Recent transformation of intertidal environments under a sea-level rise scenario: examples from northern Spain

Transformación reciente de ambientes intermareales bajo un escenario de ascenso del nivel marino: ejemplos del norte de España

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ABSTRACT

The transformation of two intertidal environments from northern Spain during the last 150 years shows an evolution from a tidal flat into a salt marsh environment, with an intermediate transitional stage. The environment of deposition was reconstructed based on benthic foraminifera and sand content. Sediments were put into a temporal framework using short-lived radioisotope activities and heavy metal concentrations. The observed natural evolution responds to the availability of abundant sediment and the current sea-level rise scenario, where intertidal environments are trying to adapt to increasing flooding periods by accreting sediment rapidly.

Key-words: *foraminifera, intertidal environment, natural transformation, sea-level rise, Santoña estuary.*

RESUMEN

La transformación de dos ambientes intermareales en el norte de España durante los últimos 150 años muestra la evolución desde una llanura intermareal a una marisma, con una etapa de transición intermedia. El paleoambiente se reconstruyó mediante el contenido en foraminíferos bentónicos y en arena. Los sedimentos fueron datados utilizando radioisótopos de vida corta y concentraciones de metales pesados. La evolución natural observada responde a la disponibilidad de abundante sedimento y al escenario actual de ascenso en el nivel del mar, donde los ambientes intermareales están tratando de adaptarse a los crecientes períodos de inundación acrecionando sedimento rápidamente.

Palabras clave: *foraminíferos, ambiente intermareal, transformación natural, ascenso del nivel marino, estuario de Santoña.*

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Introduction

Geological records from northern Spain show an average relative sea-level rise rate of 2 mm/yr in the past century (Leorri *et al.*, 2008), in agreement with regional tide gauge data (Chust *et al.*, 2009). This supposes an important departure from background Holocene values (0.53 ± 0.48 mm/yr; García-Artola *et al.*, 2018).

Unless salt marshes are able to keep pace with sea level, these and other intertidal areas are at risk of submergence. Salt marsh environmental regeneration studies in northern Spain showed that the abundant sediment available in the regional estuaries allowed rapid sedimentation rates (up to 18 mm/yr) to take place (García-Artola *et al.*, 2016). Consequently, intertidal areas, such as salt marshes from northern Spain, could potentially adapt to future sea-level rise.

The survival of intertidal environments is determined by a complex equilibrium between biotic and abiotic processes. Sediment availability is a key factor. Sedimentation in salt marshes occurs from deposition of suspended detritic sediment and *in situ* plant organic matter (Cahoon, 2006; Allen, 2009; Schile *et al.*, 2014). Moreover, the sediment capture efficiency by vegetation is an essential factor in the determination of the drowning or adaptation of a salt marsh (Day *et al.*, 2011). This efficiency might be affected by sea-level rise that increases inundation, which in turn affects plant productivity (Kirwan and Guntenspergen, 2012; Voss *et al.*, 2013). In fact, the type of vegetation influences the adaptation capacity (Janousek and Mayo, 2013).

Tidal flats lack halophytic vegetation (Pratolongo *et al.*, 2019), which is known to be of vital importance for the evolution of salt marshes in the current context of sea-level rise (Morris *et al.*, 2002; Marani *et al.*, 2013). While numerous regional studies have analysed the behaviour of salt marshes (see above), none has focused on tidal flats.

Here, we study the evolution of two tidal flat environments from the Santoña estuary (northern Spain) over the past century. These environments evolved recently into salt marshes as a response to the 20th century sea-level rise. As for salt marshes, sediment availability seems to control the regional transformation of these lower elevation environments that accrete sediment very fast to reach equilibrium with the tidal frame.

Materials and Methods

The Santoña estuary (northern Spain) is formed by the tidal part of the Asón river with an extension of 11 km length and 0.5 km width in the upper estuary and 3 km width in the lower estuary, covering a total area of 200 ha (García-Artola *et al*., 2016).

The Justreda (JU: X=461353.594; Y=4807556.389; Z=2.737 m; two 50-cm long replicates) and Primosto (PR: X= 462252.9; Y= 4804325.367; Z=2.683 m; two 46-cm long replicates) cores were extracted by hand introducing two 50-cm long and 12.5-cm diameter PVC tubes in each salt marsh characterized by *Spartina maritima* (Curtis) Fernald vegetation (Fig. 1). Precise location and elevation of the cores were measured using a RTK-GPS, with a horizontal precision of ±20 mm and a vertical precision of ±35 mm. The Z coordinate was referenced to the local ordnance datum (LOD: lowest tide at the Bilbao Harbour on September 27, 1878; located 1.73 m below the Spanish national levelling datum or MSL in Alicante). Sediment compaction during sampling was negligible due to the minerogenic nature of the sediment and the large diameter of the tube. In both cases, historical aerial photography does not show any evidence of human impact in the recent past (Fig. 1).

Each replicate was longitudinally divided into two halves. The first half was used to analyse the grain size and the foraminiferal content in order to interpret the palaeoenvironment (see García-Artola *et al*., 2016 for methodology). The second half was employed to measure the ^{137}Cs activity and the Pb concentration to develop a chronology for the recovered sediments (see Corbett *et al*., 2006 and García-Artola *et al*., 2016 for methodology).

Results and Discussion

The lower half of the JU core is formed of grey sand (with abundant mollusc shells in the lowermost 8 cm) and the upper half is made of grey mud with plant roots at the top 15 cm (Fig. 2). According to the foraminiferal content, three depth intervals (DIs) were distinguished in this core. The lowermost 22 cm (DI3) are characterised by high numbers of foraminiferal tests (mean 2846 tests/50 g). The assemblage is dominated by calcareous hyaline species (average 98%), where *Ammonia tepida* (Cushman) (average 39%), *Haynesina germanica* (Ehrenberg) (average 39%), and *Cribroelphidium williamsoni* (Haynes) (average 16%) are dominant. This interval is interpreted as a tidal flat environment based on its similarity with modern assemblages described by Cearreta (1988), Cearreta *et al*. (2002) and Leorri *et al*. (2008). The upper 4 cm (DI2) contain moderate numbers of foraminiferal tests (mean 1040 tests/50 g) characterised by a mixture of calcareous hyaline (average 65%) and upward increasing agglutinated (average 35%) forms. The assemblage is dominated

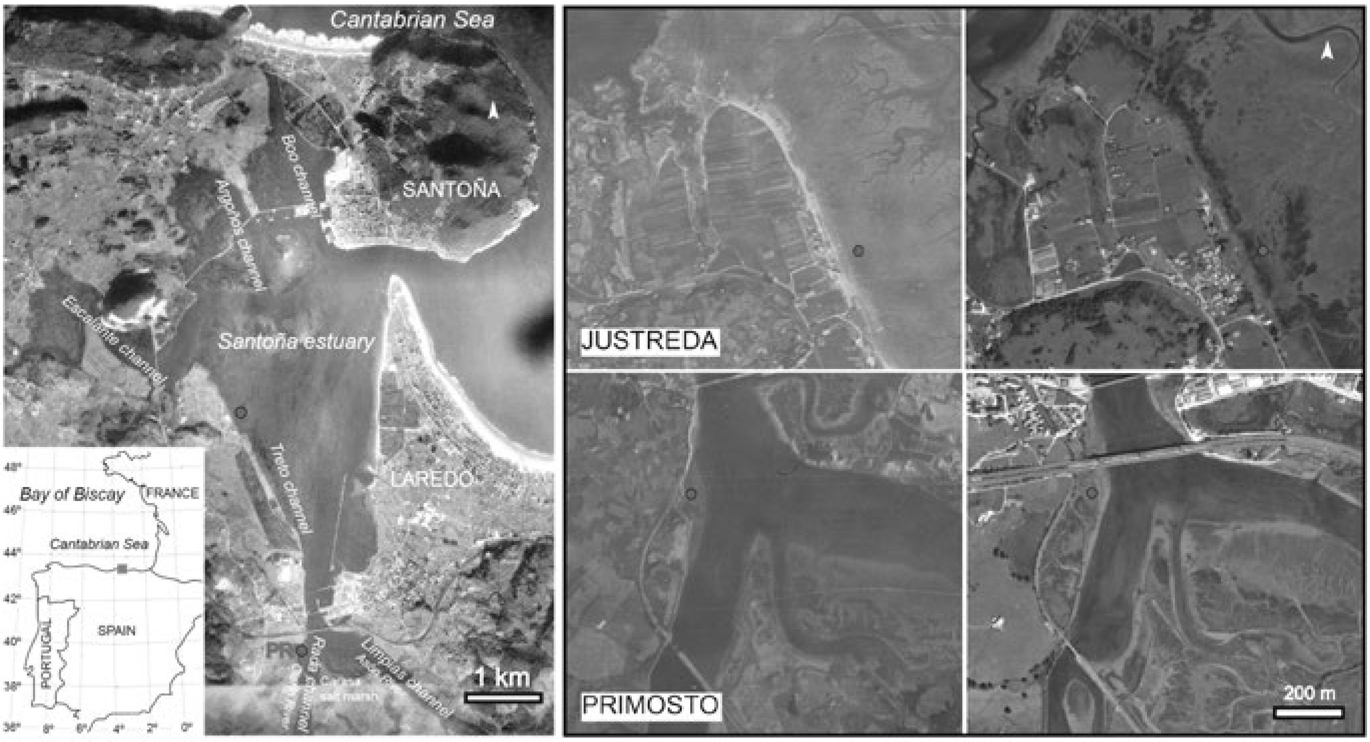

Fig. 1.- On the left, geographical location (green square) of the Santoña estuary in northern Spain and position of the JU and PR cores (red dots). On the right, detailed historical (1946: left) and modern (2011: right) aerial photographs with the position of the JU and PR cores (red dots). See color figure in the web.

Fig. 1.- A la izquierda, localización geográfica (cuadrado verde) del estuario de Santoña en el norte de España y la posición de los sondeos JU y PR (puntos rojos). A la derecha, fotografías aéreas histórica (1946: izquierda) y moderna (2011: derecha) con la posición de los sondeos JU y PR (puntos rojos). Ver figura en color en la web.

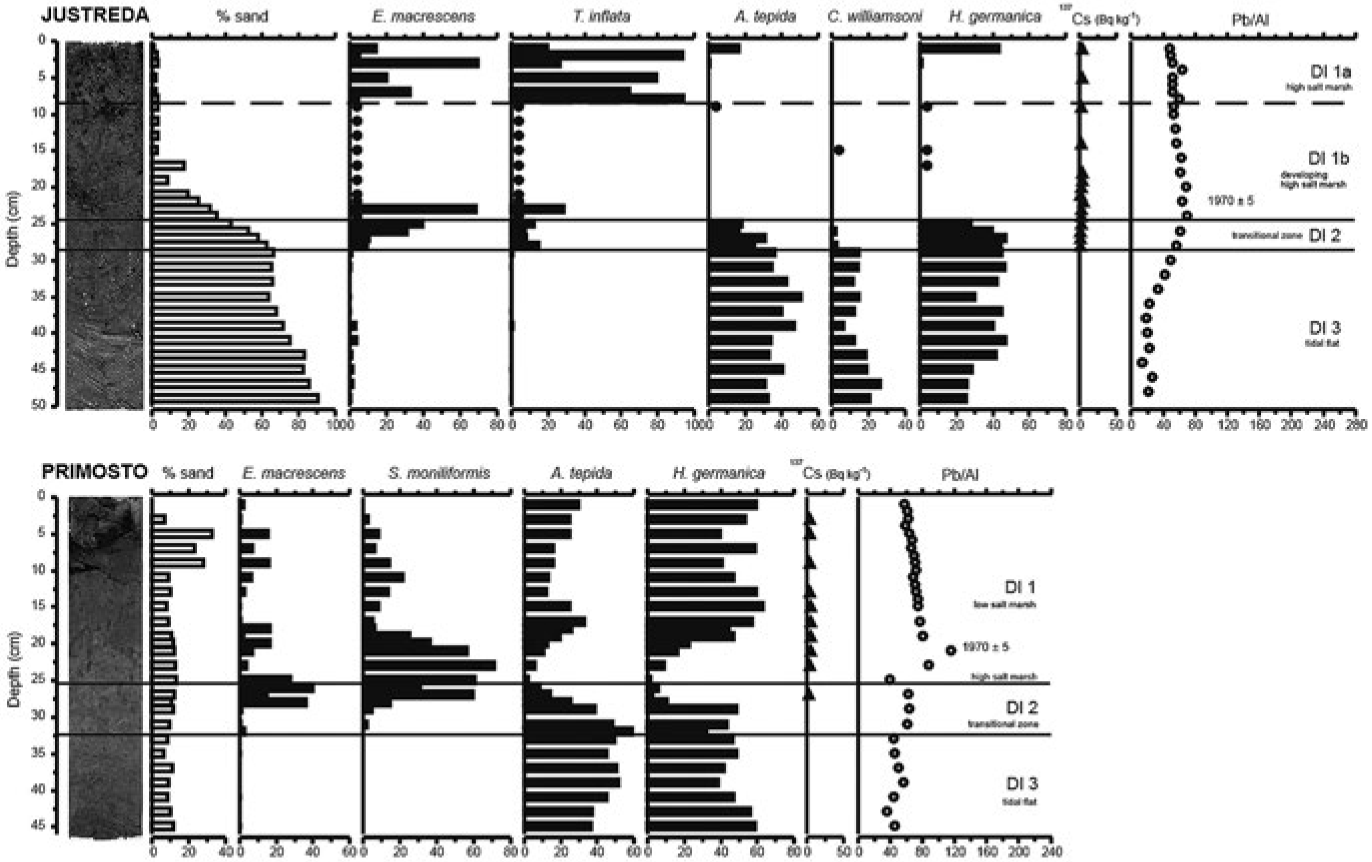

Fig. 2.- Identified depth intervals (DIs) in the JU and PR cores based on the sand content (%) and main foraminiferal species (%). 137Cs activity (Bq/kg) and Al-normalised Pb distribution with depth (cm) are also shown for chronological purposes (see text).

Fig. 2.- Intervalos de profundidad identificados en los sondeos JU y PR en función del contenido en arena (%) y las especies de foraminíferos dominantes (%). También se muestra la actividad de 137Cs (Bq/kg) y la distribución de Pb normalizado respecto a Al en función de la profundidad (cm) con fines cronológicos (ver texto).

by *H. germanica* (average 40%), *A. tepida* (average 23%), *Entzia macrescens* (Brady) (average 23%) and *Trochammina inflata* (Montagu) (average 11%). This interval might represent a transitional environment from the lower tidal flat environment towards the upper DI1. In fact, the increase of agglutinated species towards the top of this interval is interpreted as the shallowing of the environment. The uppermost 24 cm formed DI1 that is divided into two sections based on differences in foraminiferal densities. The lower 16 cm (DI1b) are represented by very low numbers of agglutinated foraminiferal tests (mean 62 tests/50 g). Finally, the upper 8 cm (DI1a) are dominated by agglutinated forms (average 99%) and a moderate foraminiferal density (mean 1584 tests/50 g), except for the uppermost 1 cm that contains abundant calcareous taxa. *Trochammina inflata* (average 72%) and *E. macrescens* (average 27%) are dominant in DI1a. This interval represents a high salt marsh environment because the foraminiferal assemblages are almost exclusively formed by agglutinated species, except for the top sample that is indicative of a low salt marsh environment. The very low foraminiferal density in the lower DI1b could be explained by the very high sedimentation rates that must have occurred so that the higher elevation salt marsh in DI1a could develop. Sand content decreases from the core bottom, where it is very high (mean 75% in DI3), to the top, where it achieves very low values (3% in DI1a). This pattern suggests that as the environment was gaining elevation it became more restricted and, therefore, the entrance of estuarine and marine sand was more limited. Sediment containing ^{137}Cs is first recorded at 28 cm depth (DI2). The ^{137}Cs record indicates the transition between the tidal flat and the salt marsh occurred after 1954 when the atmospheric nuclear weapon testing record in sediments begun (Ritchie and McHenry, 1990). Additionally, the Al-normalized Pb concentration peak at 24 cm depth (DI1b) suggests this transition occurred prior to the 1970s when maximum emissions of Pb in Europe and the main regional industrialization period coincide (Pacyna *et al*., 2007; Irabien *et al*., 2015).

The lower 24 cm of the PR core was made of brown mud and the top 22 cm are composed of soft black mud, with *Scrobicularia plana* (da Costa) bivalve all over and *Hediste diversicolor* (O.F. Müller) polychaete in the top half (Fig. 2). The core was divided into three DIs according to the foraminiferal content. The lowermost 14 cm (DI3) contain a moderate number of foraminiferal tests (mean 480 tests/50 g), almost exclusively composed of hyaline species (average 99.7%). *Haynesina germanica* (average 49%) and *A. tepida* (average 46%) are the main species. This interval is interpreted as a tidal flat environment because it was formed almost exclusively of calcareous hyaline species. The upper 7 cm (DI2) are characterized by a mixture of upwards increasing agglutinated (average 41%) and decreasing calcareous hyaline (average 59%) forms. The assemblage displays moderate numbers of foraminiferal tests (mean

410 tests/50 g), dominated by *A. tepida* (average 33%), *H. germanica* (average 24%), *Scherochorella moniliformis* (Siddall) (average 19%) and *E. macrescens* (average 16%). As in the JU core, this intermediate interval represents a transitional environment from the lower tidal flat environment towards the upper salt marsh setting. The top 25 cm (DI1) are characterised by a moderate foraminiferal density (mean 379 tests/50 g), where calcareous hyaline species increases upwards (average 61%). This upper part is dominated by *H. germanica* (average 42%), *S. moniliformis* (average 23%) and *A. tepida* (average 19%). This interval represents a low salt marsh environment that is losing elevation through time as the increase of calcareous hyaline species in detriment of agglutinated species towards the core top indicates. Sand content is rather constant throughout (average 11%) except for the top 10 cm where it increases up to 30%. This evolution of the sand content supports the idea of a topographically lower salt marsh environment towards the top, which makes it more prone to tidal inundation. In Primosto, the bottom tidal flat evolved into a high salt marsh but, unlike Justreda, the salt marsh apparently did not receive enough sediment to maintain the increasing elevation and quickly turned into a low marsh. This could be related to variations in local hydrodynamic conditions or differential river flow inputs to the Justreda and Primosto salt marshes. The Justreda salt marsh receives sediment from the main Asón river through the Limpias channel as well as from the Clarín stream, a tributary of the former, through the Rada channel (Fig. 1). The location of the Primosto salt marsh, separated from the Limpias channel by the Carasa salt marsh (Fig. 1), which has recently been regenerated (García-Artola *et al.*, 2016), could restrict sediment input to the smaller Clarín stream. Furthermore, the limited space available for salt marsh migration or changes in plant productivity could have also been responsible for the observed evolution (Schile *et al.*, 2014). The PR core presents a similar temporal evolution to the JU core, with the transitional zone beginning prior to 1954 (^{137}Cs is first recorded at 27 cm depth) and ending between 1954 and the 1970s (the Al-normalized Pb maximum is at 21 cm depth).

Conclusions

The sediment records extracted from two intertidal areas from northern Spain showed the natural transformation of a tidal flat environment into a salt marsh setting, located higher in the tidal frame. The former tidal flats accreted sediment aiming to reach equilibrium with the new tidal frame as sea level was rising. This was indicated by the upwards increase of agglutinated species, suggesting that the environment was gaining elevation. Both these records show the importance of abundant sediment availability for these environments to keep pace with increasing sea level. When sediment input was not sufficient, the otherwise high marsh environment was transformed into a low marsh environment, dominated by a mixture of calcareous and agglutinated foraminifera. These conclusions are of interest for the development of predictions regarding the adaptive response of these coastal ecosystems and their potential use as natural defences for ongoing sea-level rise.

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