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During Sea-Level Highstands:
A Global Synthesis with implications
for management of future coastal change

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Foraminiferal response to the Holocene environmental development of the Bilbao estuary, N. Spain

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Abstract

The Bay of Biscay coastal area is a typical inundation coastline, formed as a consequence of the eustatic sea-level rise that followed the last deglaciation. Erosive processes are dominant along the southern area (named Cantabrian coast of Spain), as constant wave attack causes active cliff destruction. Short and narrow estuaries are separated from the open sea by sandbars, beaches and dune deposits. The eastern area of the Bay of Biscay (known as Aquitaine coast of France) is mainly a straight and continuous sandy beach backed by a coastal dune system fixed during the 19th century. These extensive dune fields formed when sand deposits on the continental shelf were reworked during the Holocene sea-level rise. The morphology and extent of the different estuarine sedimentary environments are constantly altered by erosion and deposition of sediments, and they are sensitive to even small changes in sea level. The Holocene transgressive episode caused the deposition of large volumes of well preserved estuarine sediments that can be studied to understand environmental and sea-level changes during this interglacial. Different boreholes drilled on the main estuarine environments have been studied during recent years (e.g. Cearreta, 1994; Cearreta and Murray, 1996; Pascual et al., 1998). 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. During the last two centuries, the natural features of the Bilbao estuary have been dramatically modified by urban, industrial and port developments. The original estuary was rapidly reduced in size through land reclamation to form a tidal channel, completed by 1885. 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 activity is approximately 1000 ha (Cearreta, 1998 The aim of this study is to reconstruct palaeoenvironmental changes in this marginal marine environment since its formation following the postglacial rise of sea level.

This has been achieved by analysis of the micropalaeontological content (benthic foraminifera) of numerous boreholes taken in reclaimed areas of the middle and lower parts of the estuary (Figure 1). Integration of these results with similar data from previously studied boreholes has allowed us to reconstruct the environmental development of the Bilbao estuary during the Holocene. This environmental development has been organized into different systems tracts following a sequence-stratigraphic interpretation. Radiocarbon dating helped to locate in time the different palaeoenvironments and depositional episodes identified in the boreholes. Comparison of these data with other sedimentary sequences from different coastal areas in the Bay of Biscay allows to reconstruct a general picture of the Holocene sea-level changes and coastal evolution in this area. Sediments that compose the estuarine infill range from fluviatile through brackish estuarine to near marine and even supratidal materials. Analysis of sedimentological and micropalaeontological data indicate that, in general, boreholes exhibit fining-upward sequences ranging from gravelly materials at the base, more sandy sediments in the middle and more muddy materials on the top.

At the same time, basal coarse materials are almost barren of foraminifera, middle sandy sediments show abundant, diverse and near-marine foraminiferal assemblages, and the upper muddy deposits contain abundant, low-diversity and brackish foraminiferal assemblages. Micropalaeontological interpretation together with radiocarbon dates suggest that basal coarse materials are Lateglacial-lowermost Holocene fluvial deposits, that are followed upwards by lower and middle Holocene transgressive materials, with upper Holocene regressive sediments on top.

This general sedimentary sequence is best represented in the middle estuarine area, and its sedimentary and microfaunal features are variable depending on its palaeogeographic setting: increasing muddy sediments and absence of open-marine elements are characteristic of the upper estuary, whereas increasing sandy sediments and reworking of the basal fluviatile materials are typical of the lower estuary).

This sedimentary sequence was initiated by the last Pleistocene glacio-eustatic sea-level fall and has been deposited since then. This interval represents a eustatic cycle at approximately fourth-order scale. Although the sequence lacks an upper boundary, it contains all the characteristic elements of depositional sequences including a basal sequence boundary (SB), a lowstand systems tract (LST), a transgressive systems tract (TST), a transgressive surface (TS), a maximum flooding surface (MFS) and a high systems tract (HST). In addition to these key surfaces that define the systems tracts, another significant feature such as the tidal ravinement surface can be identified (Allen and Posamentier, 1993). Foraminiferal assemblage zones (FAZ) defined in the boreholes can be interpreted following this depositional sequences model.

Figure 2 shows schematically the sequence-stratigraphic interpretation of the Bilbao estuary fill based on the foraminiferal assemblages present in the boreholes drilled for the construction of the Bilbao Metropolitan Subway on the right bank of the estuary (Figure 1). The sequence boundary (SB) is defined by the location of unconsolidated Quaternary gravels and sands over Cretaceous basement. This boundary is overlain by a deposit of fluviatile gravel and coarse sand that corresponds to the basal FAZ in the upper and middle estuarine areas (Figure 2). These fluvial deposits, almost barren of foraminifera, are interpreted as the lowstand systems tract (LST). Due to the lack of carbonaceous material, this LST has not been radiocarbon dated, but its stratigraphic position underlying lower Holocene estuarine deposits suggests a Lateglacial-lowermost Holocene age.

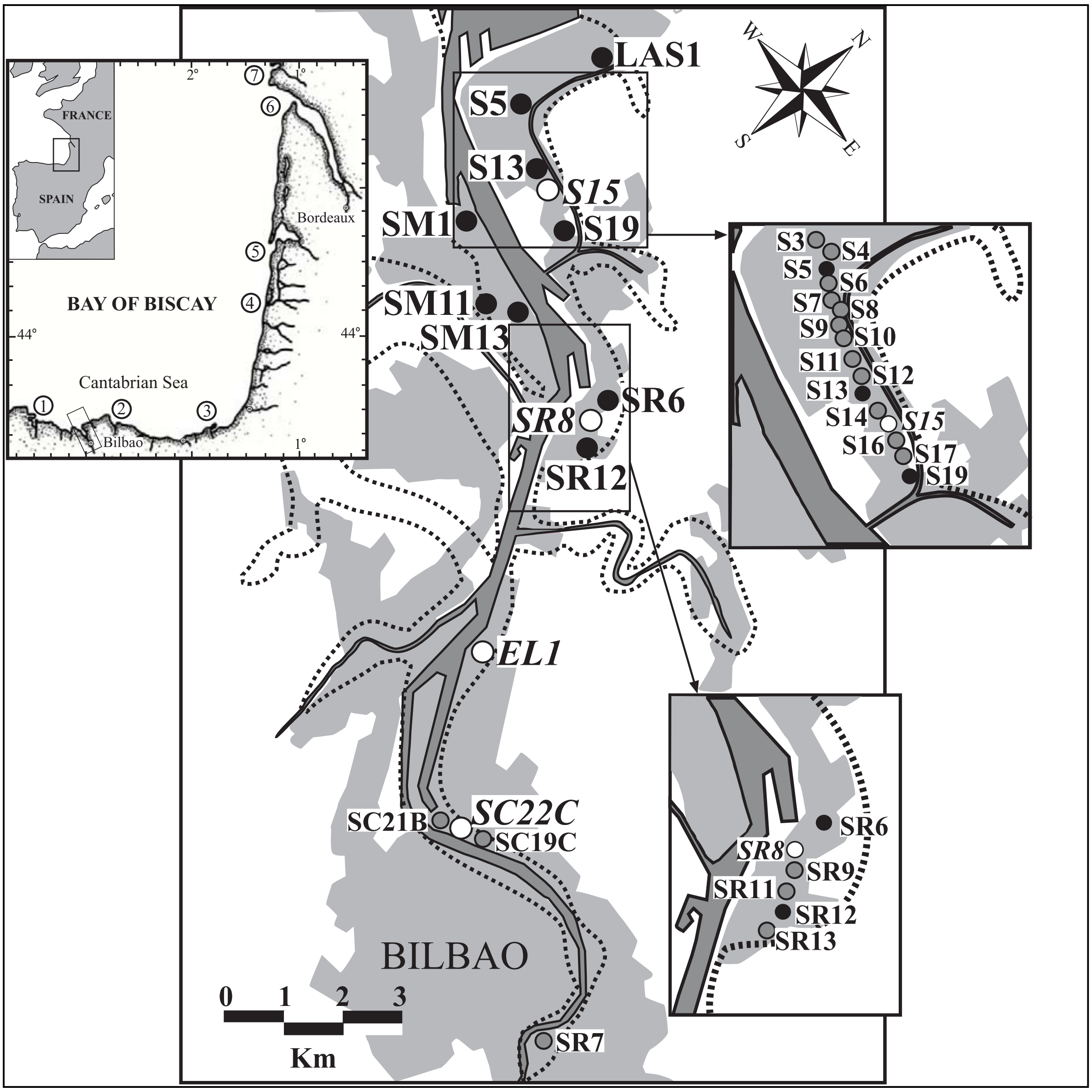

Figure 1. Geographical location of the Bilbao estuary in northern Spain, and position of the boreholes. Key: 1-Santoña estuary; 2-Gernika estuary; 3-Bidasoa estuary; 4-Aquitaine coastal dunes; 5-Arcachon bay; 6-Gironde estuary; 7-La Perroche marsh. Dashed lines represent the original extent of Holocene estuarine domains. Midgrey shaded surfaces are urban areas. Dark grey indicates modern estuary and sea.

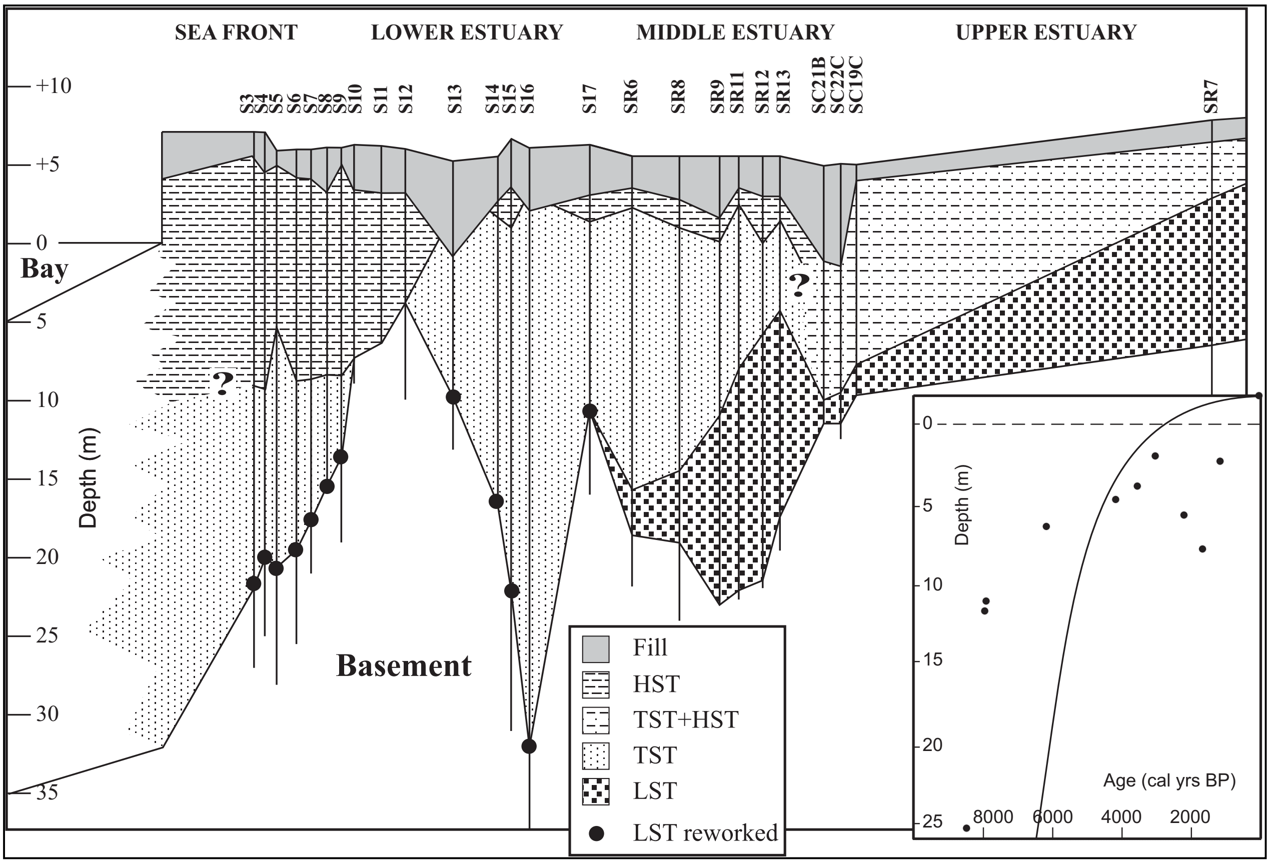

Figure 2. Sequence-stratigraphic interpretation of the Bilbao estuary Holocene deposits. Vertical lines indicate borehole locations on the right bank of the estuary drilled during the geological study for the Bilbao Metropolitan Subway. LST: lowstand systems tract; TST: transgressive systems tract; HST: highstand systems tract. Depth with reference to local ordnance datum. Box represents estuarine floor depth through time. Black dots are radiocarbon data from boreholes SM1, SM11 and SM13 located in the left bank of the lower estuary.

In the lower estuarine area these coarse sediments have been reworked during the Holocene marine transgression and, consequently, included in the following systems tract (Figure 2).

Accumulation of estuarine sediments containing abundant foraminifera over fluviatile coarse deposits clearly suggests a marine transgression within the former fluvial valley. Different FAZs were deposited during this transgressive interval, all of them exhibiting increasing numbers of exotic foraminifera and, consequently, indicating an upward increase in open-marine influence as transgression progressed with time.

These FAZs comprise the transgressive systems tract (TST) bounded by distinct stratigraphic surfaces (Figure 2). A transgressive surface (TS) can be defined at the base of these estuarine deposits separating them from the coarse LST material. As the transgression continued, the estuarine materials were overlain by sediments from the inner shelf (containing dominant exotic foraminifera) that increased near-marine conditions within the estuary. This surface between the brackish and marine conditions is an erosional surface termed tidal ravinement surface (TRS). This TRS has been previously identified as transgressive overlap boundary (TOB) in this and other Cantabrian estuaries (Cearreta and Murray, 2000). Radiocarbon dates obtained in this TST range from 8520 to 1685 cal yrs BP.

Different curves from the Bay of Biscay show that sea-level reached approximately its present position at about 3000 years BP (Pirazzoli, 1991).

The sedimentary response to this stabilization of sea level was the turnaround from eustatic transgression to relative regression, with deposition of estuarine materials similar to those of the underlying TST but containing brackish and shallower foraminiferal indicators. The uppermost FAZs in the boreholes comprise this highstand systems tract (HST) (Figure 2).

The surface between the HST and the TST represents the maximum flooding surface (MFS). Radiocarbon dates obtained from HST materials were younger than 2810 cal yrs BP. Box in Figure 2 represents variation of the estuarine floor depth through time based on radiocarbon dated samples from boreholes located in the left bank of the lower estuary.

The logarithmic regression line shows two different phases in the infill process. A rapid initial phase that chronologically corresponds to the TST is followed by a second slower phase, topographically close to datum, that represents the HST.

It is not possible to differentiate TST and HST in the upper estuarine areas due to the absence of clear mid-Holocene marine elements at such a distance from the estuary mouth (Figure 2).

Origin of main sea-level variations may be found both in the global eustatic motion, like the Holocene rise due to deglaciation during the last 10000 years, or in local subsidence or uplift of the continental margin, due to tectonic activity related to plate movements.

Although neotectonic uplift movements have been invoked to explain aspects of the evolution of the southern Bay of Biscay margin during the Neogene and Pleistocene (Mary, 1983), unfortunately, no research on Holocene neotectonics has been undertaken so far in this region. However, on the Aquitaine coast, tectonic subsidence contribution to the transgressive trend has been evaluated in the order of 0-0.7 mm $year^{-1}$ (Klingebiel and Gayet, 1995).

Hence, significant interferences between eustatic and tectonic vertical movements may have occurred in the Bay of Biscay during the Holocene.

Consequently, it can be concluded that different coastal sedimentary sequences and radiocarbon datings obtained during recent years from the Bay of Biscay indicate that, following postglacial sea-level rise, modern estuaries in the region began to develop around 8500 years BP. Furthermore, a second upward-shallowing sequence commenced around 3000 years BP, when sea level reached approximately its present position after a final transgressive event dated at that time.

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