Palaeogeography, Palaeoclimatology, Palaeoecology 374 (2013) 123–131

Contents lists available at SciVerse ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Relative sea level during the Holocene in Uruguay

Sergio Martínez *, Alejandra Rojas

Instituto de Cs. Geológicas, Facultad de Ciencias, Universidad de la República, Iguá 4225, 11400 Montevideo, Uruguay

ARTICLE INFO

Article history:
Received 4 July 2012
Received in revised form 13 December 2012
Accepted 15 January 2013
Available online 24 January 2013

Keywords:
Sea level
Storm deposits
Molluscs
Holocene
Uruguay

ABSTRACT

A curve of the relative sea level during the Holocene in Uruguay was constructed based on data from beach storm deposits. The error envelope was too great to register small but significant oscillations, but the number of points used and the coincidence between our data and that from the literature show that in Uruguay the sea level was above the present level approximately 6000 years BP and has been declining since then. The non-parametric smoothing technique used favours a smooth declining sea level curve similar to that proposed for the coast of Brazil (different slope).

1. Introduction

Relative sea levels during the Quaternary have been reconstructed for several regions of the world according to their importance in understanding and preventing future changes caused by human actions or even natural processes (e.g., van Loon, 2000; Oldfield, 2004).

Along the Atlantic coast of South America, some areas are better known than others, i.e., a considerable amount of work has been performed on the coast of Brazil (e.g., Martin et al., 1979/1980; Suguio et al., 1980, 1988; Martin et al., 1996; Angulo and Lessa, 1997; Angulo et al., 2002; Martin, 2003; Angulo et al., 2006, among others) and parts of Argentina (Aguirre and Whatley, 1995; Cavallotto et al., 2004; Schellmann and Radtke, 2010; Pedoja et al., 2011, among others), but information regarding Uruguay is scarce. Although some attempts have been made to reconstruct local Quaternary sea levels in Uruguay, they have been restricted to a few points (e.g., Bracco and Ures, 1998; García-Rodríguez and Witkowski, 2003; García-Rodríguez et al., 2004; Inda et al., 2006; Bracco et al., 2011).

The aim of this paper is to present for the first time an estimation of Holocene sea levels (MSL) in Uruguay on the basis of data from beach storm deposits and to compare the results with other curves obtained in Southern South America. No suggestions regarding the mechanism(s) underlying the sea level changes are made.

2. The coast

The Uruguayan coast is divided into a western estuarine zone (northern coast of the Río de la Plata, approximately 473 km) and an eastern marine zone (Atlantic Ocean, approximately 233 km) (Goso Aguilar et al., 2011). The Río de la Plata is the second-largest river basin in South America (drainage basin: 3.1×106 km^2, sediment load: 91×106 t y^{-1}, average ocean discharge: 22,000 m^3 s^{-1}) (Framiñan and Brown, 1996; Guerrero et al., 1997). The basin has a remarkable salinity gradient, with changing fronts, caused by the discharge of fresh water from the Paraná and Uruguay rivers into the Río de la Plata, and from there to the Atlantic Ocean. The Río de la Plata is muddy in its inner part. The mud arrives mainly from the Paraná River and flocculates by the influence of the salinity front, usually near the city of Montevideo. Winds change the location of the salinity and turbidity fronts (Larrañaga, 1894; Nagy et al., 1987).

The Atlantic coast, with salinities of approximately 30–35‰, is influenced by the warm N-S Brazilian Current and by the cold S-N Malvinas (Falkland) Current (Boltovskoy, 1966; Podestá et al., 1991; Piola et al., 2000). The subtropical warm waters converge and mix with the cold subantarctic waters at the isobaths of 100 and 200 m. Topography, seasonality, and El Niño-Southern Oscillation (ENSO) phenomena also contribute to the littoral environmental conditions (Olson et al., 1988; Podestá et al., 1991; Ortega and Martínez, 2007). In sum, the estuary and the adjacent platform have complex horizontal and vertical water mass arrangements that are further complicated by a high degree of seasonal and interannual variability. The substrate is composed mainly of silt, with few areas that are consolidated or composed of crystalline rocks (Correia et al., 1996).

The Atlantic zone of Uruguay has a wave-dominated coast with arched sandy beaches of variable size (the longest having become rather straight) between rocky headlands. The beaches have a wide range of morphodynamic grades, from dissipative to reflective, although gentle slopes and dissipative to intermediate stages predominate. Coastal lagoons are common to the east, and most of them occasionally

---

* Corresponding author. Tel.: +598 25252646; fax: +598 25258617.
E-mail addresses: smart@fcien.edu.uy (S. Martínez), alepaleo@gmail.com (A. Rojas).

0031-0182/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.palaeo.2013.01.010

open to the sea. The western side features low sedimentary cliffs in certain areas. The coastal morphology is conditioned more by its geological background than by the present dynamics (Masello and Menafra, 1997; Brazeiro et al., 2003; Gómez Pivel, 2006).

The coast has a microtidal regime; the astronomic tides have an average amplitude of 0.4 m and a maximum of ca. 50 cm, but sea level changes induced by the wind from the southern quadrant are more important. The maximum height above mean sea level (4.7 m) since 1902 (the first records of the tidal gauge station of Montevideo) was recorded during a storm on the 10th of July of 1923. A wind-induced tide of 1.4 m is considered extraordinary, 1.2 m is an ordinary tide, and the average is 0.93 m (Chebataroff, 1972; Nagy et al., 1997; Gautreau, 2006).

3. Geology

The Uruguayan territory is a tectonically stable cratonic area. The substrate is composed mainly of Precambrian–Cambrian igneous (plutonic and volcanic) and low- to medium-grade metamorphic rocks, sometimes covered by Cenozoic sedimentites (Goso Aguilar and Muzio, 2006). A detailed geological cartography for part of the coast has been published by Spoturno et al. (2004a, 2004b, 2004c), and an updated geologic map of Uruguay was given by Bossi et al. (1998).

Quaternary marine deposits crop out all along the coastline of Uruguay. The Pleistocene deposits are as high as 12 m, and the Holocene deposits are as high as 5 m (Martínez et al., 2001, 2006).

4. Methods

We used beach deposits generated by storms as a proxy of sea level. The term "beach ridges" is frequently used in the literature for deposits similar to those considered here, but this term is rather ambiguous (see Hesp, 2006). For our purposes, the genetic origin is of interest; therefore, we will use here the unambiguous and descriptive "beach storm deposit", i.e., coastline deposits generated by storms and (obviously) not later eroded (a "permanent berm"). These deposits are recognised by their grain size, taphonomical evidence (fossiliferous layers with shells of different preservation attributes but mostly entire, no size or shape sorting, mixing of species that live in rocky and in soft substrate if both environments are present in the immediate neighbourhood, chaotic disposition), and association with slightly inclined parallel lamination. These deposits are formed at some height above normal sea level and are conditioned by several factors, mainly tidal regime and coastal morphology; hence, the present height of the bed cannot be read in a straight manner.

To estimate paleo-sea levels, we used the historical records of sea level induced by wind waves (i.e., storms). As indicated in Section 2, the average storm sea level in Uruguay is approximately 0.93 m, 1.4 m is exceptional, and 4.7 m is the maximum recorded in 100 years; the first two values were taken into account separately (rounded to 1 and 1.5 m, respectively), and the corrected values taken as the minimum and maximum estimates of the past sea level (Table 1).

We only considered coastal estuarine and marine Holocene Uruguayan deposits dated with ^{14}C (AMS or conventional) on molluscan shells (one single species per locality). The material comes from parautochthonous accumulations of articulated and disarticulated shells in a coarse to medium sandy matrix broadly corresponding to storm deposits (Figs. 1–3).

Bulk samples of approximately 3 dm^3 were taken. The shells were inspected externally for evidence of reworking, and representative specimens were examined by SEM (Facultad de Ciencias, Montevideo) (see examples in Fig. 4) or X-ray diffraction (LATYR) (see Table 1).

Conventional ^{14}C dates were obtained at the Laboratorio de Datación ^{14}C, Facultad de Química, Universidad de la República, Uruguay (URU), and at the Laboratorio de Tritio y Radiocarbono, Universidad de La Plata, Argentina (LATYR). AMS ^{14}C measurements were performed at the NSF Arizona AMS Facility, The University of Arizona, USA (AA).

The program Calib 6.0 (Stuiver and Reimer, 1993) was used for calibration. Bracco et al. (1999, 2003) estimated the reservoir effect in the coastal area of Uruguay, concluding that its extent is less than the analytical error. More precisely, Angulo et al. (2005) reported for Southern Brazil a δR of 8 ± 17 ^{14}C years; this error was used for our estimations.

The data set comprises 23 sites studied by our team and 31 obtained from the literature (Figs. 1–3, Table 1). A zero point was added to indicate present mean sea level, taking the zero point of the Montevideo Port as a reference.

To produce the best-fitted curve, the probable median of the calibrated ^{14}C years BP (as provided in the output of Calib 6.0) and the average of the estimated range of paleo sea-level height were used. To fit the sea level curve, we used the non-parametric "Loess" Smoothing (0.5 smooth), with a 95% confidence interval based on 999 replicates obtained by resampling the residuals ("bootstrapping"). Although polynomial regression is sometimes used to fit sea-level curves, the data are usually not tested for adequacy for that parametric method. As expected, our data are not appropriate for parametric procedures (non-normal distribution and/or heteroskedastic).

The program Past v.2.15 (Hammer et al., 2001) was used; this program runs the algorithm "LOWESS" (Cleveland, 1979, 1981). A 0.0 point was added for both height and time.

5. Results

Table 1 shows the database as estimated by the procedures detailed in Section 4 and was used to draw the curves. Although the envelope containing the possible curves is rather broad, the data set is smoothed to a nearly straight line, with the sea continuously declining since ca. 6400 years BP using both our data (Fig. 5A) and those from the literature (Fig. 5A). Both datasets register a difference of approximately 1 m in the estimated sea level, which can be assigned to differences in height estimating (the methodology for estimation is not indicated in most of the bibliography; when performed, equivalence is postulated between the sea level and the present topographic height of the deposit). The coincidence in the timing of the deposits and in the nearly straight shape of the curve is significant, differing from others produced for the Atlantic coast of South America (also with differences among them). When combining both sources of data (ours and the literature) (Fig. 5C), again the curve is rather straight, but two gentle inflections appear: one at ca. 5000 years and another at approximately 300 years. Afterwards, the slope becomes less pronounced. The three curves (our data exclusively, data from the literature, and both combined) are shown together in Fig. 5D.

6. Discussion

Over the years, several indicators of sea level have been used: depositional, erosive, or biological, with different levels of fidelity and accuracy (according not only to the type of evidence but also to the region or species in the case of biological proxies). Fixed biological indicators seem to be the best alternative (Laborel, 1986; Baker and Haworth, 2000; Angulo et al., 2002); unfortunately, such indicators have not yet been found in the studied area. Therefore, to construct a relative sea level curve as well as possible, we used the not-so-good, but nevertheless adequate, proxy of beach deposits generated by storms, being explicitly aware of the amount of uncertainty in the data.

The mostly abundant disarticulated shells are older than the environment of sedimentation in an unknown extent due to time averaging. We assume that the time difference between the death of the