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ORIGINAL ARTICLE

Scientific, Educational and Geotourism Value of the Ballota Beach that Recorded the Old and Most Recent Geological Histories of the North-Northwest Part of the Iberian Peninsula

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Abstract

One of the enclaves that exhibits the best features to understand the old and most recent geological history of the north-northwest portion of the Iberian Peninsula is the Ballota Beach, located in Asturias, Spain. In the cliff above sea level that borders this beach to the south, a succession of Carboniferous "griotte" limestones crops out, deformed by spectacular ramp and detachment folds, as well as thrusts, backthrusts and duplexes. These structures are testimonies of the shortening produced in the cordillera originated during the Variscan orogeny of Devonian-Permian age, which extended throughout central Europe, northern Africa and eastern North America. Additionally, from a viewpoint located on the cliff, one can recognize a flat surface over the carbonate coastal cliffs and higher flat surfaces developed on quartzites. These flat surfaces, known as "rasas", are marine abrasion surfaces elevated above current sea level resulting from Cenozoic-Quaternary land uplift and/or sea level fall. This region, already mentioned in the XIX century, has an extraordinary scientific and educational value, from the Structural Geology, Geomorphology, Historical Geology and Stratigraphy points of view, and is a great geotourism attraction due to its beauty. To make this region known, we propose to declare this area a geological interest site in the Global Geosites Spain project, make this article open access, upload a virtual outcrop model we have built in open-access online repositories, make information available to public entities that promote outreach and tourism, propose the realization of a "Geolodía" (Geology day), and make a video to celebrate the Geodiversity International Day.

Keywords Fold · Rasa · Ballota Beach · La Boriza viewpoint · Geotourism

Introducción

Palaeozoic rocks unconformably covered by Quaternary sediments are common in the western part of the Iberian-Peninsula north coast (e.g., Instituto Geológico y Minero de España 2021). These rocks and the relief morphologies provide information about the old and most recent evolution of this portion of the Peninsula. These rocks crop out in many cliffs, beaches and intertidal regions, however, not all these regions exhibit good outcrop conditions and the rocks do not always display interesting characteristics. Based on previous works and on our fieldwork experience in this region, embodied in publications, PhD theses, MSc theses, final degree projects, and field trips for undergraduates and postgraduates, we have chosen an area that, in our opinion, it is excellent to decipher this part of geological history. In this area the rocks display spectacular outcrop conditions, and they are affected by very representative and

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well-developed tectonic structures. The coastal relief also shows fascinating geomorphological features and there are well-positioned observation points. All these features give this area a high value from the scientific and educational perspective, making it an important geotourism attraction in a beautiful setting.

The study area, known as the Ballota Beach, is located in the north-northwest part of the Iberian Peninsula (Fig. 1), specifically to the northeast of a small town called Andrín, in the Llanes Council, Principality of Asturias, Spain. This beach is over 300 m long and exhibits variable widths due to tides. This beach is made up of sand and a narrow gravel strip towards the land. It is slightly concave towards the sea and is approximately NNW-SSE trending (Fig. 2). The beach is bounded by cliffs both towards the land and laterally. These cliffs are usually formed by rock outcrops at the bottom and vegetation at the top; the cliff located to the south is the most abrupt one. In front of the beach there is a small island elongated in ENE-WSW direction, known as Castro Ballota. This island is formed mainly by rocks covered by low vegetation.

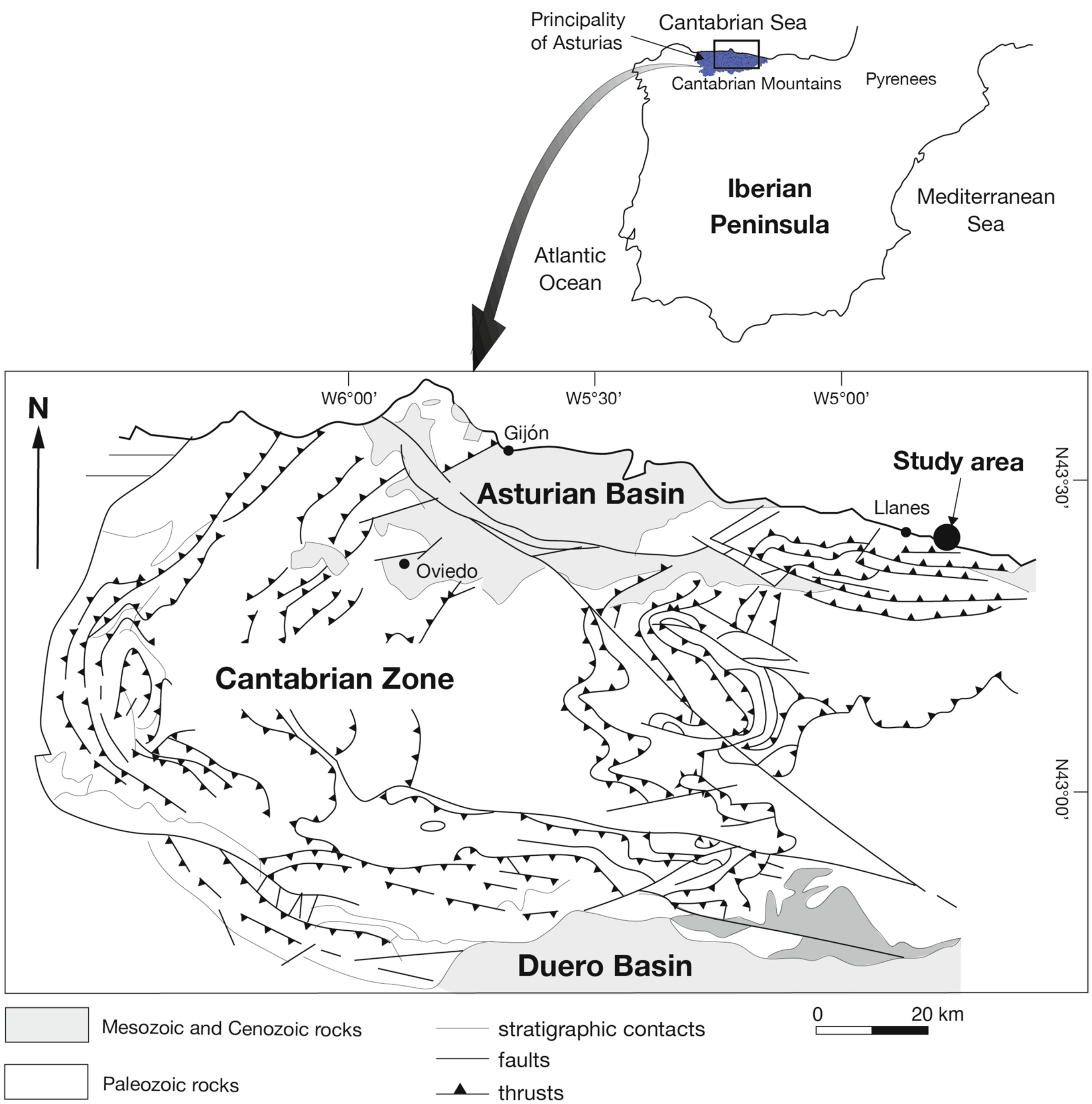
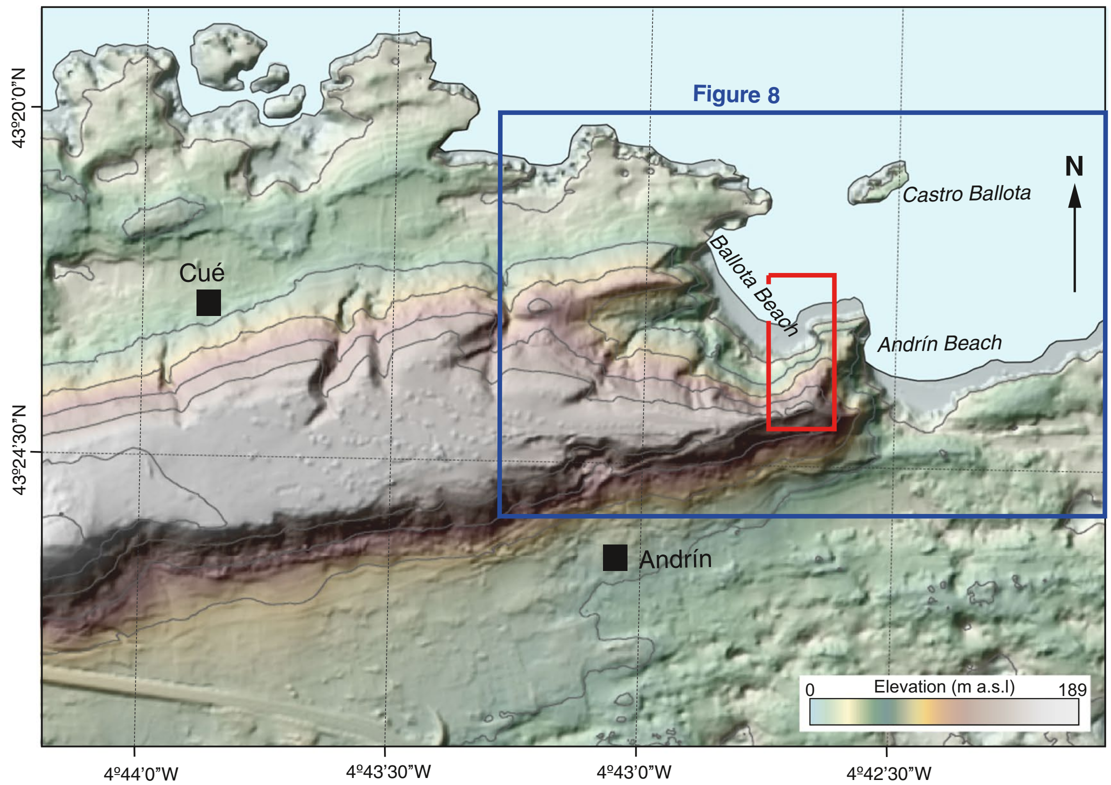


Fig. 1 Structural sketch of the north-northwest part of the Iberian Peninsula. All the area depicted in the sketch belongs to the Alpine structural unit called Cantabrian Mountains. The black circle indicates the study area and the location of Figs. 2, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15a, b, 16a and 17a

a)



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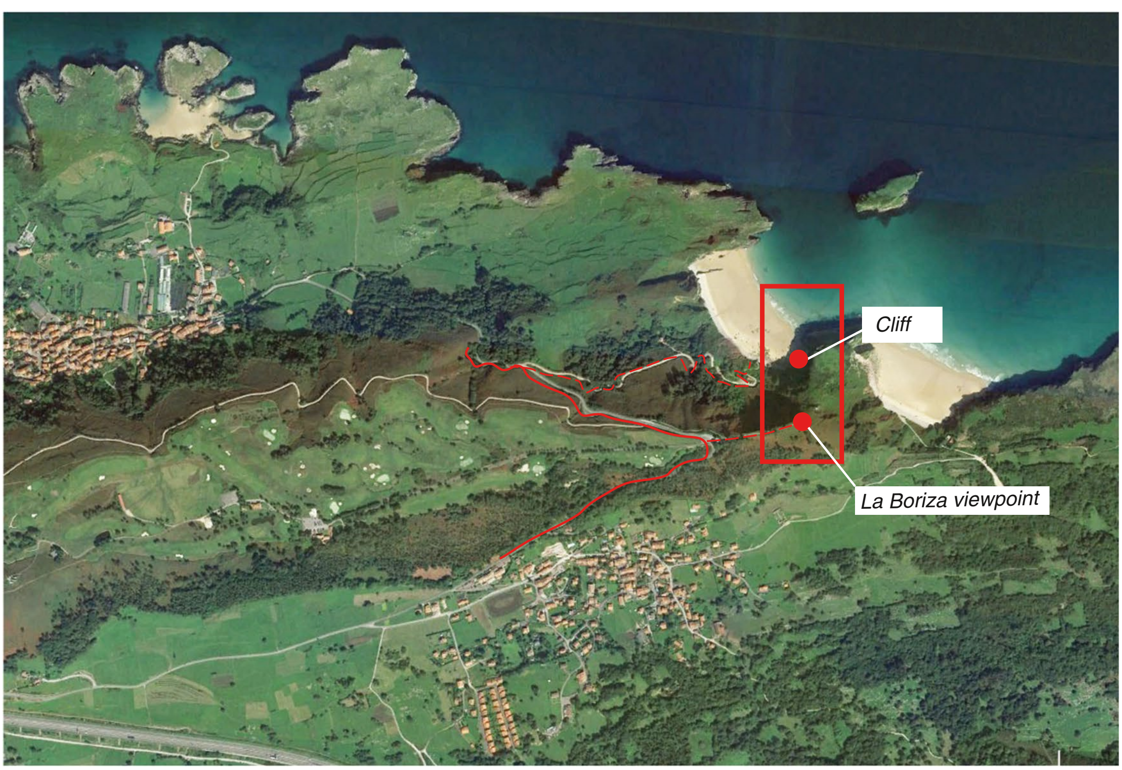


Fig. 2 **a**) Digital elevation model and **b**) image taken from "Google Earth" of the surroundings of the study area indicated with a red rectangle in both figures. Figure a) includes the location of the map illustrated in Fig. 8b

The Ballota Beach belongs to the Protected Landscape of the Eastern Coast of Asturias, one of the protection figures proposed in the Natural Resources Management Plan of Asturias, usually known as PORNA in Spanish, published in the Regional Decree 38/1994. In this plan, a Regional Network of Protected Natural Spaces is selected and the figure of Protected Landscape is applied to “those places in the natural environment that, due to their aesthetic and cultural values, deserve special protection”, highlighting “the natural values (biological and geological) and landscape of the area”.

We have selected two specific localities within the Ballota Beach that will be studied in detail. The first one is the west face of an elongated N-S cliff of more than 130 m above sea level (m.a.s.l.), which constitutes the south-southeast boundary of the Ballota Beach (Fig. 2). The cliff, formed by Palaeozoic rocks, is located in El Pandón Point. The second one is a viewpoint located on top of the cliff, and consists of a concrete structure made up of a platform and a few stairs including a telescope (Fig. 2). This viewpoint, from which beautiful views of the surrounding relief can be seen, is known as La Boriza or Andrín viewpoint.

The first location displays the result of a dynamic geological process that took place at great depths in the crust hundreds of millions of years ago. It allows the observation of various structures, such as thrust systems and different types of fault-related folds (Fig. 3a). Specifically, these processes include thrusting and folding events that occurred in the Cantabrian Zone, the foreland fold and thrust belt of the Variscan orogen in the northwest part of the Iberian Peninsula. The presence of well-developed and well-exposed structures along the coastal area makes this region an excellent example.

The second location also illustrates the result of a dynamic geological process, but this time at much shallower levels and occurring a few million years ago. This site reveals sub-horizontal surfaces near the coastline, corresponding to ancient marine terraces elevated above the current sea level, known as "rasas" (Fig. 3b). Although it is unclear when and where the term rasa was first described, it is now internationally used to denote such elevated surfaces (e.g., Pedoja et al. 2014). Alternative terms include wave-cut platforms, abrasion platforms and marine terraces used in some textbooks (e.g., Burbank and Anderson 2013). Like in the first location, the well-developed and well-preserved rasas along the coastal zone make the studied region an excellent example of surface processes combining erosive, climatic and tectonic forcing.

These two localities had already aroused interest from a geological point of view in the past. As far as we know, the first scientific reference to the cliff outcrop dates back to the end of the nineteenth century and is due to the French geologist Charles Eugène Barrois (Wikipedia 2023a). Despite the work of this geologist covered a huge region in the northwest part of the Iberian Peninsula (Barrois 1882), the outcrop caught his attention since he included a detailed drawing of it in his publication (Fig. 4). In addition, photographs of this outcrop, including general geological interpretations, appear in De Ana (2015) and Bulnes et al. (2016). La Boriza viewpoint was cited as a geological observation point in 1985, with subsequent updates until 2015, in a file made by Flor, Flor-Blanco and García Cortés at the Instituto Geológico y Minero de España (2015a), in which brief descriptions of the relief are presented.

Both the cliff and the viewpoint can be accessed via the local road Lln2, which runs between two small towns: Andrín and Cue. An approximately E-W track, a little over 750 m length, departs from the north part of the local road a little over 1 km from Andrín. This track ends at a small car park and just below it there is a bar-restaurant; the small restaurant terrace, occupied by some outdoor tables, offers excellent cliff views. The final part of the descent to the Ballota Beach and to the base of the cliff is made by a path and stairs, which also offer outstanding views of the cliff (Fig. 2). A little over 500 m from Andrín, there is a small parking area adjacent to the north part of the local road. From this parking, a sub-horizontal E-W path of little over 250 m length, which also offers excellent relief views, leads to La Boriza viewpoint (Fig. 2).

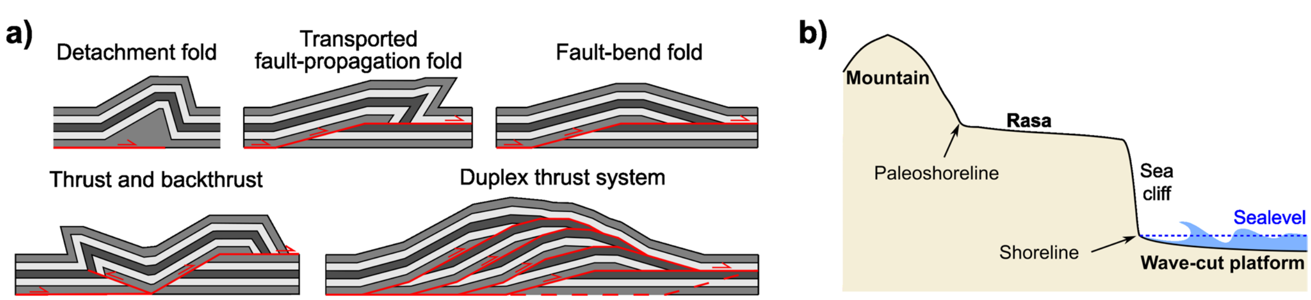


Fig. 3 **a**) Sketches of various tectonic structures observed in the Ballota Beach cliff. **b**) Sketch of a rasa such as the ones observed from La Boriza viewpoint (modified from Álvarez-Marrón et al. 2008)

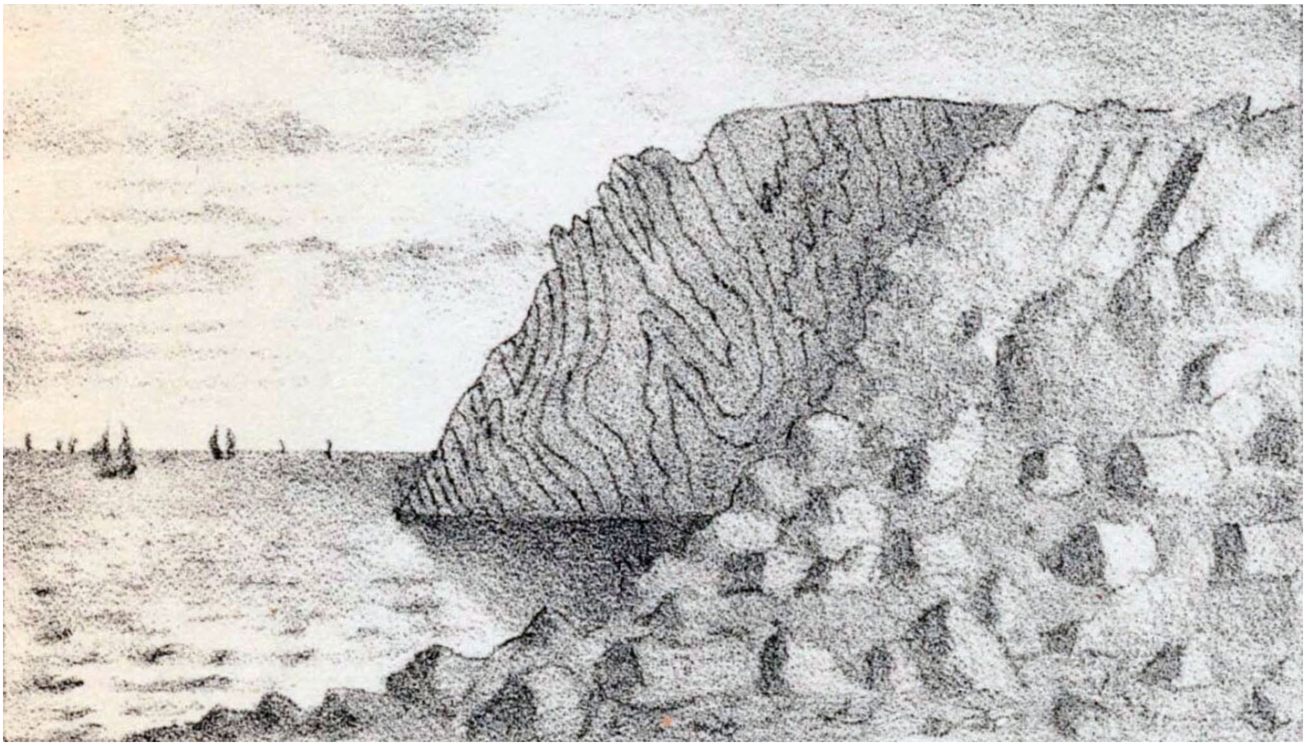


Fig. 4 Sketch, looking northeast, of the folded Carboniferous limestones in the cliff drawn by Barrois (1882)

In the vicinity of the Ballota Beach, there is a number of places interesting from the geological point of view, some of which are natural monuments, while others belong to the list of Spanish spots of geological interest (Fig. 5). The common theme in most of these spots is the presence of blowholes through the rasa along the coastline. These spots include: the Cobijeru Complex Natural Monument (Principado de Asturias 2024a); the Gulpiyuri beach Natural Monument (Principado de Asturias 2024b); the Santiuste blowhole Natural Monument (Principado de Asturias 2024c); the Arenillas blowholes Natural Monument (Principado de Asturias 2024d), which is also the geological point of interest CA037b (Instituto Geológico y Minero de España 2015b); the rasas de Cue which is the geological point of interest CA055 (Instituto Geológico y Minero de España 2015a); and the Llames de Pría blowhole which is the geological point of interest CA037 (Instituto Geológico y Minero de España 2015c). Additionally, in 2014, a "Geolodía" was organized in the vicinity of this last geological point of interest (Adrados González et al. 2014; Sociedad Geológica de España 2019). This is one of the outreach activities proposed in this manuscript for the Ballota Beach which will be explained below. In addition, the relevance of the landscape of the coast near the Ballota Beach has led to the publication of a book with

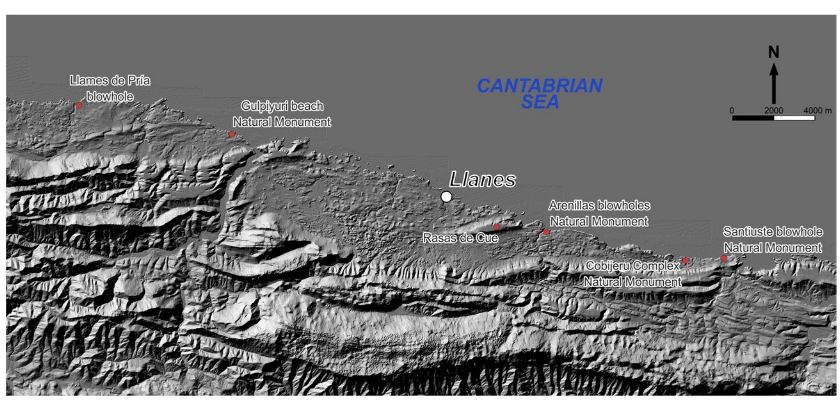


Fig. 5 Digital elevation model showing the location of the spots of geological interest near the study area. The study area is located in between the Rasas de Cue and the Arenillas blowholes Natural Monument approximately in the central part of the image

the aim of describing geological excursions on foot and by kayak (Adrados González 2014).

We describe in the next sections the most significant geological aspects of the two enclaves (the cliff and the relief seen from the viewpoint), as well as their scientific, educational and geotourism values, and the activities we propose regarding their conservation and to publicize them at a regional, national and international level.

Geological Setting

Considering the Variscan structural units, the study area is located in the northeastern part of the Cantabrian Zone and in the northern branch of the Ibero-Armorican or Asturian Arc. If, alternatively, we consider the structural units developed after the Variscan orogeny, and thus belonging to the Alpine cycle in a broad sense, the study area is located in the northern part of the Cantabrian Mountains (Fig. 1).

Cantabrian Zone is the name given to the fold and thrust belt developed in the foreland of the Variscan orogen in the northwest portion of the Iberian Peninsula (Lotze 1945; Julivert et al. 1972) (Fig. 1). In cross section, this belt shows the typical orogenic wedge morphology that tapers towards the foreland, i.e., towards the east. In map view, the structures display a curved shape with an internal core to the east and constitute the Ibero-Armorican or Asturian Arc. In the Cantabrian Zone, different types of thrust systems, such as imbricate thrusts and duplex, as well as folds related to them, such as fault-bend, fault-propagation and detachment folds, have been documented (Julivert 1971, 1979, 1981, 1983; Savage 1979, 1981; Pérez-Estaún et al. 1988; Pérez-Estaún and Bastida 1990; Aller et al. 2004 among others). The rocks that crop out in the study area show tectonic structures mainly developed during this orogeny.

The mountain chain of contractional origin, developed during the Variscan orogeny in Carboniferous times, was dismantled during an erosive episode by the end of the Palaeozoic-beginning of the Mesozoic. In Mesozoic times, a Permian–Triassic rift took place, responsible for normal faults, in some cases resulting from the reactivation of previous Variscan structures (Lepvrier and Martínez-García 1990), during which strike-slip faults also developed (Julivert et al. 1971). A thermal subsidence event during the Late Triassic and Early Jurassic gave way to an extensional stage that began by the end of the Early Jurassic and consisted of normal faulting, reactivation of previous faults, heating, and uplift (e.g., Uzkeda et al. 2016). This event may have lasted until the lower part of the Early Cretaceous (pre-Barremian), or perhaps more than one event occurred during this time lapse, causing the reactivation of previous normal faults (e.g., Alonso et al. 2018). On a large scale, this episode is related to the opening of the Bay of Biscay located to the north of the Iberian Peninsula. By the middle part of the Early Cretaceous, a new episode of thermal subsidence took place (Teixell et al. 2018).

The convergence between the Iberian and Eurasian tectonic plates from the middle-late part of the Eocene until the beginning of the Miocene (Álvarez-Marrón et al. 1997; Gallastegui 2000) caused the Alpine orogeny. This contractional event, responsible for the formation of the Cantabrian Mountains (Fig. 1) and the Pyrenees to the east, lead to the selective reactivation of previous structures, as well as the generation of new thrusts and uplifts (Lepvrier and Martínez-García 1990; Pulgar et al. 1999; Alonso et al. 2009; Uzkeda et al. 2016). The structural framework built during this contractional event was exhumed from the upper part of the Eocene to the beginning of the Oligocene (Fillon et al. 2016).

During the Early Pleistocene or before (Jiménez-Sánchez et al. 2006; Álvarez-Marrón et al. 2008; Pedoja et al. 2014), a narrow coastal strip of siliciclastic and carbonate Palaeozoic and Mesozoic rocks was eroded, and the resulting angular unconformity, including some small paleoreliefs, was covered by a thin veneer of Quaternary detrital sediments. These coastal planar surfaces, that dip gently to the sea, were elevated above present-day sea level and were called rasas (e.g., Hernández Pacheco and Asensio Amor 1964; Asensio Amor 1970; Flor 1983; Mary 1983). These surfaces have been attributed to continental, marine or mixed origin (e.g., Flor and Flor-Blanco 2014), however, nowadays most authors interpret them as ancient marine abrasion platforms currently exposed above sea level (e.g., Álvarez-Marrón et al. 2008; López-Fernández et al. 2020). Thus, their southern boundary with the mountain slopes would define the paleo shoreline, although local deposits at the mountain base, such as alluvial fans, may obscure it and alter the dip of the rasas. Tectonic origins have been assigned to the Cantabrian rasas: convergence-related uplift in an incipient subduction zone along the North Iberian margin (Álvarez-Marrón et al. 2008) and isostatic response to the Cantabrian Mountains crustal thickening during the Alpine orogeny (López-Fernández et al. 2020). On the one hand, these rasas are well identified from the viewpoint located in the study area, and on the other, today we can see the outcrops of Palaeozoic rocks studied here thanks to this terrain emersion. Neotectonic activity also include development of some new faults and reactivation of previous faults (e.g., Gutiérrez-Claverol et al. 2006; Álvarez-Marrón et al. 2008), as well as small magnitude earthquakes (e.g., López-Fernández et al. 2004) and occasional large earthquakes of low recurrence (e.g., Fernández et al. 2021; Rodríguez-Rodríguez et al. 2023).

Methodology

Cliff

Classical field work, including geological mapping and field data collection, accompanied by geological interpretation of outcrop oblique photographs and of virtual outcrop models, as well as measurement of orientation of bedding surfaces on the virtual outcrop models using the software Move and determination of fold axes using equal area projections, were carried out to decipher the main characteristics of the structures that crop out in the cliff. The procedure employed to construct the virtual outcrop models is briefly explained below.

The 3D virtual outcrop models were constructed using 822 photographs, 395 taken from the ground using a camera attached to a tripod, and 427 images taken using an unmanned aerial vehicle and shooting manually (Fig. 6). In addition, a video of a specific area was also filmed using the drone. Initially, three virtual outcrop models were created based on the drone images, both point cloud and textured mesh: a first model of the lower part of the cliff close to the beach (using approximately 200 photographs), a second model of the higher part of the cliff (using approximately 160 photographs) and a third model of the whole area (using approximately 427 photographs). Two virtual outcrop models were also built using photographs taken from the ground: one point cloud model that shows an anticline in map view (using approximately 30 photographs), and another model in both point cloud and textured mesh format of the entire area (using approximately 250 photographs). All the virtual outcrop models were created using the software “Pix4Dmapper”, except for that of the anticline that was created employing the software “VisualSfM”. The virtual outcrop models generated with “Pix4Dmapper” and drone images were automatically georeferenced using the drone's internal GPS data, and therefore, they did not require further processing. To correct the orientation and scale of the models built with ground images, we employed in-house software and the procedure described in Poblet et al. (2022) and Uzkeda et al. (2022). Thus, orientations and lengths taken in the field of easily identifiable elements, such as fractures, beds, etc., were used as reference elements. The transformation matrix was then calculated, which converted the orientation of the planes in the model to planes with the same orientation as those measured in the field. Additionally, the obtained lengths were compared with the same distances in the model to estimate a scale factor aimed at correcting the size of the models.

La Boriza Viewpoint

La Boriza viewpoint offers an excellent view of the elevated planar surfaces, so-called rasas. Their characteristics were described from fieldwork, geological photointerpretation of oblique photographs taken on the ground and of 3D images obtained through the application "Google Earth”, and remote sensing based on topographic maps, orthophotographs and digital elevation models loaded on GIS-type software. We decided not to build virtual outcrop models of the rasas due to their large dimensions and the excellent results obtained using digital elevation models and "Google Earth" 3D images when placing the observer's point of view at the sea, looking inland, i.e.,

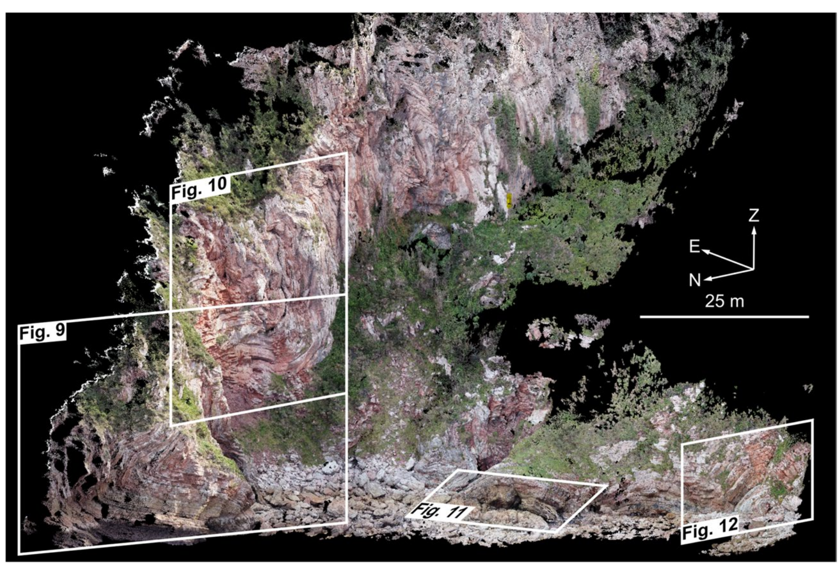


Fig. 6 Virtual outcrop model of the cliff with location of the photographs in Figs. 9, 10, 11 and 12

towards the south, and using the different moving, rotating and zooming tools.

In order to carry out a purely topographic delimitation of the rasas, we downloaded the digital elevation models freely available at the Organismo Autónomo Centro Nacional de Información Geográfica (2020) (Fig. 7). First of all, we restricted the area under investigation to the surface covered by sheet number 0032 of the 1:50,000 scale National Topographic Map. The digital elevation model chosen has a cell size of 25 × 25 m and it was selected over others with higher resolution to try to eliminate noise that may be introduced by "micro-topography". After that, we built a slope model from the digital elevation model and established a slope threshold value of 5°, so that we considered that all those pixels with slopes less than 5° could potentially correspond to rasas (Álvarez-Marrón et al. 2008; Domínguez-Cuesta et al. 2015). This allowed us to distinguish different rasas based on their height and spatial position. When the rasas delimited on the slope map were overlapped onto the geological map by Martínez-García (1980) we realized it was possible to distinguish different rasas based on their lithological substrate (Fig. 7). Thus, the information of the pixels with slopes < 5° was merged with the information derived from the geological map and we extracted; on the one hand, those pixels with slopes < 5° located on the Ordovician Barrios Fm. (quartzites), and on the other, those pixels with slopes < 5° located on Carboniferous formations (limestones). This allowed us to delimit the upper rasas developed on the quartzite substrate and the lower rasa developed on the limestones. Finally, we extracted elevations to characterize the elevations of the different rasas and show them as a histogram, as it will be shown later.

Geology

Cliff

Structural Setting

The cliff outcrop is located in the north limb of the Cue anticline (Martínez-García et al. 1981) (Fig. 8). The Cue anticline is a kilometre-scale, almost isoclinal fold with an overturned south forelimb, that dips steeply to the N, and a north backlimb, that dips gentler to the N. This anticline involves Ordovician, Devonian and Carboniferous rocks at the surface (Martínez Álvarez 1965; Martínez-García 1980; Marquínez 1989; De Ana 2015; Bulnes et al. 2016; Instituto Geológico y Minero de España 2021). In the study area the anticline axis plunges to the E and its axial surface dips steeply to the N; thus, it is a S-vergent structure. The Cue anticline is located in the hangingwall of a kilometre-scale, S-directed thrust, that dips steeply to the N, known as the basal thrust of the Llanes unit (Martínez-García et al. 1981). This thrust shows a hangingwall ramp relationship with the Cue anticline forelimb and is subparallel to the anticline backlimb. The orientation, geometry, and vergence of the anticline are consistent with the orientation, geometry, and motion sense of the thrust, pointing out that both structures are related. The geometrical relationships between the fold and the thrust suggest that this structure could be interpreted as a ramp fold, and the low anticline interlimb angle suggests that it may be a fault-propagation fold. The Cue anticline north limb, where the studied outcrop is located, includes second-order anticlines and synclines generally related to thrusts (see geological maps and sections in De Ana 2015 and Bulnes et al. 2016).

The structures described above are interpreted as contractional structures caused by the Variscan orogeny during

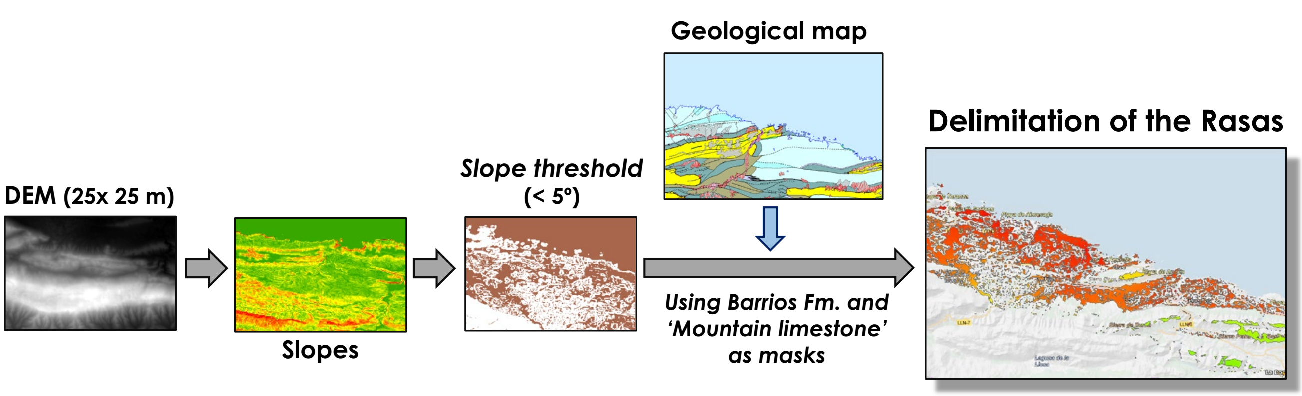


Fig. 7 Procedure followed to delineate the rasas on the map in Fig. 16a and to construct the histograms in Fig. 16b. Initially, we delimited the rasas from a purely topographic perspective. Subsequently, by overlapping the boundaries of the obtained rasas with the geological map, we discovered the influence that the substrate lithology had exerted on them

Carboniferous times. However, fold tightening, as well as fault reactivation and/or formation of new structures, produced during the Cenozoic Alpine orogeny, cannot be ruled out. Thus, this sort of processes have been documented in the Cantabrian Zone (Lepvrier and Martínez-García 1990; Pulgar et al. 1999; Alonso et al. 2009; Uzkeda et al. 2016). In fact, E-W thrusts involving Mesozoic rocks have been mapped in areas close to the studied outcrop (e.g., Martínez-García 1980; Marquínez 1989; Instituto Geológico y Minero de España 2021). In any case, it is difficult to distinguish to what extent the Alpine event modified the Variscan structures in this particular region because both the Variscan (Farias 1982; De Paz 2023) and the Alpine (Lepvrier and Martínez-García 1990; Uzkeda et al. 2016) tectonic transport directions were approximately N-S, and therefore, both are approximately perpendicular to the main structures.

Stratigraphy

The rocks in the studied outcrop belong to the Carboniferous Alba Fm., whose age is Late Tournaisian-Serpukhovian (e.g., Adrichem Boogaert 1965; Higgins 1974; Menéndez Álvarez 1978, 1991; Wagner Gentis 1980; Belka and Lehman 1998). The Alba Fm. is one of the most widespread stratigraphic units in the Cantabrian Zone, which appears in different structural units and positions within the folds and thrusts. The most complete succession of the Alba Fm. consists of three members: reddish nodular limestones at the base, followed by radiolarites and slates, and light grey limestones at the top. These members were called Gorgera, Lavandera and Canalón mbs. respectively by Wagner et al. (1971), and subsequently, other members were defined (e.g., Kullman et al. 1977; García López and Sanz López 2002). However, not all the members appear everywhere in the Cantabrian Zone, they may be ordered differently and their thickness may be variable, usually reaching tens of meters (e.g., Fernández et al. 2004).

The Alba Fm. in the study area consists of two members. The lower one is made up of centimetre-scale alternations of reddish slates and radiolarites, which may become greenish and greyish. The upper one is formed by well-bedded, centimetre to decimetre beds of reddish nodular limestones, usually wackestones, called "griotte facies", including thin horizons of red marls that are thicker and more abundant in the lower part of this member (Figs. 6, 9, 10, 11, 12). These rocks contain remains of crinoids, goniatitids, ostracods, radiolarians and trilobites (Martínez-García et al. 1981). The Alba Fm. thickness is tough to estimate in this region since it is highly deformed. The Alba Fm. is located over the Devonian Ermita Fm., made up of medium to coarse-grained sandstones and reddish and yellowish microconglomerates. Above the Alba Fm. there is a succession of dark grey, sometimes fetid, limestones, usually mudstones, that belong to the Carboniferous Barcaliente Fm., also known as "Caliza de Montaña" (Mountain limestone) (Fig. 8).

Structural Features

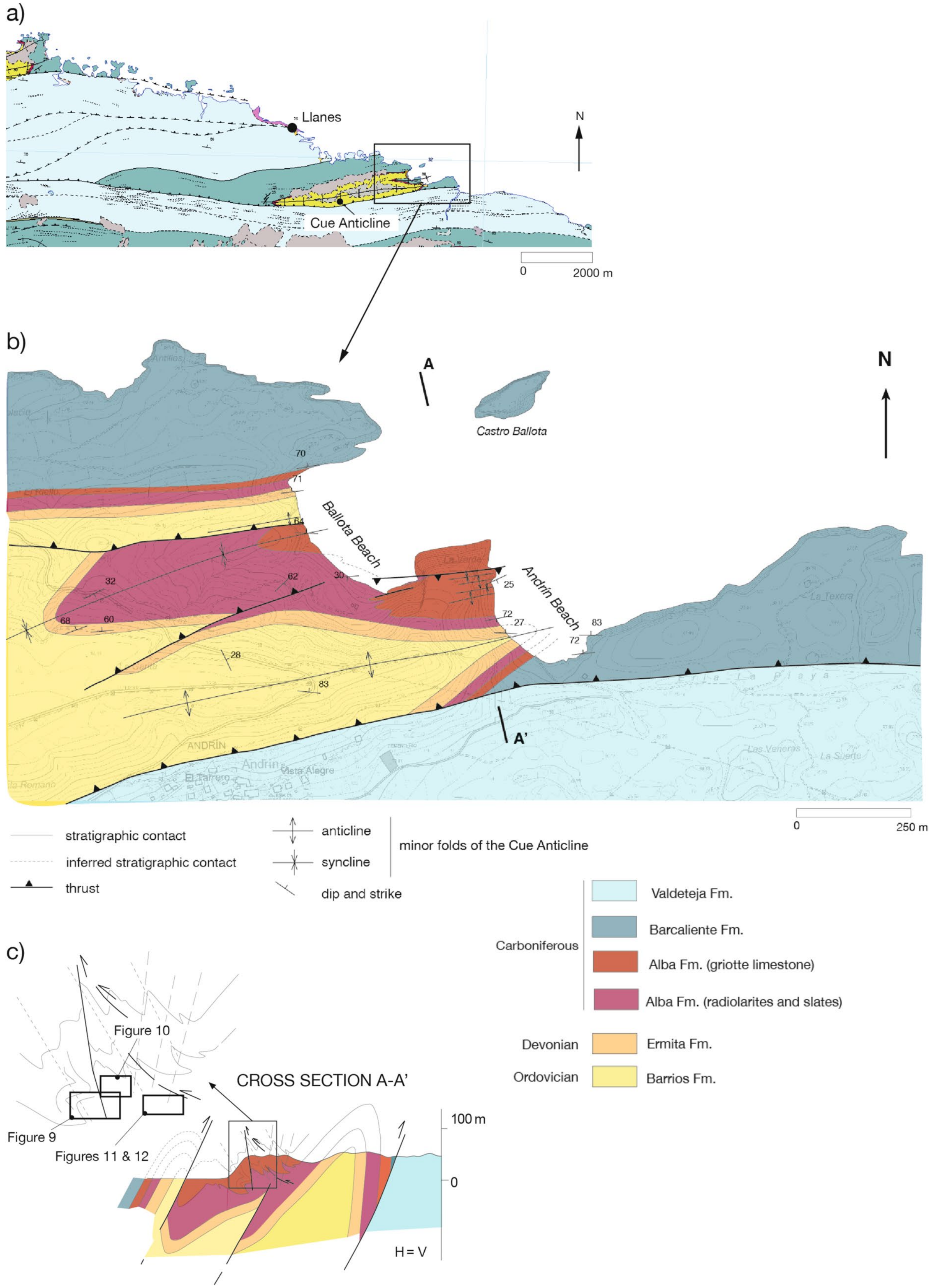
The studied outcrop is tectonically complex since it includes abundant structures of different types and different scales (Figs. 6, 9, 10, 11, 12). However, a complete understanding of the outcrop is not required to visualize its general features. Below, we will describe the outcrop focusing on the main structures and on second order structures related to folding and thrusting that deserve it due to their remarkable features.

Most of the strata are folded and the fold axes plunge gently to the E and NE (Figs. 9c, 10c, 11c, 12c), and therefore, they are consistent with the Cue anticline orientation (Fig. 8a). In the cliff, a main reverse fault, moderately to steeply dipping to the S, separates a southern uplifted fault block (hangingwall) made up of "griotte limestones", red slates and radiolarites, from a northern downthrown fault block (footwall) formed by limestones (Figs. 8c, 9).

The largest structure in the reverse fault footwall is a decametre-scale recumbent fold, that crops out at the bottom of the cliff by the sea. It is a close detachment fold related to the main reverse fault, that includes second-order disharmonic folds in its core close to the fault (Figs. 6, 9).

The structure in the reverse fault hangingwall consists of folds and thrusts. The largest fold is a decametre-scale close syncline, N-vergent, with an axial surface moderately to steeply dipping to the S (Figs. 6, 10). The most notable second-order structures within this large syncline are described below from the north to the south limb (Figs. 10a, b).

i) In the syncline north limb, very close to its hinge, subhorizontal layers are cut and offset by S-directed thrusts forming a duplex system.
ii) Just below the duplex, there is a metre-scale anticline with an S-type geometry in accordance with its position within the large syncline. This minor fold is located in the hangingwall of a N-directed thrust. The low anticline interlimb angle, the angular relationships between the anticline and the thrust, and the consistency between the orientation and asymmetry of the anticline and the orientation and motion sense of the thrust, suggest that this structure may be a transported fault-propagation fold.
iii) In the large syncline hinge, metre-scale tight anticlines and synclines exhibit M-type geometries. They are second-order folds related to the large syncline.
iv) In the south limb of the large syncline, decimetre- to metre-scale, smooth to open folds could be interpreted as fault-bend folds linked to vertical thrusts.
v) The rest of the south limb of the large syncline is formed by subvertical layers including abundant metre-scale,


a)
Llanes
Cue Anticline
N
0
2000 m
b)
A
Castro Ballota
N
Ballota Beach
Andrín Beach
A'
ANDRÍN
Andrín
Vista Alegre
El Tarrero
La Texera
Las Vaneras
La Sueño
70
71
32
62
30
25
72
27
83
72
68
60
28
83
0
250 m
stratigraphic contact
inferred stratigraphic contact
thrust
anticline
syncline
minor folds of the Cue Anticline
dip and strike
Carboniferous
Valdeteja Fm.
Barcaliente Fm.
Alba Fm. (griotte limestone)
Alba Fm. (radiolarites and slates)
Devonian
Ermita Fm.
Ordovician
Barrios Fm.
c)
Figure 10
Figure 9
Figures 11 & 12
CROSS SECTION A-A'
100 m
0
H = V

◂**Fig. 8** **a**) Simplified geological map of the Cue anticline, **b**) and **c**) geological map and geological section, respectively, of the eastern part of the Cue anticline in the surroundings of the study area, modified from De Ana (2015), Bulnes et al. (2016) and Martin et al. (2019). The location of Figs. 9, 10, 11 and 12 is indicated in the cross section depicted in figure c). See Fig. 2a for location of the map illustrated in figure b)

close to tight folds with Z-type geometries. These second-order folds are consistent with the large syncline.

The "griotte" limestones that crop out at the beach are affected by metre-scale N-vergent folds, with a marked S-type asymmetry (Figs. 6, 11, 12); therefore, they are probably located in the hangingwall of the main reverse fault within the northern limb of the large syncline. The beach outcrops close to the cliff include a quasi-isoclinal anticline-syncline pair (Figs. 6, 11) and a gently S-dipping thrust developed in the anticline core. The beach outcrops close to the stairs show a tight anticline (Figs. 6, 12) located in the hangingwall of a N-directed thrust, and a smaller tight syncline in the thrust footwall. These folds are bounded to the north by a S-directed thrust, that dips moderately to the N.

The most striking features of the studied outcrops are: i) different types of thrust-related folds occur, such as fault-bend folds (Fig. 10), fault-propagation folds (Fig. 10) and detachment folds (Fig. 9), similarly to other localities in the Cantabrian Zone (Bulnes et al. 2019); and ii) the low fold interlimb angles, as well as the abundance of faults, proves that the Alba Fm. was more shortened than the surrounding rocks, similarly to other Cantabrian Zone localities (e.g., Bulnes 1995; Bulnes et al. 2016, 2019).

Relationship with Major Structures and Conditions of Formation of the Structures

Both the dip and motion sense of the main reverse fault that crops out in the cliff are opposite to those of the basal thrust of the Llanes unit related to the Cue anticline (Fig. 8c). This suggests that the reverse fault is a backthrust developed in the Cue anticline backlimb. The presence of backthrusts in the backlimbs of thrust-related folds has been documented in field, subsurface and laboratory examples of these types of structures (e.g., Huiqi et al. 1992). Close to the studied area, the Variscan tectonic transport points towards the SSW (Farias 1982) or towards the SSE (De Paz 2023), i.e., subperpendicular to the Cue anticline and the structures mapped in the study area. Thus, we conclude that the studied structures are frontal structures with respect to the Variscan thrust system developed in this region.

A regional-scale cross-section by Martínez-García (1980) shows that the minimum thickness of the Carboniferous stratigraphic succession located above the studied outcrop could have been almost 2 km. This thickness was probably higher, but it is difficult to estimate since Cretaceous rocks lay unconformably on Carboniferous beds nearby. This minimum thickness is in agreement with the illite Kübler index (KI) and the conodont colour alteration index (CAI) obtained in this region (Blanco-Ferrera et al. 2011), which indicate deformation under diagenetic conditions.

La Boriza Viewpoint

Main Features and Age of the Rasas

The most distinctive characteristics of the rasas in the study area are (Fig. 13a, b): i) they are strips of land approximately parallel and adjacent to the coast relatively narrow in N-S direction and elongated in an E-W direction; ii) topographically they are subhorizontal or display a gentle inclination to the N; iii) their height above sea level reaches tens to hundreds of meters, so that their boundaries to the north with the Cantabrian Sea or with other similar strips of land are subvertical cliffs or steep slopes; and iv) they are limited inland, i.e., to the south, by other similar strips of land or by the Cantabrian Mountains. High-resolution topographic maps, aerial photographs, orthophotographs, and digital elevation models (Fig. 13) available in recent years have made it possible to better describe the characteristics of the rasas and outline, among other aspects, variations in the elevation of the rasas in N-S and E-W directions, as well as steps that separate portions of the same rasa with different elevations, interpreted as recent faults, generally resulting from reactivation of basement structures (Álvarez-Marrón et al. 2008; Domínguez-Cuesta et al. 2015; López-Fernández et al. 2020).

The combination of multiple cosmogenic nuclides gave a minimum age of 1 to 2 Myr, i.e., Early Pleistocene (lower part of the Quaternary), for the rasa located to the west of the studied area; this rasa reaches heights from 30 m.a.s.l. to the west to 100 m.a.s.l. to the east (Álvarez-Marrón et al. 2008). Extrapolating the U/Th dating of speleothems, Jiménez-Sánchez et al. (2006) estimated a minimum age of 290 kyr (i.e., Early Pleistocene according to the International Commission on Stratigraphy 2023) for the carbonate rasa by the current coastline east of the study area. Pedoja et al. (2014) proposed an Early Pleistocene age (i.e., approximately from 0.7 to 2.5 Myr according to the International Commission on Stratigraphy 2023) for the rasa located to the west of the study area based on its maximum elevation by extrapolating a constant rate of elevation derived from the elevation of the interglacial highstand that delimits the last interglacial maximum Marine Isotope Stage 5e.

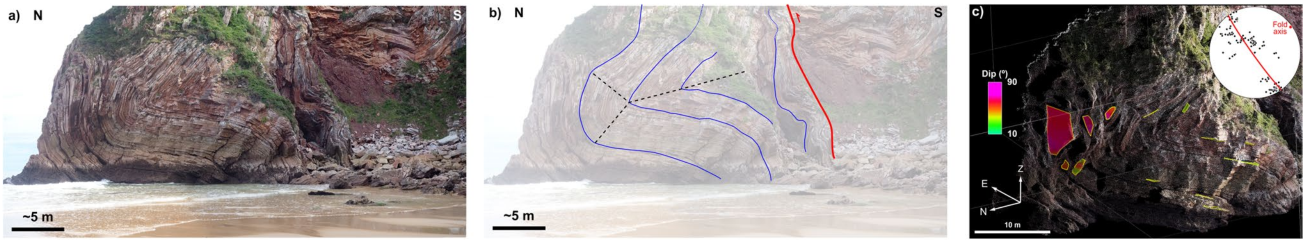


Fig. 9 **a**) Photograph of the cliff, taken from the Ballota Beach, of Carboniferous rocks (Alba Fm.) cut and offset by a N-directed reverse fault, and folded by a recumbent fold in the fault footwall. **b**) Photogeological interpretation of the photograph shown in a). Beds: blue lines, faults: red lines, and axial surfaces: dashed black lines. **c**) Portion of the virtual outcrop model of Fig. 6 illustrating the folded and faulted Carboniferous rocks shown in a) and b). The folded bedding surfaces have been coloured according to their dip using the software "Move". The equal-area projections in the lower hemisphere have been constructed using the software "Stereonet" developed by Cardozo and Allmendinger (2013). The bedding plane poles have been represented using black circles, while the fold axes have been represented using red circles

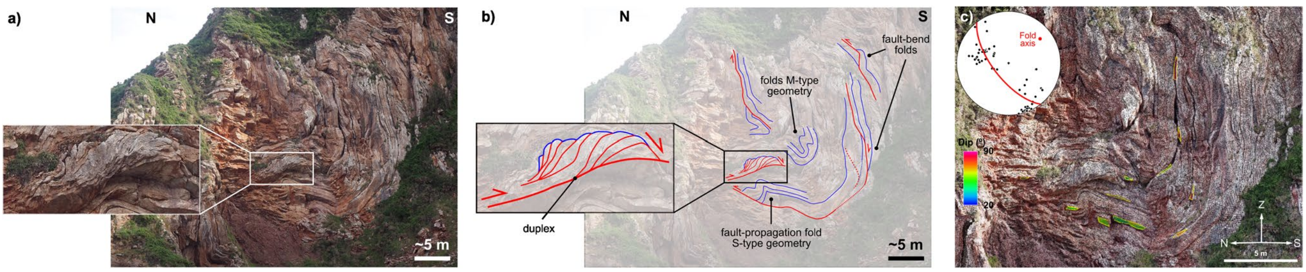


Fig. 10 **a**) Photograph of the cliff, taken from the Ballota Beach, of Carboniferous rocks (Alba Fm.) folded by a syncline, developed in the hangingwall of the N-directed reverse fault, including second-order structures such as minor folds, duplexes, transported fault-propagation folds, and fault-bend folds. **b**) Photogeological interpretation of the photograph shown in a). Beds: blue lines, and faults: red lines. **c**) Portion of the virtual outcrop model of Fig. 6 illustrating the folded and faulted Carboniferous rocks shown in a) and b). The folded bedding surfaces have been coloured according to their dip using the software "Move". The equal-area projections in the lower hemisphere have been constructed using the software "Stereonet" developed by Cardozo and Allmendinger (2013). The bedding plane poles have been represented using black circles, while the fold axes have been represented using red circles

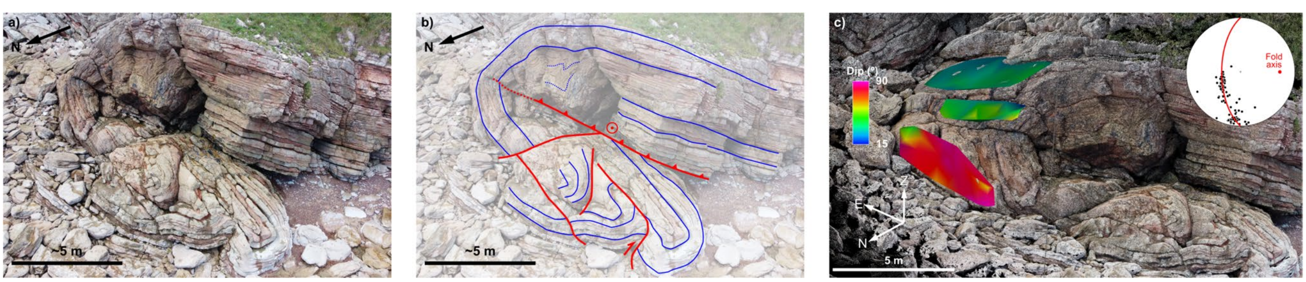


Fig. 11 **a**) Photograph of the Ballota Beach at the foot of the cliff showing Carboniferous rocks (Alba Fm.) folded by a faulted anticline-syncline pair. **b**) Photogeological interpretation of the photograph shown in **a**). Beds: blue lines, and faults: red lines. **c**) Portion of the virtual outcrop model of Fig. 6 illustrating the folded and faulted Carboniferous rocks shown in a) and b). The folded bedding surfaces have been coloured according to their dip using the software "Move". The equal-area projections in the lower hemisphere have been constructed using the software "Stereonet" developed by Cardozo and Allmendinger (2013). The bedding plane poles have been represented using black circles, while the fold axes have been represented using red circles

Different Rasas

Looking north from La Boriza viewpoint, an area just above the coastal cliffs with heights around 50 m.a.s.l. (Fig. 13b), generally occupied by meadows and low vegetation (Fig. 14a), is recognized. This subhorizontal area (Fig. 15a) extends along the coast both to the northwest and to the southeast, and it appears in the Castro Ballota Island

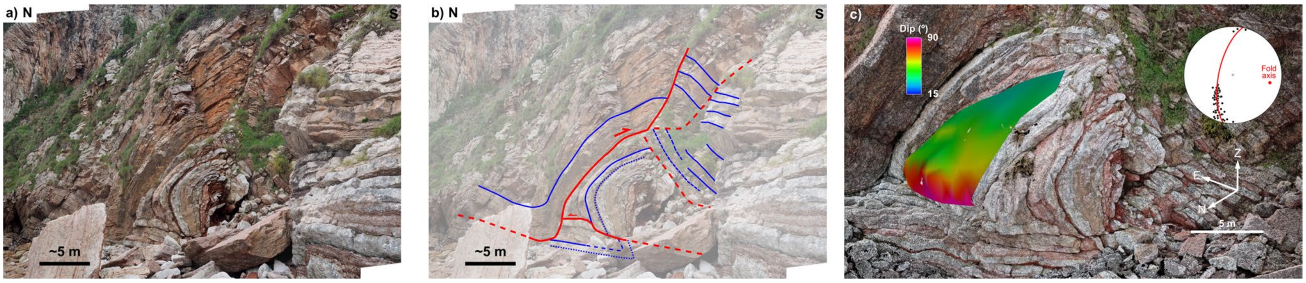


Fig. 12 **a**) Photograph of the Ballota Beach at the foot of the cliff showing Carboniferous rocks (Alba Fm.) folded by a faulted anticline, and cut and offset by a backthrust. **b**) Photogeological interpretation of the photograph shown in a). Beds: blue lines, and faults: red lines. **c**) Portion of the virtual outcrop model of Fig. 6 illustrating the folded and faulted Carboniferous rocks shown in a) and b). The folded bedding surfaces have been coloured according to their dip using the software "Move". The equal-area projections in the lower hemisphere have been constructed using the software "Stereonet" developed by Cardozo and Allmendinger (2013). The bedding plane poles have been represented using black circles, while the fold axes have been represented using red circles

as well; thus, the upper part of the island is subhorizontal and its height is slightly less than 50 m. Looking south from the La Boriza viewpoint, one can see a subhorizontal region very close to the viewpoint with similar heights and covered by the same type of vegetation. This rasa is developed on Carboniferous limestones which, apart from the Alba Fm., belong to other younger stratigraphic units defined using different names: "Caliza de Montaña" and Picos de Europa Fm. (Martínez-García et al. 1981), "Caliza de Montaña" and Cuera Limestone (Marquínez 1989), and Barcaliente, Valdeteja and Picos de Europa fms. (Instituto Geológico y Minero de España 2021) (Figs. 13c, 15b). Various types of karstic morphologies are developed on this rasa.

Looking west from La Boriza viewpoint, another area slightly higher than that of the viewpoint itself, from 140 m.a.s.l. close to the viewpoint up to 170 m.a.s.l. farther west (Fig. 13b), is recognized. This area, that exhibits subhorizontal topography (Fig. 15a), is installed on the Sierra Plana de Cue and has been used to build the Cuesta de Llanes golf course. The rocks that constitute the substratum of this rasa are quartzites of the Ordovician Barrios Fm., and are unconformably covered by Quaternary deposits (Figs. 13c, 15b).

Looking south from La Boriza viewpoint, another area, whose height ranges from approximately 230 m.a.s.l. in the Sierra Plana de La Borbolla to 260 m.a.s.l. in the Roñanzas Lake (Fig. 13b), can be identified. This area, generally vegetated by shrubs (Fig. 14b), displays an approximately horizontal topography (Fig. 15a). As in the case of the rasa described above, the substrate of this rasa is formed by quartzites of the Ordovician Barrios Fm., on which Quaternary deposits lay unconformably (Figs. 13c, 15b).

Applying the workflow described in the methodology section (Fig. 7), apparently three rasas can be distinguished in the study area according to their height above sea level and considering the rocks on which they are developed (Fig. 16). The lowest rasa is developed on a carbonate substratum. At a higher elevation than this one, there are two more rasas, both developed on the same quartzite substratum. Although most authors identify different levels of rasas (e.g., Flor 1983; Flor and Flor-Blanco 2014; Domínguez-Cuesta et al. 2015; López-Fernández et al. 2020; Goy et al. 2023), it is worth highlighting the hypothesis of Mary (1983), who interpreted the flattened surfaces on the Carboniferous limestones located among other lithologies as a result of karst erosion.

In order to analyse the spatial relationship between the two rasas developed on the quartzite substrate, a detailed geological cross-section has been constructed showing the rasa Quaternary deposits located in the Sierra Plana de Cue, in the Sierra Plana de La Borbolla and in the Roñanzas Lake. These deposits can be joined together by means of a line that would have an inclination of approximately 2° towards the north. This suggests that the two supposed rasas developed on the quartzite substrate could be part of a single rasa (Fig. 15c). This slight inclination of the rasa towards the sea is perfectly reasonable, since it can be interpreted either as an original feature of the abrasion platform at the time of its formation or as a result of neotectonic activity, which would be endorsed by the presence of some newly created faults and reactivation of previous faults (e.g., Gutiérrez-Claverol et al. 2006; Álvarez-Marrón et al. 2008), as well as by small magnitude earthquakes (e.g., López-Fernández et al. 2004) in surrounding regions.

Relations Between the Rasas and the Sea Level from their Formation to Present-Day

To determine the temporary evolution of the rasas and whether they have emerged or sunk more than once during their history, we will examine the relationship between the terrain and the sea level using different types of data.

We do not have sufficient data to determine precisely when the emersion of the rasas occurred, however, the peat deposits identified on the quartzite substrate of the

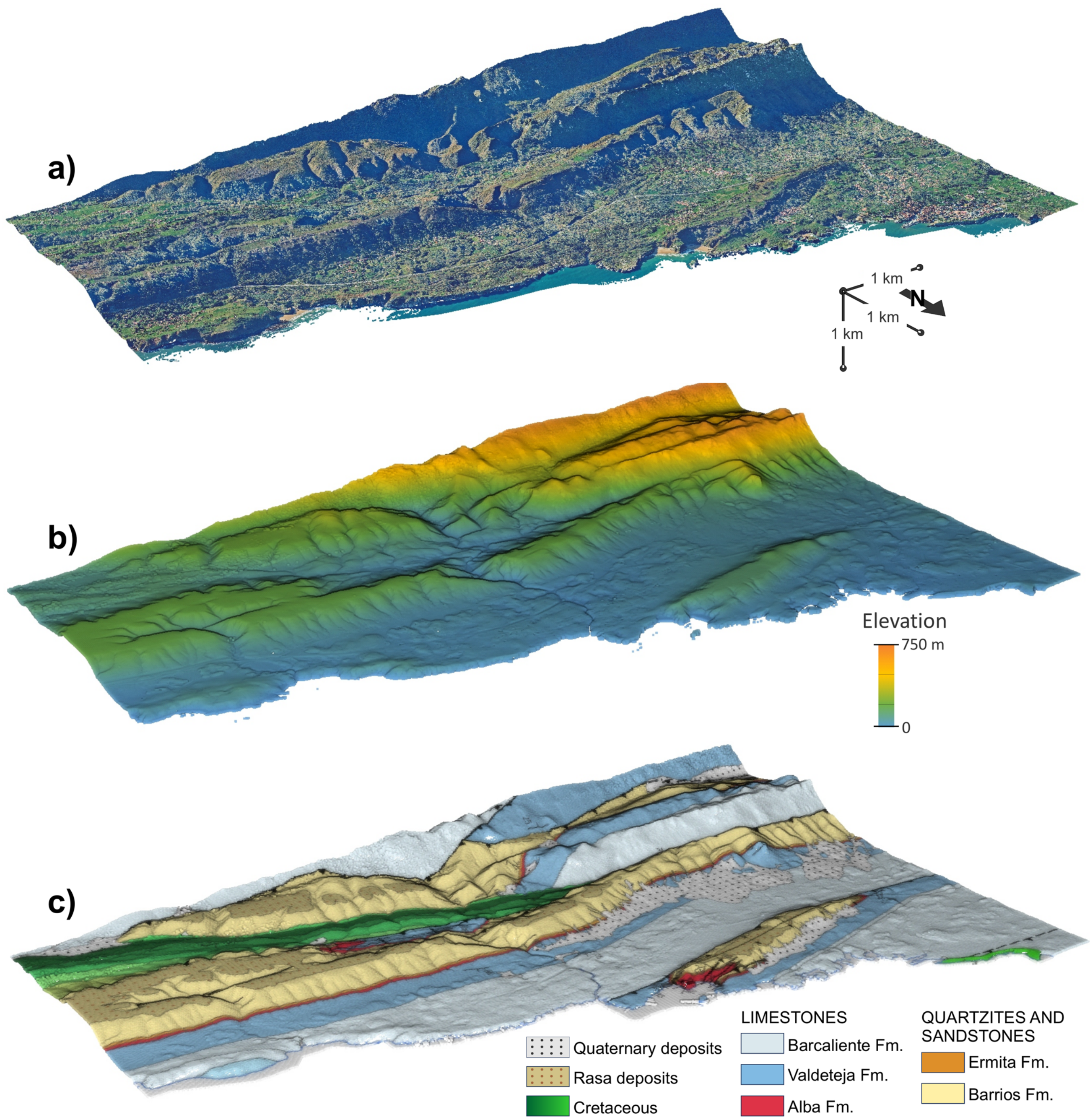


Fig. 13 Digital elevation model of the rasas in the study area coloured using **a**) natural colours and **b**) according to different elevations. **c**) Geological map draped over the digital elevation model (see also Fig. 15b for the legend of the geological map). The north boundary of the digital elevation model is the coastline. The area covered by the digital elevation model is the same one than that displayed in the slope map in Fig. 15a and the geological map illustrated in Fig. 15b

rasa (Mary 1983; Ortiz et al. 2008, 2010; Moreno et al. 2009) can provide information about it. The peat deposits in the Roñanzas Lake area (Figs. 15a, b, c, 16a), resting on the upper part of the quartzite rasa, have been dated using radiocarbon and have provided ages ranging from just over 7,000 to around 180 cal yr BP (Moreno et al. 2009; Ortiz et al. 2010). This indicates that the upper part of the quartzite rasa was emerged during this time period. Jiménez-Sánchez et al. (2006) dated speleothems using U/Th in the Pindal Cave at a height between 50 and 64 m.a.s.l. located a few kilometres to the east of the study area (see Fig. 1 in Jiménez-Sánchez et al. 2006 for location). Considering that the cave is developed in limestones and its height above sea level, we believe the dated cave is located

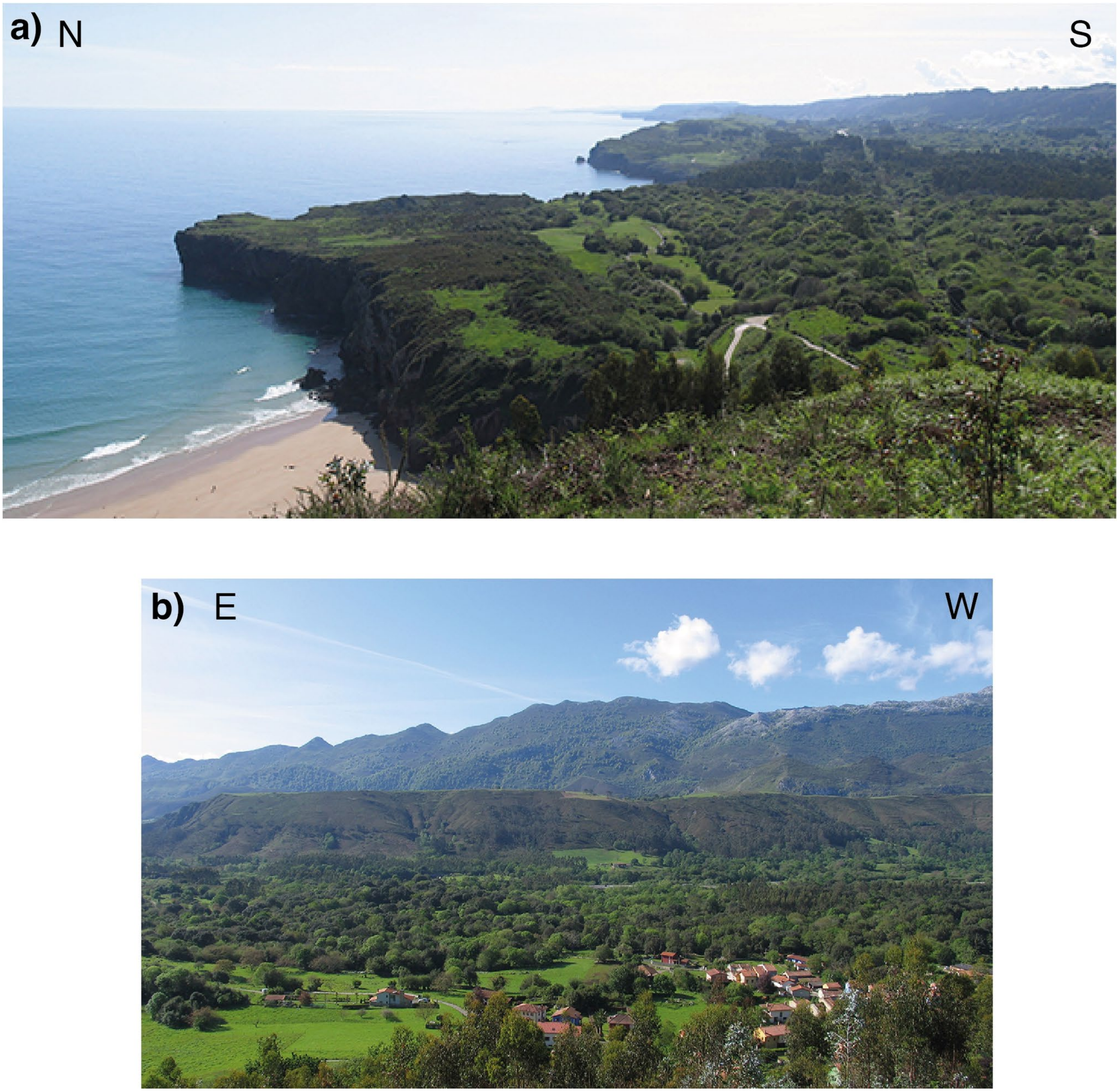
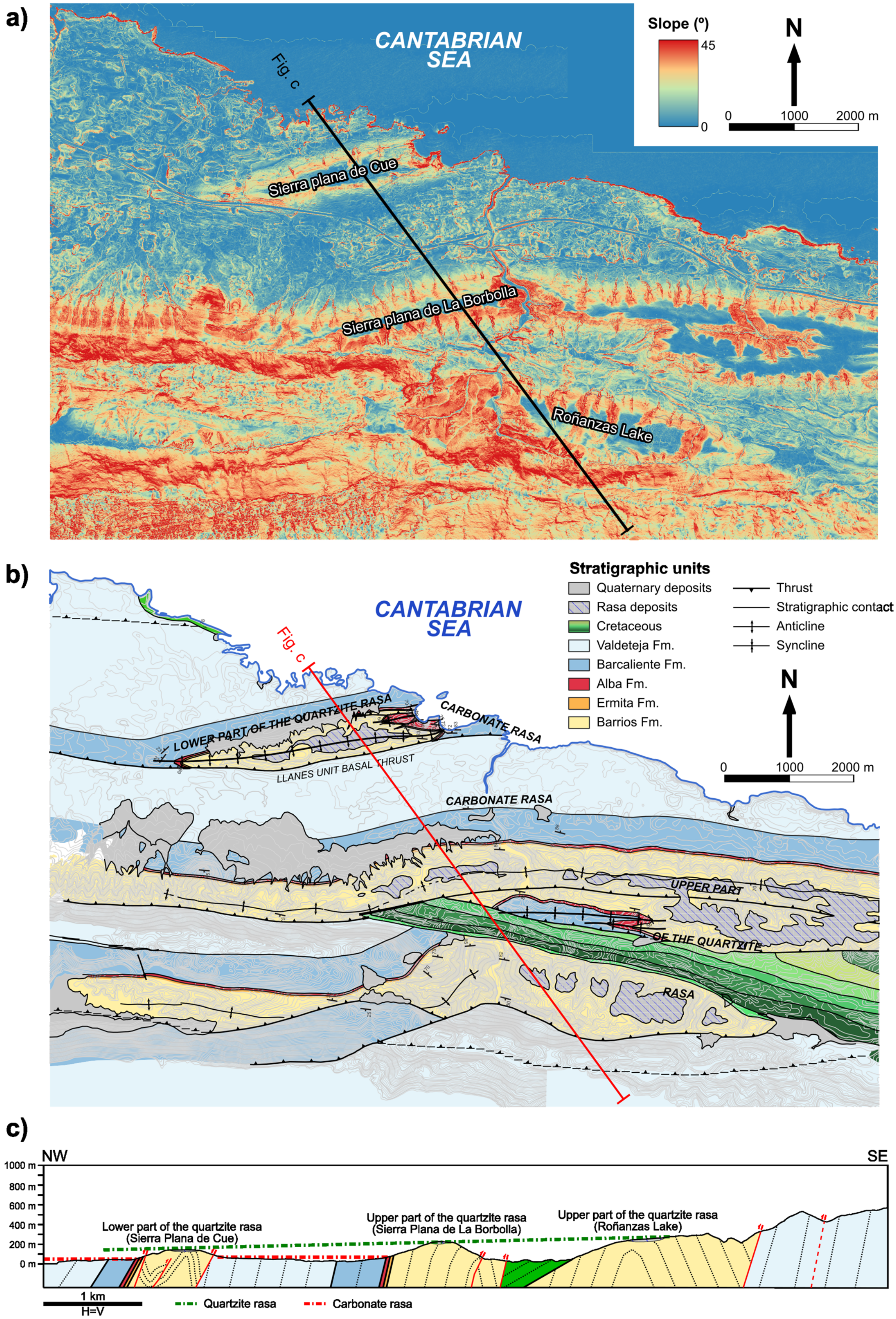


Fig. 14 Photographs of the Quaternary rasas taken from La Boriza viewpoint. **a**) Carbonate rasa located on a cliff over the Cantabrian Sea whose height is approximately 50 m.a.s.l. **b**) Carbonate rasa in the foreground, upper part of the quartzite rasa (Sierra Plana de la Borbolla), whose height is approximately 230–240 m.a.s.l. in the midground, and Cantabrian Mountains in the background

in the eastwards continuation of the carbonate rasa identified here. Jiménez-Sánchez et al. (2006) obtained ages ranging from approximately 124 to 2 kyr BP (i.e., from Late Pleistocene to Late Holocene -Quaternary- according to the International Commission on Stratigraphy 2023) and extrapolating the deposition rate for the total karst complex they obtained maximum ages 290 kyr BP (i.e., Early Pleistocene according to the International Commission on Stratigraphy 2023). Thus, these data indicate that the carbonate rasa remained emerged from the Late Pleistocene to the Late Holocene. However, the beginning of the rasa emersion could have occurred long before. According to Jiménez-Sánchez et al. (2006) the uplift of the carbonate rasa located to the east of the study area occurred at a rate of 0.19 mm/yr, Uzkeda et al (2025) estimated uplift rates from 0.092 to 0.194 mm/yr for a carbonate/terrigenous rasa west of the study area, and Álvarez-Marrón et al. (2008) estimated maximum uplift rates comprised between


a)
CANTABRIAN SEA
Slope (º)
45
0
N
0 1000 2000 m
Fig. c
Sierra plana de Cue
Sierra plana de La Borbolla
Roñanzas Lake
b)
CANTABRIAN SEA
Stratigraphic units
Quaternary deposits
Rasa deposits
Cretaceous
Valdeteja Fm.
Barcaliente Fm.
Alba Fm.
Ermita Fm.
Barrios Fm.
Thrust
Stratigraphic contact
Anticline
Syncline
N
0 1000 2000 m
Fig. c
LOWER PART OF THE QUARTZITE RASA
CARBONATE RASA
LLANES UNIT BASAL THRUST
CARBONATE RASA
UPPER PART
OF THE QUARTZITE
RASA
c)
NW
SE
1000 m
800 m
600 m
400 m
200 m
0 m
Lower part of the quartzite rasa (Sierra Plana de Cue)
Upper part of the quartzite rasa (Sierra Plana de La Borbolla)
Upper part of the quartzite rasa (Roñanzas Lake)
1 km
H=V
Quartzite rasa
Carbonate rasa

◂**Fig. 15** **a**) Slope map of the study area showing the location of the topographic profile illustrated in c). The area covered by the slope map is the same one than that displayed in the digital elevation model in Fig. 13 and the geological map illustrated in b). **b**) Geological map of the study area modified from Martínez-García (1990), showing the rasas and the location of the geological cross-section illustrated in c). The quartzite rasa is defined by the rasa deposits (grey colour) on top of the quartzites (yellow colour), while the carbonate rasa is approximately defined by the limestone units (blue and red colours) next to the sea. See Fig. 13c for a 3D view. The area covered by the geological map is the same one than that displayed in the digital elevation model in Fig. 13 and the slope map illustrated in a). **c**) Geological section across the study area showing the carbonate and the quartzite rasa. See a) and b) for location of the section line on the slope map and on the geological map

0.017 and 0.15 mm/yr for the quartzite rasa located to the west of the study area.

The information presented above indicates that land was reclaimed from the sea since the beginning of the Quaternary and during most of the Quaternary in this region, since the rasas remained emerged. During the Holocene up to the present, the sea recovered part of this land, according to the information sources detailed below.

i) First, we will examine sea level curves derived from the analysis of Holocene fossil remains and sediments collected in the study area and surroundings (see Fig. 1 in García-Artola et al. 2018 for location). These curves reflect the height of the sea surface relative to the solid Earth's surface. They can differ considerably from the global mean value, due to land vertical motion and geoid shift caused by a variety of processes, including surface response to past glacial isostatic adjustments and contemporary changes in land ice mass, tectonics, atmosphere–ocean system dynamics affecting surface sea height relative to the geoid, and local processes such as sediment compaction and shift of tidal range. The data provided by these authors indicate that during this time the sea level was always lower than the current one, so that the rasas remained emerged. The data available for this region during the Middle and Late Holocene document that sea level was above -10.1 m about 8,200 years ago, at -7.1 ± 2.3 m about 7,500 years ago, at -5.5 ± 2.3 m approximately 6,100 years ago and at -1.4 ± 2.3 m approximately 1,200 years ago (García-Artola et al. 2018). Thus, according to these authors, the rate of sea level rise gradually slowed down from several millimetres per year until reaching values of 0.6 ± 0.3 mm/yr in recent times.

ii) Data from tide gauges monitored by the Spanish Institute of Oceanography have been used to obtain information for more recent periods. These devices are located at various coastal points covering the whole north margin of the Iberian Peninsula and span approximately from the decade of the 40's to present-day. The primary objective of the measurement of the tide by the National Geographic Institute was to obtain an altimetric reference level for the existing terrestrial cartography. Nevertheless, periodic levelling is currently carried out in order to obtain an absolute sea level value, as well as study and control of the possible relative vertical movements of the coastal zone (Instituto Geográfico Nacional 2023). According to their records, the sea level trend in this region increases and is slightly above 2.0 ± 0.2 mm/yr (Vargas-Yáñez et al. 2010).

iii) A multi-temporal interferometric analysis based on full resolution Sentinel-1 radar images using the database provided by the Copernicus Land Monitoring Service (2023) has been carried out. The collected data show that, from January 2016 to September 2020, several ground reference points in and around the study area (Fig. 17a) experienced subsidence. The average subsidence rate estimated is approximately 1.24 mm/yr (Fig. 17b).

Summarising, the available data described above show that the sea level rise, currently taking place in the study area, resulted from a proper sea level rise combined with land subsidence. However, the sea level rise rates are low in relation to the height of the rasas, so that in case they remain constant in the future, the rasas will remain emerged at least tens of thousands of years.

It is difficult to accurately identify the paleo shoreline that separates the rasas from the mountains in the study area. The reason is that the southern part of the rasas is not very well preserved. However, we could assume that the current position of the rasa deposits located farther south may approximately represent the paleo shoreline (Fig. 15b, c). This assumption is reasonable. Thus, according to the geological cross-section, the Ordovician quartzites, located immediately to the south of these rasa deposits, give rise to steep reliefs higher than the rasa deposits. Therefore, these quartzites would not have belonged to the marine abrasion platform, but to the mountains located to the south of the rasa. Comparing the position of this possible paleo shoreline with the current position of the coastline, we realise that, from the emersion of the rasas up to the present, the balance is positive for the land with respect to the sea. Thus, the land reclaimed from the sea in this region has been approximately slightly over 4 km measured perpendicularly to the coastline.

Scientific, Educational and Geotourism Value of the Study Area

The value from the scientific point of view, both of the rocks that crop out in the cliff and of the relief seen from La Boriza viewpoint, is endorsed by different studies

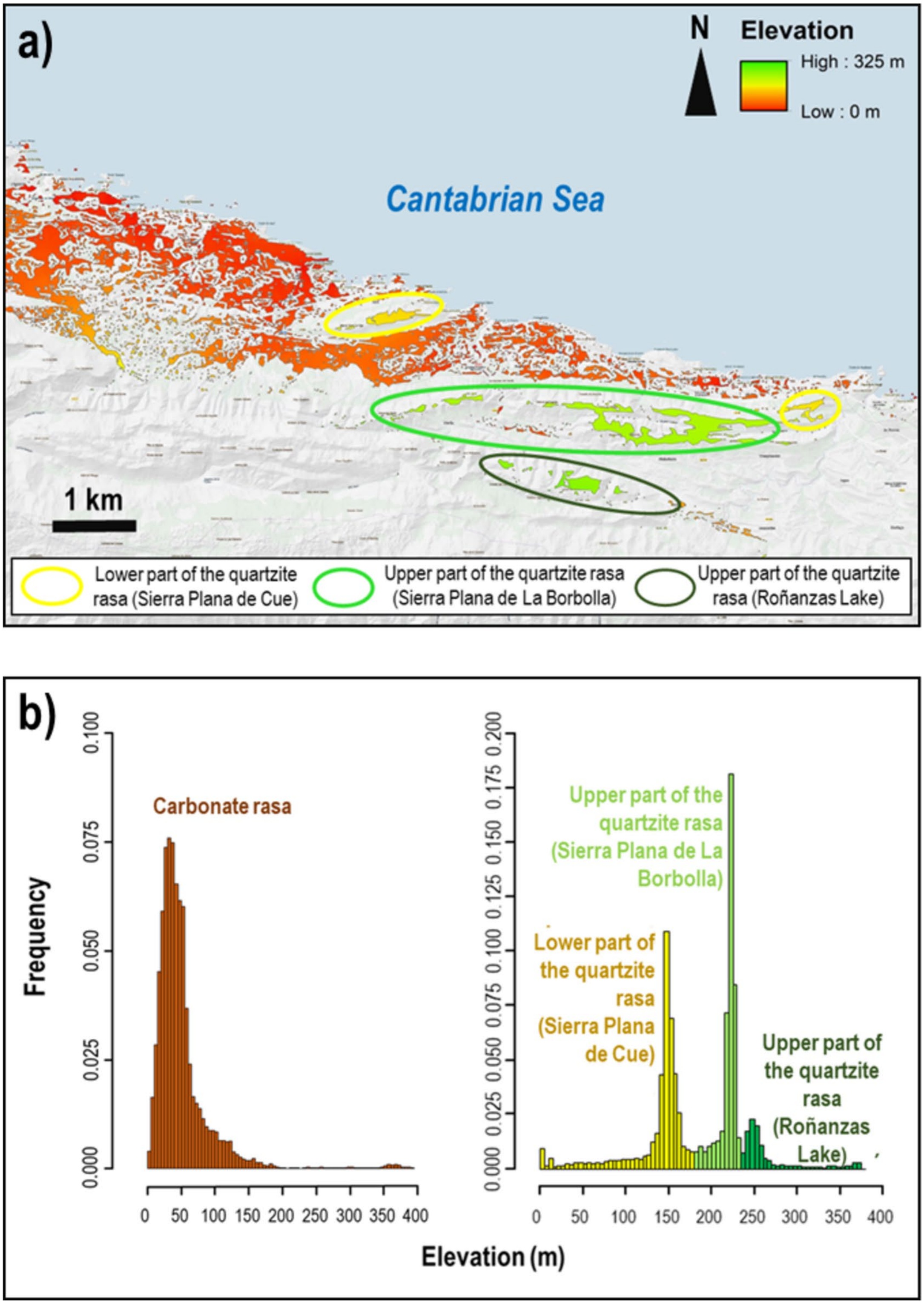


Fig. 16 **a**) Map of the study area and surrounding regions showing the different rasas, built from considering pixels with slopes < 5° in the digital elevation model and information derived from the geological map shown in Fig. 15b. This map has been constructed according to the workflow presented in Fig. 7. **b**) Histograms showing the frequency of different heights above sea level in the regions occupied by Carboniferous carbonate rocks and Ordovician quartzites in the map depicted in a). The colours used to identify the different rasas are the same ones than those used in the map illustrated in a)

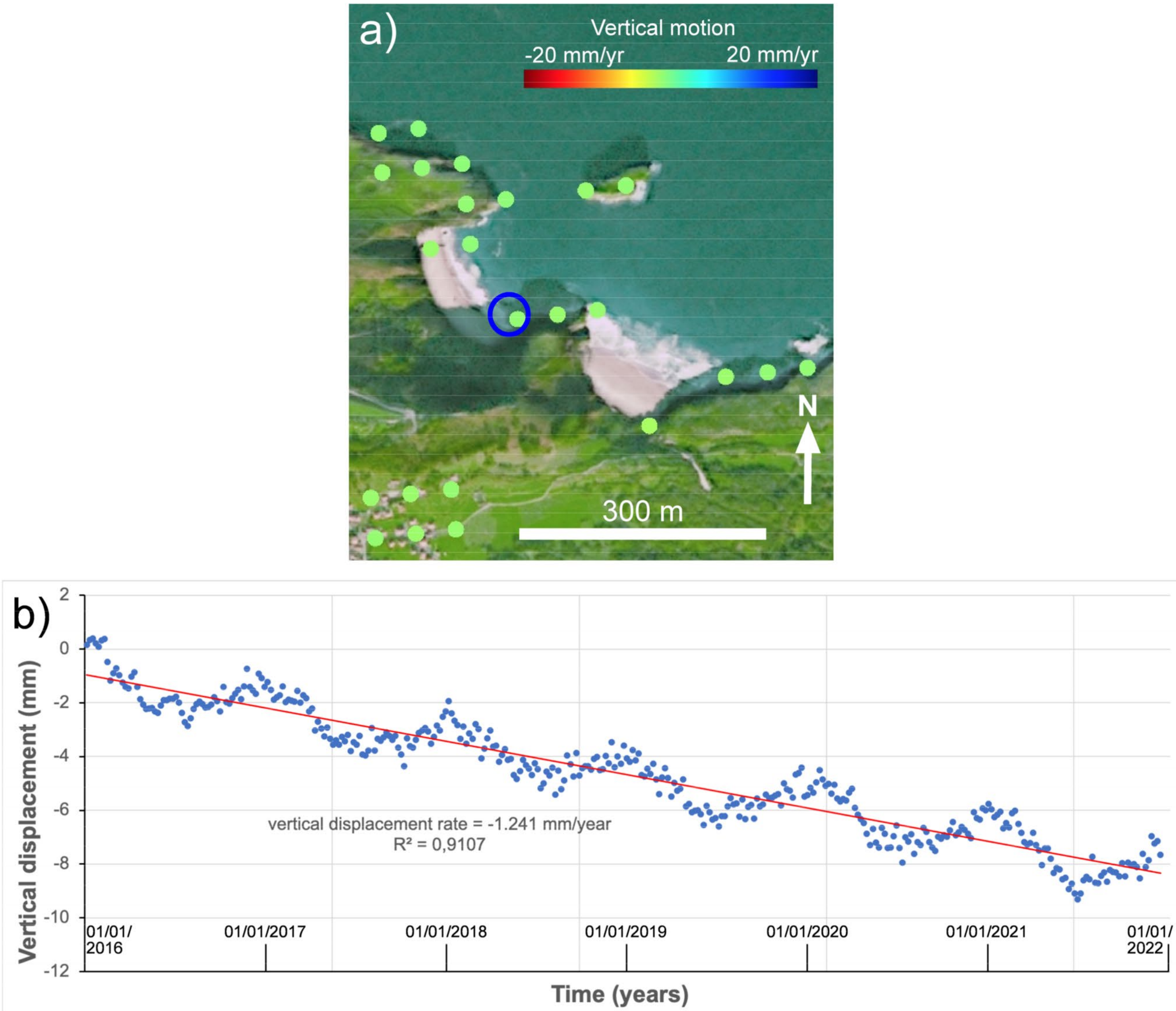


Fig. 17 **a**) Image of the study area showing the value of the average rate of land subsidence measured at 24 points from 2016 to 2020. **b**) Graph illustrating the variation over time of the vertical height of a representative average point (empty blue circle in figure a) of the points shown in figure a). The representative average point is located almost on the studied cliff. Both figures have been constructed using the Copernicus Land Monitoring Service (2023) database

published in scientific journals (see Barrois 1882; De Ana 2015 and Bulnes et al. 2016 in the case of the cliff, and Flor 1983, Mary 1983 and López-Fernández et al. 2020 among others in the case of relief). It is worth noting that the cliff outcrop was the cover of volume 36 of the open-access scientific journal "Trabajos de Geología" (Universidad de Oviedo 2023). Concerning their educational value, photographs of the tectonic structures that crop out in the cliff and of the rasa, have been and are being used in courses taught to Geology students at the University of Oviedo because of their didactic value. In addition, the cliff outcrop is part of a teaching innovation project currently carried out at this University to improve the understanding of Geology in the classroom by using 3D techniques.

The major contributions to science by the cliff outcrop come from the field of Structural Geology. Firstly, the cliff outcrop includes two major types of tectonic structures identified in nature, i.e., folds and faults; specifically, there are very well exposed examples of structures widely recognized in almost the entire planet, such as fault-bend folds, fault-propagation folds, detachment folds and duplex thrust systems (Figs. 6, 9, 10, 11, 12). These structures could be studied in detail to gain insight into their characteristics, origin and development. Secondly, the outcrop is exceptional to establish temporary relationships between structures, such as folds cut by faults, folded thrusts, etc. Thirdly, the tectonic structures developed in the cliff outcrop are testimony to the ductile behaviour of the Alba Fm. during deformation, which suggests that it could have acted as a possible secondary detachment within the Cantabrian Zone, since this type of behaviour has been documented in other regions (e.g., Bulnes 1995; Masini et al. 2010a, 2010b; Bulnes et al. 2019).

The main scientific interest of the relief seen from La Boriza viewpoint falls within the field of Geomorphology, and additionally Tectonics. On the one hand, it is formed by old elevated and abandoned marine abrasion platforms behind modern beaches (Figs. 13, 14, 15, 16); this gives rise to discuss whether the sea level fall and/or the terrain elevation in this region took place as a product of a slow convergence in an incipient subduction zone that extends along the northern coast of the Iberian Peninsula, as suggested by Álvarez-Marrón et al. (2008), due to the late post orogenic isostatic response to the thickening of the crust and equilibrium of the passive margin after the Alpine orogeny that gave rise to the Cantabrian Mountains during the Cenozoic, as proposed by López-Fernández et al. (2020), or perhaps other causes such as a possible retreat of ice generated during a glacial period. On the other hand, this rasa could be correlated with others of similar characteristics and ages in other parts of the world in order to better understand their relationships with large-scale sea level fluctuations (Pedoja et al. 2014).

The contributions of the cliff outcrop and the relief seen from La Boriza viewpoint to the knowledge of the region geological history are also notable, and they do so from different aspects. On the one hand, the cliff outcrop is a spectacular testimony of the shortening that took place in the foreland fold and thrust belt developed in the external part of the Variscan mountain range of the northwest Iberian Peninsula during Carboniferous. On the other hand, the marine abrasion platforms exposed on land, i.e., the rasas, evidence the fluctuation the coastline suffered during the Quaternary. This phenomenon allowed land to be gained to the sea and allowed the cliff outcrop to emerge from the Cantabrian Sea waters, so that we can observe it today. Finally, the incision of the river system in the rasa, highlights the recent and current evolution of the relief. These observations help to understand that the relief we observe is not static and that the confluence of geological processes with different temporal scales make up the landscape we observe nowadays.

Although the fundamental value of the outcrop of the cliff and the relief seen from La Boriza viewpoint is focused on Structural Geology, Geomorphology and Historical Geology, they also have a particular value from the point of view of Stratigraphy. Regarding the cliff, the rocks (Figs. 6, 8, 9, 10, 11, 12) belong to the Alba Fm., one of the most emblematic formations of the Cantabrian Zone that crops out continuously throughout this portion of the Iberian Massif. In addition, the outcrop is mainly made up of “griotte” limestone, the best-known rock within this stratigraphic unit, often used as ornamental rock on the facades of buildings. Finally, the cliff may be one of the most extensive outcrops of this type of limestone in the Cantabrian Zone. Regarding the relief seen from La Boriza viewpoint, a look at the upper part of the Castro Ballota Island from the viewpoint allows a quick visual estimate of the different height of the rasas, since the upper part of the Castro Ballota belongs to the carbonate part of the rasa, while the viewpoint is built approximately on the quartzite part of the rasa.

Moreover, the virtual outcrop models of the cliff (Fig. 6) contribute to increase the database of virtual outcrop models of the north-northwest part of the Iberian Peninsula currently available (Uzkeda et al. 2022) and in particular of this region. Thus, regarding the study area, apart from the models created here, there is also a model of the northern boundary of the Ballota Beach (Martín et al. 2019) and a model of the beach located immediately to the south of the Ballota Beach (Uzkeda et al. 2022).

Folds with associated minor folds, thrusts and backthrusts, duplex thrust systems, as well as various types of fault-related folds, such as fault-bend folds, fault-propagation folds and detachment folds, are widely studied structures (e.g., Boyer and Elliott 1982; Butler 1987; Poblet 2004; Brandes and Tanner 2014) that develop in various tectonic settings, including foreland fold and thrust belts, accretionary prisms and toe-thrust systems formed from the Palaeozoic to recent times in many parts of the world. One classical example is the Rocky Mountains in North America (see more examples in Poblet and Lisle 2011). This highlights the global character of the Ballota Beach cliff. Moreover, the inclusion of one of the Cantabrian rasas in the study carried out by Pedoja et al. (2014) points to the global relevance of La Boriza viewpoint from the scientific point of view, because remains of such elevated rasas occur around it. Pedoja et al. (2014) include a summary of rasas all over the world, some of them with elevations and/or ages similar to the ones studied here, such as the rasas in north Perú in South America.

The cliff and La Boriza viewpoint belong to an area highly appreciated from the tourist point of view. Thus, photographs of this region appear in various tourism promotion documents elaborated by public and private entities, especially through internet where they are easily found by typing keywords such as "Playa de Ballota" or "Mirador de La Boriza" on any of the internet search engines or travel platforms. According to Lonely Planet (2023) the Ballota beach is the most beautiful beach in Spain, whereas according to National Geographic Viajes (2023) the Ballota beach is one of the eleven best beaches in Asturias due to its beauty and wild state. In addition, both the Ballota Beach and La

Boriza viewpoint, as well as various localities on the rasa, have been the settings for three movies shot in these places, generally chosen for their beauty (Gobierno del Principado de Asturias 2009). The so-called Camino de Santiago corresponds to a set of Christian pilgrimage routes of medieval origin that go to the tomb of Santiago El Mayor, located in the cathedral of Santiago de Compostela (Galicia, Spain) (Wikipedia 2023c). This journey is travelled by many pilgrims every year. One of the routes of the so-called roads of the north of the Iberian Peninsula belonging to the Camino de Santiago passes through the Ballota Beach. The Ballota Beach offers a beautiful contrast of colours: the reddish colour of the rocks that form the cliff outcrop, very striking in comparison with the green colour of the vegetation that occupies the rasa and adjacent areas, the blue colour of the sky (or grey on cloudy days), the blue-greenish colour of the sea and the brown colour of the sand on the beach. The cliff outcrop draws the attention of people who are not seasoned in Geology due to its particular aesthetics; thus, some have described it using expressions such as "it reminds of carved wood" or "they are capricious forms of nature". The steps in the landscape marked by each rasa are also the object of tourists' curiosity, who ask about their causes. In addition, this area also has a remarkable attraction from the sporty point of view since surf is performed in the waters of the Ballota Beach, and there is a golf course located above the quartzite rasa next to La Boriza viewpoint. Thus, both the cliff outcrop and the rasa, explained at an informative level, either through tourist promotion brochures available in tourist offices, web pages or information panels in situ, could contribute to increase the landscape and recreational potential of this region to be added to the already tourist attraction.

Both the cliff outcrop and the relief seen from La Boriza viewpoint have a series of additional characteristics regarding access and viewing, that make them very attractive and contribute to increase their scientific, educational, and geotourism values described above. In the first place, access to both the outcrop and the viewpoint is relatively easy (Fig. 2), although the presence of high and low tides must be taken into account because it prevents access at any time to the base of the cliff, and some rock blocks on the beach may make walking slightly difficult when trying to get close to the outcrop. The cliff outcrop may be visualized from various points, such as from the beach, the path and the stairs leading down to the beach, and also from the bar-restaurant and its outdoor terrace. The rasas may be visualized from the viewpoint and also from the path that leads to the viewpoint. It is easy to recognize both the rocks that make up the outcrop and the rasas because they are hardly covered by debris or other types of elements. Bedding is very well developed and this allows understanding the structure of the rocks in the cliff outcrop. Lastly, both the outcrop and the rasas display large dimensions, allowing a good visualization from the distance.

The two localities within the Ballota Beach described here are not standalone entities; rather, they are part of the geological heritage of the Cantabrian Coast, already recognized by authorities and institutions in other nearby spots (Fig. 5) such as the Cobijeru Complex Natural Monument (Principado de Asturias 2024a), the Gulpiyuri beach Natural Monument (Principado de Asturias 2024b), the Santiuste blowhole Natural Monument (Principado de Asturias 2024c), the Arenillas blowholes Natural Monument (Principado de Asturias 2024d; Instituto Geológico y Minero de España 2015b), the rasas de Cue (Instituto Geológico y Minero de España 2015a) and the Llames de Pría (Instituto Geológico y Minero de España 2015c; Sociedad Geológica de España 2019), and could be integrated in a list of geological excursions such as the ones presented in Adrados González (2014).

Actions we Propose to Conserve and Promote the Study Area

It is well known that coastal cliffs undergo retreat due to waves and tides, sea level fluctuations, rain and groundwater, wind, ice and cold weather, karstic phenomena, instabilities of the slope and earthquakes among others (e.g., Hampton and Griggs 2004). The outcrop of the cliff by the Cantabrian Sea shore undergoes periodic changes, mainly due to the fall of rock blocks and landslides, usually during the autumn and winter seasons. We have been observing these phenomena since 2014 when we started working in this region. Since it is not possible to maintain the coastal cliff outcrop in its current state, we have considered that building virtual outcrop models is a good way to preserve it somehow (Fig. 6). The models built reflect the state of the outcrop during the autumn season by the end of 2022. Concerning the rasas, we believe no particular conservation actions are required, beyond the usual conservation regulations of any natural area, also considering that the digital elevation models show a beautiful view of the rasa (Fig. 13).

In order to improve the global impact of the studied area, we propose three actions detailed below.

i) Declare the outcrop of the cliff as a place of geological interest in the Global Geosites Spain project. This open-access project is promoted by the European Association for the Conservation of Geological Heritage (ProGEO) and the International Union of Geological Sciences (IUGS) with the co-sponsorship of the United Nations Educational, Scientific and Cultural Organization (UNESCO), and its objective is to list the places of geological interest and promote their conservation and recognition (e.g., García-Cortés et al. 2000; Wimbledon et al. 2000; Instituto Geológico y Minero de España 2023). Including this outcrop in the Geosites Spain project is entirely justified given that its characteristics fit one of the geological contexts of international relevance defined in this project, which would be number 16 (The Iberian Variscan orogen). La Boriza viewpoint and the rasas were already included as a place of geological interest in the Global Geosites Spain project by Flor, Flor-Blanco and García Cortés at the Instituto Geológico y Minero de España (2015a) under topic number 2 (Iberian Peninsula coasts).

ii) Considering the considerable impact and dissemination of the Geoheritage journal, we propose to make this article open access, so that all relevant geological information about this region is freely available to interested persons.

iii) The obtained virtual outcrop model of the cliff may be uploaded to the online open-access repositories of virtual outcrop models called eRock (Cawood and Bond 2019, 2023) and virtual 3D Geoscience (Buckley et al. 2021; Virtual Outcrop Geology Group 2023), widely consulted for scientific and educational purposes.

At national and regional levels, we propose the strategies described below.

i) Send all the available information to three entities, so that they may consider this area and its characteristics in their tourism and dissemination policies. The first and second entities are the Ministry of Culture, Language Policy and Tourism of the Government of the Principality of Asturias, which deals with tourism within the Autonomous Community, and the town hall of the Council of Llanes, which has a commission dedicated to the tourism promotion of the Llanes area, one of the most touristic councils in Asturias and the council to which the study area belongs. Our objective would be that these entities would include information on the study area in tourism promotion brochures and web pages, and also finance two informative panels including geological interpretations and explanations of the outcrop and the landscape. The informative panel relative to the cliff should be placed on the landing of the stairs just before accessing the Ballota Beach, and the one relative to the rasa at La Boriza viewpoint. The third entity is the University of Oviedo, to which the information will be sent in order to be published in one of its daily online newsletters and expecting that the Research Results Transfer Office (OTRI) of the University will disseminate the information to local communication media such as newspapers, as well as radio and television networks.

ii) Proposal for two field stops integrated into a "Geolodía" under the topic "a window to the ancient and most recent past" in order to explain the main characteristics of the outcrop and relief, as well as the geological history deduced from their observation. In addition, this action may serve to sensitize the population about the importance and need to protect the geological heritage. The "Geolodía" is an annual journey dedicated to disseminate Geology in Spain through geological fieldtrips in each of the more than fifty provinces that belong to the country. The fieldtrips, free and open to anyone interested, take place in places of geological interest, and are led by teams of professional geologists from universities, research councils, museums and companies (Wikipedia 2023b), who provide rigorous information at an informative level. These fieldtrips are coordinated by the Geological Society of Spain (SGE), in collaboration with the Spanish Association for the Teaching of Earth Sciences (AEPECT) and the Geological and Mining Institute of Spain (IGME). The Spanish Foundation for Science and Technology (FECYT) finances this activity, in addition to numerous local entities, such as universities, research councils, foundations, museums, town halls, provincial delegations and other types of administrations (natural parks among others).

iii) Prepare a short promotional video of the study area to upload to the website of the Geological Society of Spain under the initiative promoted by this society, in commemoration of the International Day of Geodiversity. This video should highlight the richness of this region from the structural, geomorphological, historical and stratigraphic points of view. The International Day of Geodiversity was proclaimed by the United Nations Educational, Scientific and Cultural Organization at the 41st General Conference of 2021, and is celebrated on October 6th of each year to promote the multiple aspects of geodiversity for people and for the natural environment (Asociación Española para la Enseñanza de las Ciencias de la Tierra 2022).

Conclusions

From our point of view, the outcrop located in the cliff that forms the southern limit of the Ballota Beach and the views from La Boriza viewpoint located on the cliff are two strategic locations in order to decipher the ancient and modern geological history of the north-northwest part of the Iberian Peninsula. Their value lay first in their high scientific and educational potential from the point of view of Structural Geology, Geomorphology, Historical Geology and Stratigraphy. In addition, both locations have a great geotourism attraction due to their scenic beauty that accentuates the high tourist value this region itself already has. The outcrop of the cliff shows, through spectacularly-exposed different types of tectonic structures, the shortening this region suffered during Carboniferous. This shortening gave rise to the formation of the Variscan mountain range that extends throughout central Europe, and the northern and eastern parts of Africa and North America respectively. From La Boriza viewpoint, rasas can be recognized, which correspond to ancient marine abrasion platforms elevated above the current sea level. These rasas are a testimony of land reclaimed from the sea by sea level falling and/or land uplift occurred during the Quaternary on the coasts of the northern margin of the Iberian Peninsula. We believe that this region, apart from making itself known through this article, it deserves additional actions such as a declaration of a place of geological interest in the Global Geosites Spain project, uploading of a virtual outcrop model in online platforms, publicity by the institutions whose mission is to promote tourism in this region, organization of a “Geolodía” in which the studied area would constitute two stops, and creation of a short promotional video to celebrate the Geodiversity Day.

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Data Availability The data used for the research are included in the article.

Declarations

Competing of Interest The authors have no competing interests to declare that are relevant to the content of this article.

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