PALAEO 3

A reply to "Relative sea level during the Holocene in Uruguay"

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ABSTRACT

Martínez and Rojas (2013) published a paper about the relative sea level during the Holocene in Uruguay. The paper of Martínez and Rojas could be handled as an attempt to construct a sea-level curve from data collected from different sources: open-ocean coast, the Río de la Plata coastline and the outlet of Uruguay River. In this sense, several processes were involved: storm effects at open-ocean beaches, the Holocene enclosing of coastal lagoons, storms within the funnel-shaped estuary and the floods of the Uruguay River. However, they included a series of omissions, inaccuracies, errors and critics to our work, that need to be amended, rectified and argued. In response we present a historical background about the research on this issue in Uruguay. We refute the comments about the empirical framework used to construct the first sea-level curve for Uruguay (Bracco et al., 2008, 2011b). We point out that the assumptions on which the curve proposed by Martínez and Rojas (2013) is based are mistaken. In addition, there are limitations of the performed statistical techniques, and errors — mainly systematic — within their formulation. We present evidence that the decrease in sea level from middle Holocene would not have been constant. Instead, a rapid sea level decrease would have taken place by 4300 yr BP. Finally, we not only compare our sea level curve with that proposed by Martínez and Rojas, but also we corrected the altimetry errors incurred in their formulation. We conclude that the similarity supports the validity of our curve.

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1. Holocene sea level changes in Uruguay

During the 1970s and 1980s Brazilian research on Holocene sea level change was strongly linked to archeology (Fairdridge, 1976) and to Uruguayan prehistory as considered by Fairbridge (1974) in the construction of an archeological sequence of the Merín Lagoon basin (Naue, 1973; Schmitz, 1976). In agreement with this line of evidence, in the frame of paleoenvironmental and geoarcheological studies undertaken during the 1990s in the same basin, several landforms attributed to different Holocene sea levels were recognized along the Uruguayan shore. When radiocarbon ages of these landforms became first available, a remarkable consistency with the proposed chrono-altimetric sea level curves for this period (Martin and Suguio, 1989, 1992; and Suguio et al., 1984 for southern Brazil; see Bracco and Ures, 1998) was observed.

Since the year 2000 paleoenvironmental and geoarcheological research was further developed. By linking coastal lagoons and marine coastal records, the history and evolution of littoral lagoons and associated wetlands as well as the regional paleoclimatic history and the relationship with pre-historic mound-builders were reconstructed (García-Rodríguez et al., 2004a–c; Bracco et al., 2005a–b, 2011a; del Puerto et al., 2006; García-Rodríguez, 2006, 2012; Inda et al., 2006; del Puerto, 2009; Inda, 2009). A large amount of multiproxy data related to sea level oscillations was generated during this decade. The consistency and coherence of such data with regional models allowed the generation of the first relative sea level curve for the Uruguayan shore (Bracco et al., 2008). An updated version of this curve was published by Bracco et al. (2011b). This publication can be freely downloaded from http://www.csic.edu.uy/renderPage/index/pageId/1024.

2. On the construction of our sea level curve

Martínez and Rojas (2013) have reported that our research related to sea level changes has been restricted to just a few points. Nevertheless, Fig. 1 shows the sites surveyed by us along the fluvial, estuarine and marine coast of Uruguay, corresponding to multiple indicators,

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Fig. 1. Location of surveyed sites. Section A: lower reaches of Uruguay River, section B: Río de la Plata Estuary and section C: Atlantic coast.

Fig. 2. Satellite image of beach ridge system on the Merín Lagoon coast and radiocarbon dates.

i.e., beach ridges, sand barriers, tidal plains, intertidal deposits, lagoon bottom cores, erosion terraces and archeological sites.

Samples represent different dates from 6000 to 1200 yr BP. The number of dated samples totals 35, from which 19 correspond to Castillos Lagoon (Bracco et al., 2008, 2011a) (Fig. 1). Martínez and Rojas (2013: Table 1) in turn reported just 15 additional sampling points and 8 new radiocarbon ages for localities previously sampled by us. No single disagreement in radiocarbon age reported by the above-mentioned authors was observed.

Martínez and Rojas (2013) stated that they used "coastline deposits generated by storm and not further eroded: 'permanent berm' as sea level proxies". They reported that "beach ridge" is commonly used in the available literature to define deposits such as those they analyzed, and reported following Hesp (2006), that "beach ridge" is a rather ambiguous term (see Otvos, 2000 and Hesp et al., 2005, among others, for a discussion on the topic). Martínez and Rojas (2013) omitted part of Hesp et al.'s (2005) explanation and, also misinterpreted it to some extent. Hesp (1999) redefined beach ridges as swash aligned, swash and storm wave built deposits or ridges formed primarily of sand, pebbles, cobbles (gravel) or boulders, or a combination of these sediments. In addition, Hesp et al. (2005) reported that the critical difference between a berm and a beach ridge is that berms are generally not persistent forming part of the intertidal to slightly above high tidal active swept prism.

Secondly, Martínez and Rojas (2013) misinterpreted the nature and origin of deposits. The vast majority of the deposits that were sampled and dated by us — which were redefined by Martínez and Rojas (2013) as storm deposits or permanent berms — were recognized as beach ridges (Bracco and Ures, 1998: Table 1; Bracco et al., 2011a: Table 1). According to Hesp et al. (2005) such deposits are sand beach ridges on some modality of low beach (open coast, lagoon or estuary). Moreover, Hesp et al. (2005) also presented an explanation about the frequency of such deposits in the Lower Uruguay River, Río de la Plata Estuary and littoral lagoons, which describes them as sand beach ridges
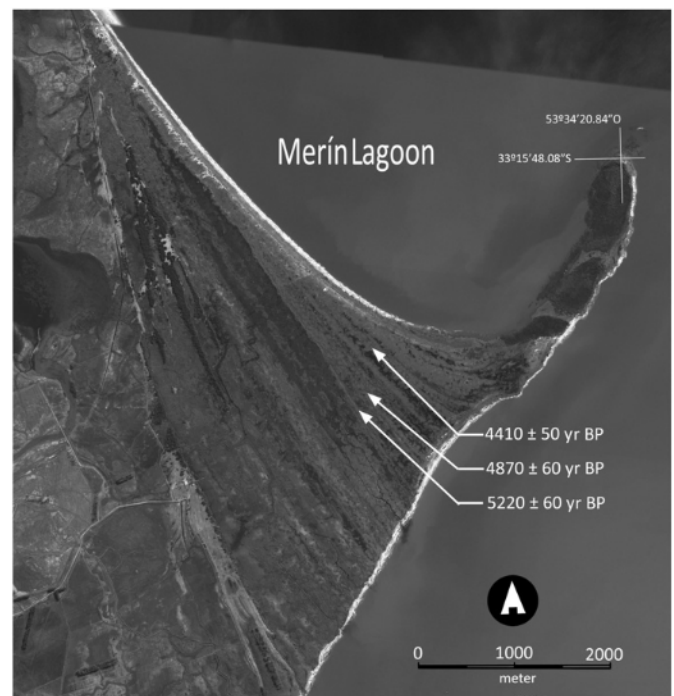
with coarse to fine sand on some modally low energy beaches (open coast, lagoon or estuary) (Fig. 2).

The reason why Martínez and Rojas (2013) assigned all deposits to storm deposits in their sea level curve, is based on the need to link the height of the landforms to sea level at the time of formation. Thus, they made the assumption that storm deposit heights were placed somewhere between average and exceptional sea level for the Río de la Plata Estuary, calculated from historical series: around 1 to 1.5 m (Martínez and Rojas, 2013: 124). Regrettably, such an assumption did not consider the fact that these values are related to the "zero level" at Montevideo Harbor (i.e., the former Zero Wharton) (SOHMA, 2012). Such "zero level" is placed 0.91 m below the topographic "official zero" and thus the height assigned by Martínez and Rojas (2013) to the deposits has been underestimated (i.e., by 0.91 m). In addition to such systematic error in height assignment, and the lack of empirical evidence to support the assumption of storm deposits for the entire set of landforms, other shortcomings must be highlighted, when the mean storm sea level is used for sea level estimation. Firstly, the fact that highest sea levels reached at severe storm events were not considered and, at the time scale of the entire Holocene, the frequency of such events is far from insignificant and cannot be neglected (see Fig. 3). In addition, they did not consider neither the wave height variation due to different beach profiles and orientation, nor the existence of subaquatic structural control in the inner estuary. They also assumed that the Río de la Plata historical storm averages were representative for the entire Holocene for the whole Uruguayan coast, i.e., from the Río Uruguay mouth to the Atlantic shore, including littoral lagoons. The risk of such an extremely actualistic assumption became apparent when the incidence of the aeolian variable over regional sea levels was considered (Laborde, 1997; Nagy et al., 1997). Significant climatic variations have been inferred for the region throughout the Holocene (del Puerto, 2009). Such oscillations were related to atmospheric circulation variations (see, for example, Muhs and Zárate, 2001; Zárate, 2003; Piovano et al., 2009). Second, it must be pointed out that they did not consider the possibility of differential continent ascents or descents due to neotectonic movements in some sectors of the coast, nor the incidence of the Paraná and Uruguay River flows in the height reached in the inner estuary.

According to Martínez and Rojas (2013: 127) "Bracco et al. (2011b: 85) constructed by hand a curve of relative sea level in Uruguay based
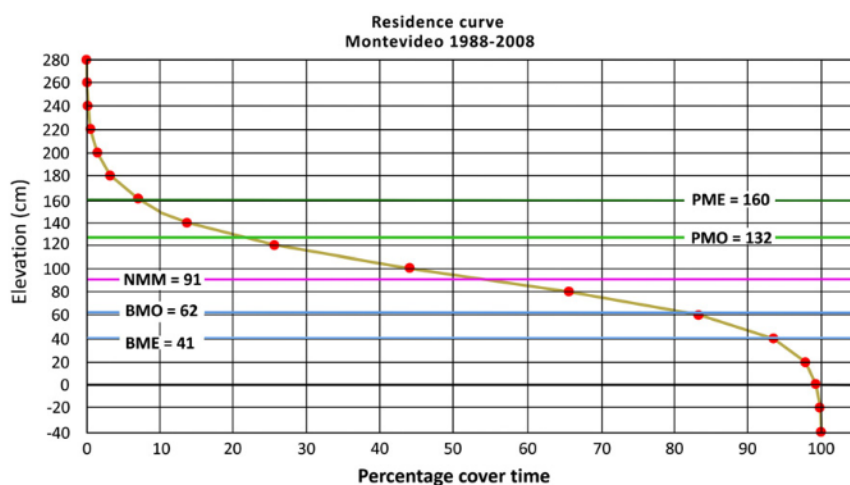
Fig. 3. Sea level residence curve for Montevideo (BME = extraordinary low sea level; BMO: ordinary low sea level; NMM: calculated mean sea level for Montevideo [i.e., 91 cm above the gage of Montevideo Harbor (ex-Wharton)]; PMO: ordinary high tide level, PME extraordinary high tide level.
Source: Bidegain et al., 2009).

on their data according to a methodology and data that were unfortunately not explained in detail". Since the beginning of geoarcheological and paleoenvironmental research in Uruguay, it was recognized that Castillos Lagoon exhibits the best record to infer Holocene sea level changes. Castillos Lagoon (34°19′17.49″ S, 53°55′41.97″W) is one of the coastal systems contained in the lagoon-cordon of the Uruguayan littoral which extends to the southeast coast of Brazil (Panario and Gutiérrez, 2011). The water body is 80 km^2 and the watershed is 1265 km^2. The lagoon maintained an active Holocene connection to the Atlantic Ocean (Inda, 2009). Currently, the lagoon connects with the ocean via Valizas stream. In the littoral of the water body a vast array of landforms can be distinguished (Fig. 4). These landforms were formed above and below lagoon average level (terraces, tidal plains, sand bars, beach ridges and cheniers) and most of them contain bivalve lens levels (Fig. 4). The significance of such deposits is that they consist of a spatially constrained record, without altimetric differences related to average sea level, or environmental conditions for different locations. In addition, because the water body is shallow, the height difference

between wave originated deposits and mean level is lower than those of the open sea shore conditions. In this sense, Hesp et al. (2005: 500) postulated that "Beach ridges (sensu stricto) typically form above the normal high spring tide level on open ocean beaches or mean water level in lagoons and estuaries and are generally persistent". Consequently, from the record of Castillos Lagoon we inferred the majority of our data about Holocene sea levels, and this dataset, represented the starting point to develop a sea level curve for the Uruguayan coast (Bracco et al., 2008, 2011b). It must be noted that this curve was empirically constructed. As it is stated in the figure legend of Bracco et al. (2011b: Fig. 3, page 85) the line was drawn above the data-points belonging to deposits formed above lagoon mean level, and below the data-points from deposits formed below lagoon mean level (in other words, sand bars and beach ridges, respectively). Both categories were graphically discriminated using two different symbols in the representation (Bracco et al., 2011b: Fig. 3). In the text, Bracco et al. (2011b) also mentioned that the sea level curve considered the altimetry information of other landforms, which age was inferred relative to their
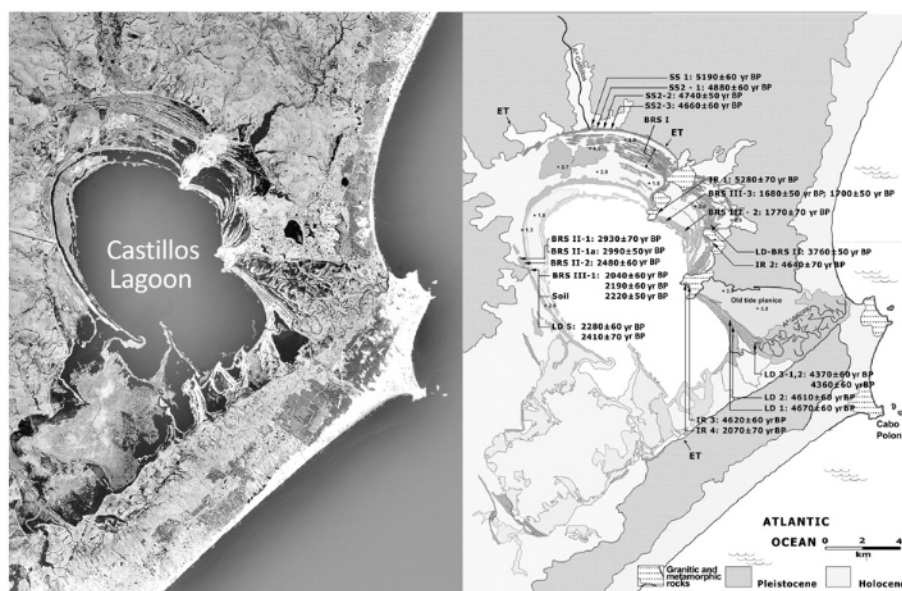

Fig. 4. Left: satellite image of Castillos Lagoon, right: sea level change geomorphological indicators and radiocarbon dates. ET: erosion terrace, SS: barrier system, IR: beach ridges, BRS: beach ridge system, LD: littoral deposit.
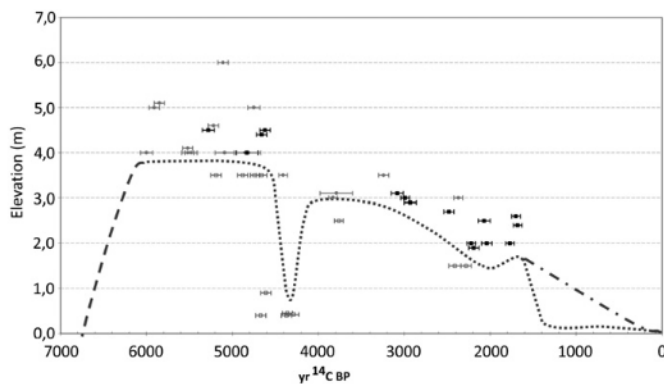Modified from Bracco et al. (2011b).

Fig. 5. The sea level variation change curve inferred from Lagoon Castillos records. Black squares: Castillos Lagoon deposits formed above mean sea level. White squares, Castillos Lagoon deposits formed below mean sea level. Gray circles: samples taken outside Castillos Lagoon (i.e., samples 1 through 9 and 29 through 35 in Fig. 1).
Modified from Bracco et al. (2011b).

horizontal position. That was the case of the higher terrace, which originated over late Pleistocene deposits. This terrace has a minimum height of 6.0 m amsl at the top, and 4.5 m amsl at the basal section, thus indicating the maximum possible height of the lagoon during the Holocene (Bracco et al., 2011b: 83). At this time, the current lagoon was a bay or gulf (Inda, 2009). In order to strength the empirical basis of the sea level curve, chronological and altimetric data obtained along the Uruguayan littoral were added to the curve (Fig. 5).

3. Comparison of sea level curves

Unfortunately Martínez and Rojas (2013) did not show our sea level curve in their paper, and they did not make any direct comparison with their proposed new sea level curve. Nevertheless, they did estimate a difference of 1 m between their curve (constructed with their own data and methods) and our curve, constructed with the same methods but using data from our own contributions (Martínez and Rojas, 2013: Fig. 5B to D). We believe this comparison is far from correct due to three main aspects: 1) the systematic error observed in height assignment for the entire set of deposits, 2) if the table presented by Martínez and Rojas (2013: Table 1) is observed in detail, at least six values (rows 13; 19; 22; 36; 42 and 51 in Table 1) of minimum mean sea level were calculated by subtracting 2.0 m instead of the proposed 1.5 m. In other case, the maximum mean sea level was obtained by subtracting 1.5 m instead 1.0 m (row 25, in Table 1 Martínez and Rojas, 2013). In addition height is arbitrarily attributed to two deposits where altimetry data were not reported in cited publications (see Table 1 in Martínez and Rojas, "Esmeralda 8" and "Esmeralda 9" points and Bracco, 2003); and 3) as it was already mentioned, all our data were attributed by Martínez and Rojas (2013) to storm deposits, when they are clearly not. The observed erratic treatment of data is severely compromising the reliability of the other two sea level curves presented by Martínez and Rojas (2013: Fig. 6A and B).

Even if the above mentioned differences are not considered, if the sea level curve presented by Bracco et al. (2008, 2011b) is compared with those proposed by Martínez and Rojas (2013), only two main differences can be distinguished: the height reached by the sea across the Holocene and the existence of short-term oscillations. The difference in height is ca. 1 m, probably very close to the resolution capabilities of the records considered for the Uruguayan coast. Taking into account the state of the art about this issue, such difference is not significant at this scale of analysis. Nevertheless, this difference could be substantially reduced if the height assignment error is corrected (by not neglecting that tides are measured from the "zero" placed at Montevideo Bay, i.e., −0.91 m). In this scenario, the sea level curve proposed from Castillos Lagoon data is even more consistent (Fig. 6A and B). On the other hand, the occurrence of minor oscillations deserves further attention.
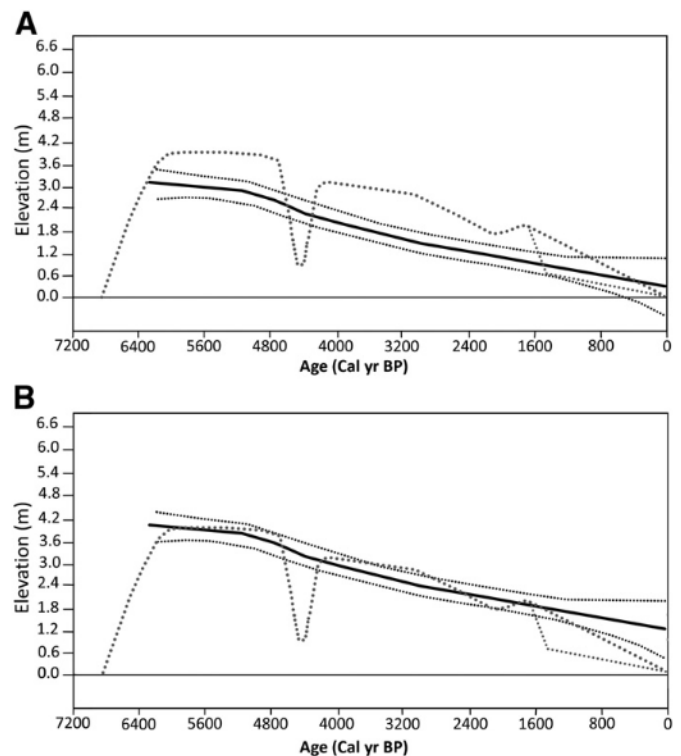

Fig. 6. A: Comparison of the sea level curve of Martínez and Rojas (2013: Fig. 5D; solid line: envelope and smoothed curve) and Bracco et al. (2011b) dotted line. B: Comparison of the sea level change curve of Martínez and Rojas (2013) corrected for the calculated mean sea level for Montevideo [i.e., 91 cm above the gage of Montevideo Harbor (ex-Wharton)]. The data that exhibited wrong elevations in Martínez and Rojas (2013) were removed from this analysis.

The non-parametric statistical techniques approach of Martínez and Rojas (2013: 124) severely limited the possibility of identifying short-term sea level oscillations. Nevertheless, the authors debated the existence of such oscillations in their discussion and conclusions (Martínez and Rojas, 2013: 128 and 130). In this sense, we have reported the existence of a deposit located in the Valizas stream bed, placed between + 0.4 and 0 m amsl (Bracco et al., 2011b) which is not considered by Martínez and Rojas (2013). Sediment data and morphological features that are visible from satellite images (Panario and Gutiérrez, 2011) coupled with the presence of entire/articulated *Tagelus plebeius* shells in life position allowed the interpretation of such landform as a tidal plain. The radiocarbon age of these bivalves was estimated at three sampling points separated ca. 100 m apart from each other, yielding the following ages 4360 ± 60 yr ^{14}C BP [Cal. 4334–4715 BP (p = 0.998), 4757–4762 BP (p = 0.002)] 4370 ± 60 yr ^{14}C BP [Cal. 4355–4722 BP (p = 1.000)] (Bracco and Ures, 1998) and 4300 ± 60 yr ^{14}C BP (URU 0556) [Cal. 4235–4595 BP (p = 1.000)]. The spatial extension and grouping of valves is indicating a narrow functioning lapse of the tidal plain. According to Iribarne et al. (1998) the bivalve *T. plebeius* lives in estuaries and tidal zones, between − 0.3 and + 0.9 m in relation to minimum mean tidal level (MMTL), with higher density just below the MMTL. Thus, the MMTL for the Uruguayan coast, tidal plains and associated *T. plebeius* in life position could be indicating a sea level very close to current sea level ca. 4700–4300 yr BP. This evidence is in close agreement with data from Brazil reported by Suguio et al. (1984), Martin and Suguio (1989, 1992), Martin et al. (2003) and from Argentina reported by Cavallotto et al. (2004).

4. Final remarks

The sea level curves proposed by Martínez and Rojas (2013: Figs. 5 and 6) are in fact very similar to that of Bracco et al. (2011b). The

similarity increases when the above-mentioned systematic height error assignment to deposits is corrected. Martínez and Rojas (2013) did not show sea level curves together in order to make comparisons (Fig. 6A and B). The most significant difference between Martínez and Rojas sea level curves and our curve is that their model failed to identify short-term oscillations.

Acknowledgments

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