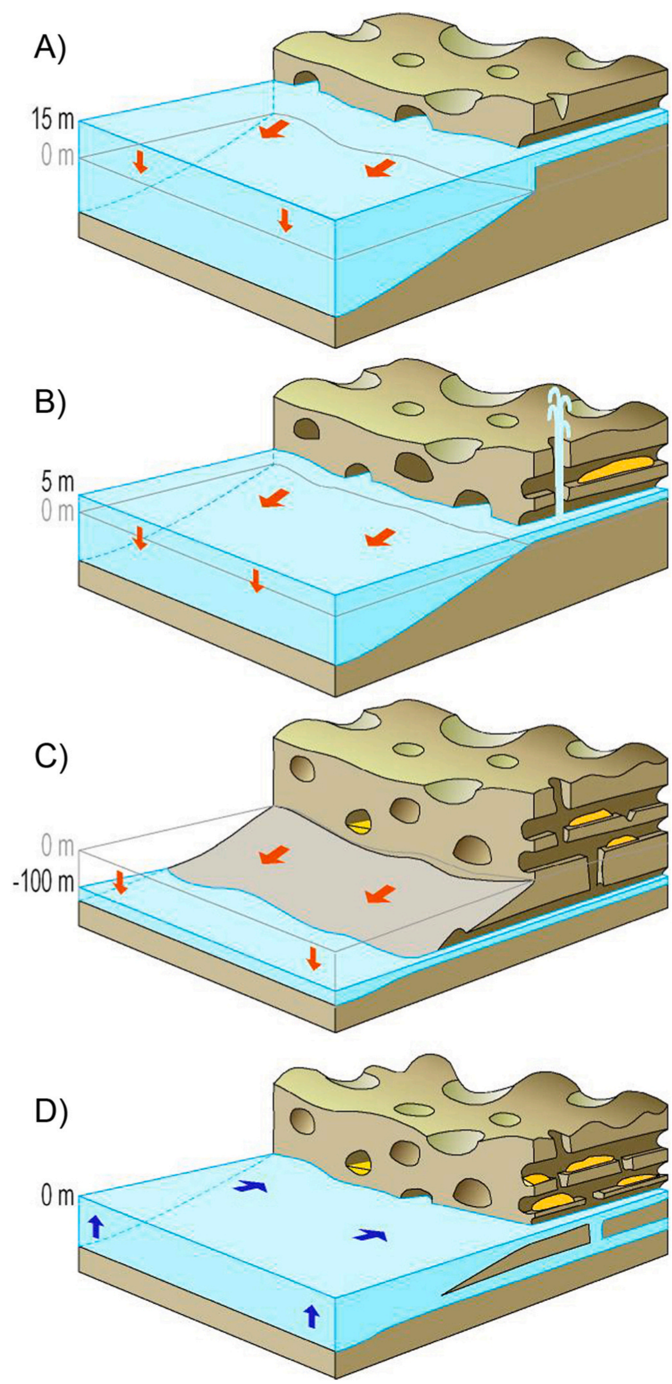

Fig. 10. Conceptual model of the coast evolution in sectors A to D (modified from Adrados González, 2011).

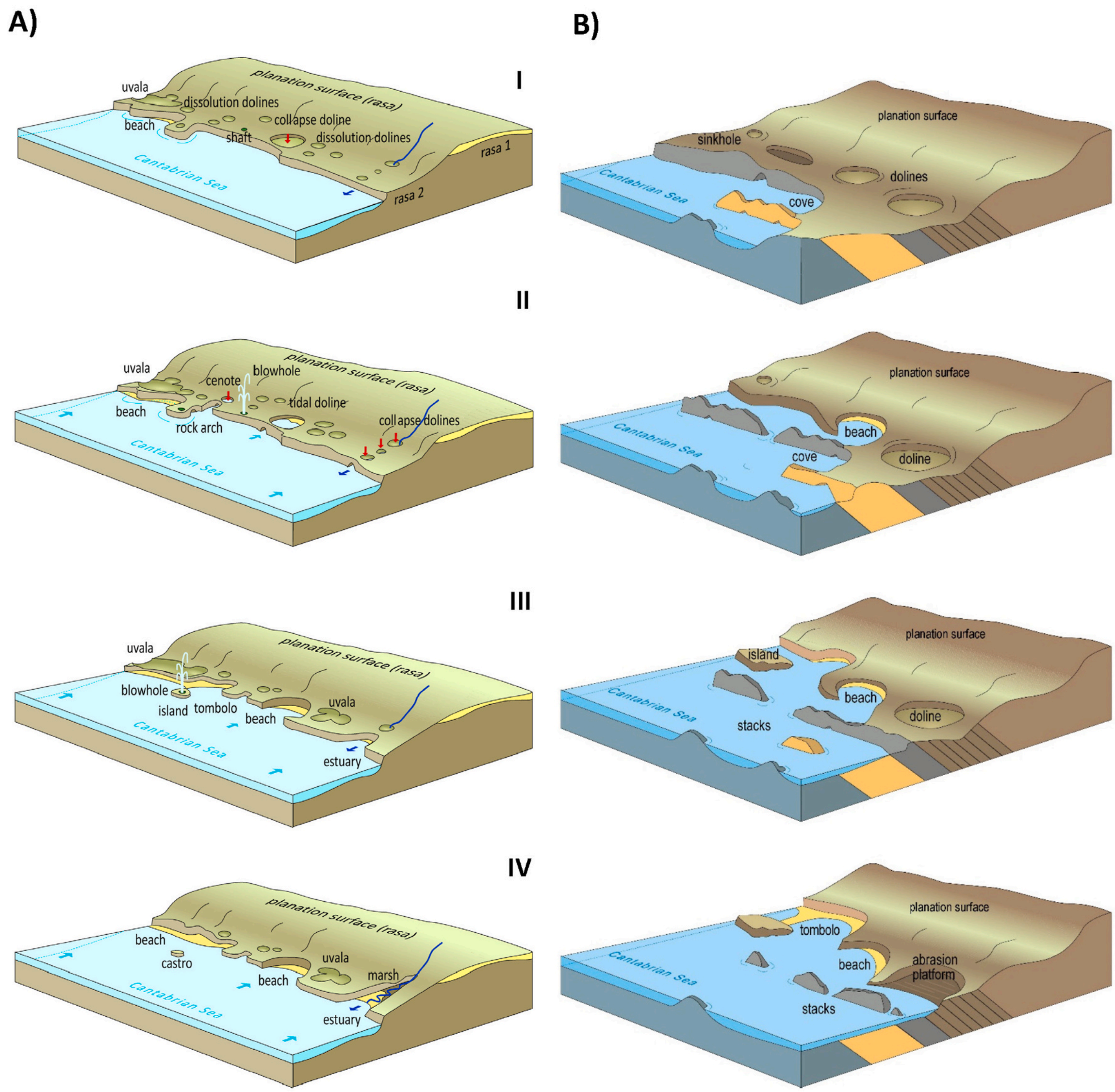

Fig. 11. Stages of coastal evolution and morphologies developed: A) in Sectors A, B, C and D (modified from Adrados González, 2011); B) in sector E (modified from BruschiRemondo, 2019).

rasa VIII, following classical evolution models on rocky coasts (Trenhaile, 1987), and the rise would have generated cliffs exposed to wave action (Figs. 10A and 11A.I and 11B.I).

Concurrently, karstic processes generated exokarstic forms on the planation surfaces, while the endokarst morphologies (caves and sinkholes) are formed due to the groundwater streams that open cavities at depths equivalent to the average sea levels of today (Figs. 10A and 11AI). Although it is very difficult to establish when the caves began to form, the Pindal cave in Sector C is related to the rasa level VIII (average height of 50–65 m), evolving with progressive decreases in the base level. Dating of some old deposits suggests an age of 166.74 ± 3.28, kyr BP (Jiménez-Sánchez et al., 2009), although the upper rasa level VIII would be very much older, since the calcareous massif must first be hollowed out, installing the underground karstic complex, and later the carbonate and clastic sedimentation taked place. This is supported by the fact that *rasa* XI would already have a somewhat older age, than the older dated speleothem.

5.1.2. *Stage 2*

A series of steps and rasa levels (IX and X) were incorporated into continental subaerial processes which altered some coastal stretches. Currently, different cave levels develop at different heights, which are related to regional mainly uplift and to relative sea level falls, which would have produced a consequent falling of the regional base level (Fig. 10B and C). On the surface, karst rejuvenation triggered doline deepening, the generation of new depressions, collapse sinkholes, blowholes, and uvalas (Figs. 10B, 11AI and 11BI). In this situation, some caves became perched while new ones were formed at lower positions.

In this stage, the quartzite littoral ranges, located just to the southern areas, some of them culminating as upper *rasa* levels, are eroding. For this reason, a lot material was transported through the karstic conduits, hence, quartzite clasts with different degrees of rounding are generally found in the galleries close to the coast (Fig. 10B) and in some active beaches.

The cave sediments allow us to record the periods when the caves were filled in as mentioned in the previous stage. For this reason, we acknowledge that two episodes of sedimentation occurred at c. 130–150 kyr and c. 60–70 kyr (Ballesteros et al., 2017) in the Cobijero cave (Sector C). The oldest episode (c. 130–150 kyr) is related to rasa XI, as well as with the gravelly beach in the overlying deposits of the abrasion surface of La Franca/Bendía in Sector C (Mary, 1983). The younger episode (c. 60–70 kyr) coincides with the end of the aeolian sedimentation on the terrace of Oyambre (Flor et al., 2014; Sainz de Murieta et al., 2021), and the upper gravelly beach deposits in La Franca (Mary, 1983).

Ancient beach deposits in SW Galicia (NW Iberian Peninsula) suggest that sea level was about 2–3 m higher than today's during MIS 5 or Eemian interglacial (Trenhaile et al., 1999; Blanco-Chao et al., 2003). In the outer mouth of the Ria of Pontevedra, a 8 m-thick deposit of sand and gravel of beach, elevated at a maximum heigh of 5 m is linked to a raised erosive surface at 1.8–4.5/5.0 m (Pérez-Alberti et al., 2018). Basal deposits were dated by quartz-OSL resulting an age of 121 ± 9 kyr (MIS5), and upper sucession was 29 ± 2 kyr (MIS 3-2), which can be correlated with deposits of the Asturian and Cantabrian *rasa* level XI, despite the distance between the two outcrops.On the other hand, the proximity of such morphologies to the cliffs and the presence of fractures and cracks favoured the formation of collapse sinkholes and closed beaches (Fig. 11A.I-II), and the initial stages of closed estuary generation (Figs. 8F and 11A.I). Moreover, karren, blowholes, arches, and subsidence holes are associated with sinkhole collapses and caves developed at different heights, such as Cobijero in Sector C (Ballesteros et al., 2017). There are also portions of the old cliff that are beginning to be disconnected, giving rise to islets (11B.I).

Taking into account that the oldest espeleothem of the Pindal Cave was dated 166.74.3 ± 3.28 kyr BP, and a maximum uplift rate is established about 0.14 mm/yr and the minimum age of the *rasa* VIII that culminates the calcareous massif (50–64m of average height) would be specified in 407.0 kyr (Jiménez-Sánchez et al., 2009).

In this paper, an attempt to relative date the different surfaces is suggested by assigning the age of the XI *rasa* at Oyambre (near Sector D) to about 130 kyr (MIS 5), dated by OSL in basal deposits (Sainz de Murieta et al., 2021). Deducing the height of the *rasa* XI in 7 m in the upper limit at the old steep-cliff base with respect to the official topographic reference (Flor and Flor-Blanco, 2014; Domínguez-Cuesta et al., 2015), the cortical elevation rate is 0.0538 mm/yr.

Awaiting future in situ dating of the defined levels, provisionally, the *rasa* VIII (65 m) is aged 1.208×10^3 kyr, *rasa* IX (35 m) = 0.650×10^3 kyr and *rasa* X (20 m) = 0.372×10^3 kyr. The lower *rasa* XII would have an age of 74.35 kyr, an age far from that suggested by Mary (1983) before 35 kyr, occupying the same active platform position nowadays.

5.1.3. Stage 3

In this stage (Fig. 10D), the activity of erosive processes on the cliffs became increasingly apparent due to the concentration of these around a single level. Nevertheless, sedimentary and geomorphological records show different pulses of sea level rise along the Atlantic coast (Leorri and Cearreta, 2004; Flor and Lharti, 2008; Leorri et al., 2008; Pascual and Rodríguez-Lázaro, 2006; Edeso-Fito et al., 2017; Blanco-Chao et al., 2019), which is very similar to other regions in the SW Atlantic coast of Europe (Clave et al., 2001). As a result, the cliffs retreated, the distance between ancient islets and the shoreline increased, and new islets were formed (Fig. 11A.III and 11B.III).

The remains of prehistoric human settlements have been discovered in some caves, while others have been natural traps for animals during the Quaternary (Turrero et al., 2013). Coastal caves are present along the whole area, especially in the Asturias region, where they are catalogued as nature protection areas (Sectors A–D). Many of them are very important sites of geological and archaeological interest (Durán et al., 2004). Inside a hollow in Sector C, named La Silluca cave ("*Small Seat Cave*") by Mary (1983), fossil remains of a Mammoth were discovered in a sandy beach rock (Flor, 1999), classified as *Elephas (Palaeoloxodon) antiquus* Falconer&Cautley by Mazo (1995), and Pinto Llona and Aguirre (1999). Stuart (2005) gave a radiocarbon date of this fossil of La Silluca: 23.575 ± 1.125 kyr (Ua-13598).

On the basis of the records studied in the Cantabrian mountain range, sea level fell associated with the last glacial maximum, approximately 19–23 kyr ago (Rodríguez-Rodríguez et al., 2015) as shown in Fig. 10C.

5.1.4. Stage 4

The relative stabilisation of sea levels during the Late Holocene favoured sedimentation processes in some headland-bay systems and in coves, beaches, and estuaries, which represent the final step of evolution after the last eustatic cycle. Each regression, caused by sea-level fall (Fig. 10C) is followed by a high stand (Fig. 10D). During this stage, two transgressions are manifested.

The first transgression (Flandrian), probably a fast event, that would reach heights of 4–5 m, has been confirmed when sea level achieved the high stand on the Iberian Peninsula, around 5.8 kyr in the Cantabrian Sea or between 6.8 and 5.0 kyr B.P. on the Portuguese coast (Pérez-Alberti et al., 2009), and about 6.50 kyr cal BP (Pozo et al., 2010) in S Andalusia. During the Dunkirkian transgression, terraces culminated by sands (beach origin) like the one formed in Bañugues has been dated in 2.20 ± 0.23 kyr (Álvarez-Alonso et al., 2020).

In Sectors A, B, C and D, the evolution model is quite developed (Fig. 11A.III), with sandy beaches oriented WNW-ESE protected by islets, as in the case of Sector B (Fig. 5D). In this area, some inner estuaries were drained by small streams promoting sand filling, which will be transformed into sandy coves in future stages (Sectors B and C). Locally, the strong structural control of the shoreline, which adapted to the geometry of strata (such as in Costa Quebrada in Sector D), prevents the accumulation of sand (Figs. 7D and 11B.IV). In that area, it is possible to observe all stages of the evolutionary model in accordance with a retreating cliff coast (Fig. 11B.III): First, islets are formed that are disconnected from the coastline, followed by the generation of some collapsed holes, dolines, and filled uvalas. Ultimately, sedimentation of some beaches protected by islets and stacks (Sectors B and D) occurs, which in some cases generate sandy tombolos (Sectors B, C, and D, Figs. 4, 5D and 7F, and 11B.IV).

In the final evolutionary stage, some small estuaries are currently being filled by sediments (Sectors A and B, Figs. 4 and 11A.IV). Other estuaries with an important drainage basin (such as the Tina Mayor and Tina Menor estuaries in Sector C) supply surplus sediments to the east side through prevalent littoral drift (Flor-Blanco et al., 2015; Flor-Blanco and Flor, 2019).

5.2. General discussion and future scenarios

As a summary of the previously described forms, lithology, structural features, coastal dynamics, uplift, sea-level changes, gravity, and karstic processes are the main factors that control the evolution of the calcareous coastlines of Asturias and Cantabria. However, it is difficult to establish when the current landscape began to generate in relation to sea level changes, mainly due to the scarcity of datable records associated with those changes in the study area.

It is evident that the main lithological contacts, faults, and joints are the starting point for the development of the described structural morphologies. Many mechanisms promote the erosion of rocky coasts as the pneumatic action of seawater and air contained in the breaking waves hit directly over the massive limestones and other rocks, where many structural discontinuities are widened (Trenhaile, 1987, 2011; Sunamura, 1992).

These effects promoted the amplitude of the main structural and karstic forms, evolving along the directions of the anisotropies, which are either formed by sedimentary or tectonic processes. The observations recorded in Fig. 9 summarise all the structures (at the local scale) that play a role in providing pathways for meteoric waters to infiltrate the carbonate formations in the substrate. This process facilitates the advance of coastal erosion by a combination of dissolution and mechanical weathering of the rocky coast. The orientation pattern in each of the studied areas also highlights variations in the dominant structures in the areas.

In a broad sense, all the studied coastline presents a concave line, with the western half (the Asturian coast, 39.4 km long) ESE–WNW oriented and the eastern half (Cantabrian coast, 52 km long) tending to

NE–SW.

The orientation of the primary fabric in the rock formations in the substrate (i.e., bedding planes) and the arrangement of tectonic structures established a first control on the orientation of the trend of large segments of the coastline. Meanwhile, secondary structures locally determine the development of coves and elongated beaches, dissolution fissures, blowholes, and the estuary axis (Fig. 9). Moreover, the Cantabrian coast evolved in this region in a context of crustal uplift mainly operating since the Miocene. This has been associated with a uniform elevation rate along the whole littoral (Jiménez-Sánchez et al., 2006; Álvarez-Marrón et al., 2008) or locally to pulses in relation to tectonic structures (López-Fernández et al., 2020).

On the other hand, sea-level fall episodes during the Pleistocene-Holocene (30–120 m below the present level, according to Purdy and Winterer, 2001) caused the relative elevation and emersion of most of the coastal karstic landforms, facilitating their development and extension. Thus, the cave speleothems recorded could be used for palaeoclimatological studies (Fairchild et al., 2000; Hellstrom and McCulloch, 2000) and seasonal climatic oscillations (Stoll et al., 2007).

It is clear that the combination of eustatic and isostatic processes has been reflected in hanging surfaces (Flor, 1983; Domínguez-Cuesta et al., 2015; López-Fernández et al., 2020), of which there are 12 cases identified (Flor and Flor-Blanco, 2014). Moreover, recent studies have located up to 12 other submerged terraces in the Bay of Biscay between −34 and −77 m (Bilbao-Lasa et al., 2020), demonstrating these changes.

Regarding to recent and present sea-level changes, these are being studied using tide gauges or through sediment dating in estuaries. The results indicate a present sea level rise for the Bay of Biscay of approximately 2.08 ± 0.33 mm y^{-1} (Chust et al., 2010), or 1.7 ± 0.2 mm y^{-1} (García-Artola et al., 2015), althought the rate has been increasing, 3.2 mm/year (IPCC, 2019) and growing at a rate of 0.8 mm/year (Nerem et al., 2018). Therefore, considering a human temporal scale, cliff erosion and changes in the morphological and sedimentary distribution of beaches, coves, and estuaries are expected to be very important over the next decades according to sea-level predictions for the 21st century. This rise is estimated to be approximately 0.50 m in this region (Chust et al., 2010).

Due to this relentless rise, cliffs will be one of the morphologies most affected by rises in sea level (Brooks and Spencer, 2012), causing significant modifications to the shoreline and to the rest of the karstic elements located behind them. In fact, some important erosive processes on cliffs and aeolian dune fields in the study area have been detected through different analyses carried out over the last decades by various driving agents (Flor and Flor-Blanco, 2005; Lorenzo et al., 2007; BruschiRemondo, 2019; Cendrero et al., 2020; Flor-Blanco et al., 2021), Recent studies on the Cantabric cliff coast have indicated variable recession rates depending on the type of lithology and the degree of fracturing of the cliff front. Based on a study by Domínguez-Cuesta et al. (2019), the Asturian coast presents different types of landslides, with a predominance of rockfall (50%) over flows (14%) and slides (13%). Specifically, on the central coast of Asturias, rates of 0.27–2.19 m y^{-1} have been reached in the last 15 years (Domínguez-Cuesta et al., 2020). In comparison, the average recession for the entire cliff formation near San Vicente de la Barquera (near Sector D) was values over40 m during the period 1956–2020, with a small acceleration of the retreat in the 21st century (de Sanjosé Blasco et al., 2020).

Taking into account the coastal microerosion of shore platforms made from siliciclastic materials in the NW Iberian Peninsula, it oscillates between 0.13 and 1,8 mm y^{-1} (Blanco-Chao et al., 2007), with a mean rate of 0.37 mm y^{-1} (Pérez Alberti et al., 2011). The retreat values estimated for calcareous materials in different coastal cliffs of the Iberian Peninsula are as follows: 0.006 y^{-1} for Miocene carbonate rocks in the Algarve (Teixeira, 2006), where there are rock falls and karst collapses similar to Costa Quebrada (Sector E); 0.003 mm y^{-1} in limestones and marls (Marques, 1997); and 0.10–0.15 mm y^{-1} in Cretaceous marly limestones in Hendaya, Basque Country (Aubie et al., 2011). The different retreat rates recorded along the Iberian coast result in a wide variety of situations, rates of sediment yield supplied to adjacent beaches, and shoreline trends.

Rising sea levels will play an important role to be taken into account, causingan acceleration of cliff erosion (especially in Costa Quebrada in Sector E) due to the structural conditions and the alternation of soft rocks (marls) and limestones. Moura et al. (2006) considered that the exposition to main wave fronts together with the lithology and structural trends of the different rock layers influence shore platform sculpturing and its dimensions in a similar study in the Algarve (Sof the Iberian Peninsula). Moreover, karstic processes are linked to climate factors, which in this case are strongly influenced by the North Atlantic Oscillation (NAO) (Trigo et al., 2004; Jiménez-Sánchez et al., 2008), as detected in the records of Pindal Cave (Moreno et al., 2010). Although karstic dissolution processes are not expected to increase under the current climatic conditions, warmer and wetter conditions could change the patterns of rainfall and CO_2 production. This could modify the endokarstic water budgets when recharging groundwater in karstified carbonate rocks (Baker and Fairchild, 2012). Several rainfall episodes registered in the area have increased endokarstic processes by triggering collapses and landslides inside cavities (González-Lemos et al., 2015). However, the recurrence of waves and the intensity increasing over 21stcentury (Guisado-Pintando and Jackson, 2019; Flor-Blanco et al., 2021) is the factor that most influences coastal landscape change, within the scenario of climate change that we are experiencing, even more so than sea level rise itself. The most damaging historical wave storms occurred in February and March 2014, which increased erosion processes along the whole coast sector (Flor-Blanco et al., 2021). The importance of storm waves in this area is such that, during these historic storms, most of these beaches practically lost their sand, with limestone alteration clays coming to the surface (Flor et al., 2014). In a scenario of continued strong storms that did not respect the sedimentary recovery period of the beaches, the configuration of the entire coastline studied could be altered.

Finally, regarding estuaries, the prevalent process at present is an acceleration of upstream sedimentary filling (Bruschi et al., 2013; Flor-Blanco and Flor, 2019) that suggests a migrating the estuarine forms upstream and the intrusion of coastal sands. This situation will imply changes in barrier configuration and in the sedimentation of associated marshes. This has been happening over the last half century with the disappearance of much of the vegetation and the modification of this type of habitat, with a drastic 85% reduction in the occupied surface (Aranda et al., 2020). The filling of estuaries will continue, and they will transform into infill estuaries or directly beaches with an elongated shape according to the river valley as Guadamía-Pría (Fig. 2A1), Poo, Niembro (Figs. 2B and 5D) and Purón (Fig. 1). Closed beaches that already exist will notably increase in size. Further, in the medium-long term (the next centuries) and with continued increases in sea levels, singular closed beaches such as Cobijeru and Gulpiyuri (Sectors B and C) and closed estuaries such as Marimuerto will become completely silted. In summary, the variety of processes linked to future evolution scenarios for the study area can be divided into short–medium term (hundreds to thousands of years) and very long term (tens to hundreds of thousands of years).

In the short–medium term, a continued sea level rise will create new sinkholes and a deepening (or collapse) of current ones, an increase of landslide activity on cliffs, increasingly continuous activity of blowholes, partial elimination of sedimentary material from the supratidal area of the beaches, and an acceleration of sediment filling in estuaries. In the very long term, in the case of a hypothetical new fall in sea levels, endokarst would experience a new rejuvenation phase and there would be renewed deepening of galleries, the creation of new ones, and abandonment of the presently active ones. Meanwhile, the present sea level would be reflected in the landscape by a new *rasa* o planation surface level.

In essence, the proposed evolution model represents base knowledge to justify the need for establishing mitigation and impact-correction measures, policy management, and protection for coastal cliffs. Calcareous cliffs will be one of the areas most affected by sea level rise and this, will result in significant modifications of the shoreline, which will subsequently affect the karstic units and forms located behind.

The coastal sectors described herein are in proximity to urban areas, and in some cases correspond to populated areas. However, the appeal of the landscape attracts visitors during summer, which constitutes a pressure on the area. The main problems that could affect conservation and protection of the area are related to urban development, parking infrastructure, and vehicular access.

Most of the sites described here to define the evolution model are included in the National Inventory of the Sites of Geologic Interest, because they are examples of some geomorphologic features and processes in the northern coast on Cantabrian Sea.

Moreover, the sector showed in Fig. 3E is part of the Costa Quebrada Geologic Park which has obtained last year, the support of the National Commission of UNESCO Cooperation for the application to the UNESCO Global Geoparks Network Programme.

One of main important criteria used by the National Commission to select which territories have to be supported for them inclusion in the UNESCO Global Geoparks Network Programme, is the International Relevance of Sites of Geological Interest included in it. Therefore, we consider that a very important part of the coastline shown in this article meets this premise due to its degree of natural conservation, the uniqueness of certain morphology and the high concentration of examples (e.g. blowholes) with respect to other areas of the world.

In the case of the Costa Quebrada Geologic Park, due to the evolution model proposed herein, a coastal sector located in Cantabria has been included in the Global Geosite Project, within the Geological Framework of International Relevance No. 19, corresponding to the “Coasts of the Iberian Peninsula” (García-Cortés, 2009; Context No. 2, Law 33/2015, September 21, about Natural Heritage and Biodiversity).

Such inclusion corresponds to a clear declaration of international value of sites together with its representativeness as elements of Iberian Peninsula Cost.

On the other hand, and for what concerns Asturias region, the area of Gulpiyuri (Fig. 2, A2) is included in the Global Geosite San-Antolín-La Huerga (CC002b) with an important geomorphologic interest and representative of calcareous cliff associated to karstic features.

6. Conclusions

This paper focused on an exceptional calcareous rocky coastal belt in the north of Spain where up to 19 different landforms originated by a combination of marine, fluvial, karstic, and gravitational processes were identified, including: coastal planation surfaces or *rasas*, coastal karren, shore platforms, islets, coastal caves, sinkholes and uvalas, collapse sinkholes, blowholes, coves, beaches and closed beaches, some scarce perched beaches, tombolos, and different types of estuaries. A database was then created in the GIS environment, and the studied area was divided into five sectors. Within these sectors quantitative and qualitative studies have been carried out in some of them, such as the shore platforms, the two most important fields of blowholes, as well as the characterization and measurements of the 3 types of notches analyzed.

The major control in the formation and orientation of the coastline has been determined y the stratification of the layers, the alternation of materials of different competence (Sector E) and the tectonic structure mapped, which was recently affected by the Alpine convergence that led to the rise of the Cantabrian Mountains. However, at the local scale, secondary structures play a role in providing access for surficial fluids to infiltrate the carbonatic substrate, promoting the enlargement of cavities by dissolution over geological time. Local variations in the orientation of these secondary structures are also reflected by the various orientations and alignments of the karstic elements. Faults trending ENE–WSW are present in all sectors, however, the other sets are formed by faults with a northwesterly trend and NNW. The case of Sector E, where the stages of the retreating coastal cliffs are mainly controlled by alternating limestones and marls (less resistant to erosion), the predominant fracture directions are ENE-WSW, as well as fractures parallel to the strata and a series of vertical faults perpendicular to the direction of them.

Many of these forms correspond to different stages of evolution. Accordingly, it was possible to establish an evolutionary model in four steps that provides clues about cliff evolution. A first stage of initial dissolution (exokarst) on the exposed old marine planation surface (rasa), giving way to uplift and a relative drop in sea level that favours the incision of the karstic network and the filling of cavities, together with the beginning of the formation of islets, head land-bays, collapse dolines, etc., until reaching the period of lowest sea level. Finally, the transgressive periods during the Holocene follow one after the other, giving rise to the configuration we have today, with well-developed beaches and estuaries, sinkholes in different degrees of evolution and disconnected islets up to 250 m from the current cliff, which mark the ancient coastline.

The model also facilitates predicting how this coast would evolve in the future at different time scales and what type of new geomorphic forms would appear as a consequence of sea level changes.

By contrast, the presented coastal evolution model predicts important geomorphological processes such as landslides, floods, and cavity collapses, which will represent a clear threat to human safety due to their intensity and frequency.

All the geomorphological features and processes highlighted in the study are affected by climate change. Accordingly, this is the reason why coastal sectors are good areas to observe and analyse the consequences of global change.

The studied sites constitute an outstanding geological heritage, hence, knowledge of them is very important for their conservation. This is particularly in some cases because they represent unique examples of morphologies that are quite vulnerable to natural and human modification. This is the case of the two closed beaches and the exceptionally closed estuary of Marimuerto, apparently unique in the world, and the high concentration of blowholes with two fields with dozens of examples that are difficult to see in other coastal limestone areas.

From another perspective, good accessibility of the coastal sectors and good observation conditions of the outcrops provide an excellent scientific, didactic, and dissemination resource. Thus, at a human temporal scale, this contribution represents a useful base for the following: development of geomorphological and risk maps, the establishment of some indicators to monitor the effects of climate change, and correct protection and management of all these spectacular natural landforms.

From the point of view of geological heritage, the eastern sector has recently been declared a Global Site by UNESCO and several sectors of the study area could acquire the same recognition due to their state of preservation and their uniqueness on a global level.

CRediT authorship contribution statement

G. Flor-Blanco: Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **V. Bruschi:** Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **L. Adrados:** Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **M.J. Domínguez-Cuesta:** Writing – review & editing, Validation, Formal analysis. **F.J. Gracia-Prieto:** Writing – review & editing, Validation, Supervision. **S. Llana-Fúnez:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **G. Flor:** Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial

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