Anthropocene versus Holocene relative sea-level rise rates in the southern Bay of Biscay

Rangos de ascenso marino relativo en el sur del Golfo de Vizcaya durante el Antropoceno frente al Holoceno

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ABSTRACT

Con el fin de evaluar la aceleración en el ascenso relativo del nivel marino durante el Antropoceno, se han comparado los resultados previamente establecidos para el siglo XX con los resultados obtenidos a partir del estudio de 61 nuevos puntos indicadores del nivel marino durante el Holoceno en el sur del Golfo de Vizcaya. Estos resultados indican un ascenso rápido hasta los circa 7000 años cal BP que se puede estimar en 9-12 mm año^{-1}. Desde entonces, el nivel del mar ha ascendido suavemente en concordancia con los datos proporcionados a nivel global, con una velocidad media de 0,7 mm año^{-1}. Esta velocidad contrasta netamente con la tasa de ascenso registrada durante el siglo XX de 1,9 mm año^{-1}, confirmando la aceleración detectada a nivel global como resultado de las actividades antropogénicas. Aunque los resultados obtenidos son altamente satisfactorios, los diferentes rangos de error proporcionados por ambos estudios hacen necesarios más estudios de este tipo para reducir los errores asociados a estas reconstrucciones.

Key words: *Foraminíferos bentónicos, estuarios, Holoceno, nivel marino, Golfo de Vizcaya*

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Introduction

Leorri and Cearreta (2009a) calibrated the foraminiferal assemblages of two salt-marsh cores from two estuaries using a regional transfer function constructed to the southern Bay of Biscay. The foraminifera-based reconstructions were placed into a temporal framework using ^{137}Cs, heavy metal concentrations, and ^{210}Pb-derived sediment accumulation rates. The resulting relative sea-level curves were integrated with the Santander tide-gauge data providing a regional relative sea-level rise of 1.9 mm yr^{-1} for the 20th century. This result contrasts with the almost negligible sea-level rise proposed for the same area during the 19th century by Leorri *et al*. (2008b), supporting the idea of a global acceleration in the rates of sea level at the turn of the 19th century linked with human-induced climatic change.

It is, therefore, desirable to obtain new high-resolution sea-level data from the Holocene, as they represent the fundamental basis for comparison with the historical and present changes. They provide a benchmark against which one must measure the additional sea-level rise that has occurred over the last 100-150 years (Church and White, 2006; Holgate, 2007). Available sea-level data from the North Atlantic Ocean provide a broad picture of fast sea-level rise since 15,000 cal yr BP (from 100-120 m below current level) until 6000 or 5000 cal yr BP when sea level reached its present position. Since then, sea level has been relatively stable (Lambeck, 1997).

We hypothesize that foraminiferal and sedimentological analysis combined with 14-C dating of the Holocene estuarine infilling would provide high-quality data from the Bay of Biscay to examine the issue of Holocene changes in the rate of relative sea-level rise. In this paper, we use the modern inferred relationship of foraminiferal assemblages with elevation derived from three different estuarine areas (Leorri *et al*., 2008a) to provide a Holocene sea-level curve. However, we argue that a single estuarine area could reflect local rather than regional forcing factors. Consequently, we study here multiple Holocene cores from two estuaries (Bilbao and Urdaibai).

Study area

This study was conducted in two estuaries with similar mesotidal ranges (mean tidal range: 2.5 m; Leorri *et al*., 2008b). The Bilbao estuary was originally the most extensive estuarine area on the Cantabrian coast of northern Spain. The modern estuary is 15 km long and is formed by the tidal part of the Nervion river, although four other rivers (Kadagua, Asua, Galindo and Gobelas) discharge into the main course. Today the Bilbao estuary is a largely artificial system which bears little resemblance to the original estuary. It has been calculated that the total amount of the original estuarine surface lost through human

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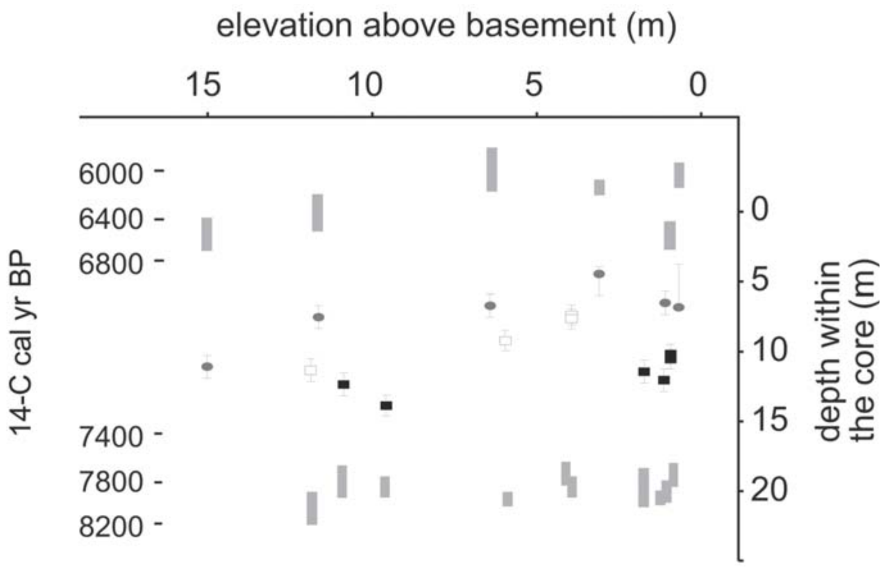

Fig. 1.- Plot of sea-level index point points, showing depth within the core (m) against elevation above the contact with the basement (m) and calibrated age for some samples used to correct for autocompaction. Different symbols represent groups of similar radiocarbon ages (only two groups are presented). Grey bars indicate the age range for samples represented as dots and boxes (white and black) located in the middle area. White boxes are muddy samples (more autocompacted) and black boxes are sandy samples (less autocompacted). Dots are sandy samples of younger age. Greater elevation above the basal contact correlates with greater depth as a result of the autocompaction. Estimated vertical errors associated with different depositional environments are also indicated.

Fig. 1.- Gráfico de los puntos indicadores del nivel marino, mostrando la profundidad dentro del sondeo (m) frente a su elevación respecto al contacto basal (m) y la edad calibrada de algunas de las muestras usadas para corregir la autocompactación. Los diferentes símbolos representan grupos similares de edades de radicarbono (sólo se presentan dos grupos). Las barras grises indican el rango de edades para las muestras representadas como puntos y cajas (blancas y negras) situadas en la zona media de la gráfica. Las cajas blancas son muestras fangosas (más autocompactadas) y las cajas negras son muestras arenosas (menos autocompactadas). Los puntos son muestras arenosas de edad más joven. Las mayores elevaciones respecto a los contactos basales correlacionan con las mayores profundidades como resultado de la autocompactación. Los errores verticales asociados a los diferentes medios deposicionales también aparecen indicados.

activity is approximately 1000 ha (Leorri and Cearreta, 2004). On the other hand, the Urdaibai estuary (Urdaibai Biosphere Reserve) is formed by the tidal part of the Oka river, covers an area of 765 ha, and occupies the flat bottom of the 11.6 km long, 1 km wide alluvial valley (Leorri *et al*., 2008b).

Materials and methods

In order to establish the general framework of the relative sea-level rise during the Holocene at the regional level, 61 samples recovered from 20 boreholes and one trench were selected and analyzed for sedimentological and micropalaeontological contents and radiocarbon dated. Samples were chosen as representative of different estuarine subenvironments and elevations. All data are presented relative to current mean tidal level at the Bilbao tide gauge; 2.4 m above local ordnance datum (lowest tide at the Bilbao Harbour on 27th September 1878). The boreholes were drilled using a rotary drill that produced a core approximately 10 cm in diameter. In each case, the borehole terminated in Cretaceous basement.

Sedimentological and Micropalaeontological sample preparation followed standard methods and are described in Leorri and Cearreta (2004). Beta Analytic Inc. (USA) and NSF-AMS Facility at the University of Arizona (USA) carried out radiocarbon dating on forty five shell samples, four samples of foraminiferal tests (*Ammonia tepida*), eleven wood samples, and one bone sample. Twenty seven of them were large enough for radiometric analysis and C-14 content was quantified by measuring emanating radiation which occurs during the decay process. Of those, four samples contained less than 1 gr of final carbon and were analyzed with extended counting to enhance precision. The other thirty four samples were very small and required direct atomic counting using an accelerator mass spectrometer. All radiocarbon dates were calibrated into calendar years before present (cal yr BP) using CALIB 5.0.1 (Stuiver *et al*., 2005); Marine04 curve was used for marine samples and IntCal04 was used for non-marine samples (i.e., wood and bone samples). The dates obtained on shell material have been also corrected for the marine reservoir effect (apparent surface-water age), which has been estimated to be around 400 years on the Bay of Biscay (Leorri and Cearreta, 2004).

Sea-level indicative meaning and sources of error

The vertical position of a sea-level index point (SLIP) relative to mean tidal level (MTL) is calculated as (Massey *et al*., 2008):

$$SLIP = H - D - I + C + A,$$

where H is the height of the core top relative to MTL, D is the depth of the sample in the core, I is the height of deposition of the sample (indicative meaning) relative to MTL as inferred from table I, C is the core compaction, and A is the autocompaction. Derived rates of sea-level rise were calculated using linear regression analysis.

Based on the sedimentological and micropalaeontological contents of modern environments and their relationship with elevation described by Leorri *et al*. (2008a; 2008b), Cearreta *et al*. (2008), and Leorri and Cearreta (2009b), we infer the environment in which the samples originated («indicative meaning» of the SLIPs; Table I) following Gehrels *et al*. (2006), Ruiz *et al*. (2005), and Mauz and Bungenstock (2007). Although samples close to the contact with the basement, basal SLIPs, would be less prone to error (e.g., less autocompaction) as it happens with basal peat samples, the materials overlaying the Cretaceous basement are always fluvial gravels that in many cases have been reworked during the Holocene sea-level rise (Leorri and Cearreta, 2004) seemingly precluding the use of these materials for sea-level reconstructions.

There are different sources of error when creating SLIPs, some of them being more relevant than others. The vertical error calculation follows Shennan and Horton (2002) (total error= $\sqrt{(e_1^2+e_2^2+...e_n^2)}$) and includes the sum of field levelling (± 0.02 m), sample levelling within the core (± 0.05 m), modern vertical distribution of the different environments (different environments have different tidal ranges). However, from all possible sources, autocompaction (loss of porosity due to the load of overlying sediments) introduces the greatest vertical errors, especially from unconsolidated peat sequences (Gehrels, 1999). Boreholes obtained in both the Bilbao and Urdaibai estuaries indicate that the depth of the stratigraphic contact between the basement and the Quaternary sediments greatly varies between 4 and more than 30 m from the upper to the lower estuary, respectively. These sediments are composed mainly by gravels and coarse sands at the base; they vary however in the mud (silt and clay) content, with the presence of some organic-rich lenses (Leorri and Cearreta, 2004). Thus, although minerogenic sediments dominate and the sand content is very high, the great length of some cores and the variable mud content suggest that additional accommodation space due to autocompaction can be responsible for at least part of the observed sea-level rise. Hence, in order to address autocompaction we have directly compared samples with statistically similar radiocarbon ages recovered at different elevations above the basement-Quaternary contact (Fig. 1), following Gehrels (1999). One limitation of our approach is that samples do not necessarily represent equivalent depositional environments and, therefore, this model should be considered carefully. Nevertheless, the results obtained allow to infer reasonably well the actual extent of autocompaction.

Based on the vertical errors mentioned and the substantial age errors (true ages lie somewhere in a time span between 100 and over 650 years) the obtained sea-level curve has to be interpreted in terms of metre scale vertical resolution and sub-millennial scale age resolution.

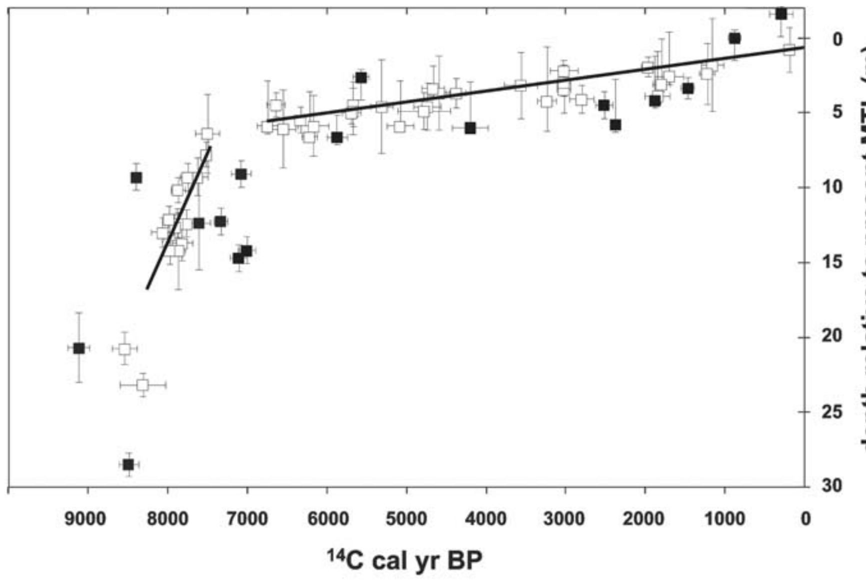

Fig. 2.- Plot of Holocene sea-level index points from the Bilbao and Urdaibai estuaries, showing calibrated age against depth relative to present mean tide level (m). Vertical and age errors are also represented. Black boxes indicate samples not included in the trend estimations.

Fig. 2.- Gráfico de los puntos indicadores del nivel marino en los estuarios de Bilbao y Urdaibai, mostrando las edades calibradas frente a la profundidad relativa al nivel medio de la marea actual (m). Los errores de elevación y edad también se presentan. Los cuadrados negros indican las muestras no incluidas en las estimaciones de las tendencias.

Results and Discussion

Figure 2 illustrates observations of sea-level change for the past ca. 9000 years from the Bilbao and Urdaibai estuaries based on the sand content and foraminiferal assemblages. From the new 61 samples analyzed here as SLIPs, forty five can be considered good SLIPs, ranging from ca. 8500 cal yr BP to ca. 200 cal yr BP. Fourteen samples plot significantly lower or higher than expected and are considered to be the result of reworked materials, and therefore discarded as SLIPs (black squares in Fig. 2). Similar age inversions have been reported by Cearreta and Murray (2000) when attempting to date transgressive surfaces in the Bilbao and Santoña estuaries. Three fluvial samples are used as limiting dates (i.e., sea level must be below these points) although they are not considered as valid sea-level index points. SLIPs from both estuaries exhibit a very good agreement and, consequently, will be discussed together. The overall trend exhibits two main phases: 1- fast relative sea-level rise prior to 7000 cal yrs BP, that ranges between 9 to 12 mm yr^{-1}; and 2- a relative sea-level rise of 0.7 mm yr^{-1} since ca 6700 cal yr BP until 19th century (Fig. 2). This trend represents both sea-level rise and vertical land movements, unfortunately, no research on Holocene neotectonic movements has so far been undertaken in this region, although such causes have been invoked to explain aspects of the evolution of this margin during the Neogene and Pleistocene (Mary, 1983).

The initial phase of sea-level rise presents few and disperse samples and, therefore, they could provide a misleading interpretation. This probably responds to a highly energetic depositional environment. The estimation of relative sea-level rates derived from all the SLIPs younger than 7000 cal yr BP provide a figure of 0.7 mm yr^{-1} for the pre-anthropogenic sea-level rise, in agreement with estimations of the eustatic contribution from melting of land-ice base, although this is still a matter of content (see Gehrels *et al*., 2006). This figure could be even smaller if autocompaction has not been fully corrected. It is now generally recognised that sea level has been relatively stable over the last 7000-6000 years (Church *et al*., 2008) as found here. However, the rate of sea-level rise changes abruptly when recent relative sea-level variations are analyzed. Leorri and Cearreta (2009a) obtained a RSL curve based on foraminiferal transfer functions from salt marshes coupled with local and regional tide-gauge records that provided a regional sea-level rise of 1.9 ± 0.3 mm yr^{-1} since 1920, seemingly related to the anthropogenic impact of the global warming. Although isostatic corrections should be performed (Lambeck, 1997), a similar vertical movement will be applied to both pre-anthropogenic and anthropogenic rates and so the difference between them should remain constant.

Although these results are encouraging, in order to better constrain pre-anthropogenic sea-level changes, further analysis has to be done to narrow down current reconstruction errors of the Holocene reconstructions.

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Environment	lower range	mid point	upper range
	(m above MTL)		
Fresh water tidal mudflat	5.0	5.5	7.0
High marsh	3.5	4.0	4.5
Low marsh	3.3	3.8	4.3
Tidal creeks and tidal mudflat	2.4	3.1	3.8
Tidal mixed flat	1.6	2.4	3.2
Tidal sand flat	0.3	1.2	2.1
Subtidal	-3.0	0.0	0.2

Table I.- Indicative meaning of lithofacies based on surveys of modern depositional environments, plant zones and associated foraminiferal assemblages. Fresh water tidal mud flat upper limit and subtidal lower limit have been overextended considering that a) both types of samples represent upper and lower bounds respectively for the mean tide level (MTL), and b) in the past they could have presented greater ranges than today.

Tabla I.- Valor indicativo de las litofacies en base a muestreos de los ambientes deposicionales actuales, zonación vegetal y asociaciones de foraminíferos. Los límites de los ambientes de marisma mareal de agua dulce y ambiente submareal han sido extendidos considerando que a) ambos ambientes representan los límites superior e inferior del rango mareal y b) en el pasado esos rangos han podido ser mayores.

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