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GIS as a tool to detect flat erosional surfaces in coastal areas: a case study in North Spain

M.J. DOMÍNGUEZ-CUESTA M. JIMÉNEZ-SÁNCHEZ J.A. GONZÁLEZ-FERNÁNDEZ L. QUINTANA G. FLOR G. FLOR-BLANCO

Department of Geology, University of Oviedo
C/ Arias de Velasco s/n, 33005, Oviedo, Spain. Fax: 00 34 985 103 103
Domínguez-Cuesta E-mail: mjdominguez@geol.uniovi.es Jiménez-Sánchez E-mail: mjimenez@geol.uniovi.es
González-Fernández E-mail: jose.antonio.gonzalez.fernandez77@gmail.com Quintana E-mail: quintana@geol.uniovi.es
Flor E-mail: gflor@geol.uniovi.es Flor-Blanco E-mail: gfb@geol.uniovi.es

ABSTRACT

The delimitation of flat surfaces, such as marine or continental terraces, can be easily done if they are well preserved by using classic techniques such as fieldwork and photointerpretation. However, subsequent landscape erosion can modify their initial morphology, hindering their recognition. This paper presents a methodology designed to identify and delineate flat erosional surfaces (known as *rasas*) in a sector of 1,228km^2 in the Cantabrian coast (eastern Asturias, N Spain). The spatial distribution of *rasas* was quantitatively established by comparing the Digital Terrain Model (DTM) with previously available information about flat surfaces already mapped. From a lithological point of view, *rasas* are modelled on Ordovician quartzite (9.7km^2 of 1,228) mainly between 132–232m above sea level (a.s.l.) altitude and on Carboniferous limestone (2.9km^2 of 1,228) mainly between 24–69m a.s.l. The use of Geographic Information Systems (GIS) combined with a quantitative analysis of the relief (using the hypsometric method) allowed us to develop a predictive approach for flat erosional surface detection. The methodology has been tested and validated in areas in which there were no erosional surfaces previously mapped. The results reveal new surfaces modelled on Ordovician quartzite (0.43km^2), at altitudes ranging from 200 to 250m, on Jurassic mixed formations (35.9km^2) at 150–175m altitude, and on Eocene limestone (1.1km^2) at 110–120m altitude.

KEYWORDS **Flat erosional surface. Rasa. GIS. Asturias. Spain.**

INTRODUCTION

The relief of northwestern Iberian Peninsula is defined by a complex orography in which the Cantabrian Mountain Range (~400km length) trending E–W appears as the main landscape unit. It has been modelled by a variety of processes (glacial, fluvial, karst and slope processes) during the Cenozoic. Altitudes descend to the north from up to 2.500m a.s.l. to smooth reliefs and pre-littoral ranges towards the Cantabrian Sea. There are some flat surfaces at 325m a.s.l. and higher altitudes clearly linked to a continental origin (Pérez-Alberti, 1993; Pagés and Vidal Romaní, 1998; Flor and Peón, 2004; Miranda Duque *et al.*, 2004) under subarid climate conditions (Flor and Flor-Blanco, 2014).

Since last century, rocky coasts have been studied from a geomorphological and evolutionary point of view (Sunamura, 1978; Trenhaile, 1987; Sunamura, 1991; Trenhaile, 2002; Henaff *et al.*, 2006; Naylor *et al.*, 2011; Trenhaile, 2014). Several studies have emphasized the morphological features, processes or heights in the Atlantic and Cantabrian coasts of the Iberian Peninsula (Blanco-Chao *et al.*, 2003; Moura *et al.*, 2006; Álvarez-Marrón *et al.*, 2008; Feal-Pérez *et al.*, 2009; Flor and Flor-Blanco, 2009).

The Cantabrian coast is a steep coastline with flat erosional landforms referred in classic works (Schulz, 1858; Barrois, 1882). Since last century, several studies have shown the importance of these flat areas, known as *rasas*, in the landscape configuration of both littoral and pre-littoral areas of the Cantabrian coast, in northern Iberian Peninsula. *Rasas* appear as outstanding landscape features, clearly recognized thanks to the preservation of a variable number of levels of flat and raised surfaces, which run roughly parallel to the coast (Flor, 1983; Mary, 1983, 1985; Moñino, 1986; Moñino *et al.*, 1988; Rodríguez-Asensio *et al.*, 1999; Rivas, 2000; Jiménez-Sánchez *et al.*, 2002, 2004, 2006; Flor and Peón, 2004; González-Amuchástegui *et al.*, 2005; Flor-Blanco, 2007; Moreno *et al.*, 2009; Álvarez-Marrón *et al.*, 2008; Flor and Flor-Blanco, 2014).

The continental or marine origin of these flat surfaces is being discussed and remains unclear. Some authors defend the idea that there is a single Plio–Pleistocene flat surface (Birot and Solé-Sabarís, 1954; Hoyos-Gómez, 1989). Other authors note that a sole surface is visible in the western part of the Cantabrian coast, which corresponds to the northern coast of Galicia (Flor and Flor-Blanco, 2014). Towards the east, it is possible to distinguish up to 12 levels of staggered *rasas* between the Nalón Estuary, in the middle of the Cantabrian coast, and the eastern end of the Cantabrian coast in the Basque Country. Among these 12 levels, there are up to eight continental *rasa* levels (I to VIII, in Table 1), at altitudes ranging between 285 and 95m, covered by alluvial and slope deposits and peat (Flor and Flor-Blanco, 2014). Below these altitudes, the same authors recognize four marine *rasa* levels located at 35, 20, 7 and 4m, respectively (IX to XII, in Table 1).

TABLE 1. Altitude of flat erosional surfaces (FES) detected in this work compared with previously defined *rasa* levels (modified from Flor and Flor-Blanco, 2014)

RASA LEVEL	FOOT / NICK POINT ALTITUDE (m)	ALTITUDE FES DETECTED BY GIS (m)	MAIN DEPOSITS
I	285		alluvial/peats
II	230	200-250	alluvial/peats
III	185		alluvial/slope
IV	160	150-175	alluvial/slope
V	145		alluvial/slope
VI	115	110-120	alluvial/slope
VII	95		alluvial/slope
VIII	65	61-63	beach/aeolian dunes
IX	35		beach
X	20		beach/slope
XI	7		beach/aeolian dunes/slope/peats
XII	4		beach

Different hypotheses have been proposed to explain the origin of *rasas*. Classically, *rasas* were interpreted as the result of a crustal tilting to the west, including a lower elevation rate of the Galician block, with some pauses (Llopis Lladó, 1954). Some authors defend that these platforms are related to crustal elevation processes occurred after the Miocene (Flor and Peón, 2004) with differences in height mainly linked to changes in bedrock lithology (Mary, 1985). Other authors consider that the tectonic factor explains the elevation differences (Mary, 1983; Álvarez-Marrón *et al.*, 2008). In fact, in the western coast of Asturias, some faults in metric displacements affecting marine deposits of *rasas* have been reported (Gutiérrez Claverol *et al.*, 2006).

In the western Asturian coast, Álvarez-Marrón *et al.* (2008) reported a marine terrace located between Cape Peñas and Ribadeo Estuary extending for ~100km. Absolute dating (multiple cosmogenic nuclides: ^{21}Ne, ^{10}Be, ^{26}Al) gave ages of at least 1–2Ma.

Most of the *rasas* are predominantly modelled on siliceous bedrocks, particularly in western Asturias (*e.g.* Álvarez-Marrón *et al.*, 2008). Several levels of flat surfaces modelled on Ordovician quartzite can be distinguished in eastern Asturias. Some examples can be observed in the Bedón River outlet area, where different levels of *rasa* are preserved at different altitudes: 285, 230, 185, 115, 80, 35 and 20m, respectively (Flor, 2000); different levels can also be observed in the area of Colombres (125–170m, Jiménez-Sánchez *et al.*, 2006). However, in limestone bedrocks, the delimitation of *rasas* cannot be carried out so easily. This is the case of the described levels at 70–80m near Ribadesella (Jiménez-Sánchez *et al.*, 2004) or between 50 and 64m in the area of Colombres (Jiménez-Sánchez *et al.*, 2002, 2006).

When *rasas* are well preserved, they can be accurately mapped with the use of classical techniques including fieldwork and photointerpretation. However, the activity of subsequent landscape erosion processes may have modified their initial morphology and, therefore, the flat surfaces that serve as recognition criteria may not be preserved. In these cases, the identification and mapping of *rasas* is a more subjective task.

Several studies about marine flat surfaces have been published and some detailed maps of these surfaces in the Cantabrian coast are available, especially maps of the eastern coast, where bedrock includes an alternation of siliceous and calcareous lithology (*e.g.* Flor, 2000; Jiménez-Sánchez *et al.*, 2004 and 2006). Moreover, the series of National Geological Maps 1:50.000 (MAGNA series), published by the Spanish Geological Survey (IGME), compile part of the geomorphological information related to the cartography of *rasas* in the North of Spain.

Considering prior knowledge within the area (regardless of the age and the marine or continental origin of these flat surfaces), the aims of this paper are:

i) to design a methodology for landscape study, based on both the use of GIS and a quantitative analysis of the relief, that allows the identification of *rasas*.

ii) to apply the methodology to detect flat erosional surfaces not previously reported.

Setting

The study area is located in the Cantabrian shore (N Spain) and it extends over 1,228km^2, including the eastern Asturian coast (Fig. 1). It is included in five geological maps of 1:50.000 MAGNA series: 15-Lastres (Pinatelli *et al.*, 1972), 30-Villaviciosa (Beroiz *et al.*, 1972), 31-Ribadesella (Navarro, 1984), 32-Llanes (Martínez García, 1980) and partially 33-Comillas (Portero *et al.*, 1974).

The rocks that crop out in the study area range from Cambrian to Oligocene ages and can be divided into two sequences related to two orogenic episodes (Fig. 2). The first sequence, exposed in the central-eastern part of the study area, belongs to the Cantabrian Zone. This sequence ranges from Lower Cambrian to Upper Carboniferous and was deformed during the Variscan Orogeny. The second sequence, mainly represented in the west, includes outcrops from Permian to Cenozoic that were deformed during the Cenozoic Alpine Orogeny (Fig. 2). This Orogeny is responsible for the present relief of the Cantabrian Mountains.

Most rocks deformed during the Variscan Orogeny are very competent with high dips. They are repeated by vertical Variscan thrusts, of W–E trending in the eastern area, and SW–NE, in the western zone (Martínez García, 1980; Navarro, 1984) (Fig. 2). Major lithostratigraphic units comprising this sequence are the Barrios Quartzite Formation, Ordovician in age, and the Barcaliente, Valdeteja, Cuera, Picos de Europa and Beleño Formations, all of them Carboniferous in age.

The Permo–Meso–Cenozoic materials show a greater lithological range, and a predominance of incompetent rocks that produce low reliefs. These materials present low dips and crop out in three basins: Gijón-Villaviciosa, Oviedo-Cangas de Onís and Basque-Cantabrian (Fig. 2). The first two basins, located to the west, are separated by the Llanera fault, while the materials of the third basin, located to the east, are limited to the north by Variscan thrusts that were reactivated during the Alpine deformation (Tosal, 1968).

The stratigraphic succession of the second sequence initiates with terrigenous Permo–Triassic rocks. The sequence continues with a Jurassic succession consisting of carbonate units (Gijón and Rodiles Formations), terrigenous units (Ñora and Vega Formations) and mixed units (Tereñes and Lastres Formations). The Cretaceous rocks consist of alternating siliciclastic and carbonate units with a predominance of the second ones in the Upper Cretaceous. The lower middle half Cenozoic is a continuation of the carbonate sedimentation of Late Cretaceous, which has a marine origin, that reaches the Middle Eocene. Finally, in the Middle Eocene–Oligocene, a mainly terrigenous succession of continental origin was deposited in relation to the uplift of the Cantabrian Mountains (García-Ramos and Gutiérrez Claverol, 1995).

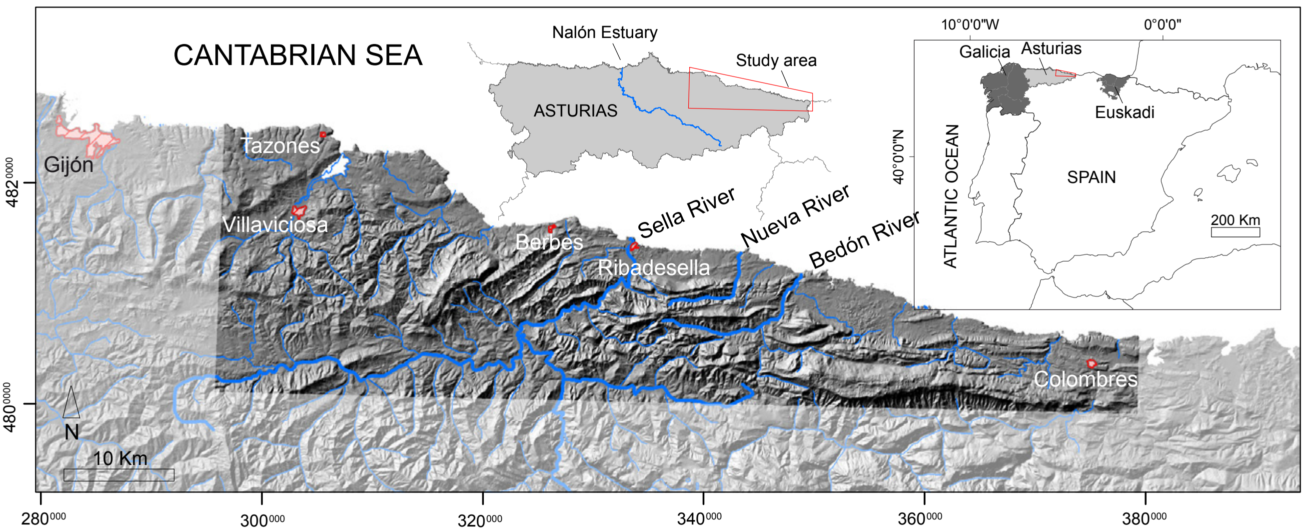

FIGURE 1. Location of the study area.

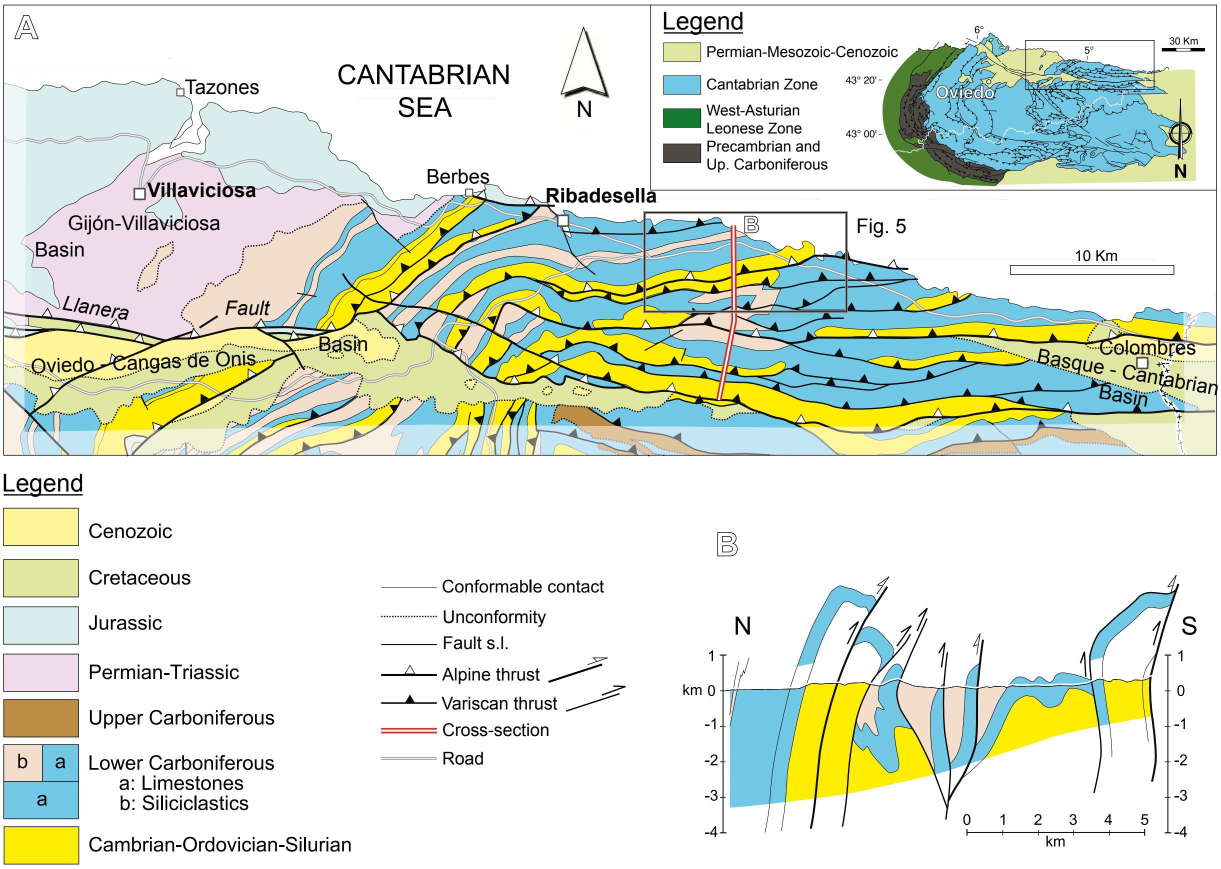

FIGURE 2. A) Geological map of the study area. Modified from Aramburu and Bastida (1995) and completed with data from Marquínez (1987) and Pulgar *et al.* (1999). The location of Fig. 5 and the cross-section of B are indicated. B) Geological cross-section across the central part of the study area.

Finally, there are several Plio–Quaternary deposits among which *rasa* deposits must be mentioned, since these platforms are the main objective of this work. Under the heading of "marine *rasas*" the MAGNA cartography shows a series of surficial formations composed of gravels, sands, black shale and peats. No erosive landforms are included in these maps. Those surficial formations cover flat erosional surfaces modelled on bedrocks corresponding both to Barrios Quartzite and to Cuera Limestone.

METHODOLOGY

The methodology designed in this work includes the following tasks: i) collection and checking of digital data, ii) building a database using GIS, iii) GIS information management, iv) topographic profile creation and application of the hypsometric method to detect new *rasas*, and v) testing and validation of the detected surfaces.

Collection and checking of digital data

Altimetry information used in this work comes from the digital elevation model (DEM) produced and published by the Cartographic Survey of Asturias (cell size 5m). This DEM has been checked and processed to detect drainage artifacts and to transform it into a hydrologically correct model by using ArcHydro Tools, v.1.4 (terrain preprocessing, sink evaluation and artifact filling). Digital layers corresponding to the lithology and structure of the geological bedrock (1:50,000 scale) in vector format, were downloaded from the website of the Geological Survey of Spain (IGME, http://cuarzo.igme.es/sigeco) and merged by GIS. It also has been compiled information regarding surface formations published by the Asturias Government (Principado de Asturias, 2002). This information is available in vector format at a 1:25,000 scale and contain a classification of surface formations based on both lithological composition of the clasts (siliceous, calcareous or mixed) and relative percentage of matrix. In addition, genetic information related to alluvial, littoral and karstic origin is also included. This information is useful in order to discriminate and map only those landforms interpreted as flat erosional surfaces.

Building a database using GIS

Data processing was carried out using the commercial software provided by ESRI, ArcGIS 10.0. A digital slope model (DSM) 5x5m cell was derived from the hydrologically corrected DEM and it was reclassified in variable interval ranges (1, 5 or 10º). Furthermore, a triangulated irregular network (TIN) was constructed from the DEM. It will be used to create 3D model by using ArcScene module of ArcGIS.

GIS information management

The management of digital information with GIS has allowed us to characterize the surfaces identified as *rasas* in the geological maps available in digital format (IGME, http://cuarzo.igme.es/sigeco). The crossing of this information with rasters corresponding to the DEM and DSM has allowed establishing that the *rasas* mapped by IGME are modelled in gentle reliefs under 5º slope that dip slightly towards the sea. This is consistent with the slope values reported for erosional flat surfaces in other works (between 1–3º according to Anderson *et al*. (1999) or between 1–5º according to Gutiérrez Elorza, 2008 or Álvarez-Marrón *et al*., 2008). It allows the establishment of patterns of spatial distribution of slope values in the study area.

Subsequently, we have combined layers containing information about altitude, slope or distance from the coast with layers of surface formations in order to differentiate *rasas* from other landforms with similar topographical features, such as alluvial plains and terraces.

Topographic profile creation and application of the hypsometric method to detect new *rasas*

The relationship between the spatial distribution patterns of *rasas* and altitude is established using 3D terrain models combined with hypsometric studies. This will permit to identify areas that have not been yet recognized as *rasas* or flat erosional surfaces. TIN three-dimensional analysis was performed in ArcScene module and profiles were extracted using the ArcGIS 3D analyst extension. In hypsographic curves, the maximum surface values will represent abundance of the same altitude (Ebert *et al*., 2011), which may correspond to a flat surface that has undergone erosion or weathering.

Testing and validation of the detected surfaces

In order to evaluate the accuracy of the methodology, it has been carried out a comparison of the GIS resulting model, including the detected surfaces and the spatial distribution of other flat surfaces previously mapped in the study area (*e.g*. Jiménez-Sánchez *et al*., 2004 and 2006). This has allowed us to test and validate the methodology.

RESULTS AND DISCUSSION

Quantitative relationships between landscape and lithology

In the study area, the bedrock lithology shows a predominance of limestone formations (46.0%) compared to those of siliceous (30.1%) and mixed composition (23.9%). The predominant siliceous formation corresponds to the Ordovician quartzite (Barrios Formation), which occupies an area of 188km^2. With regard to calcareous formations, the more extensive one is the Carboniferous limestone (Barcaliente Formation) with a surface of 137km^2.

The map of surficial formations (Principado de Asturias, 2002) shows that most of the study area (74.2%) is free of them. There is a predominance of mixed type formations (15% of the study area), while the siliceous clastic formations reach a value of 13.5% and the calcareous formation only represent a 2.3% of the whole.

DEM shows that the altitude ranges from 0 to 1,315m, with more than 20% of the surface area within the range of 150–250m (Fig. 3A). Figure 3B shows that low slope values are mainly distributed along a 3–4.5km wide band trending roughly E–W, parallel to the coast, or following major rivers, with trends variable from E–W to NW–SE and to NE–SW. A 68% of the study area shows slope values between 10º and 40º.

The crossing of the DEM and the surface formations layer has allowed discriminating a set of almost flat surfaces that are not *rasas*, including alluvial plains, fluvial terraces or karstic infills, with a pattern similar to the previous one described for the slope spatial distribution. All of them show slope values under 5º but can be discriminated by their position in valley bottoms (alluvial plains and fluvial terraces) or in closed depressions (karstic infills).

Relationships between *rasas* and DTM

The crossing of the *rasas* previously mapped in the geological map (IGME) with bedrock lithology and DTM data, has shown that most of them are developed on Barrios Quartzite bedrock, with an area of 9.7km^2 in which 48% has a slope value under 3º and 69% under or equal to 5º. The representation of hypsometric of *rasas* developed on quartzite bedrock highlights a significant concentration between 202 and 232m (with a maximum at 220m altitude, 6% of *rasas*) and between 132 and 162m (25.8%) (Fig. 4A). Regarding the limestone bedrock, *rasas* are mainly linked to Cuera Limestone bedrock occupying an area of 2.9km^2, in which 61.3% show slope values under or equal to 5°. They are concentrated in two altitude ranges: 24–34m (32.3%) and 59–69m (24.3%) (Fig. 4B).

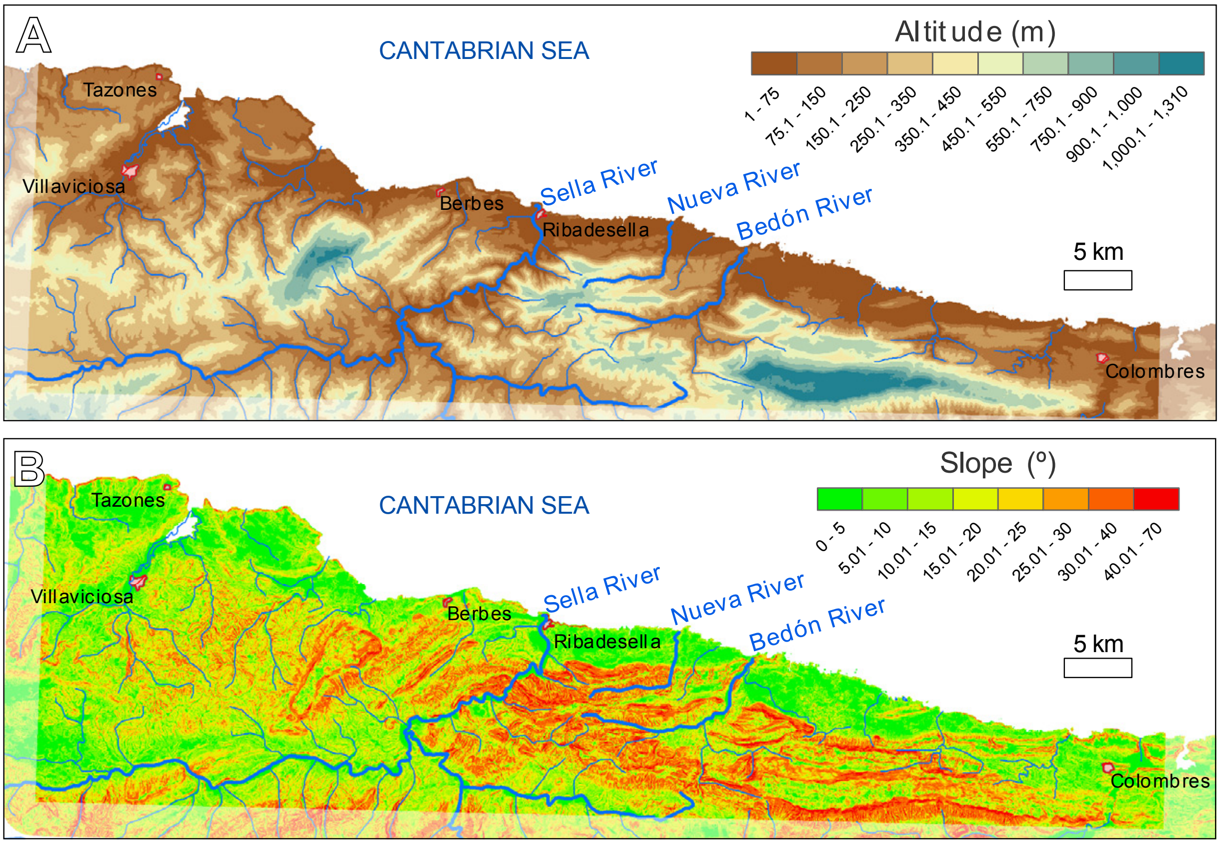

FIGURE 3. A) Digital elevation model of the study area. B) Digital slope model of the study area.

Topographical profiles shown in the geological cross sections performed on quartzite bedrock near the Bedón River (Fig. 5A–D) define a "plateau" morphology limited at their ends by steep slopes. In detail, there is a series of flat surfaces slightly inclined (*ca.* 1º) towards the shore that are individualized by deeply eroded river valleys and whose altitude is decreasing eastward.

These flat areas located on the left bank of the Bedón River are not preserved westward, disappearing just in the west margin of Nueva River (Fig. 5B). Thus, the profile in Figure 5 shows that altitude on both slopes of Nueva River valley is quite different, reaching 200–250m to the east, while to the west the altitude ranges between 300 and 500m. Since the bedrock is composed of Barrios Quartzite (Fig. 5A–D), this altitude changes along with changes in morphology (flat in the east, hilly in the west), and it could be explained by different hypotheses. One of them would be a different position of the coast palaeo-line, southward in the east of the Nueva River, emerging the western part represented by an abrupt relief modelled on Ordovician Quartzite. Other hypotheses would be the existence of a fault that would have been active after the formation of the *rasa* in this area, uplifting the mentioned relief located westward. Although there have been cited faults affecting *rasa* deposits in the Cantabrian coast (Gutiérrez Claverol *et al.*, 2006), they have been displaced just a few meters. Moreover, no fault evidence has been found during fieldwork. Therefore, we consider

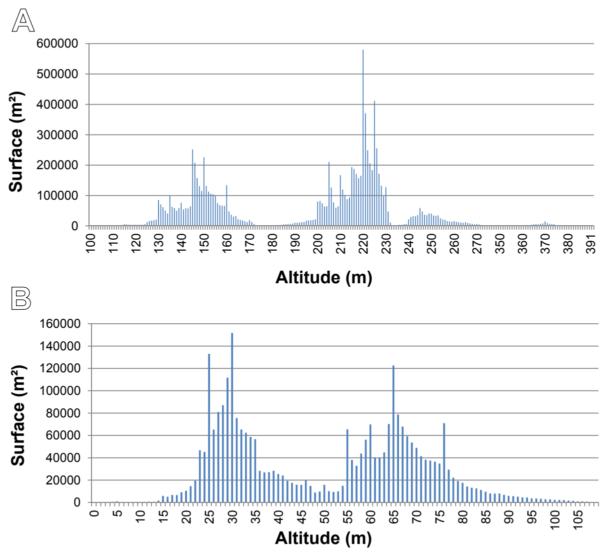

FIGURE 4. Altitude distribution in rasas registered in MAGNA geological maps (IGME) on Barrios Quartzite Formation (A) and on Cuera Limestone Formation (B).

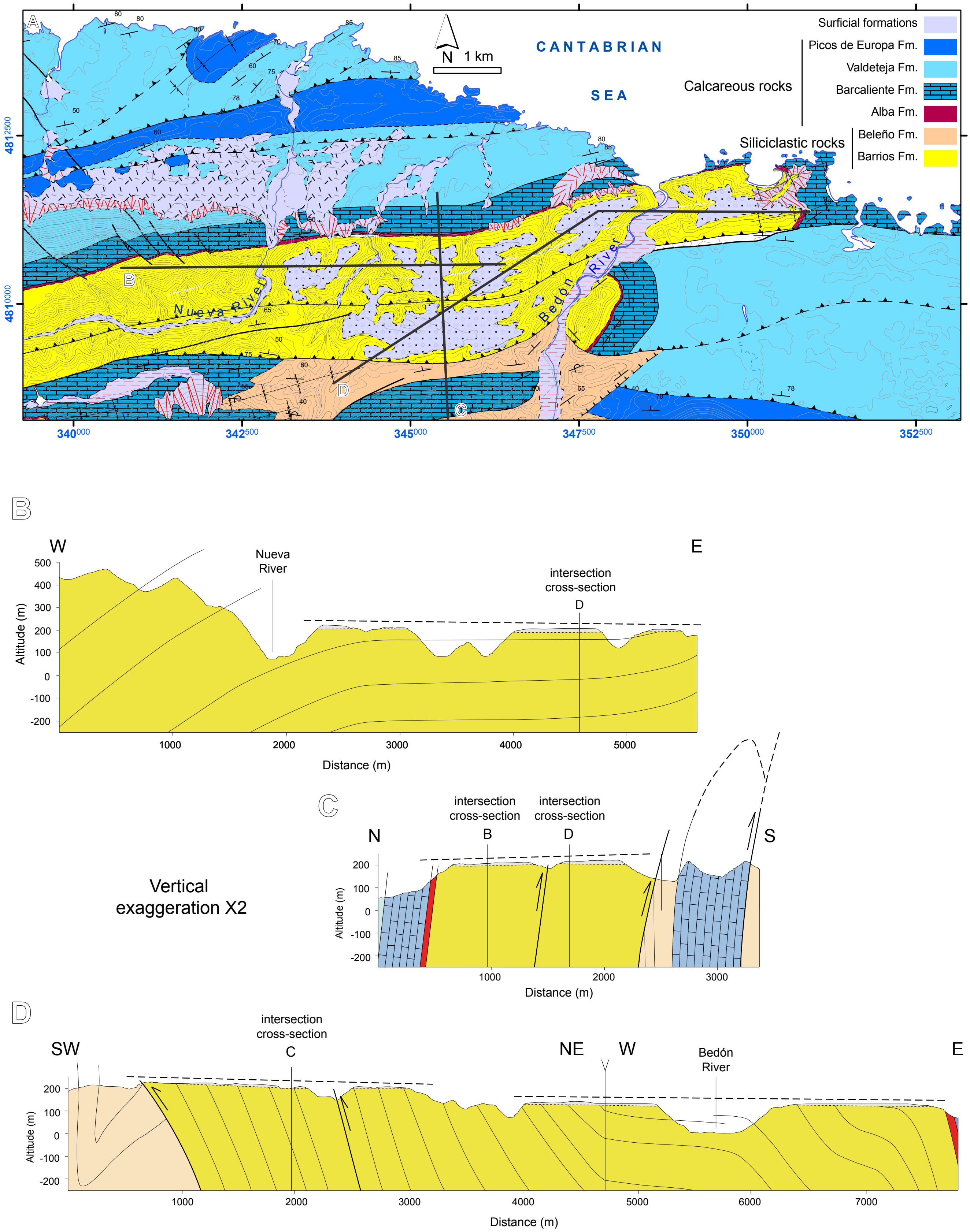

FIGURE 5. A) Detailed geological map of the surroundings of the Bedón and Nueva rivers (Merino-Tome *et al.*, 2011). B, C and D) Geological cross-sections showing the main Variscan structures and the flat erosional surfaces (dashed lines) developed on the Barrios Quartzite Formation.

the first hypothesis as the more plausible explanation to be checked in future research.

A predictive approach for flat erosional surfaces detection

Taking into account all the above it has been possible to locate *rasas* defined in previous works (Table 1), but not represented in the MAGNA maps, and to define new rasas surfaces, that was unknown until present (González-Fernández, 2012).

On the left bank of the River Sella mouth, on the Carboniferous Cuera Limestone, there is a surface (Fig. 6) with variable slope values (the most abundant between 10–15º) and altitudes between 61–73m that was not defined as a *rasa* in the MAGNA, although it had already been cited in previous works (Jiménez-Sánchez *et al.*, 2004 and 2006) and can be assigned to *rasa* level VIII according to Flor and Flor-Blanco (2014). This finding can be significant to check and validate the approach of the developed methodology.

New landscape features have been identified as *rasas* with our methodological approach (Fig.6). Thus, to the east (Colombres area, Fig. 6A) on the Eocene limestone, we have defined an area of 1.1km^2 in which the 45% of the surface is located at altitudes ranging from 110 to 120m, that could be the *rasa* level VI (Flor and Flor-Blanco, 2014) of continental origin; 30% of it have a slope under 5º. Also, near the Berbes locality (Fig. 6B), on the Ordovician Barrios Quartzite, it has been defined a new *rasa* of 0.43km^2, with slope values under 5º and altitude values ranging from 200 to 250m that could be *rasa* level II following Flor and Flor-Blanco (2014). Finally, to the west of the study area (Tazones area, Fig. 6C), on the Jurassic mixed formations known as Tereñes Formation and Lastres Formation, another new *rasa* has been defined, with an area of 35.9km^2, slope values minor than 5º and predominant altitude ranging from 150–175m, equivalent to *rasa* level IV (Flor and Flor-Blanco, 2014).

The resolution of the DEM (5m) determines the possibility to distinguish small changes in the relief. Small

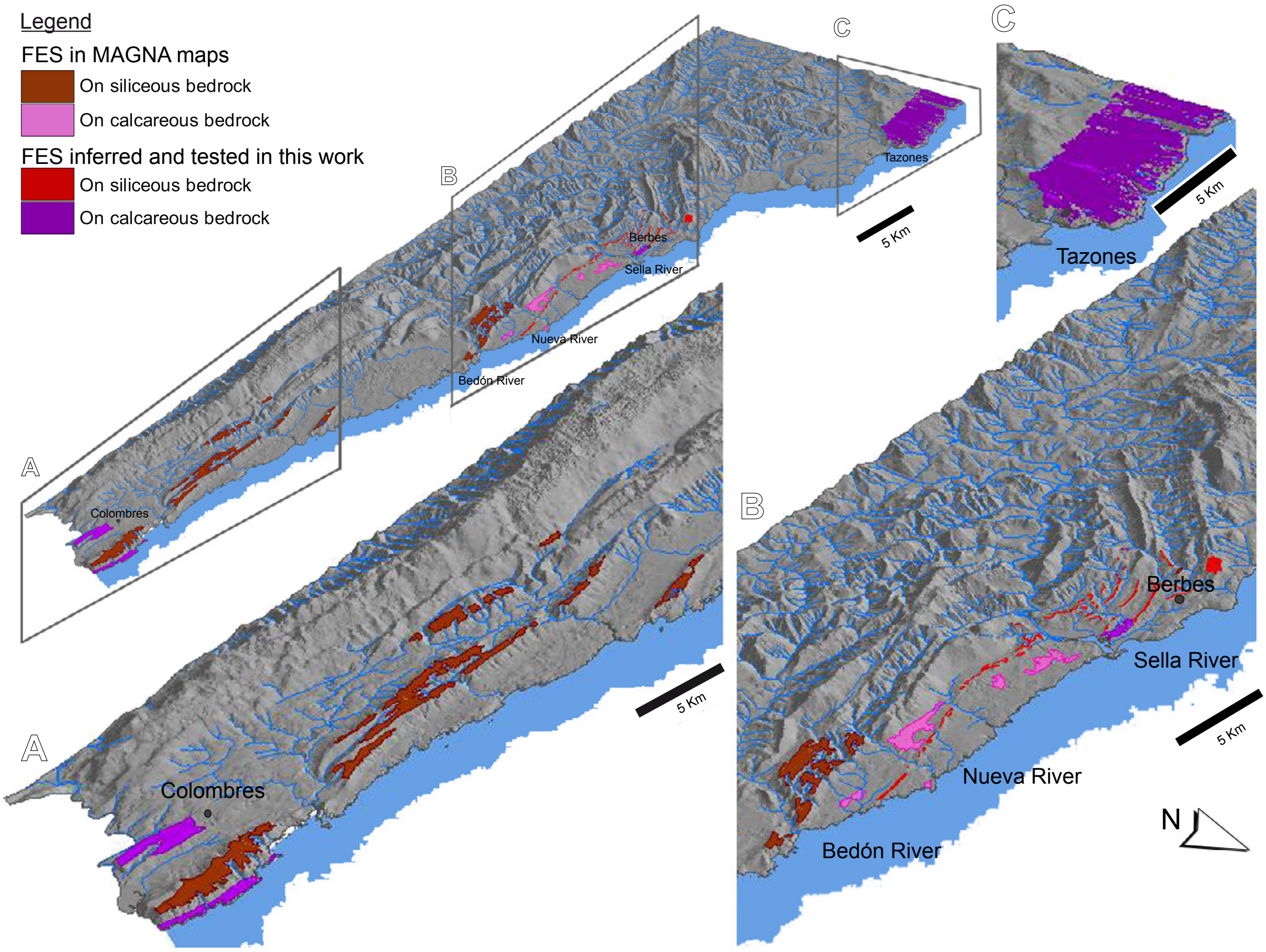

FIGURE 6. Distribution of new Flat Erosional Surfaces (FES) detected in this work and previously mapped FES.

or underrepresented flat erosional surfaces would need a more detailed DTM to be detected.

CONCLUSIONS

The use of digital slope models allows delimitating areas with less than 5º slope, whose origin could correspond to flat erosional surfaces of marine origin. This approach complements others as the distance to the current coastline, or the presence of Quaternary cover, allowing discarding some flat areas linked to different origin, particularly floodplains and alluvial terraces.

When the bedrock is mainly resistant siliciclastic or quartzitic lithology, the classic method based on photointerpretation and fieldwork is accurate enough to define the spatial distribution of *rasas*. However, in calcareous lithologies, the exclusive use of this criterion is not discriminatory, because karstification processes modify *rasas* morphology after their formation. In this regard, the representation of hypsometry and performing topographic profiles have allowed us to draw enveloping polygons defining *rasa* surfaces, most of them not referred in any previous mapping. Thus, new flat surfaces have been detected at different altitude ranges: 61–73, 110–120, 150–175 and 200–250m.

Consequently, the methodology derived from the application of GIS tools can be useful to:

i) detect flat surfaces and discriminate them according to their geomorphological origin.

ii) predict the spatial distribution of new flat surfaces.

iii) validate the position of predicted flat surfaces by comparing them with previously known flat erosional surfaces.

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