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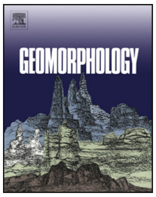

Comprehensive characterization of elevated coastal platforms in the north Iberian margin: A new template to quantify uplift rates and tectonic patterns

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ABSTRACT

The Cantabrian margin, at the northern Iberian Peninsula, shows elevated coastal platforms extending from west to east for >200 km. These erosional surfaces are several kilometers wide, and are bounded inland by a paleoshoreline, and towards the sea by the retreating current cliff. The origin and evolution of these geomorphologic markers remains controversial, one of the main challenges arising from the difficulties in correlating the patchy distribution of the platforms and their variable heights along the margin due to lithological differences, local tectonism, and varying degrees of preservation. With the aim of understanding recent coastal evolution, a systematic quantitative GIS analysis of LiDAR elevation models (5 m resolution) was carried out along 4.000 km^2 of the Cantabrian coast between 4.15°W and 7.30°W longitude. The coastline runs parallel to the Cantabrian Mountains, which are supported by an orogenic root present only beneath the eastern half of the coastline under study. The integration on the GIS template of the crust-mantle boundary as a controlling factor of landscape development has helped in the understanding of the recent evolution of the coastal platforms, and in the interpretation of previously unexplained features of their distribution.

The two main outcomes of this multiscale approach are: 1) the correlation of most of the fragmented rasas as part of an original unique coastal platform along the Cantabrian margin, and 2) the differentiation of two sectors separated by a highly tectonized area associated to the Ventaniella fault. The western sector has one main, continuous surface showing a 0.08° tilt towards the west, sometimes interrupted by local and recent minor faults with net slips of meters to tens of meters. The eastern sector has several steps of erosional surfaces spread out at various heights without tilt. The Ventaniella fault, separating both sectors, produces an apparent vertical offset of 50 m in the main erosional surface. Our study shows that this fault also separates two distinct evolutions in the elevation of the coastal platform: (1) the western coast, which has risen continuously, probably in response to a lateral gradient in crustal thickness; and (2) the eastern coast, where uplift is discontinuous over time since several of these surfaces formed below the main paleoshoreline. The Cantabrian coast captures the influence that crustal structure has on the expression and evolution of geomorphologic markers at the surface. And vice versa, landform features at the surface can be very sensitive to differential crustal thickness while responding to the same external and climatic forces. In the context of the western European framework, our work provides a regional template within which future absolute geochronological dating can be based to improve our knowledge of the recent evolution of the Atlantic margins.

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1. Introduction

1.1. Rasas

One of the most distinctive features of the geomorphology along the E-W trending North Iberian coast is the ubiquitous presence of emerged erosional platforms up to 6 km in width, known as rasas (Fig. 1a,b). The term *rasa* has been traditionally used to refer to these elevated erosional planar surfaces following the coast (Pedoja et al., 2011, 2014), not only

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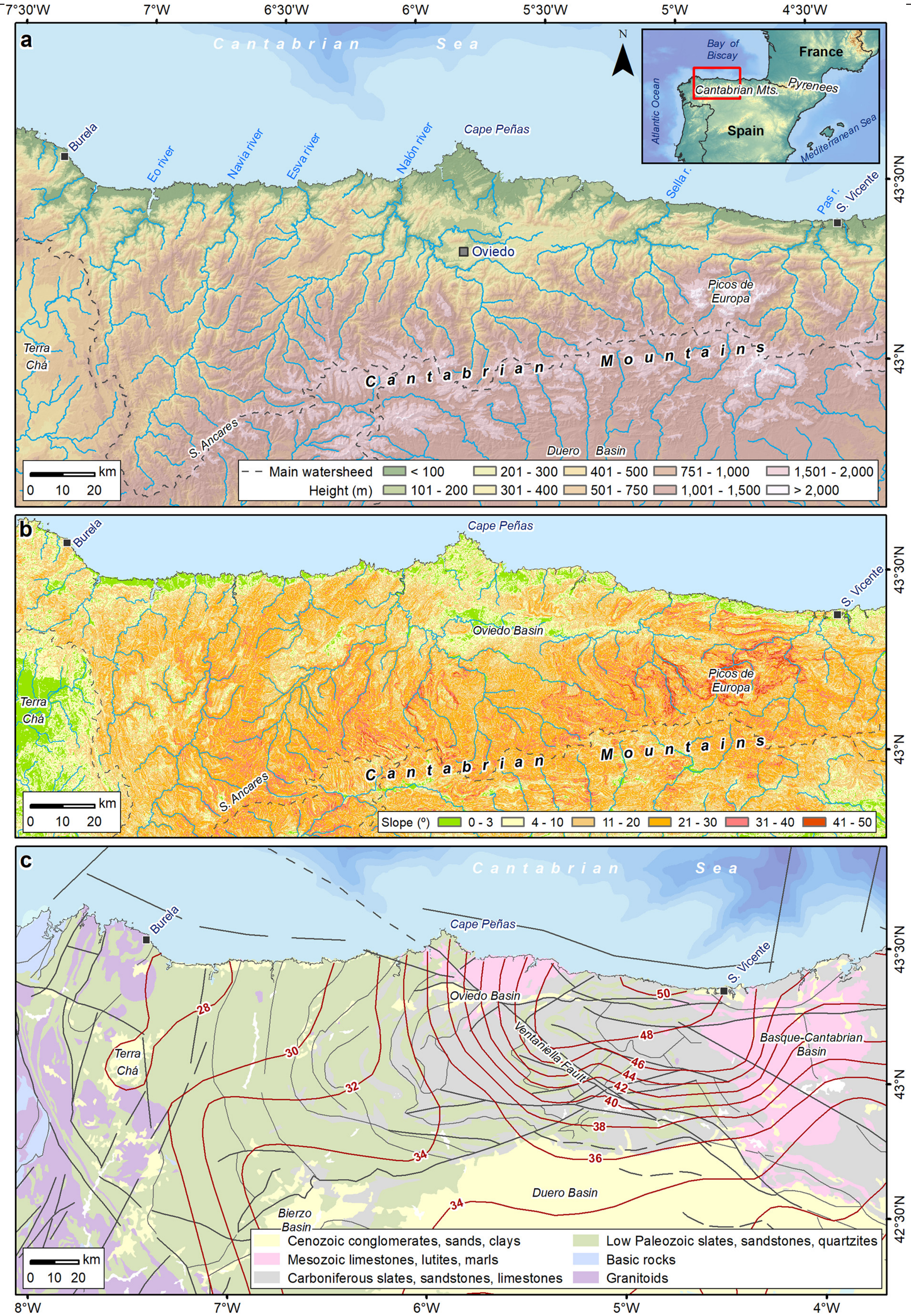


Fig. 1. Digital models of elevations (a) and slopes (b) of the Cantabrian margin of Iberia. The geological synthesis of the study area is based on the continuous digital geological map of Spain (https://info.igme.es/cartografiadigital/geologica/Geologicos1M.aspx) (c). The solid red lines indicate the Moho depth expressed in kilometers according to Cadenas et al. (2018).

in Spain, but also often in other places along the Atlantic coast of Europe and northern Africa. The sequences of rasas and marine terraces are interpreted as wide late Cenozoic coastal erosion surfaces. They can be up to several km in width in western Europe and other tectonically stable regions, and can be observed sometimes at >200 m above sea level (Pedoja et al., 2011, 2014, 2018). The *rasas*, which will be the term we will use throughout this work, are polygenic in origin and age. In slowly uplifting coastal rasas, the number of terraces observed can vary drastically depending on paleogeography, uplift rates and landform preservation (Kelsey and Bockheim, 1994; Hsieh et al., 2004; Marquardt et al., 2004; Alvarez-Marrón et al., 2008; Orrù et al., 2011; Jara-Muñoz et al., 2016; Simms et al., 2016). Geomorphological and evolutionary features of rocky coastlines have been studied worldwide (Sunamura, 1991, 1992; Trenhaile, 1987, 2000, 2014; Liu et al., 2011; Matsumoto et al., 2016). There is abundant literature trying to determine uplift rates from marine terraces, uplift that may be attributed to glacial, isostatic, tectonic, epeirogenic and/or thermal processes (Merritts and Bull, 1989; Rosenbloom and Anderson, 1994; Cucci, 2004; Westaway and Bridgland, 2007). The marine origin of the platforms is a result of a complex suite of biological erosion processes, subaerial weathering, and wave erosion. The sea level during origin must remain at approximately the same position with respect to the landmass. Their exposure requires an uplifting continent or a drop in sea level (Burbank and Anderson, 2011). In general, they show a very gentle slope dipping seaward (<3°) and a width, when active, which does not exceed 0.5 km at any one time. The development of wider surfaces is not uncommon and may occur in the case of a repeated reoccupation of the platform by the sea (Kelsey and Bockheim, 1994; Burbank and Anderson, 2011).

Vertical crustal motion is almost always invoked to understand the presence of the rasas along coasts, as estimates of eustasy frequently fail to explain the magnitude of the apparent drops in sea level that rasas need. Nevertheless, the staircase morphology of many coasts reveals the combination of general uplift overprinted by sea level fluctuations caused by glacial cycles. Eustasy due to changes in water volume explain the lowest surfaces, but the higher ones cannot be explained by sea level changes as some models indicate that the present height will only have been surpassed by 10–20 m during the last million years or so (Bintanja and Van De Wal, 2008). Moreover, these surfaces are frequently much higher than the maximum elevation reached by the sea during the Quaternary interglacial stages (Trenhaile, 2002; Berger et al., 2016). Their formation, then, has been attributed to long periods of high sea levels during the Tertiary (Trenhaile, 2002), and some authors (e.g. Pedoja et al., 2018) interpret the >2000 km of coastal platforms in western Europe as a fully uplifted crustal segment due to the increasing lithospheric compression that accompanies Cenozoic orogenies.

1.2. The Cantabrian rasas

In the northern Iberian Peninsula, the rasas are bounded to the North by the rocky Cantabrian cliffs, while landward they are limited by coastal mountain chains (Fig. 2). With elevations below 1300 m, these coastal chains present N-S and NW-SE orientations in the western sector of the study area, adopting an E-W disposition to the east. The boundary line defined by these coastal chains, corresponding to the old coastline, is horizontal in origin and constitutes a key structural marker for tectonic or epeirogenic deformation of the crust. Relative changes in its position with respect to sea level or in its tilting, may be considered as related to uplift or deformation of the crust. The rasas of the Cantabrian coast are well preserved over a siliceous basement to the west of Cape Peñas (Fig. 1). However, to the east, the abundance of carbonates, mainly limestones, hinders their direct identification, due to moderate weathering by karstic processes once exposed to subaerial conditions (Jiménez-Sánchez et al., 2006; Alvarez-Marrón et al., 2008; Domínguez-Cuesta et al., 2015).

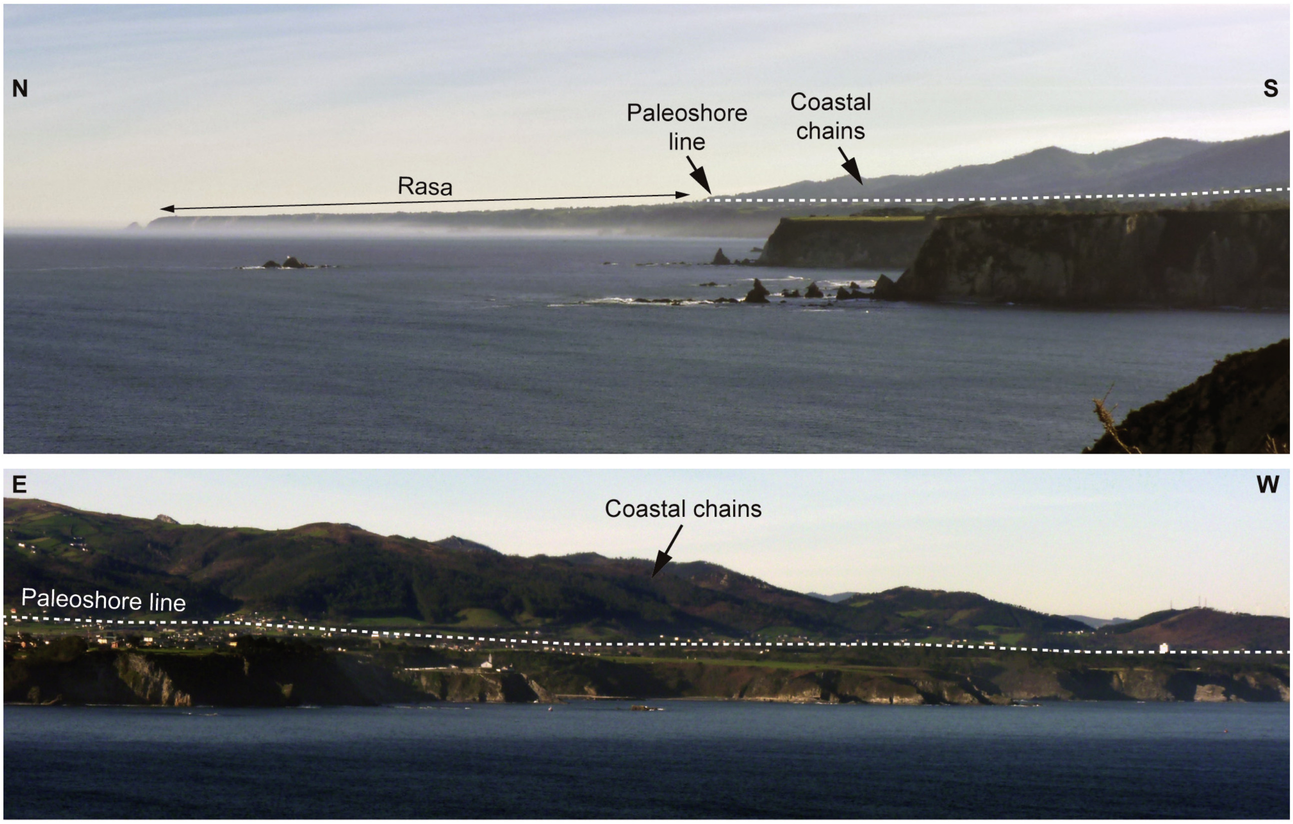


Fig. 2. Rasa located to the north of the coastal chains on the western Cantabrian Coast. Photos by Germán Flor-Blanco.

Some of the major geomorphological parameters of the Cantabrian rasas, such as altitude and sometimes extension, have previously been described in the literature (Flor, 1983; Mary, 1983, 1985; Blanco-Chao et al., 2003; Moura et al., 2006; Alvarez-Marrón et al., 2008; Feal-Pérez et al., 2009). However, a full comprehension of these landforms within the regional context or the correlation between the different fragments and heights has been unsuccessful until now, partly because detailed local studies commonly missed the crustal scale, and partly due to the absence of efficient digital mapping methods at the time of the studies.

Compared to neighbouring coastal platforms in the Galicia region to the W of the study area (Fig. 1), for instance, the most recent Cantabrian terraces have not been uplifted, and are affected by a general decline due to sea level rise. Alonso and Pagés (2007) and Moñino et al. (1988) have noted that a comparison between Late Pleistocene coastal deposits in Galicia and the raised platforms in the Cantabrian margin shows that the latter have been uplifted 2–3 m more than the former since the last interglacial period. Elsewhere, terraces in the Mondego river in Portugal are considered glacial eustatic with some local differential uplift attributed to local minor faulting (Ramos et al., 2012). At the other side of the Bay of Biscay, in Normandy, Coutard et al. (2006) have attributed the origin of the terraces to glacial cycles within a strongly expressed slow uplift.

1.3. Aim and objectives of the study

The purpose of the present study, based on a Geographical Information System (GIS) analysis, was to approach the assessment and parameterization of the characteristics of the rasas at a multiscale level, something not addressed until now. We also introduce a crustal scale parameter in the vertical direction, the topography of the crust-mantle boundary. In this area this parameter shows important variations from west to east, and was traditionally ignored in geomorphologic surface studies. The introduction of the Moho topography in the rasas parameterization and calculations was extremely valuable in helping us to understand some of the otherwise enigmatic changes occurring from west to east in the elevation of past erosional platforms.

The specific objectives can be summarised as: i) characterization at regional scale of the rasas of the Cantabrian margin, taking advantage of the digital terrain model based on LiDAR images and geomorphological techniques supported by GIS; ii) determination of how tectonic activity has contributed to the past and current evolution of Cantabrian rasas; iii) delivery of a coherent framework for future geochronological dating of events and processes.

Our approach in this particular region, where deep structure is known to be very variable along the length of the studied coastline, provides an opportunity to constrain the relative contribution by tectonic or climatic mechanisms in the formation of these surfaces. This is not a straightforward task in geomorphological studies as landscapes often respond in a similar way to tectonics and climatic events. We hope to make the Cantabrian coast a reference case in the study of rasa evolution.

2. The geological setting of the Cantabrian rasas

This study focuses on part of Cantabrian margin, between 4.15°W and 7.30°W longitude (Fig. 1), covering an area of an extension >4000 km^2 (Fig. 1). The main regional relief feature in the area are the Cantabrian Mountains, an alpine mountain belt parallel to the coast that reaches 400 km in length and has an average width of 100 km (Fig. 1a). The highest elevations >2500 m are located in the central part of the mountain belt, in the Picos de Europa Massif, with elevation decreasing progressively to the west to the plains of the Terra Cha in Galicia (Fig. 1). The axis of this belt, from west to east, is located between 65 km to 35 km away from the coast. A hydrographic network has developed over this system, with small rivers discharging to the North. The river network draining to the north of the main regional watershed, is now incising into the elevated rasa surface.

2.1. The rise of the Alpine collisional orogen: the Cantabrian Mountains

The Cantabrian Mountains formed during the late Paleogene as a result of the convergence between Eurasia and Africa, which also produced the Pyrenees (Teixell et al., 2018). The substrate of the range is mostly Palaeozoic (Fig. 1c) and was initially and predominantly deformed during the Variscan orogeny, and partially overprinted later in the Cenozoic during the Alpine convergence (e.g. Alonso et al., 1996). Mesozoic and Cenozoic sediments are limited to restricted and disconnected basins (Santanach Prat and Santanach i Prat, 1994; Alonso et al., 2010). To the east of the mountain range lies the Basque-Cantabrian Basin, which comprises a thick succession originated during several episodes of rifting during the Mesozoic, and also deformed during the Alpine convergence (Tugend et al., 2015; Cadenas et al., 2018).

The continental crust under the Cantabrian Mountains has thickened to almost 50 km east of 6°W (Pulgar et al., 1996; Gallastegui Suárez, 2000; Díaz and Gallart, 2009; Cadenas et al., 2018) (Fig. 1c). The thickening of the crust represents the crustal root of the orogen and appears offset to the north with respect to the main mountain belt at the surface, which lies a few kilometers to the south (Fernéndez-Viejo et al., 1998; Llana-Fúnez et al., 2020). To the west, the crust presents a constant thickness of 30–32 km similar to other parts of the Iberian crust elsewhere (Fernández-Viejo et al., 2000; Díaz and Gallart, 2009). To the north, the root terminates abruptly under the Bay of Biscay, where the crust has a thickness at the continental platform, close to the ocean-continent transition, of 20–25 km (Fernéndez-Viejo et al., 1998; Ruiz et al., 2017). In summary, the Cantabrian rasa has formed and evolved along a continental margin with significant lateral variations in crustal thickness, locally higher than 10–15 km.

2.2. The origin and age of the Cantabrian rasas

Hernandez Pacheco and Asensio Amor (1963, 1964) described the Cantabrian rasas as surfaces of continental origin, later invaded by the sea, estimating ages from Pleistocene to Holocene. To this genesis, Guilcher (1974) adds a marine and erosive contribution from piedmont glaciers. Up to 18 platform levels have been identified between 5 and 264 m above the current sea level (Flor, 1983; Mary, 1983, 1985; Flor and Flor-Blanco, 2014). The latter group of authors point to a marine or mixed origin, estimating in agreement with Lamboy (1976) Aquitaine-Langhian ages for those located at a higher level (>200 m), Lower Pliocene for those located at 150 m, and Pleistocene for those located at a lower height. Flor (1983) and Mary (1983) have attributed the existence of different levels and have related areas of the rasa to sectors of the Cantabrian orogen to the discontinuous uplift of the continent. They proposed a final Oligocene age for the easternmost part, late Santonian for the central sector, and Berriasian to Barremian for the westernmost part. They also indicated that in the western half of the Cantabrian Mountains there was continental flattening during an arid period in the Tertiary, while in its eastern sector there was active uplift of the more mountainous relief. Recently, Alvarez-Marrón et al. (2008) proposed that the rasas located west of the Cape Peñas were formed over tens or hundreds of thousands of years by successive marine reoccupation, and assigned them a minimum age of 1–2 Ma, while Jiménez-Sánchez et al. (2006) estimated a minimum age of 300 ka for a rasa level located in the eastern sector of the Cantabrian Mountains.

2.3. Regional uplift and denudation rates

Detailed knowledge about the exhumation of the Cantabrian Mountains in their central-western sector is limited as a result of the shortage of Cenozoic outcrops and the absence of rock conditions suitable for thermochronological analyses. Some authors (Carrière, 2006; Grobe et al., 2010; Martín-González and Heredia, 2011) have considered that in the western sector of the Cantabrian Mountains there is no significant alpine exhumation. Nevertheless, published data indicate a decrease in the age, quantity and rate of exhumation from the central part of the mountain belt towards its western end (Martín-González et al., 2012). The estimated elevation rates differ depending on who the authors are, and if the rate estimates refer to the eastern area (Smart, 1984; Jiménez-Sánchez et al., 2006; Grobe et al., 2010; Fernández and Piedrabuena, 2011; Ballesteros et al., 2019; Fillon et al., 2016) or the western area of the mountain belt (Ribeiro et al., 2002; Alvarez-Marrón et al., 2008; Martín-González et al., 2012; Viveen et al., 2014) (Table 1).

3. Methods

Geomorphological techniques involving the analysis of high resolution digital terrain models have been successfully applied in all kind of topographical research, whether generic (Remondo and Oguchi, 2009; Lucchesi et al., 2013; Napieralski et al., 2013; Kolejka, 2018; Verbovšek and Popit, 2018), tectonic-geomorphological (Font et al., 2010; Partabian et al., 2016; Padgett et al., 2019), morphometrical (Das and Pardeshi, 2018; Sahu et al., 2018; Balasubramani et al., 2019), or coastal evolutionary (Mujabar and Chandrasekar, 2013; Mattheus, 2016), among others. Regardless of the efficiency in the treatment and indexation and further analysis of vast amounts of geomorphologic data, it is still difficult to separate how the different factors, whether glacial, tectonic or sea-level changes, contribute to the formation of the coastal surfaces. The methodology used to study the Cantabrian rasas is based on a GIS management and analysis. Data processing was carried out using the software ArcGIS v10.3 (by ESRI). All topographical data in digital format (LiDAR digital elevation models and orthophotos) are made available by the Spanish Geographical Institute (available at http://centrodedescargas.cnig.es/CentroDescargas). The sources for the Geological maps in vector format at 1:50.000 come from the Spanish Geological Survey (IGME) (available at http://www.igme.es/).

The starting template was built from the detailed, 5 m cell size digital elevation models (DEM), which came from 17 LiDAR files that fully covered the study area. A digital slope model (DSM) was extracted from the initial DEM template. All surfaces with slopes over 3° were removed on the basis that slopes steeper than this in this area cannot qualify as emerged marine surfaces (Anderson et al., 1999; Elorza, 2008). Likewise, all those surfaces with an elevation higher than 350 m were removed. The DSM was then combined with the updated geological map to discriminate shore platforms from other landforms with minimal slope but with other origins, such as alluvial plains and terraces, marshes or man-made deposits. Finally, a meticulous, painstaking manual revision of all detected planar surfaces was made in order to eliminate any other possible artefacts that did not correspond to erosional surfaces.

The boundaries of the rasas are the paleoshoreline in the south, and the cliff line or the current edge of coastal erosion in the north. The identification of the old shoreline and the cliffline points and their distribution along the coast was based on the elaboration of 50 topographical profiles perpendicular to the coast (Fig. 3). The topography of the crust-mantle boundary (i.e. the Moho) was extracted from published results of deep seismic soundings and other geophysical methods (Fernández-Viejo et al., 2000; Díaz and Gallart, 2009; Ruiz et al., 2017; Cadenas et al., 2018). This topography was incorporated into the geological map (Fig. 1c) and used in cross sections to offer context for the surface features with respect to the crustal thickness (Fig. 4).

4. Results: distribution of erosional surfaces along the western Cantabrian coast

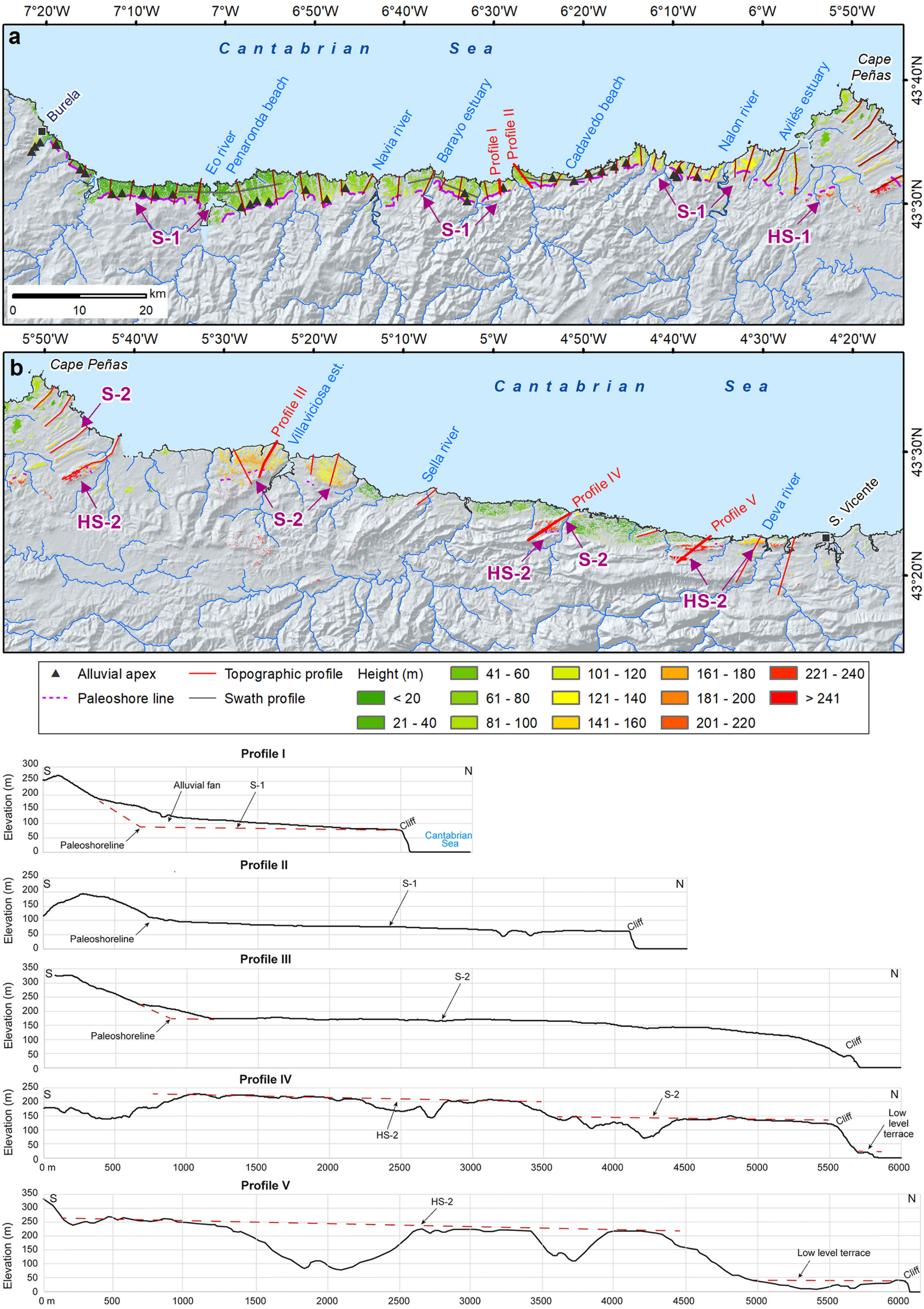
The high-resolution multiscale analysis of the relief along the Cantabrian coastline provides two major outcomes. The first one is that most of the rasas seem to have been part of a unique continuous surface approximately 200 km in length and of variable width, currently retaining a maximum width of 6 km (Fig. 3ab; Table 2). Therefore, the first surprise is that the final number of regional rasas is much lower than that proposed in previous studies. The second important outcome is that according to the number, geometry and distribution of these surfaces, we can distinguish two sectors, separated by a transition zone around Cape Peñas, which seems to be determined by a crustal structure, the Ventaniella fault. A detailed description of these two sectors follows.

4.1. Western sector

This sector is characterized by the presence of a rasa that extends continuously for 122 km between the localities of Burela (7° 20′W) and Avilés (5° 55′W) (Fig. 3a). It comprises a well-preserved area of 137.1 km^2 distributed in patches and reaching a maximum width of

Table 1
Published data of uplift of the western sector of the Cantabrian margin.

Main sector	Subzones	Uplift rate (mm/year)	Time lapse	Indicator	Reference
Eastern Cantabrian Mountains	Eastern coast	0.19	124 ka	Speleothem $^{234}U/^{230}Th$ dates	Jiménez-Sánchez et al. (2006)
	Picos de Europa Massif	0.1–0.3	350 ka	Perched phreatic conduits	Smart (1984)
		0.24	37 ka	Fluvial terraces	Fernández and Piedrabuena (2011)
		0.15–0.25	2.1–0.5 Ma	Cave deposits $^{26}Al/^{10}Be$ burial age	Ballesteros et al. (2019)
Central Cantabrian Mountains	Asturias	0.014	100 Ma	Apatite thermochronology	Grobe et al. (2010)
	Asturias	0.24–0.3 (1.1 at maximum activity)	Paleogene-Oligocene	Apatite thermochronology	Fillon et al. (2016)
Western Cantabrian Mountains	Western coastal rasa	0.07–0.15	1–2 Ma	Cosmogenic nuclides	Alvarez-Marrón et al. (2008)
	Western range	0.02–0.06	Paleogene-Neogene	Apatite thermochronology	Martín-González et al. (2012)
West of the Cantabrian Mountains	Flat reliefs of Lugo	0.02	100 Ma	Apatite thermochronology	Grobe et al. (2010)
	Miño River	0.1	600 ka	Fluvial terraces	Viveen et al. (2014)
	Ancares/Courel ranges	0.08	Neogene	Apatite thermochronology	Martín-González et al. (2012)
	North-eastern Portugal	0.1–03	2–3 Ma	Marine terraces	Ribeiro et al. (2002)


a
7°20'W
7°10'W
7°W
6°50'W
6°40'W
6°30'W
6°20'W
6°10'W
6°W
5°50'W
43°40'N
43°30'N
Cantabrian Sea
Cape Peñas
Burela
Eo river
Penaronda beach
Navia river
Barayo estuary
Profile I
Profile II
Cadavedo beach
Nalon river
Avilés estuary
S-1
S-1
S-1
HS-1
km
0
10
20
b
5°50'W
5°40'W
5°30'W
5°20'W
5°10'W
5°W
4°50'W
4°40'W
4°30'W
4°20'W
43°30'N
43°20'N
Cape Peñas
Cantabrian Sea
S-2
HS-2
Profile III
Villaviciosa est.
S-2
Sella river
Profile IV
HS-2
S-2
Profile V
Deva river
HS-2
S. Vicente
Alluvial apex
Paleoshore line
Topographic profile
Swath profile
Height (m)
< 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 160
161 - 180
181 - 200
201 - 220
221 - 240
> 241
Profile I
Elevation (m)
S
N
Alluvial fan
S-1
Paleoshoreline
Cliff
Cantabrian Sea
Profile II
S-1
Paleoshoreline
Cliff
Profile III
S-2
Paleoshoreline
Cliff
Profile IV
S-2
HS-2
Cliff
Low level terrace
Profile V
HS-2
Low level terrace
Cliff
0 m
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
0
50
100
150
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300
350

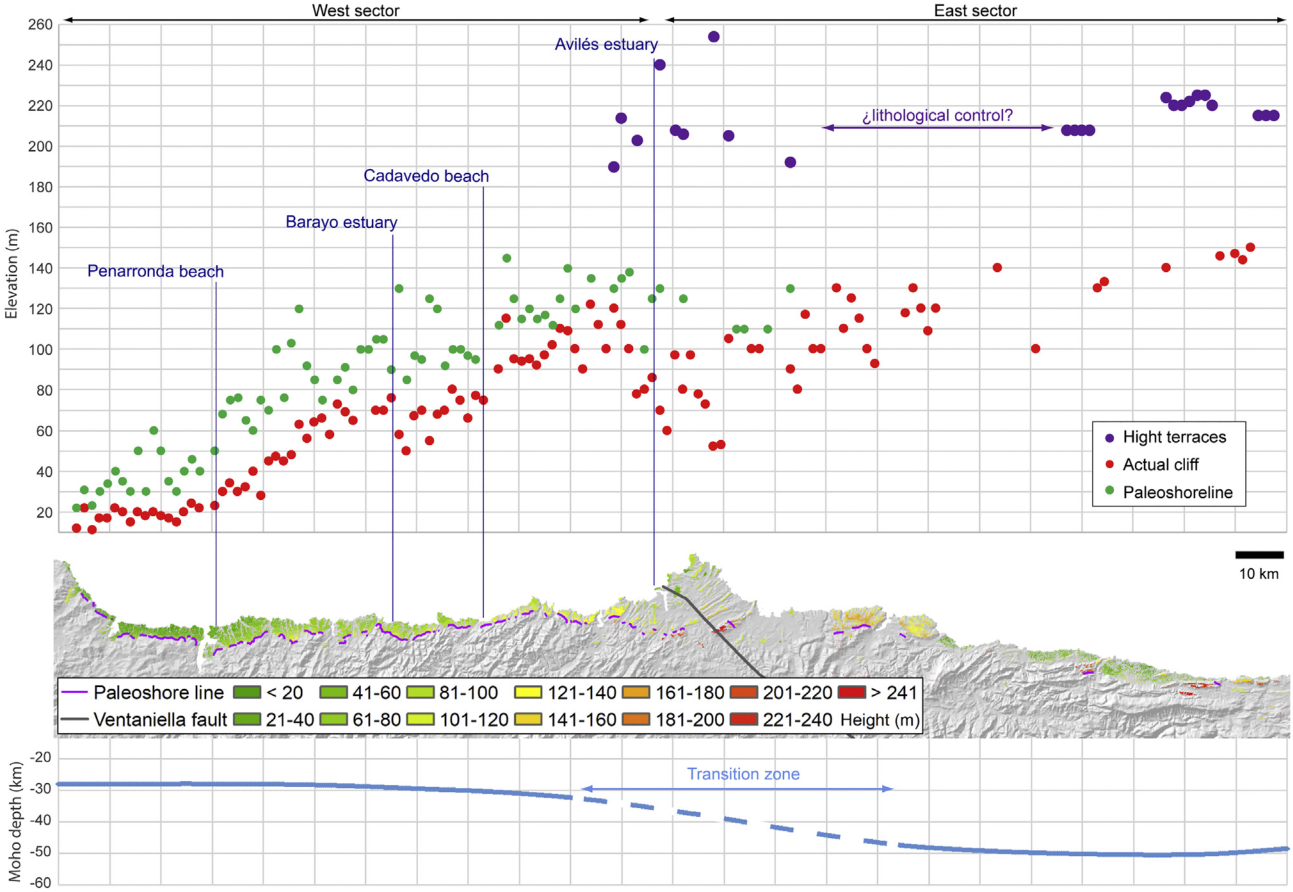

Fig. 4. Maximum elevation of the cliffs projected on a longitudinal profile along the Cantabrian margin. Also projected is the paleoshoreline and the representative altitude of the highest rasa identified in this study. At the bottom of the figure a line represents the topography of the crust-mantle boundary or Moho proposed by (Cadenas et al., 2018) at the latitude of the actual coastline.

6 km. This part of the rasa developed mainly over a basement composed of siliceous Palaeozoic rocks. The structural fabric of these rocks is generally oriented NNE-SSW and it does not determine the orientation of the surface on top (Fig. 1c). Over this rasa, there are abundant examples of coalescent alluvial fans that formed at the foothills of the coastal chains and whose apex zones partly cover the paleoshoreline (Fig. 3 Profiles I and II). The distal deposits of these fans occasionally reach the cliff edge and show an average inclination of 2.05°N. In previous studies, the inclination of some of the alluvial fans was incorporated as part of the rasa (e.g. Alvarez-Marrón et al., 2008), providing steeper angles for the rasa surface which would require recent crustal deformation to explain.

This regional and continuous rasa is gently inclined 0.58° towards the sea, causing fluctuation of the seaward slope values between 0.28° and 0.96°. The elevation of the paleoshoreline decreases from 155 m near the Avilés estuary to sea level near Burela (location in Fig. 3). Likewise, the height of the cliffs in the modern shoreline is close to 120 m near the Avilés estuary, decreasing progressively westwards until its disappearance near Burela (Fig. 4). Thus, the rasa following this trend presents a global tilt to the west with a mean slope of 0.08°. Locally, we have identified vertical offsets attributed to minor faults: 5 m at Penarronda beach, 5–10 m in the Barayo estuary and 25–30 m at Cadavedo beach (Fig. 5). It is important to note the absence of other surfaces below this main rasa in the western sector. The only indication of a secondary platform may be found in the area situated between the Nalón river estuary and Cape Peñas, where isolated relics of a higher surface (>180 m) can be recognised.

4.2. Eastern sector

To the east of Cape Peñas (5° 55′W), and as far as the town of San Vicente de la Barquera (4° 25′W), the landforms are different. We can distinguish here two levels of rasa at 120–170 m and 230–265 m, respectively (Fig. 3 Profiles III, IV and V). Both levels extend along the coast discontinuously for 80 km, showing a similar width to that of the western sector of the rasa. Together they add up to a preserved area of 27.5 km^2. Below, there are evidences of the presence of another shore platform at <40 m, 29.9 km^2 of which are preserved (Fig. 3b). Compared with the western sector, these rasas are more intensely degraded, mostly due to the fact that they formed over Mesozoic and Carboniferous carbonate rock sequences, as shown in profiles III, IV and V (Fig. 3).

The major difference with the western sector is that here the rasa maintains its height laterally, with no lateral tilting observed: the altitude of the cliffs in the entire eastern sector remains constant at 120–150 m (Fig. 4).

Fig. 3. Distribution of the rasas considered in this study, and location of the paleoshoreline in the western (a) and eastern (b) sectors. Black triangles indicate the situation of the main alluvial fans identified on top of the shore platforms. The bottom part of the figure shows four transverse topographical profiles representative of the main rasa. In the western sector, profile I is a representative example without alluvial fan, while profile II includes an alluvial fan. In the eastern sector, profile III is a representative example without alluvial fan, while profiles IV and V preserve up to three levels of rasa.

Table 2
Summary of parameters for the three zones defined in the Cantabrian rasa. For details, see the text. S-1, S-2, S-3, S-4, S-5, S-6, HS-1 and HS-2 location in Figs. 3 and 6. LL: Low Level of rasa in the eastern sector.

	Western sector		Transition zone								Eastern sector		
	HS1	S1	HS1	HS2	S1	S2	S3	S4	S5	S6	HS2	S2	LL
Height of rasas (m)	180 / 225 m	0–155 m, dipping 0.08° W	190–210 m	240–260 m	72–135 m	85–165 m	80–100 m	50–60 m	80–100 m	30–45 m	230 / 265	120 / 170	40 / 60
Length of rasas along the coast (km)/Width of rasas, perpendicular to the coast (km)	17 / < 1.5 km	122 / < 6 km					4 km / < 1.5 km	4 km / 2 km	4 km / < 1.5 km	1.5 km / 0.6 km	30 km / < 2.5 km	90 km / < 4.5 km	55 km / < 3.5 km
Area of rasas (km^2)	2.1 km^2	137.1 km^2					0.6 km^2	1.9 km^2	0.8 km^2	0.3 km^2	2.4 km^2	27.5 km^2	23.6 km^2
Predominant lithologies	Siliceous Palaeozoic rocks		Carbonated Mesozoic rocks and siliceous Palaeozoic rocks								Carbonated Mesozoic rocks, Carboniferous rocks and, locally, siliceous Palaeozoic rocks		
Preservation of surfaces	Good		Poor, especially in Mesozoic and Carboniferous materials								Poor, especially in Mesozoic and Carboniferous materials		
Moho depth	28–30 km		28–50 km								50 km		

S-1, S-2, S-3, S-4, S-5, S-6, HS-1 and HS-2 location in Figs. 3 and 6. LL: Low Level of rasa in the eastern sector.

4.3. The transition zone in the Cape Peñas area

The area between the two sectors around Cape Peñas shows a complex pattern of local rasas. The area is characterized by abundant faulted blocks containing the surfaces and delimited by NNW and NNE conjugated faults, probably Permian in age since they bound upper Permian formations. To the west of the Aviles estuary, we identify the principal rasa level in the western sector, S-1 (Fig. 6), which developed over the Palaeozoic siliceous formations, and extends from a height of 135 m in the old paleoshoreline to 72 m at the current cliffs. On the eastern shore of the Avilés estuary there are other well–defined rasa levels between 80 and 100 m in height (S-3, S-5), and independent of the eastern surface S-2. To the north, we can identify S-4, a 50–60 m high surface over Silurian sandstones, and a third rasa, S-6, in the river mouth between 30 and 45 m high. All these smaller surfaces vary in orientation and in dip (Fig. 6).

Towards the south, independent and behind the regional surface (S-1), we identify another surface (HS-1, Fig. 6), between 190 and 210 m and developed on shales. Continental deposits up to 6 m thick cover sandstones from the Devonian and Ordovician quartzarenites. This surface, on the basis of its relative location with respect to the main regional rasa and its extent, is correlated with HS-2 to the east of the Aviles estuary, where it reaches an elevation of 240–260 m.

The paleoshoreline trace and the geometrical distribution of the planar surfaces are indicative of a net limit between western and eastern sector that coincides with the trace of the Ventaniella fault (swath profile in Fig. 6). This structure disrupts and displaces the main rasa producing an

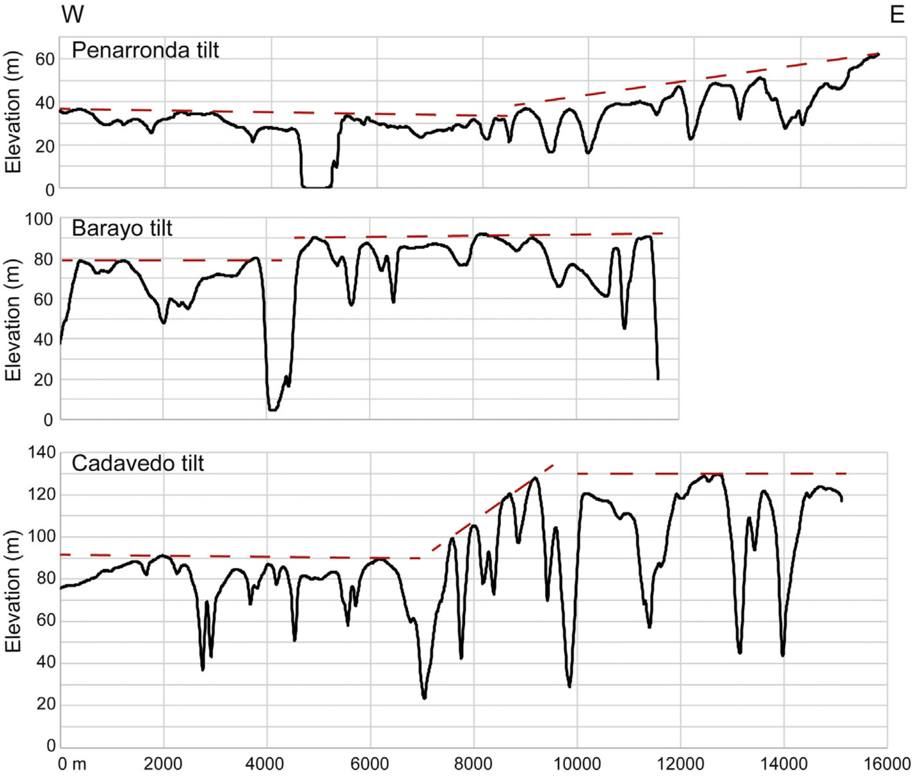

Fig. 5. Local vertical offsets observed on the rasas in the western Sector.

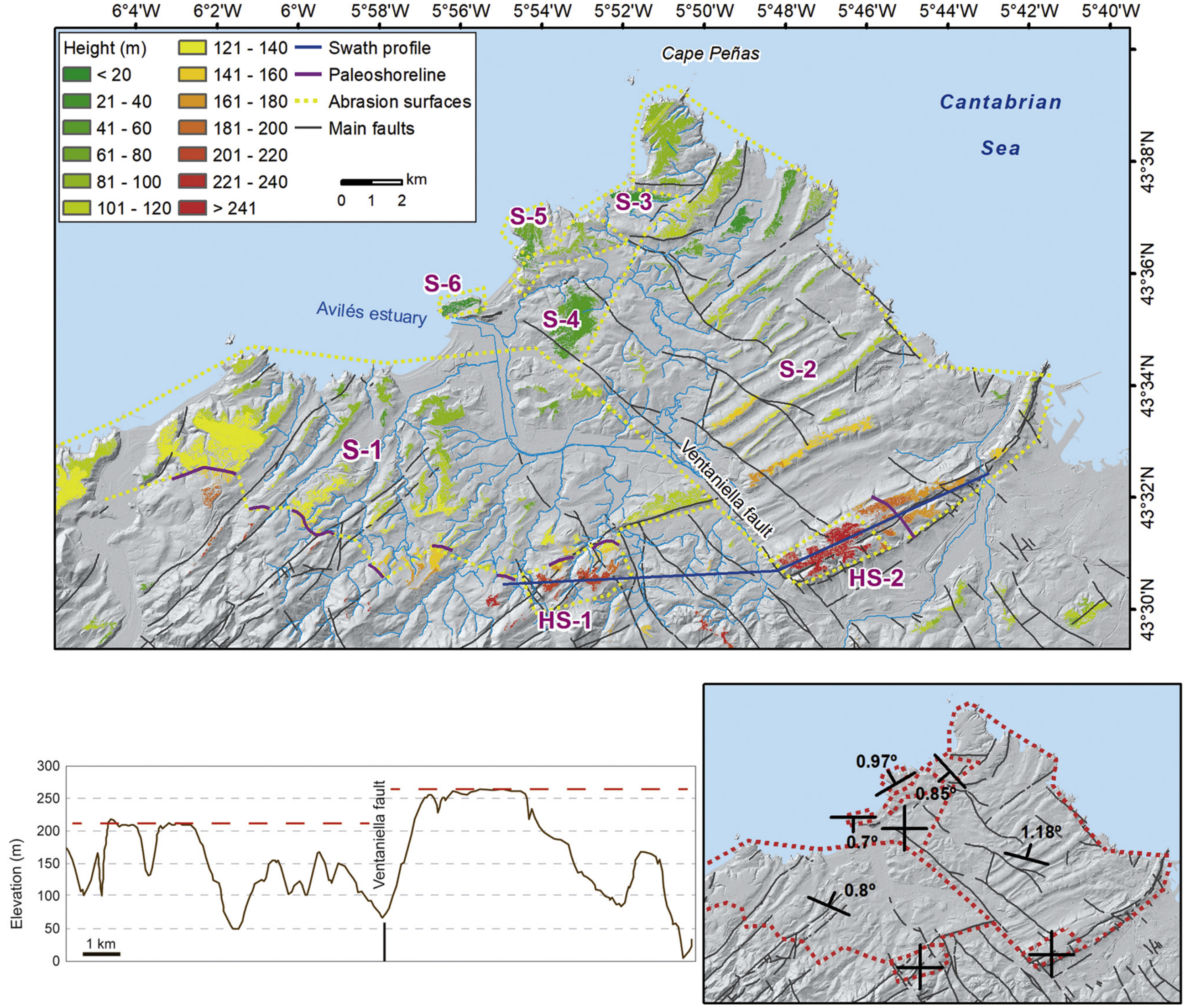

Fig. 6. Above: distribution of emerged platforms in the transition zone around Cape Peñas. Bottom left: swath profile (400 m width) drawn along two geologically considered homologous sectors (blue line in the map above). Bottom right: dip and dip direction of the identified rasas.

apparent vertical offset of approximately 50 m in a swath profile running approximately E-W (Fig. 6). The inset in Fig. 6 also shows that the main rasa to the NE is the same on both sides of the Ventaniella fault, being slightly steeper to the east. The varying directions of inclination and tilt of the smaller fragments of rasas in between the main S-1 and S-2, such as S-3 through to S-6, support the idea that the minor faults that separate them have been reworked slightly during the recent Alpine cycle, after the formation of the main regional rasa.

5. Discussion

5.1. Distribution pattern of rasas in the Cantabrian coast

The existence of a continuous rasa in the western sector of our study area, as well as the recognition of its tilt, has already been suggested in the regional literature (Flor, 1983; Mary, 1983; Alvarez-Marrón et al., 2008; Flor and Flor-Blanco, 2014), (Fig. 5). On the basis of its extent and attitude, we have related the main rasa level to the west of Cape Peñas (150 m high) with the main rasa level to the east, which is higher, and which maintains the elevation throughout the study area, in contrast to the Western sector (Fig. 7). Thus, the surface at 120–170 m in the eastern sector may correspond to the described rasa in the western sector at 120 m, while the surface at 230–265 m could correlate with the relics at 180–225 m in the western sector. Future geochronological dating will support or deny these hypotheses.

The studied fragmented rasa surfaces show different preservation states depending on the lithology on which they were formed, which probably hindered in some locations their recognition as part of a unique regional surface. That occurs particularly to the east of Cape Peñas, where karst dynamics predominate over dominant carbonate substrate, as already indicated different authors (e.g. Flor, 1983; Domínguez-Cuesta et al., 2015), and also due to its higher altitude, which further increases the erosion factor and makes its preservation difficult.

One of the main outcomes of this work is that what was previously regarded in the literature as fragmented planar surfaces corresponding to up to ten different levels in a staircase pattern (Flor, 1983; Mary, 1983; Feal-Pérez et al., 2009, among others) are now considered as part of a single, regional surface. Thus, a first summary of our work is that attending to the inclination and distribution pattern of all studied rasa surfaces, we can recognize a main regional level of rasa running continuously for >200 km along the Cantabrian coast (Fig. 7), with a maximum width of 6 km. Its original width, developed as a consequence of successive marine reoccupations, was probably greater, but this

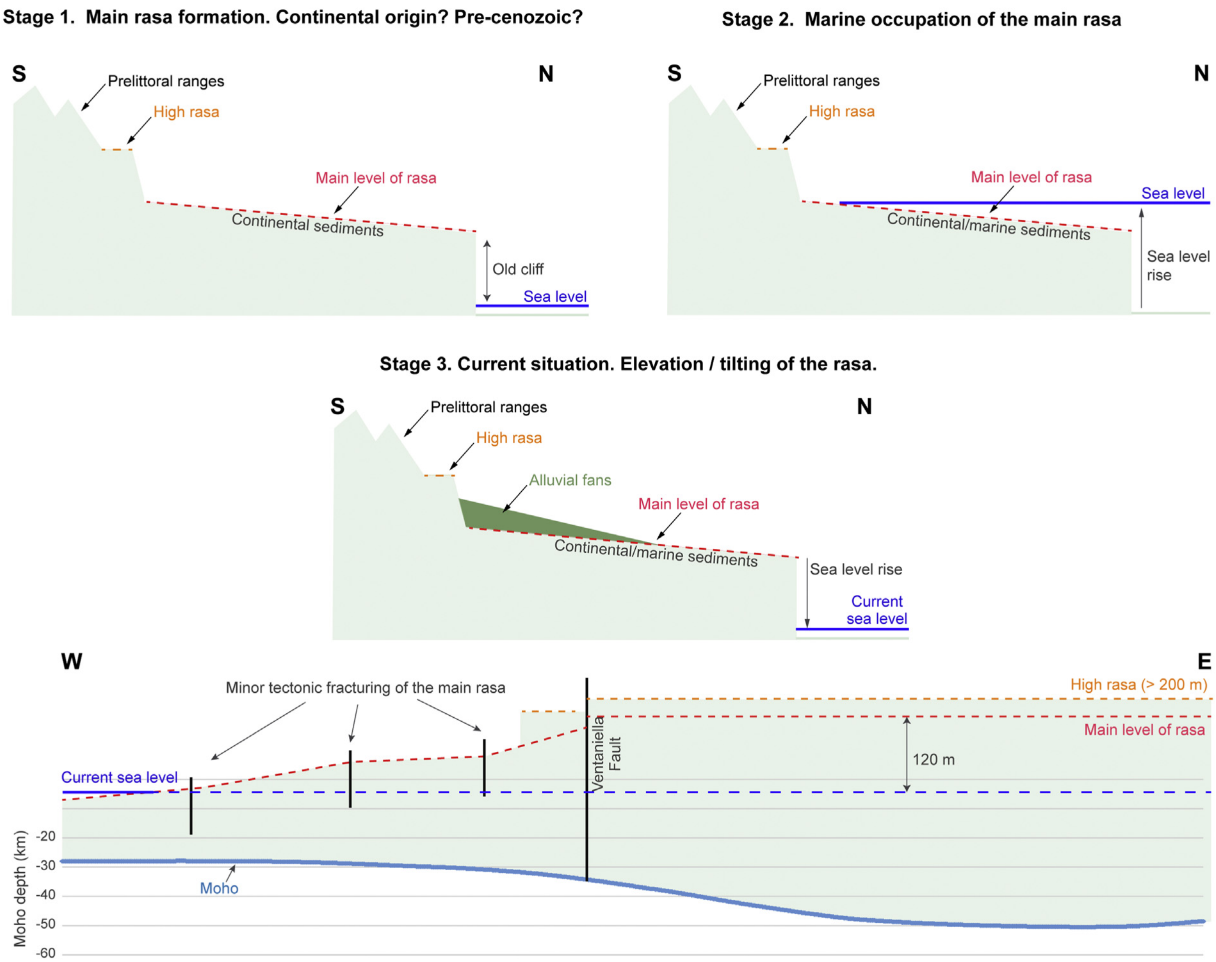

Fig. 7. Conceptual synthesis of the evolution of the main regional rasa in the Cantabrian margin. Top and middle are transverse profiles (N-S) of the rasa; the profile at the bottom is a longitudinal sketch (W-E) along the coast. Middle and bottom illustrate the current situation.

should be confirmed by ongoing studies of the receding coastal cliffs (Domínguez-Cuesta et al., in press) that make up the northern boundary of the current rasa.

We also recognize a higher flat platform 200 m high in the eastern part, whose origin continues under discussion. For this surface, Flor (1983) and Mary (1983) proposed a possibly continental genesis, although Trenhaile (2002) indicated that surfaces over 200 m in western Europe are much higher than the maximum elevation reached by the sea during the Quaternary interglacial stages so they must have been formed during long periods of high sea level in the Tertiary; other authors (e.g., Roberts and Parfitt, 1999) proposed that heights of this sort in marine platforms necessarily imply uplift. Based on our results, and taking into account the crustal pattern we discuss below, both processes may have been involved.

In origin, the regional rasa and the old shoreline formed sub-horizontally and thus constitute relevant geomarkers to constrain subsequent events of crustal deformation. Our report of lateral gradient in elevation as well as the magnitude of the elevation in the Eastern sector points to recent deformation either of tectonic origin or related to deep crustal processes in the formation of the current architecture of the coast in major parts of the Cantabrian coast of N Spain (Fig. 7).

5.2. The role of tectonic structures: the Ventaniella fault

The boundary between the western and eastern sectors of the Cantabrain rasas matches with the Ventaniella fault, which also produces a net apparent vertical offset of 50 m between the two sides of the rasa. Our systematic analysis of small rasa surfaces in the transition between the Western and Eastern sectors, provides clear evidence of the relevant role of the Ventaniella fault in the tectonic evolution of this sector for the first-time. The Ventaniella fault also affects the remnants of a higher, older rasa inland. This fault is a quasi-vertical structure, oriented NW-SE and >400 km long, that continues beneath the sea to the north within the continental platform. The fault line represents moderate to low intensity seismicity along some parts of its trace (e.g. López-Fernández et al., 2018). Its effects are apparent in the cartographic imprint in relation to both Palaeozoic and Mesozoic materials, and its most recent movement corresponds to a dextral sense of up to 5 km (e.g. Julivert et al., 1971), with a degree of inverse movement, resulting in a minor elevation of the North-eastern block (Álvarez-Marrón, 1989; Marquínez, 1992; Jiménez Sánchez, 1999; Alonso et al., 2010; Tavani et al., 2011; Viejo et al., 2014; López-Fernández et al., 2018).

Many unknowns remain as to the recent geological history of the area around Cape Peñas, where the Ventaniella fault first crops out onshore. Without a doubt, it is possible to consider the Ventaniella fault as a crustal feature whose origin dates back to the initial stages of continental fragmentation after the Variscan orogeny (Cadenas et al., 2018), and which is probably acting as a link between the surface and the deep structure. The distribution and elevation pattern of Cantabrian rasas depicts the most recent part of the tectonic history of the Ventaniella fault. The rasas also show how geomorphologic markers can be used to infer crustal unbalances present on after the last orogenic pulses in a region such as in the Cantabrian range, and not only eustatic or local isostatic changes. It also provides links to the idea that rasas are evidence of the crustal scale behaviour of western Europe as well, an idea already suggested by Pedoja et al. (2014)

The elevation of the Cantabrian coast is interpreted in this paper as the late post-orogenic isostatic response to the crustal thickening and equilibration of the passive margin after the Alpine orogeny, which elevated and transformed the crustal architecture of North Iberia (Gallastegui Suárez, 2000; Díaz and Gallart, 2009; Diaz et al., 2016; Cadenas et al., 2018). Towards the west, the rasa passively tilts westward. This interpretation is consistent with Mary (1983), who noted a more recent age for the eastern planar surfaces and an older one for the western ones. Isostatic processes along the margin were indicated by Alvarez-Marrón et al. (2008) and Pedoja et al. (2011, 2014), who have also suggested regional tectonic uplift as the driving force to elevate the former marine platform. Our work shows in more detail that the regional isostatic response is reflected differently in different parts of the coast, with the Ventaniella fault acting not just as the structure that bounds different crustal evolution at depth (López-Fernández et al., 2018) but, as we now show, also on the surface. In addition, the elevational style of the main rasa to the west of the Ventaniella fault, which has shown a constant upward movement, contrasts drastically with the elevation of the eastern sector, where we find more than one surface below the main one. This indicates that the Ventaniella fault must have had some control on uplift history of the crust in the Cantabrian Mountains.

Correlations between rasa evolution and deep crustal processes in active zones have been noted by Bridgland and Westaway (2008) in southern Italy, Matsu'ura et al. (2014) in the Shimokita Peninsula, Cucci (2004) in the Calabrian arc, relating to subduction processes, or Melnick (2016) along the Andean coast, relating deep earthquakes to uplift of the coast at the scale of centimeters. In the latter case, the slip is located below the locked portion of the plate interface and therefore may translate into permanent deformation in the overlying plate causing uplift of the coastline. Uplift due to large-scale processes such as thermal anomalies has also been suggested as an explanation of the elevation of rasas (Conway-Jones et al., 2019). Global processes such as climate change and erosive isostasy (Champagnac et al., 2006; Pederson et al., 2002), are also proposed as the main processes behind the increased worldwide relief observed during the Quaternary (Bridgland and Westaway, 2008). Since we are in a passive, tectonically stable part of the continent, away from currently active plate boundary in southern Spain, we attribute the differences along the Cantabrian rasas to crustal re-equilibration processes associated to the post-tectonic evolution of the Cantabrian Mountains. A task to be undertaken after our analysis is to apply dating techniques along the rasas from west to east to accurately determine which geological process is being dated, and also to provide a quantitative measure of uplift rates. The lack of sufficient quality sampling, as already noted (Jiménez-Sánchez et al., 2006; Alvarez-Marrón et al., 2008), hinders the establishment of a full chronology of events within the history of Cantabrian margin erosional and uplifting. Our contribution provides clear geometric constraints and certainly facilitates sampling campaigns for future chronological studies.

6. Conclusions

The multiscale GIS analysis has proved a useful tool to objectively characterize partly disconnected rasa surfaces along the Cantabrian coast (N Iberia) between 4.15°W and 7.30°W longitude. A regional pattern with certain relevant features emerges from the distribution of more or less isolated and degraded fragmented surfaces.

The first major conclusion of our analysis is that most of the identified shore platforms belong, in fact, to a unique regional surface approximately 200 km long, and with a medium height of 100–150 m. This original unique surface is divided now into two zones according to the arrangement and distribution of surfaces: in the western sector the surface is continuous and dips 0.08° to the West; the eastern sector is levelled, has no associated tilting, but it is located higher than the western sector. In the eastern sector, there is at least one further surface of significance below the main one. There are small relics of a higher flat surface above the main one in both sectors.

The second major conclusion of our work is that the break in slope of the regional erosional surface coincides with an apparent vertical offset of 50 m across the trace of the Ventaniella fault. The vertical offset affecting the main regional rasa clearly implies relatively recent tectonic activity.

In addition, the joint analysis of the topography of the surface and of that of the crust-mantle transition under the Cantabrian Mountains along the coast, has led to the establishment of a comprehensive tectonic context. If we take into account the presence of a regional rasa and a paleoshoreline elevated in excess of 150 m in the eastern sector and decreasing in elevation as it moves away from the orogenic root towards the west, the elevation pattern points strongly to an isostatic response as the underlying process driving surface processes by the coast.

The differential uplift of the originally subhorizontal surface is therefore controlled by the lateral difference in crustal thickness. The Ventaniella fault serves as a crustal scale boundary, having a measurable impact at the surface in its most recent evolution. It may also have controlled uplift, since the more elevated sector also shows episodic uplift in the form of different rasa surfaces. In summary, this paper shows the strength of a top-to-bottom analysis, which shows itself to be particularly useful at regional scale when interpreting geomorphologic landscapes.

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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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References

Alonso, A., Pagés, J.L., 2007. Stratigraphy of Late Pleistocene coastal deposits in northern Spain. J. Iber. Geol. 33, 107–220.

Alonso, J., Pulgar, J., García-Ramos, J., Barba, P., 1996. Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain). In: Friend, P., Dabrio, C. (Eds.), Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics (World and Regional Geology, pp. 214-227). Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511524851.031.

Alonso, J.L., Pulgar, J.A., García-Ramos, J.C., Barba, P., 2010. Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain), in: P. Friend & C. Dabrio (Eds.), Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics. Cambridge University Press., Cambride, pp214–227. https://doi.org/10.1017/cbo9780511524851.031.

Llana-Fúnez, S., López-Fernández, C., Fernández-Viejo, G., Domínguez-Cuesta, M.J., Jiménez-Sánchez, M., 2020. Orographic Evolution of the Cantabrian Mountains and its Relation to Alpine Crustal Structure (N Spain).

Álvarez-Marrón, J., 1989. La estructura geológica de la Región del Ponga (Zona Cantábrica, NW de España). Ph.D. Thesis. University of Oviedo, pp. 1–223 (in Spanish).

Alvarez-Marrón, J., Hetzel, R., Niedermann, S., Menéndez, R., Marquínez, J., 2008. Origin, structure and exposure history of a wave-cut platform more than 1 Main age at the coast of northern Spain: a multiple cosmogenic nuclide approach. Geomorphology 93, 316–334. https://doi.org/10.1016/j.geomorph.2007.03.005.

Anderson, R.S., Densmore, A.L., Ellis, M.A., 1999. The generation and degradation of marine terraces. Basin Res. 11, 7–19. https://doi.org/10.1046/j.1365-2117.1999.00085.x.

Balasubramani, K., Gomathi, M., Bhaskaran, G., Kumaraswamy, K., 2019. GIS-based spatial multi-criteria approach for characterization and prioritization of micro-watersheds: a case study of semi-arid watershed, South India. Appl. Geomatics. 11, 289–307. https://doi.org/10.1007/s12518-019-00261-y.

Ballesteros, D., Giralt, S., García-Sansegundo, J., Jiménez-Sánchez, M., 2019. Quaternary regional evolution based on karst cave geomorphology in Picos de Europa (Atlantic margin of the Iberian Peninsula). Geomorphology 336, 133–151. https://doi.org/10.1016/j.geomorph.2019.04.002.

Berger, B., Crucifix, M., Hodell, D.A., Mangili, C., McManus, J.F., Otto-Bliesner, B., Pol, K., Raynaud, D., Skinner, L.C., Tzedakis, P.C., Wolff, E.W., Yin, Q.Z., Abe-Ouchi, A., Barbante, C., Brovkin, V., Cacho, I., Capron, E., Ferretti, P., Ganopolski, A., Grimalt, J. O., Hönisch, B., Kawamura, K.A., Landais, A., Margari, V., Martrat, B., Masson-Delmotte, V., Mokeddem, Z., Parrenin, F., Prokopenko, A.A., Rashid, H., Schulz, M., Vazquez Riveiros, N., 2016. Interglacials of the last 800,000 years. Rev. Geophys. 54, 162–219. https://doi.org/10.1002/2015RG000482.

Bintanja, R., Van De Wal, R.S.W., 2008. North American ice-sheet dynamics and the onset of 100,000-year glacial cycles. Nature 454, 869–887. https://doi.org/10.1038/nature07158.

Blanco-Chao, R.B., Casais, M.C., Cortizas, A.M., Alberti, A.P., Trenhaile, A.S., 2003. Evolution and inheritance of a rock coast: western Galicia, Northwestern Spain. Earth Surf. Process. Landforms 28, 757–775. https://doi.org/10.1002/esp.496.

Bridgland, D., Westaway, R., 2008. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon. Geomorphology. 98, 285–315. https://doi.org/10.1016/j.geomorph.2006.12.032.

Burbank, D.W., Anderson, R.S., 2011. Tectonic Geomorphology, second ed. Wiley-Blackwell, Chichester. doi:https://doi.org/10.1002/9781444345063.

Cadenas, P., Manatschal, G., Fernández-Viejo, Gabriela, Welford, J.K., 2018. Margin segmentation during polyphase rifting in the southern Bay of Biscay. Atl. Geol. 54, 409–470. https://doi.org/10.4138/atlgeol.2018.014.

Carrière, K.L., 2006. Neoproterozoic to Holocene tectonothermal evolution of the southern Cantabrian Mountains NW Iberia, Revealed by Apatite Fission-Track Thermochronology. PhD thesis. Rüprecht-Karl Universität Heidelberg, Heidelberg 289 pp.

Champagnac, J.D., Sue, C., Delacou, B., Tricart, P., Allanic, C., Burkhard, M., 2006. Miocene lateral extrusion in the inner western Alps revealed by dynamic fault analysis. Tectonics. 25, TC 3014. doi:https://doi.org/10.1029/2004TC001779.

Conway-Jones, B.W., Roberts, G.G., Fichtner, A., Hoggard, M., 2019. Neogene Epeirogeny of Iberia. Geochem. Geophys. Geosystems. 20, 1138–1163. https://doi.org/10.1029/2018GC007899.

Coutard, S., Lautridou, J.P., Rhodes, E., Clet, M., 2006. Tectonic, eustatic and climatic significance of raised beaches of Val de Saire, Cotentin, Normandy, France. Quat. Sci. Rev. 25, 595–611. https://doi.org/10.1016/j.quascirev.2005.02.003.

Cucci, L., 2004. Raised marine terraces in the northern Calabrian Arc (southern Italy): a ~ 600 kyr-long geological record of regional uplift. Ann. Geophys. 47, 1391–1406. https://doi.org/10.4401/ag-3350.

Das, S., Pardeshi, S.D., 2018. Morphometric analysis of Vaitarna and Ulhas river basins, Maharashtra, India: using geospatial techniques. Appl Water Sci 8, 158. https://doi.org/10.1007/s13201-018-0801-z.

Díaz, J., Gallart, J., 2009. Crustal structure beneath the Iberian Peninsula and surrounding waters: a new compilation of deep seismic sounding results. Phys. Earth Planet. Inter. 173, 181–190. https://doi.org/10.1016/j.pepi.2008.11.008.

Diaz, J., Gallart, J., Carbonell, R., 2016. Moho topography beneath the Iberian-western Mediterranean region mapped from controlled-source and natural seismicity surveys. Tectonophysics 693, 74–85. https://doi.org/10.1016/j.tecto.2016.08.023.

Domínguez-Cuesta, M.J., Jiménez-Sánchez, M., González-Fernández, J.A., Quintana, L., Flor, G., Flor-Blanco, G., 2015. GIS as a tool to detect flat erosional surfaces in coastal areas: a case study in North Spain. Geol. Acta 13, 97–106. https://doi.org/10.1344/GeologicaActa2015.13.2.2.

Domínguez-Cuesta, M.J., Ferrer Serrano, A., Rodríguez-Rodríguez, L., López-Fernández, C., Jiménez-Sánchez, M., 2020. In press. Análisis del retroceso de la costa cantábrica en el entorno del Cabo Peñas (Asturias, N España). Geogaceta. 68.

Elorza, M.G., 2008. Geomorfología. Pearson Education, Madrid.

Feal-Pérez, A., Blanco-Chao, R., Valcárcel-Díaz, M., 2009. Plataformas de abrasión, plataformas litorales y terrazas marinas o rasas, in: Flor, G., Flor-Blanco, G., Gallastegui, J. Martín-Llaneza, J. (Eds.), Nuevas Contribuciones Al Margen Ibérico Atlántico (MIA09). Oviedo (Spain), pp. 177–180.

Fernández, J.R., Piedrabuena, M.Á.P., 2011. Las terrazas fluviales del río Cares: aportaciones sedimentológicas y cronológicas (Picos de Europa, Asturias). Estud. Geogr. 270, 173–202. https://doi.org/10.3989/estgeogr.201108.

Fernández-Viejo, G., Gallart, J., Pulgar, J.A., Córdoba, D., Dañobeitia, J.J., 2000. Seismic signature of Variscan and Alpine tectonics in NW Iberia: crustal structure of the Cantabrian Mountains and Duero basin. J. Geophys. Res. Solid Earth 105, 3001–3018. https://doi.org/10.1029/1999jb900321.

Fernéndez-Viejo, G., Gallart, J., Pulgar, J.A., Gallastegui, J., Dañobeitia, J.J., Córdoba, D., 1998. Crustal transition between continental and oceanic domains along the North Iberian margin from wide angle seismic and gravity data. Geophys. Res. Lett. 25, 4249–4252. https://doi.org/10.1029/1998gl900149.

Fillon, C., Pedreira, D., Van Der Beek, P.A., Huismans, R.S., Barbero, L., Pulgar, J.A., 2016. Alpine exhumation of the central Cantabrian Mountains, Northwest Spain. Tectonics 35, 339–356. https://doi.org/10.1002/2015TC004050.

Flor, G., 1983. Las rasas asturianas: ensayos de correlación y emplazamiento. 13, 65–82. Trab. Geol. 10.17811/tdg.13.1983.65-83

Flor, G., Flor-Blanco, G., 2014. Raised beaches in the Cantabrian Coast. In: Gutiérrez, F., Gutiérrez, M. (Eds.), Landscapes and Landforms in Spain. Springer, Dordrecht, pp. 239–248. https://doi.org/10.1007/978-94-017-8628-7_20.

Font, M., Amorese, D., Lagarde, J.L., 2010. DEM and GIS analysis of the stream gradient index to evaluate effects of tectonics: the Normandy intraplate area (NW France). Geomorphology 119, 172–180. https://doi.org/10.1016/j.geomorph.2010.03.017.

Gallastegui Suárez, J., 2000. Estructura cortical de la cordillera y margen continental cantábricos: perfiles ESCI-N. Trab. Geol. 22, 1–221.

Grobe, R.W., Alvarez-Marrón Joaquina, J., Glasmacher, U.A., Menéndez-Duarte Rosana, R., 2010. Low-temperature exhumation history of Variscan-age rocks in the western Cantabrian Mountains (NW Spain) recorded by apatite fission-track data. Tectonophysics 489, 76–90. https://doi.org/10.1016/j.tecto.2010.04.006.

Guilcher, A., 1974. Les «rasas»: un problème de morphologie littorale générale. Ann. Georgr. 455, 1–33. https://doi.org/10.3406/geo.1974.18924.

Hernandez Pacheco, F., Asensio Amor, I., 1963. Materiales sedimentarios sobre la rasa cantábrica. V. Tramo comprendido entre el valle del río Porcía y la ría del Eo. Boletín la Real Soc. Española Hist. Nat. 30, 159–172.

Hernandez Pacheco, F., Asensio Amor, I., 1964. Recientes investigaciones sobre la génesis de la rasa litoral cantábrica. Tramo final del valle del río Navia (Asturias). Boletín la Real Soc. Española Hist. Nat. 62, 61–89.

Hsieh, M.L., Liew, P.M., Hsu, M.Y., 2004. Holocene tectonic uplift on the Hua-tung coast, eastern Taiwan. Quat. Int. 115-116, 47–70. https://doi.org/10.1016/S1040-6182(03)00096-X.

Jara-Muñoz, J., Melnick, D., Strecker, M.R., 2016. Terrace M: a MATLAB® tool to analyze marine and lacustrine terraces using high-resolution topography. Geosphere. 12, 175–195. https://doi.org/10.1130/GES01208.1.

Jiménez Sánchez, M., 1999. Geomorfología fluvial en la cabecera del río Nalón (Cordillera Cantábrica, Noroeste de España. Trabajos de Geología 21, 189–200.

Jiménez-Sánchez, M., Bischoff, J.L., Stoll, H., Aranburu, A., 2006. A geochronological approach for cave evolution in the Cantabrian Coast (Pindal Cave, NW Spain). Z. Geomorphol. 147, 129–141.

Julivert, M., Ramírez del Pozo, J., Truyols, J., 1971. Histoire Structurale Du Golfe De Gascogne. Technip, Paris, France.

Kelsey, H.M., Bockheim, J.G., 1994. Coastal landscape evolution as a function of eustasy and surface uplift rate, Cascadia margin, southern Oregon. Geol. Soc. Am. Bull. 106, 840–854. https://doi.org/10.1130/0016-7606(1994)106<0840:CLEAAF>2.3.CO;2.

Kolejka, J., 2018. Landscape mapping using GIS and Google Earth Data. Geogr. Nat. Resour. 39, 254–260. https://doi.org/10.1134/S1875372818030095.

Lamboy, M., 1976. Géologie marine et sous-marine du plateau continental au Nord-Ouest de l'Espagne. Université de Rouen, Genèse des glauconies et des phosphorites.

Liu, C., Fulthorpe, C.S., Austin, J.A., Sanchez, C.M., 2011. Geomorphologic indicators of sea level and lowstand paleo-shelf exposure on early-middle Miocene sequence boundaries. Mar. Geol. 280, 182–194. https://doi.org/10.1016/j.margeo.2010.12.010.

López-Fernández, C., Fernández-Viejo, G., Olona, J., Llana-Fúnez, S., 2018. Intraplate seismicity in northwest Iberia along the trace of the ventaniella fault: a case for fault intersection at depth. Bull. Seismol. Soc. Am. 108, 604–618. https://doi.org/10.1785/0120170215.

Lucchesi, S., Giardino, M., Perotti, L., 2013. Applications of high-resolution images and DTMs for detailed geomorphological analysis of mountain and plain areas of NW Italy. Eur. J. Remote Sens. 46, 216–233. https://doi.org/10.5721/EuJRS20134612.

Marquardt, C., Lavenu, A., Ortlieb, L., Godoy, E., Comte, D., 2004. Coastal neotectonics in southern Central Andes: uplift and deformation of marine terraces in northern Chile (27°S). Tectonophysics. 394, 193–219. https://doi.org/10.1016/j.tecto.2004.07.059.

Marquínez, J., 1992. Tectónica y relieve en la Cornisa Cantábrica. In: Cearreta, A., Ugarte, F. M. (Eds.), The late Quaternary in the western Pyrenean region, pp. 141–157.

Martín-González, F., Heredia, N., 2011. Complex tectonic and tectonostratigraphic evolution of an Alpine foreland basin: the western Duero Basin and the related Tertiary depressions of the NW Iberian Peninsula. Tectonophysics. 502, 75–89. https://doi.org/10.1016/j.tecto.2010.03.002.

Martín-González, F., Barbero, L., Capote, R., Heredia, N., Gallastegui, G., 2012. Interaction of two successive Alpine deformation fronts: constraints from low-temperature thermochronology and structural mapping (NW Iberian Peninsula). Int. J. Earth Sci. 101, 1331–1342. https://doi.org/10.1007/s00531-011-0712-9.

Mary, G., 1983. Evolución del margen costero de la Cordillera Cantábrica en Asturias desde el Mioceno. Trab. Geol. 13, 3–35.

Mary, G., 1985. Les éboulis périglaciaires le long du littoral asturien et galicien, in: Actas I Reunión Del Cuaternario Ibérico. pp. 119–126.

Matsumoto, H., Dickson, M.E., Kench, P.S., 2016. An exploratory numerical model of rocky shore profile evolution. Geomorphology 268, 98–109. https://doi.org/10.1016/j.geomorph.2016.05.017.

Matsu'ura, T., Kimura, H., Komatsubara, J., Goto, N., Yanagida, M., Ichikawa, K., Furusawa, A., 2014. Late Quaternary uplift rate inferred from marine terraces, Shimokita Peninsula, northeastern Japan: a preliminary investigation of the buried shoreline angle. Geomorphology 209, 1–17. https://doi.org/10.1016/j.geomorph.2013.11.013.

Mattheus, C.R., 2016. GIS-based geomorphologic study of Presque Isle Peninsula, a compound lacustrine barrier-spit system along the south-central Lake Erie margin. J. Great Lakes Res. 42, 336–347. https://doi.org/10.1016/j.jglr.2016.01.001.

Melnick, D., 2016. Rise of the central Andean coast by earthquakes straddling the Moho. Nature Geosci. 9, 401–407. https://doi.org/10.1038/ngeo2683.

Merritts, D., Bull, W.B., 1989. Interpreting Quaternary uplift rates at the Mendocino triple junction, northern California, from uplifted marine terraces. Geology 17, 1020–1024. https://doi.org/10.1130/0091-7613(1989)017<1020:IQURAT>2.3.CO;2.

Moñino, M., Díaz de Terán, J.R., Cendrero, A., 1988. Pleistocene sea level changes in the Cantabrian Coast, Spain. In: Singh, S., Tiwari, R.C. (Eds.), Geomorphology and Environment. The Allahabad Geographical Society. Allahabad, India, pp. 351–364.

Moura, D., Albardeiro, L., Veiga-Pires, C., Boski, T., Tigano, E., 2006. Morphological features and processes in the central Algarve rocky coast (South Portugal). Geomorphology. 81, 345–360. https://doi.org/10.1016/j.geomorph.2006.04.014.

Mujabar, P.S., Chandrasekar, N., 2013. Shoreline change analysis along the coast between Kanyakumari and Tuticorin of India using remote sensing and GIS. Arab. J. Geosci. 6, 647–664. https://doi.org/10.1007/s12517-011-0394-4.

Napieralski, J., Barr, I., Kamp, U., Kervyn, M., 2013. Remote Sensing and GIScience in Geomorphological Mapping, in: Treatise on Geomorphology. 3, 187–227. doi:https://doi.org/10.1016/B978-0-12-374739-6.00050-6

Orrù, P., Solinas, E., Puliga, G., Deiana, G., 2011. Palaeo-shorelines of the historic period, Sant'Antioco Island, South-Western Sardinia (Italy). Quat. Int. 232, 71–81. https://doi.org/10.1016/j.quaint.2010.06.004.

Padgett, J.S., Kelsey, H.M., Lamphear, D., 2019. Upper-plate deformation of late Pleistocene marine terraces in the Trinidad, California, coastal area, southern Cascadia subduction zone. Geosphere. 15, 4. https://doi.org/10.1130/ges02032.1.

Partabian, A., Nourbakhsh, A., Ameri, S., 2016. GIS-based evaluation of geomorphic response to tectonic activity in Makran Mountain Range, SE of Iran. Geosci. J. 20, 921–934. https://doi.org/10.1007/s12303-016-0106-x.

Pederson, J.L., Mackley, R.D., Eddleman, J.L., 2002. Colorado Plateau uplift and erosion evaluated using GIS. GSA Today 12, 4–10. https://doi.org/10.1130/1052-5173(2002)012<0004:CPUAEE>2.0.CO;2.

Pedoja, K., Husson, L., Regard, V., Cobbold, P.R., Ostanciaux, E., Johnson, M.E., Kershaw, S., Saillard, M., Martinod, J., Furgerot, L., Weill, P., Delcaillau, B., 2011. Relative sea-level fall since the last interglacial stage: are coasts uplifting worldwide? Earth Sci. Rev. 108, 1–15. https://doi.org/10.1016/j.earscirev.2011.05.002.

Pedoja, K., Husson, L., Johnson, M.E., Melnick, D., Witt, C., Pochat, S., Nexer, M., Delcaillau, B., Pinegina, T., Poprawski, Y., Authemayou, C., Elliot, M., Regard, V., Garestier, F., 2014. Coastal staircase sequences reflecting sea-level oscillations and tectonic uplift during the Quaternary and Neogene. Earth Sci. Rev. 132, 13–38. https://doi.org/10.1016/j.earscirev.2014.01.007.

Pedoja, K., Jara-Muñoz, J., De Gelder, G., Robertson, J., Meschis, M., Fernandez-Blanco, D., Nexer, M., Poprawski, Y., Dugué, O., Delcaillau, B., Bessin, P., Benabdelouahed, M., Authemayou, C., Husson, L., Regard, V., Menier, D., Pinel, B., 2018. Neogene-Quaternary slow coastal uplift of western Europe through the perspective of sequences of strandlines from the Cotentin Peninsula (Normandy, France). Geomorphology 303, 338–356. https://doi.org/10.1016/j.geomorph.2017.11.021.

Pulgar, J.A., Gallart, J., Fernandez-Viejo, G., Perez-Estaun, A., Alvarez-Marron, J., Alonso, J.L., Gallastegui, J., Marcos, A., Bastida, F., Aller, J., Farias, P., Marín, J., García-Espina, R., Martínez-Catalán, J.R., Comas, M.C., Banda, E., Dańobeitia, J.J., Córdoba, D., Heredia, N., Rodríguez, R., 1996. Seismic image of the Cantabrian Mountains in the western extension of the Pyrenees from integrated ESCIN reflection and refraction data. Tectonophysics 264, 1–19. https://doi.org/10.1016/S0040-1951(96)00114-X.

Ramos, A.M., Cunha, P.P., Cunha, L.S., Gomes, A., Lopes, F.C., Buylaert, J.P., Murray, A.S., 2012. The River Mondego terraces at the Figueira da Foz coastal area (western central Portugal): geomorphological and sedimentological characterization of a terrace staircase affected by differential uplift and glacio-eustasy. Geomorphology 165–166, 107–123. https://doi.org/10.1016/j.geomorph.2012.03.037.

Remondo, J., Oguchi, T., 2009. GIS and SDA applications in geomorphology. Geomorphology 111, 1–3. doi:https://doi.org/10.1016/j.geomorph.2009.04.015.

Ribeiro, A., Ribeiro, A., Mateus, A., 2002. Global tectonics with deformable plates. In: Ribeiro, A. (Ed.), Soft Plate and Impact Tectonics. Springer, Berlin, Heidelberg, pp. 51–173. https://doi.org/10.1007/978-3-642-56396-6_3.

Roberts, M.B., Parfitt, S.A., 1999. Boxgrove. A Middle Pleistocenehominid site at Eartham Quarry, Boxgrove, West Sussex. Archaeological Report 17. English Heritage, London https://doi.org/10.1002/1520-6548(200012)15:8%3C819::AID-GEA5%3E3.0.CO;2-Z.

Rosenbloom, N.A., Anderson, R.S., 1994. Hillslope and channel evolution in a marine terraced landscape, Santa Cruz, California. J. Geophys. Res. 99, 14013–14029. https://doi.org/10.1029/94jb00048.

Ruiz, M., Díaz, J., Pedreira, D., Gallart, J., Pulgar, J.A., 2017. Crustal structure of the North Iberian continental margin from seismic refraction/wide-angle reflection profiles. Tectonophysics 717, 65–82. https://doi.org/10.1016/j.tecto.2017.07.008.

Sahu, U., Panaskar, D., Wagh, V., Mukate, S., 2018. An extraction, analysis, and prioritization of Asna river sub-basins, based on geomorphometric parameters using geospatial tools. Arab. J. Geosci. 11, 517. https://doi.org/10.1007/s12517-018-3870-2.

Santanach Prat, P., Santanach i Prat, P., 1994. Las Cuencas Terciarias gallegas en la terminación occidental de los relieves pirenaicos. Cad. do Lab. Xeolóxico Laxe Rev. Xeol. galega e do hercínico Penins. 19, 57–71.

Simms, A.R., Rouby, H., Lambeck, K., 2016. Marine terraces and rates of vertical tectonic motion: the importance of glacio-isostatic adjustment along the Pacific coast of central North America. Bull. Geol. Soc. Am. 128, 81–93. https://doi.org/10.1130/B31299.1.

Smart, P.L., 1984. The geology, geomorphology and speleogenesis of the eastern Massifs, Picos de Europa, Spain. Cave Sci. 11, 238–245.

Sunamura, T., 1991. The elevation of shore platforms: a laboratory approach to the unsolved problem. J. Geol. 99, 761–766. https://doi.org/10.1086/629537.

Sunamura, T., 1992. The Geomorphology of Rocky Coasts. Chichester: Wiley. https: //doi.org/10.1177%2F030913339401800416

Tavani, S., Quintà, A., Granado, P., 2011. Cenozoic right-lateral wrench tectonics in the western Pyrenees (Spain): the Ubierna Fault System. Tectonophysics 509, 283–253. doi:https://doi.org/10.1016/j.tecto.2011.06.013.

Teixell, A., Labaume, P., Ayarza, P., Espurt, N., de Saint Blanquat, M., Lagabrielle, Y., 2018. Crustal structure and evolution of the Pyrenean-Cantabrian belt: a review and new interpretations from recent concepts and data. Tectonophysics 724–725, 146–170. https://doi.org/10.1016/j.tecto.2018.01.009.

Trenhaile, A.S., 1987. The Geomorphology of Rock Coasts. Oxford University Press, Oxford, UK. 10.1177%2F030913338801200215

Trenhaile, A.S., 2000. Modeling the development of wave-cut shore platforms. Mar. Geol. 166, 163–178. https://doi.org/10.1016/S0025-3227(00)00013-X.

Trenhaile, A.S., 2002. Rock coasts, with particular emphasis on shore platforms. Geomorphology. 48, 7–22. https://doi.org/10.1016/S0169-555X(02)00173-3.

Trenhaile, A., 2014. Modelling the effect of Pliocene-Quaternary changes in sea level on stable and tectonically active land masses. Earth Surf. Process. Landforms 39, 1221–1235. https://doi.org/10.1002/esp.3574.

Tugend, J., Manatschal, G., Kusznir, N.J., 2015. Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics, and timing of the Iberian-European plate boundary. Geology. 43, 15–18. https://doi.org/10.1130/G36072.1.

Verbovšek, T., Popit, T., 2018. GIS-assisted classification of litho-geomorphological units using Maximum Likelihood Classification, Vipava Valley, SW Slovenia. Landslides. 15, 1415–1424. https://doi.org/10.1007/s10346-018-1004-2.

Viejo, G., López-Fernández, C., Domínguez-Cuesta, M.J., Cadenas, P., 2014. How much confidence can be conferred on tectonic maps of continental shelves? The Cantabrian-Fault case. Sci. Rep. 4, 3661. https://doi.org/10.1038/srep03661.

Viveen, W., Schoorl, J.M., Veldkamp, A., van Balen, R.T., 2014. Modelling the impact of regional uplift and local tectonics on fluvial terrace preservation. Geomorphology. 210, 119–135. https://doi.org/10.1016/j.geomorph.2013.12.026.

Westaway, R., Bridgland, D., 2007. Late Cenozoic uplift of southern Italy deduced from fluvial and marine sediments: coupling between surface processes and lower-crustal flow. Quat. Int. 175, 86–124. https://doi.org/10.1016/j.quaint.2006.11.015.