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Stratigraphy of Late Pleistocene coastal deposits in Northern Spain

Estratigrafía de los depósitos costeros pleistocenos en el noroeste de España

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Abstract

Stratigraphical and sedimentological analysis, geological mapping and geochronological dating (luminescence, uranium/thorium, and radiocarbon) were undertaken on Late Pleistocene coastal deposits (raised beaches and periglacial deposits) in north-west Spain. Correlation of the 26 outcrops studied and their geometric relationships allowed the establishment of four stratigraphic units: Unit 1, sandy and gravelly raised beaches located above a rocky abrasion platform 1.5 –3.5 m above the modern mean sea level; Unit 2, matrix-supported breccias of head deposits; Unit 3, muddy peats formed in swamp depressions; and Unit 4, clast-supported conglomerates, breccias, and sands, deposited by intermittent current activity. Thermoluminescence (TL) and infrared-stimulated luminescence dating (IRSL) assigned Unit 1 to OIS 5; Unit 2 to OIS 4/3; and Unit 4 to OIS 3–2. Radiocarbon dating confirmed the results obtained for Units 2 and 4 and that Unit 3 was contemporaneous with Unit 2. Comparison of these outcrops with others from raised beaches located in the central part of the northern Spanish coast (Cantabria) showed that the Cantabrian sector has been uplifted 2–3 m more than the north-west coast since the Last Interglacial. It is probable that Galicia acted as a hinge line between the uplifting north and the active, faulted atlantic margin of the Iberian Peninsula.

Keywords: Spain, Late Pleistocene, stratigraphy, sedimentology, raised beaches, head deposits, dating

Resumen

En este trabajo se analizan los depósitos del Pleistoceno final en el sector costero del noroeste de la Península Ibérica desde el punto de vista estratigráfico y sedimentológico. Se han estudiado y correlacionado 26 afloramientos, lo que ha permitido la diferenciación de cuatro unidades litoestratigráficas, cuya edad ha sido obtenida mediante las técnicas de luminiscencia, radiocarbono y uranio/torio. La Unidad 1 corresponde a playas levantadas arenosas y de gravas, que descansan sobre una plataforma de abrasión rocosa situada entre 1,5 y 3,5 metros sobre el actual nivel medio del mar. La Unidad 2 consiste en brechas matriz soportadas originadas como depósitos de ladera y de arroyada al pie de paleopendientes. La Unidad 3, formada por fangos orgánicos y turbas, corresponde a turberas en zonas deprimidas encharcadas. La Unidad 4, que consiste en conglomerados, brechas y arenas, se formó como depósitos aluviales, generalmente en corrientes esporádicas. Las dataciones por luminiscencia (teniendo en cuenta las limitaciones del método en este tipo de materiales), indican que la Unidad 1 corresponde al OIS 5, la 2 a los estadios 4 – 3, la 3 es contemporánea de la 2 y la 4 se formó durante los estadios isotópicos 3 – 2. Las dataciones de radiocarbono confirman los resultados obtenidos para las unidades 2 y 4. La comparación de estos afloramientos con las playas levantadas de Oyambre y Merón en Cantabria, muestran que este último sector ha sufrido un levantamiento de entre 2 y 3 metros más que el norte de Galicia desde el Último Interglacial. Es posible que Galicia norte actuara durante el Cuaternario final como una zona relativamente estable entre el Golfo de Vizcaya, en el que se produce levantamiento y la costa atlántica peninsular, con claros indicios de neotectónica.

Palabras clave: Pleistoceno final, estratigrafía, sedimentología, playas levantadas, solifluxión, corrientes efímeras, dataciones, España

1. Introduction

A significant number of continental and uplifted Quaternary marine deposits outcrop along the Spanish and Portuguese littoral, particularly along the southern Atlantic and Mediterranean coasts. Knowledge of these coastal deposits varies greatly due to difficulties in their identification and, above all, their suitability for dating. In a recent synthesis, Zazo *et al.* (2003) described raised terraces of the Canary Islands, the south Mediterranean coast, and the Balearic Islands. Several levels were characterized and dated using palaeontological data, U-series, and amino-acid zonation. The morphology, dynamics, and tectonic behaviour of the northern coast of Spain (Galicia and the coast of the Bay of Biscay) are very different from those of better-known areas. Several Late Pleistocene outcrops have been studied along this coast, in both Galicia (Costa Casais *et al.*, 1996; Cano *et al.*, 1997; Alonso and Pagés, 2000a) and the Bay of Biscay (Mary *et al.*, 1975; Monino Saez *et al.*, 1988; Edeso *et al.*, 1993). However, the Last Interglacial and the Early Glacial record have never been accurately dated here, due predominantly to the absence of fossil remains and to the characteristics of the basement and sediments.

Marine terraces and emerged beaches are frequently used to reconstruct former sea-level positions, and an increasing number of researchers focus on climate changes from the Last Interglacial to present times. Several researchers have dealt with these issues on European coasts, e.g., Balescu *et al.* (1997), Mauz (1999), Mauz and Hassler (2000), and Tzedakis *et al.* (2002) in the Mediterranean; Loyer *et al.* (1995), Lambeck (1997), Haslett and Curr (1998, 2001); Haslett *et al.* (2000); Bates *et al.* (2003), and Regnauld *et al.* (2003) on the Atlantic coast of France and the English Channel; Zazo *et al.* (2002) and Zazo *et al.* (2003) on the southern coast of Spain and the Balearic and Canary Islands; and Araujo (1997), Carvalho and Granja (1997), Granja and Carvalho (1995), and Granja (1999) in Portugal. Pleistocene chronostratigraphy and correlations are usually based on marine oxygen isotope stratigraphy. However, the correlation of marine terraces and continental sediments with former sea-level positions based on deep-sea and ice cores is rather problematic (Zazo, 1999). Geochronological (U-series, aminostratigraphy, luminescence), palaeontological, and morphostratigraphical methods have all also been applied to achieve better results.

In Galicia, additional problems arise with dating because of the sediment characteristics. The acidity of soils and vadose waters dissolves calcareous shells, and organic material is rarely abundant. Coastal marine levels have been described by several authors (Trenhaile *et al.*, 1999; Alonso and Pagés, 2000a; Martínez-Graña *et al.*, 2000), but few attempts at dating have been made, and the age is usually inferred to be “Last Interglacial” (sometimes Eemian) based on morphological and stratigraphical considerations, or relative to other European examples. Alonso and Pagés (2000b) presented preliminary results of luminescence dating (TL and OSL) in one of the palaeobeach outcrops studied in Galicia, confirming its Last Interglacial age.

In this paper, the entire sequence of units that form the Late Pleistocene record on the northern coast of Spain is dated for the first time. The stratigraphy of emerged beaches and periglacial deposits has been established, as well as the chronology of events from the Last Interglacial period to the Pleniglacial period. Radiocarbon and luminescence (thermoluminescence [TL] and infrared-stimulated luminescence [IRSL]) techniques were used for dating. We discuss the problems of dating on this part of the Spanish coast and the results are compared with those obtained from emerged palaeobeaches in Cantabria. We address the problem in sedimentological, stratigraphical, and palaeogeographical terms. A final remark is made about the different heights of Last Interglacial palaeobeaches in the northern coast of the Iberian Peninsula, undergoing a process of uplifting after subduction (Monino Sáez *at al*., 1988; Santanach Prat, 1994).

2. Setting

The littoral of Galicia, in north-western Spain, is a high-energy irregular coast comprised predominantly of granites and metamorphic rocks. Its morphology dis-

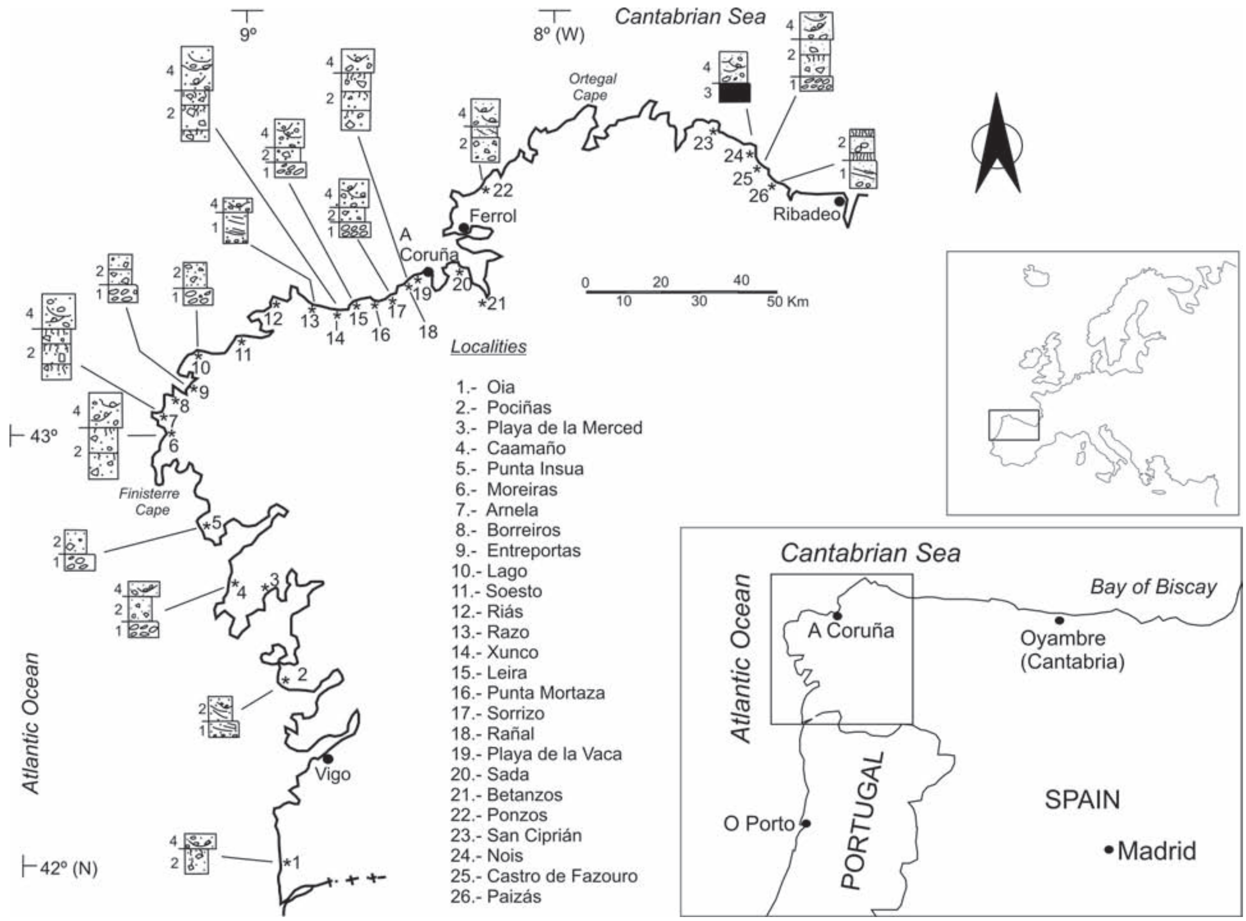

Fig. 1.- Location of the study area and investigated sections. The stratigraphic units are outlined. Inset: the northern coast of Spain showing the locations of Galicia and Oyambre in Cantabria. Roman numerals indicate the stratigraphic units described in the text.

Fig. 1.- Localización de la zona de estudio y de las secciones trabajadas. Se señalan las unidades estratigraficas. Insertado se muestra la costa norte de España mostrando las localizaciones dentro de Galicia así como la de Oyambre dentro de Cantabria. Los números romanos indican las unidades estratigráficas descritas en el texto.

plays composite cliff profiles 150–200 m high, with convex slopes undercut at the base by wave action. Its main features are pocket beaches separated by headlands, embayed beach barriers, and deep marine embayments, locally called "rias". These are former fluvial valleys flooded during the Holocene sea-level rise, which have a wide marine embayment and an inner estuary. Coastal profiles and their Pleistocene evolution correspond to the slope-over-wall model (Bird, 2000), where the cliffs were degraded by periglacial processes during the Glacial period, with the altered mantle moving downslope by solifluction and translational landsliding. During this process, the Interglacial highstand levels were covered and remained protected (raised beaches). The sedimentary apron at the toe of the cliffs is now being removed by wave erosion.

In this context, several scattered outcrops of marine and continental sediments still remain in many places along the coast of Galicia (Fig. 1), sheltered in the irregularities of the coast or carpeting the slopes, whereas in other places, the polycyclic palaeocliffs have been exhumed or are clearly receding (Alonso and Pagés, 2000a; Pagés *et al.*, 2002). Raised marine levels are evidence for an interglacial highstand, represented by gravel and sand palaeobeaches on rocky abrasion platforms above the present mean sea level (m.s.l.). They are buried by the abundant periglacial sediments that extend along the entire coast of Galicia, consisting mainly of debris flows and breccias (Alonso and Pagés, 2000a). These features are similar to those of Pleistocene deposits in Brittany and along the English Channel (Haslett and Curr, 2001; Bates *et al.*, 2003; Regnauld *et al.*, 2003).

3. Stratigraphy: Studied Sections and Facies

Late Pleistocene outcrops are widely distributed along the coast of Galicia (Fig. 1), but are more frequent along the stretch from A Coruña to Cape Finisterre. Some of them are particularly interesting because the geometry of the sedimentary units is preserved and their interrelationships can be studied. Twenty-six outcrops, four in the Cantabrian sector and 22 on the Atlantic margin, have been studied. Emerged marine levels have been described at 17 sites and dated in four localities. Outcrops of continental sediments are frequent along the coast; nine significant ones were chosen and dated in nine localities, and are described here (Fig. 2). Facies are compared with two outcrops of emerged beaches in Oyambre, Cantabria (Fig. 1). Facies analysis, correlations, geometric relationships, and dating have allowed us to define four stratigraphical units (Alonso and Pagés, 2000a; 2000b). Their characteristics and depositional interpretation are described below.

3.1. Raised beaches

Unit 1 (Castro de Fazouro Fm., after Alonso and Pagés, 2000a). Unit 1 is found as isolated outcrops in sheltered coastal embayments, and is overlain by the head deposits of later units. It is up to 3 m thick, generally formed of conglomerates except at four sites, where it consists of well-sorted sandstones with thin conglomerate layers. The best site for studying the sandy facies is the beach at Razo (Fig. 2), were the facies crops out for about 1 km along the beach. Other sites are Os Riás and Pociñas on the Atlantic, and Paizás in the north. The conglomeratic facies are well represented in the outcrops of Sorrizo, Leira, Xunco, Borreiros, and Punta Insua in the Atlantic sector. On the Cantabrian stretch, Castro de Fazouro (Fig. 2) is the most representative site due to its clear relationships with other units. All outcrops are currently being eroded, with some close to disappearance, as at Castro de Fazouro itself.

Unit 1 is always located above a rocky abrasion platform cut in the bedrock. The shore platform is fairly well preserved, particularly in metamorphic rocks, with a gentle slope to the sea in the intertidal part, and a steeper slope in the supratidal part. Trenhaile *et al.* (1999) deduced that this surface was cut during the Last Interglacial (oxygen isotopic stage [OIS] 5), and that the intertidal portion is probably inherited from several interglacial stages.

The base of the unit in different outcrops varies from 1.5 to 3.5 m above modern mean sea level (Table 1). This interval is consistent with the current mesotidal range of the coast, which is thought to have been the same or similar during the Last Interglacial (Trenhaile *et al.*, 1999). Sands and gravels outcrop on either smooth surfaces or irregular surfaces, filling depressions and adapting to the topography. In very high-energy environments, chaotic heterometric breccias filled cavities prior to beach settling. At some sites, raised beaches outcrop along the cliff–shore platform junction.

LOCALITY	**BASE HEIGHT (Above MSL)**	FACIES
Paizás	2,5 m	Sandstones
Castro de Fazouro	2 m	Conglomerates
Playa de La Vaca	1,5 m	Sandstones
Sorrizo	1,5 m	Conglomerates
Punta Mortaza	2 m	Conglomerates
Leira	2 m	Conglomerates
Xunco	2 m	Conglomerates
Razo	2 - 3,5 m	Sandstones
Dos Riás	2 – 3,5 m	Sandstones
Lago	2,5 m	Conglomerates
Entreportas	2 - 3 m	Conglomerates
Borreiros	3,5 m	Conglomerates
Punta Insua	2 – 3 m	Conglomerates
Caamaño	2 – 3 m	Conglomerates
Playa de la Merced	2,5- 3,5 m	Conglomerates
Pociñas	3 m	Sandstones

Table 1.- Base height above mean sea level
Tabla 1.- Altura base sobre el nivel del mar

Facies associations:

1. Conglomerates. These are clast supported, well sorted to poorly sorted, with well-rounded clasts. Clast sizes range from pebble to boulder, with an average diameter of 8 cm. They are well arranged and imbricated, inclined towards the present coastline. Conglomerate clasts are predominantly quartz, schists, and granites in the Atlantic sector, whereas shales, schists, quartzites, and marbles dominate the Cantabrian sector. The upper part of the unit is variably affected by pedogenesis.

2. Sands and conglomerates. These are composed of well-sorted medium-to-fine-grained siliciclastic sands, with abundant laminae of heavy minerals. A level of conglomerates, up to 30 cm thick, strongly cemented by iron and with a mean clast size of 5 cm, always appears at the base. The sands show ripple and low-angle cross-lamination, inclined towards the present coastline. Laminae are disturbed by bioturbation and fluid-escape structures. Scattered rounded clasts and discontinuous levels of conglomerates can be observed in places. At the Razo Beach site, two levels can be distinguished, each one representing a sedimentary sequence (Fig. 2). Root concretions are visible in the topmost part of the underlying sequence.

The unit is interpreted as palaeobeach deposits formed when a former sea level reached a mean position 2–3 m higher than the present m.s.l. The morphology of the coast included heads, pocket beaches, and embayments in which both gravelly and sandy beaches developed, and which can still be seen forming today. A surface, very probably polycyclic, was cut by abrasion and became the

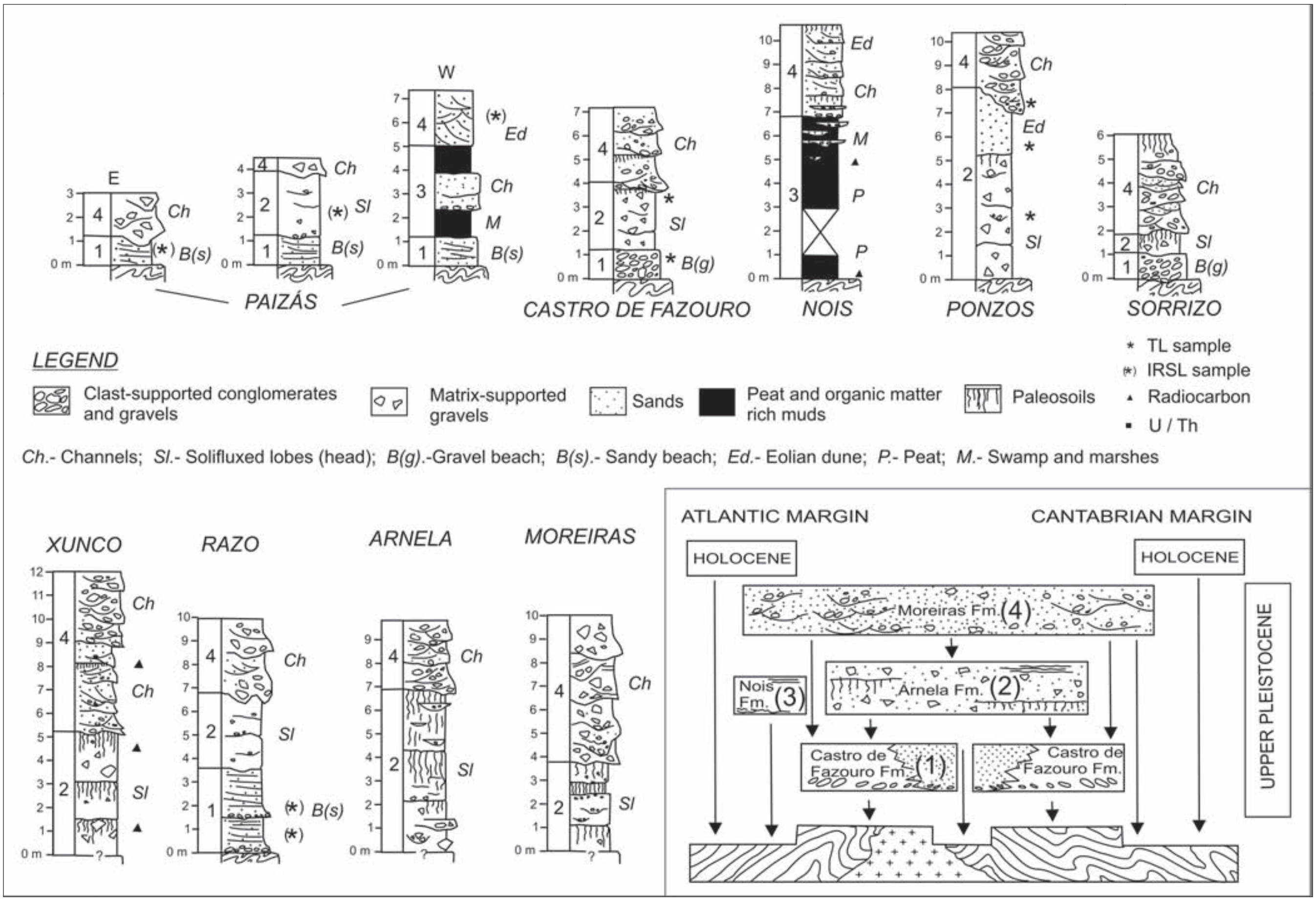

Fig. 2.- Selected sections and facies. Paizás, Castro de Fazouro and Nois are located on the Cantabrian coast, all other sites in the Atlantic realm. Inset: Stratigraphic Units (modified from Alonso and Pagés, 2000b).

Fig. 2.- Columnas y facies seleccionadas. Las de Paizás, Castro de Fazouro y Nois están localizadas en la costa Cantábrica y el resto en el dominio atlántico. Incorporado en la figura aparecen las unidades estratigráficas (modificado de Alonso y Pagés, 2000b).

base of the unit. Conglomeratic beaches were fed by cliff erosion, stream floods, and gullies. Sandy beaches were mostly marine supplied, although fluvial sediments are also present at several sites.

3.2. Continental deposits

Unit 2. (Arnela Fm. after Alonso and Pagés, 2000a). This is a complex unit, with important variations in facies and thickness (up to 10 m), formed of coarse, poorly sorted sands with scattered boulders and pebbles, matrix-supported poorly sorted breccias, black sands, soils, and sandy conglomeratic lenses. The matrix is sometimes black due to significant amounts of organic matter. Clast sizes range from boulders to pebbles. Pedogenic structures are evident in the whole unit and charcoal fragments are conspicuous in the Atlantic margin outcrops. The unit appears as a sedimentary apron at the toe of the steep palaeocliffs overlying the raised beach unit, carpeting the slopes or the shore platform.

There is a change in the type of facies between the slopes (breccias, unsupported heterometric conglomerates) and the centres of the palaeovalleys that they cover (black coarse sands with clasts, muddy matrix, and high organic matter content). The unit is interpreted as soliflucted deposits, with high-density lobes or debris flows. In some places, the morphology of the lobes is preserved (Rañal) and up to three mass-wasting episodes can be distinguished, each one finishing in a palaeosoil (Xunco, Leira, Arnela, and Moreiras, Fig. 2). Solifluction lobes have slid downslope, along the depressions and valleys that incised the cliffs. In the central part of the valleys, there are facies that correspond to sporadic streams that circulated and extended onto grasslands, swamps, and even peaty zones formed in the incipient littoral lowland that gradually emerged during coastline retreat (Arnela). At the Ponzos site, a horizon of very fine and rounded laminated sands can be observed. The horizon overlies head deposits and represents aeolian dune deposition.

The disseminated but very frequent charcoal fragments are interpreted as the results of spontaneous combustion of vegetal cover or peat bogs, mixed with high-density deposits during flows. The pollen content (Alonso and Pagés, 2000a) shows an absence of arboreal pollen, and most grains are broken. The most abundantly recorded taxa are Gramineae and Ericaceae. All the facies of the unit correspond to sediments formed in periglacial environments, at the beginning of climatic deterioration and the initial retreat of the coastline. Sand dunes were blown across the gradually widening coastal plain, to be deposited on the solifluted lobes and soils that carpeted the steep old cliffs.

Unit 3. (Nois Fm., after Alonso and Pagés, 2000a). This unit is formed of black muddy peat, clays, and very thin layers of sands and clasts. The basal levels are rich in wood remains and reeds, passing upwards into black and grey clays, silts, and small lenses of sands and micro-conglomerates. The organic matter content never exceeds 26%. Nois Beach, in the Cantabrian sector, is the only place where the unit is well developed (Fig. 2), occupying a depression and with a thickness of 6.10 m in the central part of the outcrop. It is also present at the Paizás site, although here it is formed mostly of grey clays and sands. The base is usually covered by the present beach sands. It rests on a shore abrasion platform in Nois and on Unit 1 in Paizás.

This unit, which changes laterally to Unit 2, corresponds to peat and swamps formed in depressions and the central parts of the valleys that drained the littoral plain, which gradually widened during the sea-level decline at the beginning of the Last Glacial period. The increasing number of stream-bed intercalations in the upper part of the unit could indicate climatic deterioration, increasing sea-level drop, better drainage, and impoverished vegetation.

Unit 4. (Moreiras Fm., after Alonso and Pagés, 2000a). The unit is complex, formed by conglomerates, breccias, and sands (Fig. 2). The facies are mainly: a) clast-supported cross-stratified conglomerates and breccias, with poorly sorted, angular clasts. Trough cross-stratification dominates and the matrix is formed of coarse, poorly sorted sands; b) matrix supported breccias; c) heterolitic and heterometric trough cross-stratified sands. Grains are angular, disseminated clasts are abundant, and the facies is rich in dark heavy minerals and micas. Channel-fill sequences are distinguishable, some capped by soil horizons. The base of the unit is strongly erosive, generally overlying Unit 2 (from Oia to Castro de Fazouro; see figure 1), but also Unit 1 (Dos Riás, Pta Mortaza, Razo, and Paizás), Unit 3 (Nois), or the basement (Rañal and San Ciprián). The pollen content (Alonso and Pagés, 2000a) also shows an absence of arboreal pollen, and Gramineae and Ericaceae are the most abundant recorded taxa. This confirms the conclusions of facies analysis, which indicate sparse herbaceous vegetation in soils developed on solifluted material under cold climatic conditions.

The unit is thus interpreted as the result of localized stream currents in valleys that incised older slopes. Generally, tractive currents and sporadic channels were active during high discharges. Solifluction lobes were formed on the slopes, resulting in inter-layered debris-flow sediments. The soils were formed during stabilization periods. Colder conditions are reflected by the sparseness of the vegetation. However, there is no evidence of permanent ice on the coast, although most general reconstructions of Atlantic conditions consider this latitude as the limit for icebergs at this time (Uriarte Cantolalla, 2003; p. 96).

4. Dating

4.1. Luminescence

The dating of Unit 1 and the lower parts of Units 2 and 3 is a problem for several reasons: a) the radiocarbon ages of the overlying units show that they are beyond the scope of this method, and b) the organic matter content is too low and contamination by terrigenous materials too high to use uranium/thorium (U/Th) methods (demonstrated by an analysis performed during the development of this research); c) no calcareous remains are preserved due to the acid of composition of soils, so neither palaeontological nor amino-acid racemization methods can be used. Previous authors (Costa Casais *et al.*, 1996; Cano *et al.*, 1997; Alonso and Pagés, 2000a; Martínez-Graña *et al.*, 2000) attributed the raised beaches to the Eemian using speculative arguments. Here, for the first time, the dating of systematically sampled marine and periglacial levels proves the presence of Last Interglacial to Pleniglacial deposits.

Thermoluminescence (TL) and infrared-stimulated luminescence (IRSL) methods were used, which have proven useful for dating raised beaches and coastal sediments (Balescu *et al.* 1997; Mauz, 1999; Mauz and Hassler, 2000; Zazo, 1999), although the results must be assessed carefully and they require more analysis than other methods to achieve accurate results (Forman *et al.*, 2000). The authors are aware that Galicia is, to a certain extent, a problematic place for the application of these methods, because the basement that underlies the Pleistocene record on the Atlantic coast is formed by igneous and metamorphic rocks, which are not the most suitable materials for radiogenic analysis. Furthermore, the acidity of soils and vadose water is also a source of error, because these can alter the dose rate of luminescence samples, and the environmental settings of Units 2 and 3 are not ideal for full resetting during burial. However, while conscious of all these problems and the strong possibility of an underestimation in the results, we used this method as the only one feasible in this area.

Sampling was undertaken on both the Atlantic and Cantabrian margins, where the compositions of the basements differ markedly, which can minimize the anomalies due to basement composition. The data obtained were very homogeneous. Some of the outcrops of the upper units were also dated with radiocarbon and the results compared. The samples dated by luminescence appear to be 20% to 25% younger than those dated with radiocarbon, so an underestimation can be assumed.

TL and IRSL methods were used for Units 1, 2, and 4. Analyses were performed in the Laboratorio de Datación y Radioquímica of the Universidad Autónoma de Madrid. Fifteen samples were collected from four localities.

Sample collection. Several problems can limit the accuracy of luminescence dating: insufficient sunlight exposure before burial, post-depositional weathering, secondary mineral precipitation, etc. (Forman *et al.*, 2000). Three of these are most relevant to our study area. First, there is a chance of radon (from granites and migmatites) spreading through the sediments, which would cause changes in the dose rate. Fortunately, most outcrops are located in areas where schists (Atlantic sector) or quartzites and marbles (Cantabrian sector) predominate, and the method used indicated that no radon diffusion occurred. Second, the feldspar grains in the matrices of conglomeratic beaches are coarse and the sediments are heterogeneous. To minimize these problems, sandy beaches have been sampled where possible, to obtain fine-grained equigranular sands. The results obtained from conglomerate matrices do not differ significantly from those of fine beach sands. Third, changes in pore-water content since burial can lead to underestimates of age as large as 25%–50% (Forman *et al.*, 2000). This is a real problem in this area for several reasons, including the high rainfall and marine water splashing. To minimize this problem, samples were obtained by penetrating the outcrop horizontally as much as possible. However, the importance of very probable vadose washing was considered.

Samples were taken after detailed stratigraphical and sedimentological analysis, to determine the precise unit dated and to understand the formation processes, the possibility of sunlight exposure during deposition, and the diagenetic events that have occurred since burial. The samples were obtained for the laboratory technicians in two field campaigns, in May 2001 and May 2002. A drill core was used to penetrate the outcrop horizontally for about 30 cm, to obtain maximum uniformity of the dose rate during burial. Samples were isolated immediately in black canisters wrapped with aluminium foil to avoid sunlight exposure and evaporation. Measures of environmental radiation were taken at every outcrop at the same time, using a field gammaspectroscope.

Laboratory procedures. The TL measurements were made using a DA-10 TL-IRSL system developed by Riso National Laboratory, in which the integral light signal, transmitted via broad optical filters (Chance Pilkington HA 3) and a heat-absorbing filter (Corning 5-60), is detected by a photomultiplier tube (EMI 9635Q) as the sample is heated to 500 ºC at a heating rate of 5 ºC s^{-1} under a nitrogen atmosphere.

All samples were subjected to anomalous fading tests. After the erasure of the natural TL, the samples were given a dose of beta radiation and stored in the dark for 240 h. The subsequent TL was compared with that obtained immediately after a similar beta radiation dose. The loss of signal was always less than 1%. Therefore, the fine grain method was selected for further TL analyses (Zimmerman, 1971) and a mineral fraction of 2–10 μm was chosen. Nevertheless, short-term fading was eliminated by storing the radiated and corresponding natural samples at 50 ºC for a week.

Samples were also dated by IRSL as an alternative to TL, because the periglacial soliflucted sediments were poorly light-exposed and emission, when illuminated in the near-infrared, is more sensitive to solar resetting. X-ray diffraction analysis showed that the samples were mainly composed of quartz, feldspars, and some other minerals. The IRSL of feldspars, in particular, has been widely investigated by a number of authors because of its importance in sediment dating (Hüt *et al.*, 1988).

IRSL decay was measured with a TL/IRSL compact system model (Riso TL-IRSL DA-10). This system is equipped with an array of 32 infrared diodes (model TEMT 484) emitting at 880 ± 80 nm. These diodes were run at about 50 mA, delivering an intensity of about 40 mW cm^{-2} to the sample. Luminescence emission was also detected with an EMI 9635Q photomultiplier tube after passing through an HA 3 (Chance Pilkington) optical filter, which removes the IR excitation light, leaving a UV–visible bandpass from 300–600 nm. Additive dose growth curves were constructed using the integrated light sum for the first five seconds of exposure to infrared stimulation.

For both TL and IRSL measurements, laboratory beta radiation doses were given with a Sr^{90}/Y^{90} source and alpha radiation doses with a 241Am source, to determine the effectiveness of alpha particles in producing TL and IRSL. Dosimetry measurements were made in the labora-

UNIT	SITE	SAMPLE	LITHOLOGY	DEP. SYSTEM	TL Age (Ka)	OSL Age (Ka)	**OIS Stage**
1	Paizás	M - 7	Fine to medium size laminated sands	Sandy beach		75,8 +/-5,9	5
	Castro de Fazouro	M - 12	Conglomerates, coarse sandy matrix	Pebbly beach	74,3 +/- 6,7		5
	Os Riás	Riás 2 (bis)	Cemented sands	Sandy beach		69,0 +/- 5,8	5 /4
		Riás 3	Conglomerates, coarse sandy matrix	Pebbly beach	69,1 +/- 5,4	73,6 +/- 5,7	5
		Riás 4	Conglomerates	Pebbly beach	66,7 +/- 5,4	65,7 +/- 5,3	5 /4
	Razo	Razo 1	Fine laminated sands	Sandy beach	55,7 +/- 4,7	53,7 +/- 4,3	4/3?
		Razo 2	Fine to medium size laminated sands	Sandy beach	53,9 +/- 4,1	54,3 +/- 4,2	4/3?
2	Ponzos	M – 3	Pebbly coarse sands	Channel	63,0+/-10,2		4
		M – 4	Fine homometric sands	Dunes	41.8 +/- 3,7		3
	Paizás	M - 10	Matrix supported conglomerates	Soliflucted lobe		34,1 +/- 2,7	3
	Castro de Fazouro	M - 13	Coarse sands and angular clasts. Cross lamination	Soliflucted lobe. Soils	24,1 +/- 2,1		3/2
4	Ponzos	M - 5	Clast supported conglomerates	Channels	33,5 +/- 7,2		3/2
	S Ciprian	M - 16	Heterometric conglomerates. Coarse sandy matrix	Fluvial channel		23,5 +/- 1,9	2
	C de F / Nois	M - 14	Clasts supported breccias. Laminated sands	Alluvial channels	18,0 +/- 1,4		2
	Paizás	M – 11	Homometric sands	Eolian dunes		3.018 ± 433	1

Table 2.- Interpretation of luminescence dating
Tabla 2.- Interpretación de las dataciones por luminiscencia.

tory using thick source alpha counting for uranium and thorium, and thick source beta counting to discriminate between U chain and Th chain counts.

Results. Seven samples were processed and dated for Unit 1, four for Unit 2, and three for Unit 4 (Table 2). The results obtained for the samples from Unit 1 (raised beaches) yielded an age range from 74.3 ± 6.6 to 53.9 ± 4.1 ka with TL determinations and from 75.8 ± 5.8 to 53.7 ± 4.3 ka with IRSL analysis. These results indicate that samples from the Paizás and Castro de Fazouro sites on the Cantabrian coast are slightly older than those from the sites at Razo and Os Riás. Unit 1 results correspond to the end of the Last Interglacial period. Younger ages, up to OIS 4, which correspond to the samples from the beach at Razo, might reflect rejuvenation due to recurrent post-burial weathering, because they were located at the mouth of quite an important drainage channel.

Unit 2 was dated at the Ponzos (Atlantic), Paizás, and Castro de Fazouro (Cantabrian) localities. The lower levels at Ponzos gave an age of 63.0 ± 10.2 ka, whereas the overlying levels of aeolian dunes gave an age of 41.8 ± 3.7 ka. At the Paizás site, a solifluted lobe yielded a result of 34.1 ± 2.7 ka. A sample belonging to Unit 2 at Castro de Fazouro gave an age of 24.1 ± 2.1 ka. However, it is considered anomalously young because the soil developed above it yielded an age of > 38,000 years by ^{14}C dating.

Unit 4 was dated at Castro de Fazouro, San Ciprián, and Ponzos localities. The age of this unit can be better assessed by radiometric dating. Luminescence samples yielded an age of 18.0 ± 1.4 ka for stream channels at Castro de Fazouro and 23.5 ± 1.9 ka at San Ciprián for a well-defined high-energy channel. In Ponzos, age was measured in a strongly erosive channel to be 33.5 ± 7.2 ka, slightly older than expected. Several of the series are topped by recent aeolian dunes. One of them was dated by IRSL at the Paizás site (Fig. 2), with an age of 3.0 ± 0.4 ka.

4.2. Radiocarbon

The radiocarbon method was used to date Units 2, 3, and 4 at three localities in the Atlantic sector and one in the Cantabrian sector. All samples were treated and measured at Beta Analytic Inc. in Miami, FL, USA. The dates were calibrated, where possible, to calendar years using the INTCAL98 curve (Stuiver *et al.*, 1998), which is based on a sample set of dendrochronologically dated tree rings, U/Th-dated corals, and varve-counted marine sediments. The results showed that the samples from the lower parts of Units 2 and 3 are too old for the range of applicability of the method (Table 3).

Unit 2 was analysed at Soesto, in the upper part of the unit, corresponding to a soliflucted lobe. The sediment is rich in organic matter and coal fragments. The analysis was made in the organic-rich sands to avoid problems of inheritance, and resulted in an age of 27,370 – 270 yr BP (C^{13}/C^{12} values were estimated). At Nois, the sample was obtained from a soil developed on soliflucted sediments; its age was older than 38,000 yr BP. Unit 3 was sampled at both the base and the top, but was always older than the range of applicability of the method (> 45,740 yr BP and > 40,470 yr BP, respectively). Finally, an age of 13,050 ± 40 yr BP (calculated BP range, 16,010–15,240 yr) was obtained for a sample corresponding to a soil developed on swamp muds in the inner part of the Mandeo Estuary at Betanzos.

Apart from the samples studied in this research, the authors and other researchers have previously published radiocarbon dating results for some of the outcrops described here. Those results are also considered, and are given in Table 3. Alonso and Pagés (2000a) always obtained ages for Units 1 and 2 at Sorrizo, Rañal, Leira, and Sada (Atlantic sector) that were older than the time range of the method's applicability. At Arnela and Caamaño (same sector), Blanco Chao *et al.* (2003) obtained two series of sediment samples that can be correlated with Unit 2. From the base to the top of the outcrops, the samples yielded ages between 37,550 ± 690 and 28,750 ± 900 yr BP. The peats that correspond to Unit 3 were also dated by Mary (1993) in the type locality (Nois) and the results prove that they are older than 38,000 yr BP, which is in agreement with our own results. Unit 4 was dated by the same author in Nois and the results ranged from 16,780 ± 400 to 15,950 ± 300 yr BP. Alonso and Pagés (2000a) reported ages of 24,410 ± 385 yr BP for a bulk soil sample from Leira. Finally, Blanco Chao *et al.* (2003) reported an age of 20,160 ± 270 yr BP for channel sediments at a level that correspond to the same unit in Caamaño.

4.3. U/Th

The U/Th method was applied to samples from Unit 3 in the Laboratory Jaume Almela Consejo Superior de Investigaciones Científicas, Barcelona. The samples included a low percentage of organic matter (11%–26%), making them unsuitable for dating. Coal fragments from one sample were floated and concentrated. However, the analysis demonstrated that the sample was contaminated by Th^{232}. The age obtained was 115,600 ± 6,500 yr but, taking into account that the Th^{230}/Th^{232} ratio was very low (0.8), this age cannot be considered accurate. Although it can be inferred that the real age is more recent than the one obtained, it is coherent with the Last Interglacial period.

5. Discussion

Multiple outcrops of Late Pleistocene age in north-west Spain allow us to reconstruct the evolutionary development of the coast from the Last Interglacial stage to the beginning of deglaciation. Correlation of sedimentary series, sedimentological and stratigraphical analysis, and the dating of units allow the establishment of a sequence of events.

5.1. Evolutive phases

1. Gravelly and sandy beaches (Unit 1) were formed during a sea-level highstand episode, registered in the area very probably during OIS 5. Underestimations in dating prevent us from determining the substage. The sea level reached a mean position 2–3 m higher than the present sea level. The beaches were on a rocky-shore platform cut in the igneous and metamorphic rocks of the basement, and occupied embayments, entrances sheltered by headlands, or stream mouths. They appeared frequently at the cliff–shore junction. Both the cliffs and the coastal abrasion platform were polycyclic. They were carved during the Last Interglacial period and previous phases of high sea levels, through the combined action of waves

UNIT	SITE	SAM-PLE	LAB. Num.	LITHOLOGY	DEP. SYSTEM	Conv. AGE (y BP)	2 σ CAL. AGE	**AUTHOR**
	Nois	C-1	β 154346	Black sands	Soil	> 38.540	----------	This paper
2	Soesto	S- I.1	β 154344	Coarse black sands and pebbles	Soliflucted lobe	27.370 +/- 270	Out of range	
	Sada	S.1	β 165864	Organic muds	Soil	> 39.920	----------	
3	Nois	N.Inf.	β 154342	Black clays and wood	Peat, swamps	> 45.740	----------	
	Nois	Al-2	β 154343	Black muds	Swamps	> 40.470	----------	
4	Betanzos	Bet S.1	β 165868	Black muds	Soil	13.050 +/- 40	cal BP 16.010–15.240	
1	Sorrizo	ZO-4	Ua-11996	Black Ssnds	Beach	> 38.000		Alonso and Pagés (2000a)
	Rañal	RA-2	Ua-11994	Edaphied sands	Soliflucted lobe	> 38.000		
	Leira	LE-1	Ua-11992	Coarse sands and charcoal	Soliflucted lobe	> 38.000		
2		LW-2	Ua.11991	Black sands	Soils	> 38.000		
	Arnela	7 sam-ples			Soliflucted lobes	37.550 - 31.050		Blanco Chao *et al.* (2003)
	Caamaño	5 sam-ples			Soliflucted lobes and laminated flow deposits	36.050 – 27.750		
3	Nois			Peat	Peat, swamps	> 38.000		Mary (1993)
4	Nois				Soil	16,780 +/- 400		
					Soil	15.950 +/- 300		
	Leira	LE-2	Ua-11993	Black sands	Soil	24.410 +/- 385		Alonso and Pagés (2000a)
	Caamaño				Stream floods	20.160 +/-270		Blanco Chao *et al.* (2003)

Table 3.- Radiocarbon ages.
Tabla 3.- Dataciones por radiocarbono.

and the abrasive effects of sediments.

2. During the first phase of regression, the shore platform was progressively exposed and coastal systems migrated in response to the new position of the coastline. Beaches remained isolated and disconnected. The knick point in the junction was soon covered by soliflucted sediments that slid down the steep slopes of old cliffs (Unit 2). These covered the raised beaches and expanded onto the abrasive rocky platform surfaces. The streams drained the inland regions and re-used the valleys and gullies carved in the cliff slopes. They deposited their load at the change in slope (as alluvial fans) and then flowed down the coastal plain that was progressively widening.

3. On several parts of the coastal plain, poorly drained areas developed into marshes and swamps, generating

the organic sediments of Unit 3. The vegetation consisted mainly of shrubs and grasses on the old cliffs and sparse trees in the swamps. Peat bogs must have developed on the slope or on the mountain and were affected by episodes of spontaneous combustion, reflected in Unit 2 by many carbonized wood fragments in the matrix. This phase lasted from the end of the Last Interglacial to around 25.0 ka BP, and thus includes OIS 4 and 3.

4. Unit 4 clearly reflects different climatic conditions, visible in a less extensive development of vegetation and an increase in gelifraction processes. The unit is characterized by deposits with erosive bases, cross-stratification, clast-supported conglomerates and cross-laminated sands, deposited by streams that drained the valleys and excavated the old cliff front. Sporadic deposits of debris flows can be identified that correspond to slope mass failures, although tractive deposits are more dominant. Soils are scarce and deposits represent high-energy episodes. Towards the top, sand and pebbles predominate and some soil levels appear. This phase was developed mainly during OIS 2, from 25.0 to 15.0 ka BP, including at least the Last Glacial Maximum and the beginning of deglaciation. The sample dated at Ponzos seems to indicate that the change of Unit 2 to Unit 4 was perhaps a little earlier, by the end of OIS 3.

5. The end of this phase until the beginning of the Holocene is poorly documented due to the scarcity of dated outcrops. The phase is sporadically represented in the subaqueous parts of the present estuaries (Rey Salgado, 1993) and at the base of the Holocene record, infilling the internal parts of the estuaries (Alonso *et al.*, 2003). In several of the outcrops studied there is a level of aeolian sands which lie above Pleistocene deposits (dated in the outcrop of Ponzos at 3.0 ± 0.4 ka by IRSL). At present, the erosive processes on the coast are very active and the cliffs are retreating. The abrasion surface is being lowered to the present water level, and the Pleistocene and Holocene outcrops are disappearing.

5.2. Chronostratigraphy

The chronostratigraphic model presented in this research broadly matches the general evolutive scheme for the cycle from the Last Interglacial to the Last Glacial Maximum in Western Europe, although there are some differences that should be analysed further. The most problematic aspect is the age of the raised beaches that have been dated as OIS 5. Generally, OIS substage 5e (Eemian) is accepted as the most important and most frequently recognized event in OIS 5, when the marine isotope record suggests that the sea level reached a few metres above the present sea level (Imbrie *et al.*, 1984; Cutler *et al.*, 2003), in a context of climatic stability with temperatures a few degrees above present temperatures. In Brittany (Haslett and Curr, 2001; Regnauld *et al.*, 2003; Morzadec-Kerfourn, 1999) and the English Channel (Keen *et al.*, 1996; Bates *et al.*, 2003), marine terraces buried by periglacial deposits, in a scenario similar to ours, have been described. In Brittany, raised beaches have been dated back to 90.0 ka and attributed to the Last Interglacial. On the English Channel, detailed coastal sections have been described and raised marine levels of substage 5e identified, although absolute datings are not yet available. No OIS substage 5a marine levels have been identified, but Keen *et al.* (1996) recognized 5a climatic fluctuations in the soils developed on head deposits.

In contrast, marine terraces corresponding to OIS substage 5a have been described in Spain and Italy. Garzón *et al.* (1996) studied a raised beach level in the central part of the Bay of Biscay coast, dated to 71.0 ka BP with the amino-acid racemization method. Zazo *et al.* (2003) identified levels (at 3.5–2 m above sea level [a.s.l.]) with poor isotopic results, but attributed to OIS 5a a complex set of raised terraces in the south of the Iberian Peninsula and the Balearic Islands. On the Italian peninsula, Mauz (1999) identified raised levels corresponding to OIS substages 5c and 5a (at 2–3 m a.s.l.), and stage 3. Mauz considered tectonic processes to be responsible for the absence of substage 5e, because active faults exist in the area. In the south of Italy, Mauz and Hassler (2000) identified OIS substages 5e and 5a (at 18 m a.s.l.), and also OIS 3. Tectonics is also a very important controlling factor here.

For the moment, the data obtained from this research, together with those for Cantabria, are the only available absolute dating values for the raised beaches on the northern Spanish coast. In all cases, the results point to deposition at the end of the Last Interglacial period, that is, substage 5a, accepted to have occurred at 85–74 ka BP (Imbrie *et al.*, 1984; Wright, 2000; Potter *et al.*, 2004; Schellman *et al.*, 2004). Several features, although none of them conclusive, could support the hypothesis: The results are relatively homogeneous, in both the Atlantic sector and the Cantabrian (environmental factors would thus be minimized, as they are different in both sectors) and the ages coincide with those obtained by amino-acid racemization for the raised beaches of Oyambre (Cantabria) by Garzón *et al.* (1996). However, we are conscious that OIS substage 5e or even 5c cannot be rejected, because the model fits very much with that described for Brittany and the English Channel, the raised beach heights are very similar to that generally accepted for substage 5e, and because an underestimation in the ages calculated must be assumed considering the regional

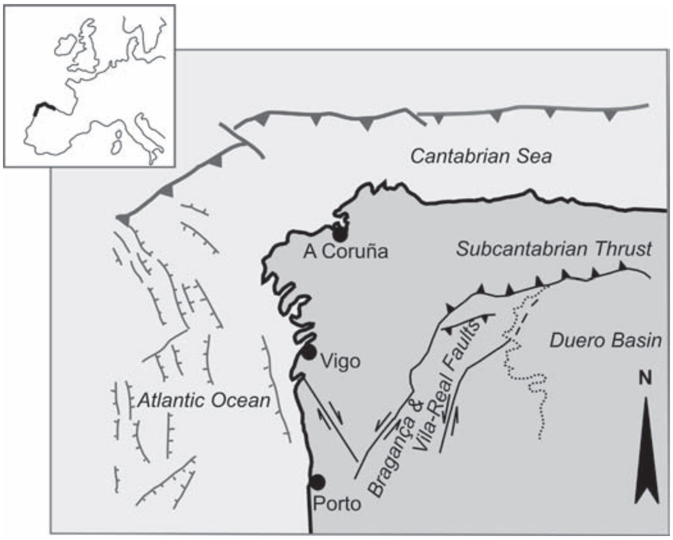

Fig. 3.- Tectonic setting (modified from Santanach Prat, 1994).
Fig. 3.- Localización tectónica (modif. de Santanach Prat, 1994).

setting and lithological characteristics.

The remains of older episodes of sea-level highstands are almost unknown on this coast. An outcrop of rounded pebbles in a sandy–clayey matrix elevated 15 m above m.s.l. (A Coruña), has been interpreted by Gutiérrez-Bécker *et al.* (2004) as a raised beach, although its age is unknown. We consider that older levels were probably eliminated due to the rapid retreat of the cliffs (a feature that is very important today) and the unstable locations of Late Quaternary sediments, which make them extremely sensitive to erosion.

5.3. Tectonic remarks

The present topographic heights of the older marine levels cannot be used as indicators of the former positions of sea level because they are basically dependent on regional tectonic behaviour (Bates *et al.*, 2003). The northern coast of Spain is situated between the sub-Cantabrian thrust and the zone of subduction of the Cantabrian sea floor under the Iberian subplate (Fig. 3) (Santanach Prat, 1994). It is undergoing a process of isostatic uplift following the end of this subduction (Monino Sáez *et al.*, 1988). This recent tectonic behaviour seems to be in response to a generalized vertical movement rather than to the differential movements of blocks.

Whether it is considered the OIS substage 5a, 5c, or the 5e hypothesis, it must be taken into account that there is a difference in uplift of between +2 and +3 m on the coast of the Bay of Biscay (Oyambre) relative to that in Galicia. Mary (1979) considered that tectonic uplift in the eastern sector of the Bay of Biscay coast was higher than that in the west, although he did not find this feature relevant during the sedimentation of the Late Pleistocene materials. However, this work proves that it is relatively important and that it has continued to be active since the Last Interglacial. The region north of Galicia probably behaves as a rigid block and acts as a hinge zone between the uplifting north and the active atlantic margin of the Iberian Peninsula (Pazos *et al.*, 1994; Granja *et al.*, 1999; García Gil *et al.* 1999).

5. Conclusions

1. Facies correlation and sedimentology are useful instruments with which to reconstruct the architectural stratigraphy of the Pleistocene record on the northern coast of Spain, where outcrops are fragmented and sparse.

2. Luminescence (TL and IRSL) is, for the moment, the only feasible method for dating Last Interglacial and Early Glacial sediments in this sector. However, the physical limitations of the method must be considered and results must be carefully assessed. The results presented here are reasonably consistent but some underestimation of absolute ages must be considered.

3. Four stratigraphical units have been differentiated. Unit 1, which is formed of gravel and sands, is interpreted as beaches resting on an abrasion shore platform 2–3 m above the present day m.s.l. IRSL dating has allowed the unit to be dated at ≥ 76–54 ka. However, taking into account the rejuvenation values for the upper units given by radiocarbon dating, 100–73 ka could be more realistic. Thus, it is considered that Unit 1 belongs to the Last Interglacial (OIS 5). A comparison has been made with some raised beaches (5–6 m above m.s.l.) in Cantabria, with an age of 71.0 ka by amino-acid racemization dating.

Unit 2 was formed during the Early Glacial (OIS 4 and 3) and corresponds to classical slope deposits: soliflucted lobes, debris flows, and soils. These buried the raised beaches and the distal part of the unit extended onto the rocky shore platform. Unit 3 corresponds to peat and swamps formed in the lower parts of the old cliffs and in the newly exposed platform. It was contemporaneous with at least the lower part of Unit 2. Unit 4 has been dated (luminescence and radiocarbon) between 25 ka and 15 ka, which corresponds to OIS 2 and represents at least the Last Glacial Maximum and the beginning of deglaciation, although it probably started at the end of OIS 3. Lithology (breccias, angular conglomerates, and gravelly cross-laminated sands) clearly reflects a climatic deterioration.

4. The erosive surfaces that constituted the rocky shore platforms and cliffs are polycyclic features that were cut during the Last Interglacial, but were probably also inherited from former interglacial episodes. Erosion is very active today due to the continuous rise in sea level and high-energy marine climatic conditions, and the palaeo-

cliffs and platforms are being exhumed, reworked, and destroyed in the present highstand stage. In this process, most of the Pleistocene record is seriously endangered.

5. The northern coast of the Peninsula faces uplift due to deep-seated tectonic and isostatic rebound. Uplift is higher in Cantabria (2–3 m since the Last Interglacial period) than in Galicia.

6. Despite the chronological, stratigraphical, and palaeogeographical advances made in this work, more research is needed, especially in the establishment of a solid chronological framework. Considering the fragmented and sometimes complex outcrops and the total absence of biological remains, this chronology must be based on geochronometric ages.

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