Journal of Coastal Research | 27 | 5 | 973–983 | West Palm Beach, Florida | September 2011

www.cerf-jcr.org

Holocene Beach Ridges and Coastal Evolution in the Cabo Raso Bay (Atlantic Patagonian Coast, Argentina)

Adriano Ribolini[†], Marina Aguirre[‡], Ilaria Baneschi[§], Ilaria Consoloni[†], Enrique Fucks[‡], Ilaria Isola[††], Francesco Mazzarini[††], Marta Pappalardo[†], Giovanni Zanchetta[†], and Monica Bini[†]

[†]Dipartimento di Scienze della Terra
University of Pisa
Via S. Maria 53
56126 Pisa, Italy
ribolini@dst.unipi.it

[‡]Facultad de Ciencias Naturales y Museo
Universidad Nacional de La Plata
Edificio Institutos
Laboratorios y Cátedras
Calle 64 No 3
1900 La Plata, Argentina

[§]Istituto di Geoscienze e Georisorse
Via Moruzzi 1
56100 Pisa, Italy

[††]Istituto Nazionale Geofisica e Vulcanologia
Via della Faggiola 32
I-56126 Pisa, Italy

ABSTRACT

www.JCRonline.org

RIBOLINI, A.; AGUIRRE, M.; BANESCHI, I.; CONSOLONI, I.; FUCKS, E.; ISOLA, I.; MAZZARINI, F.; PAPPALARDO, M.; ZANCHETTA, G., and BINI, M., 2011. Holocene beach ridges and coastal evolution in the Cabo Raso bay (Atlantic Patagonian coast, Argentina). *Journal of Coastal Research,* 27(5), 973–983. West Palm Beach (Florida), ISSN 0749-0208.

The Holocene evolution of the Cabo Raso bay (Atlantic Patagonian coast) was reconstructed by means of geomorphological, stratigraphic, and palaeontological analyses, assisted by radiocarbon dating. Six beach ridges were individuated and mapped in the field, as well as some rocky erosional landforms, *e.g.,* inner margins of marine terraces. Thanks to quarry sections, the internal structure of beach ridges, their relationship with continental deposits, and the fossil contents were determined. Two specimens of *Aulacomya atra* and *Brachidontes purpuratus* were radiocarbon dated at 6055 and 4500 ± 20 YBP, respectively. The bedrock outcrops at the base of an analysed section allowed us to associate the age of the samples collected to the elevation of the marine transgression surface upon which the entire deposit rests. Because a beach ridge is a regressive form, the elevation of the base of the dated deposit was assumed to be equivalent to or slightly lower than the maximum sea-level stationing, represented by the inner margin of the coheval marine terrace. The altimetric correlation between the base of the beach ridge dated at 6055 ± 20 YBP and the inner margin of the corresponding marine terraces allowed us to constrain the maximum Holocene marine transgression to about 3 to 2 m above sea level. This elevation for the maximum Holocene transgression is lower than that shown by most of the previous data for Patagonian coast, but it shows a crude agreement with recent estimates coming from geophysical models that report, for this area, a departure from the eustatic value of sea level, mainly caused by glacioisostatic process. This means that the employment of marine erosional landforms, associated with other multisource field data, proved to be determinant for reconstructing the sea-level variation in the Patagonian coast.

ADDITIONAL INDEX WORDS: *Beach ridge, coastal geomorphology, sea level, radiocarbon dating, Holocene, Patagonia.*

INTRODUCTION

Palaeo–sea-level change of the Patagonian Atlantic coast has been strongly studied, because it is the largest continental landmass in the westwind zone of Southern Hemisphere and it corresponds to a passive tectonic margin generally believed to be affected by a very low or negligible tectonic uplift (Perucca and Bastias, 2008; Sylwan, 2001; Tassara *et al.,* 2007). However, recent geological data and geodynamic models do not exclude *a priori* that a modest tectonic uplift could occur in this region (Guillaume *et al.,* 2009; Pedoja *et al.,* 2010).

The peripheral position of Patagonia in respect to the centre of the large Pleistocene ice sheets covering the Andes suggests that the coast may have recorded both the isostatic response of the solid Earth to the ice unloading (isostatic component) and the influx of glacial meltwater to the oceans (glacioeustatic component) (Milne and Mitrovica, 2008; Milne, Long, and Bassett, 2005). Advanced geophysical models showed that a departure from the eustatic value caused by glaciation-induced sea-level changes could be expected for the Patagonian coast when several additional processes are incorporated in the modelling, *i.e.,* isostatic deflection of ocean floor, gravitational attraction between ice sheet and ocean water, and gravitational attraction between solid Earth and ocean water (Milne and Mitrovica, 2008; Milne, Long, and Bassett, 2005). Therefore, to decipher the sea-level change signal in such a complex situation, the availability of reliable sea-level markers coherent with convergent geomorphological, stratigraphic, and palaeontological interpretations of field data, along with chronological constrains, is crucial (Schellmann and Radtke, 2010).

Erosional landforms are dominant in the Patagonian Atlantic coast because of the high energy of this marine

---

DOI: 10.2112/JCOASTRES-D-10-00139.1 received 15 September 2010; accepted in revision 24 December 2010.

environment. Nevertheless, littoral deposits, *i.e.,* beach ridges, strictly linked to a wave motion of high intensity are numerous and well preserved. Indeed, several studies adopted the beach ridges of the Patagonian coast as markers for the reconstruction of sea-level change during the Pleistocene and Holocene. The results were interpreted as proposing causes of sea-level change that were highly discordant, claiming the contribution of tectonic uplift, glacioisostatic rebound, and eustatic rise (Codignotto, Kokot, and Marcomini, 1992; Gordillo *et al.,* 1992; Peltier, 1988; Porter, Stuiver, and Heusser, 1984; Radtke, Rutter, and Schnack, 1989; Rostami, Peltier, and Mangini, 2000; Rutter, Schnack, and Del Río, 1989; Schellmann, 1998; Vilas *et al.,* 1999; Schellmann and Radtke, 2003, 2010).

The principal problems that led to contrasting opinions are mainly linked to (i) how beach ridges form and how they can be related to sea level, (ii) what it is used as a sample for radiocarbon dating, and (iii) where the sample is located inside the beach ridge, *i.e.,* its altimetric relationship with the basal transgressive surface.

It is commonly accepted that coarse-gravel beach ridges are wave-built features formed in the supraintertidal zone (run-up zone), with an occasional contribute of storm events (Tanner, 1995; Taylor and Stone, 1996). Consequently, beach ridge genesis, grain size, orientation, and elevation above sea level are strictly related to past wave regime in the surf zone, climate conditions (*i.e.,* winds), sediment supply and source (*i.e.,* onshore, alongshore, or both types of transport), and sea level (Taylor and Stone, 1996).

In the sampling procedure for datable material, the risk exists of collecting biological remains reworked from older deposits involved in the process of beach ridge formation. Schellmann and Radtke (2010 and references therein) illustrated the requirements that must be satisfied by the sample to avoid processing of unsuitable material (as described in the Methods section of this article).

When we aim to relate the age of a beach ridge to sea level, it is mandatory to evaluate the thickness of the depositional unit, clearly individuating the basal surface (stratigraphic unconformity with an older deposit or rocky platform) that can be considered representative of the mean tide at the time of transgression. Conversely, the elevation of the beach ridge crest only represents the upper limit of the wave run-up, well above the mean high tide, and samples collected in this position or somewhere on the beach ridge surface are not suitable for accurate reconstruction of relative sea-level curve.

In this work, the tract of coast near the Cabo Raso cape was considered (Figure 1). Although this area was amongst the first studied in the systematic analysis of Patagonian coast (Feruglio, 1950), it was virtually neglected by later investigations. This is surprising because the first observations report several geomorphological and palaeontological elements potentially useful for determining the palaeoenvironmental evolution of the Patagonian coast during Pleistocene and Holocene.

Indeed, a preliminary observation of satellite images suggested to us the presence of well-preserved beach ridges, locally spaced by depressions of variable dimensions. The dissection of these beach ridges by a fluvial channel prompted us to consider this a potentially interesting area in which to reconstruct the Pleistocene–Holocene coastal dynamic, associating landforms and their stratigraphic composition.

We present the most remarkable geomorphological and stratigraphic features of the bay of Cabo Raso (Caleta Cabo Raso in the following), along with the fossil contents of the individuated main deposits. These elements, supported by some radiocarbon dating, are used to reconstruct the coastal evolution, with particular reference to Holocene sea-level variation in the Atlantic coast of Patagonia.

SETTING

Punta Pescadero to the north and the cape of Cabo Raso to the south delimit Caleta Cabo Raso, which extends for a total length of about 6 km (Figure 1). The inner zone of the bay is crosscut by a fluvial system that presently does not reach the sea because it is dammed by the most recent beach ridge system; instead, it terminates in a wide lagoonal depression (locally named *salitral*) that is occasionally inundated by flood.

Because of a barrier effect, most precipitation releases on the western slopes of the Andes ($<$2000 mm/y), whereas central Patagonia usually is characterised by less than 200 mm/y (Coronato *et al.,* 2008). Near the Atlantic coast, a slight increase ($\leq$300 mm/y) is observed. The meteorological station closest to the study area (Camarones village) usually records mean annual precipitation of 287 mm/y and mean annual temperature of 12.6°C. The strong winds generated by the contrast between the sub-Antarctic low-pressure and the subtropical high-pressure areas induce elevated soil evapotraspiration. All of these conditions make Caleta Cabo Raso an arid, poorly vegetated area like the rest of Patagonia.

Data about the oceanic tide regime are not available for Caleta Cabo Raso. However, a macrotidal regime (*i.e.,* tidal range $>$ 4 m) can be supposed that is analogous to that of most of the Patagonian coast (Isla and Bujaleski, 2008).

Jurassic rhyolitic and ignimbritic rocks of the Marifil Formation constitute the bedrock, extensively outcropping in the area of the Cabo Raso cape. Quaternary formations are represented by marine beach ridges and terrace deposits (gravel, sand, and conglomerates) at various elevations above sea level (Lema, Busteros, and Franchi, 2001).

METHODS

Observations of satellite images were preliminarily undertaken at various scales, with particular care dedicated to individuating beach ridges and other landforms directly or indirectly controlled by coastal processes. Each of the landforms identified was inspected in the field to characterise surface features, *i.e.,* peripheral limits, relationships with other landforms, erosional processes, and grade of weathering of composing clasts.

In natural or man made sections, the internal structure of the beach ridges was analysed and lithofacies and fossil contents were described. In addition, stratigraphic descriptions of fluvial and slope deposits, as well as soils, were carried out.

Fossil shells of the dominant molluscan species in the beach ridge were sampled in section or, alternatively, on the surface of these landforms. Only articulated shells (*i.e.,* in situ shells

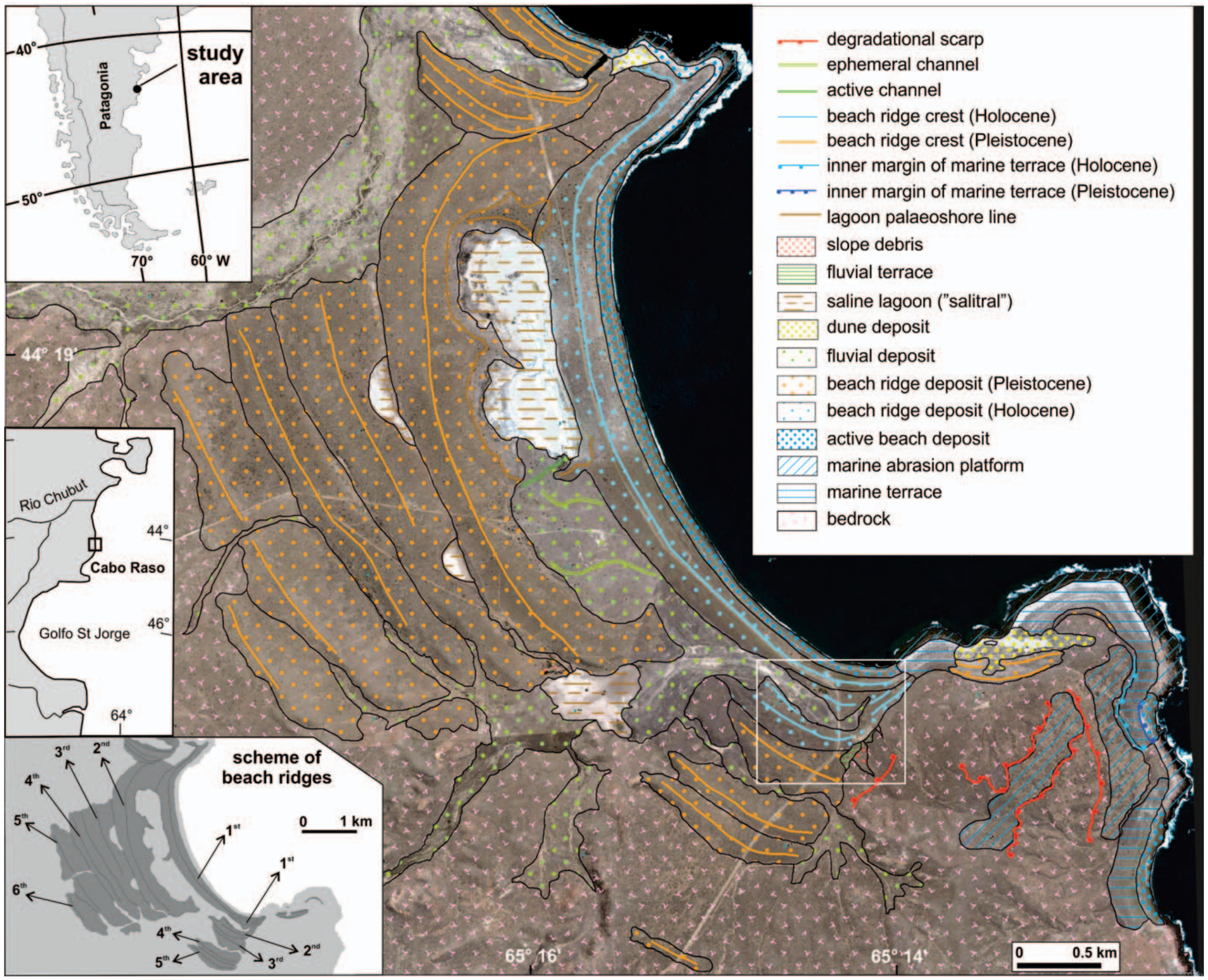

Figure 1. Geomorphological sketch of Caleta Cabo Raso. The white square corresponds to the *cantera* area, which is also mapped in Figure 4.

with valves stick together, or a "paired mollusc shell") sampled in section were eventually used for radiocarbon dating. This care is necessary to minimise the possibility of shell reworking from an ancient deposit.

In the laboratory, the shells were rinsed several times with deionised water and cleaned in an ultrasonic bath. If some part of the shells was still dirty, it was cleaned manually with a drill.

The radiocarbon ages of fossil specimens were determined at the Keck Carbon Cycle Accelerator Mass Spectrometry laboratory of the University of California, Irvine (USA) (Santos *et al.,* 2007).

RESULTS

Geomorphology and Stratigraphy

In the field, six beach ridge units were individuated and mapped, from the first facing the sea extending up to the most internal, about 2 km from the coast (in the following text, these are numbered from first to sixth moving inland) (Figure 1). Several elevation measurements were acquired with a barometric altimeter (Garmin model, ±3 m accuracy, 0.3 m resolution) in correspondence with beach ridges, as well as other relevant landforms. The presence in the surveyed area of two topographic points of the Argentinean geodetic network allowed the calibration of the barometric altimeter, which was repeated several times daily. Moving inland, the crests of the six beach ridges assume elevations, respectively, of 8 to 9, 10 to 11, 15 to 16, 27 to 28, 30 to 31, and 40 to 41 m above sea level (asl).

Overall, the beach ridges are more preserved and prominent in the northern sector of the bay, where the oldest landforms also show a lateral continuity before being sharply cut by a fluvial thalweg. In contrast, in the southern sector, the oldest beach ridges are discontinuously preserved and the most

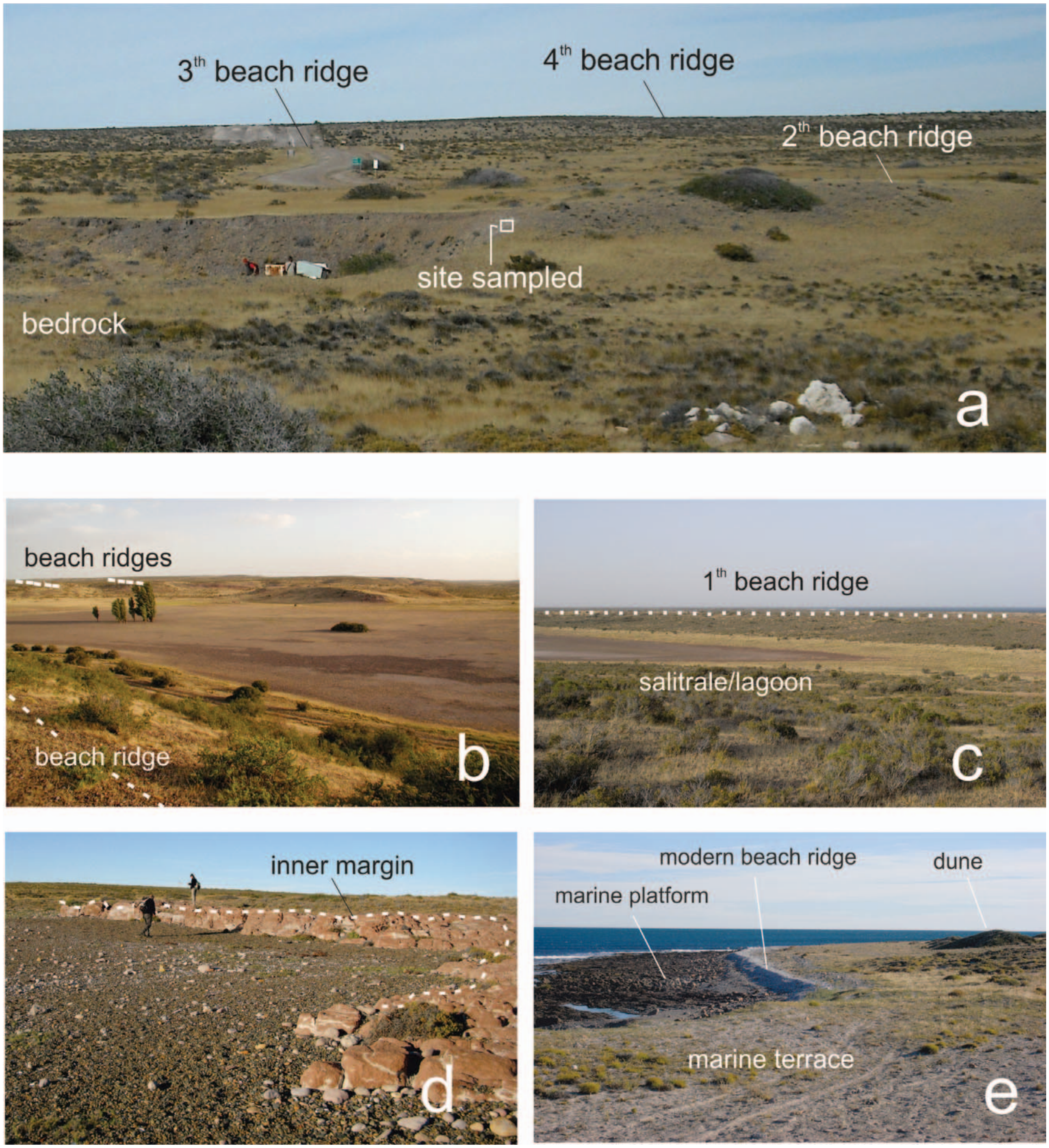

Figure 2. Typical landforms in Caleta Cabo Raso: Holocene and Pleistocene beach ridges (the *cantera* area and sampled beach ridge are indicated) (a), depression between ridges (b), alluvial area back to the first beach ridge (c), lowermost inner margin (3–2 m asl) along the Cabo Raso lighthouse terrace (d), and modern abrasion platform and active beach ridge (e).

internal consists only of a single, small, ridge-shaped deposit near the road from Cabo Raso to Camarones (Figures 1 and 2a). In all likelihood, fluvial activity relative to the drainage from the SW partly dismantled and locally covered the beach ridges internal to the first ridge facing the sea. Other beach ridges were individuated in correspondence with the capes that delimit Caleta Cabo Raso. They have small dimensions (≤max. 2 m high) and are partly covered by dune deposits.

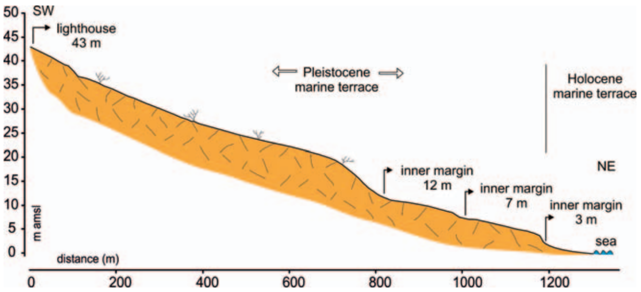

Figure 3. Inner margins along the topographic profile of the Cabo Raso lighthouse terrace.

The south and north sectors are separated by a large fluvial thalweg built from episodic floods. A main depression into the thalweg indicates the area with the most prolonged water stagnation, while the areas backing the first beach ridge seem to be invaded by the most intense floods, as suggested by palaeochannels carved in the muddy-flat area (Figure 1). Beside the small "eye-cat"–shaped depressions between the third and the fourth beach ridges, a prominent *salitral* is evident on the backside of the first beach ridge in the north (Figure 2c). The planar shape suggests that this *salitral* results from the joining of two adjacent depressions nearly circular in origin. In addition, evidence of ancient water levels was mapped along the slopes bordering the depression. Ephemeral channels carved in the planar area between the *salitral* and the fluvial thalweg indicate an occasional water supply infilling the depression.

The rock dorsal that delimits to the south of the bay and terminates in the Cabo Raso cape is shaped overall by a slightly inclined platform, that extends downwards from the elevation of the lighthouse (42 m asl) towards the coast. This platform was interpreted by Feruglio (1950) as a marine terrace *(terraza de Cabo Raso)* with fossil remnants discontinuously preserved. The planar continuity of this surface is interrupted by scarps, at various elevations, that mark the existence of inner margins of former marine terraces, nowadays discontinuously covered by thin, sandy-gravel deposits with rare fossils. The inner margins detected are about 12, 7, and 3 m asl (Figures 2d and 3).

In the area of the Cabo Raso cape, a partly vegetated dune system was mapped, as well as active beach ridges built up by the current upwashing of oceanic storms (Figure 2e). These landforms stand on the marine terrace with an inner margin at 7 m asl. Besides depositional processes, the high-intensity wave motion caused supratidal erosion, leading to the partial exhumation of the abrasion platform beneath the terrace.

The most recent beach ridges in the area are characterised by the presence of thin, poorly developed soils, whereas older beach ridges have thick, well-developed, usually polycyclic soils, characterised by thick Bk horizons, often with truncated horizons.

Overall, beach ridges are internally composed of clast-supported gravels organised into sets and cosets of well-sorted decimetric beds, often showing reverse grading with local accumulation of fossils shells.

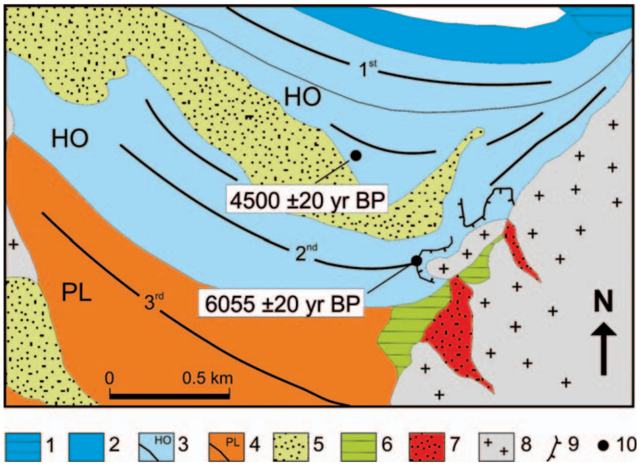

Figure 4. Geological and geomorphological map of the *cantera* area. 1 = marine terrace, 2 = active beach deposit, 3 = Holocene beach ridge deposit and crest (black line), 4 = Pleistocene beach ridge deposit and crest (black line), 5 = fluvial deposit, 6 = fluvial terrace, 7 = slope debris, 8 = bedrock, 9 = quarry scarp in the *cantera* area, 10 = radiocarbon dated sample, HO = Holocene, PL = Pleistocene. For the location of the map, see Figure 1.

The area of the Cabo Raso quarry *(cantera),* a few hundred metres south of the Cabo Raso village, was particularly useful in inspecting the internal structure of Holocene beach ridges, as well as their relationship with continental deposits, *i.e.,* slope debris (Figure 4). In detail, it is possible to distinguish three lithostratigraphic units lying on the bedrock (volcaniclastic rocks of Marifil Complex) (Figure 5). The lower unit (unit 1) is composed by alternating poorly to moderately sorted sandy and rounded polygenic gravelly layers, with general horizontal stratification containing rich fauna of marine molluscs. These latter are usually disarticulated and abraded. This unit is covered, with distinct erosional contact, by a succession of poorly sorted, matrix-supported, angular, gravelly deposits with no fossil remains (unit 2). The series terminates with poorly developed soil, which is in turn overlapped with a beach ridge deposit.

The two lower continental units correspond to the deposit of the small terrace bordering the SE part of the *cantera*, which is covered by a second beach ridge (unit 3) and seals the third beach ridge (Figures 2a and 4).

Fossil Contents

The biogenic content of Pleistocene and Holocene shell concentrations preserved in the beach ridges along the entire coastal area between Bahía Vera (slightly to the north of study area) and Cabo Raso consist of 80 to 95% molluscan skeletons (mostly gastropods and bivalves) (Table 1). The associated invertebrate macrofauna includes skeletons of corals, bryozoans, terebratulid brachiopods, cirripeds (balanids).

These molluscan concentrations can be considered as parautochthonous assemblages (Kidwell, Fürsich, and Aigner, 1986), because they include shells transported for very short distances from their original habitats, principally by the effect of storms.

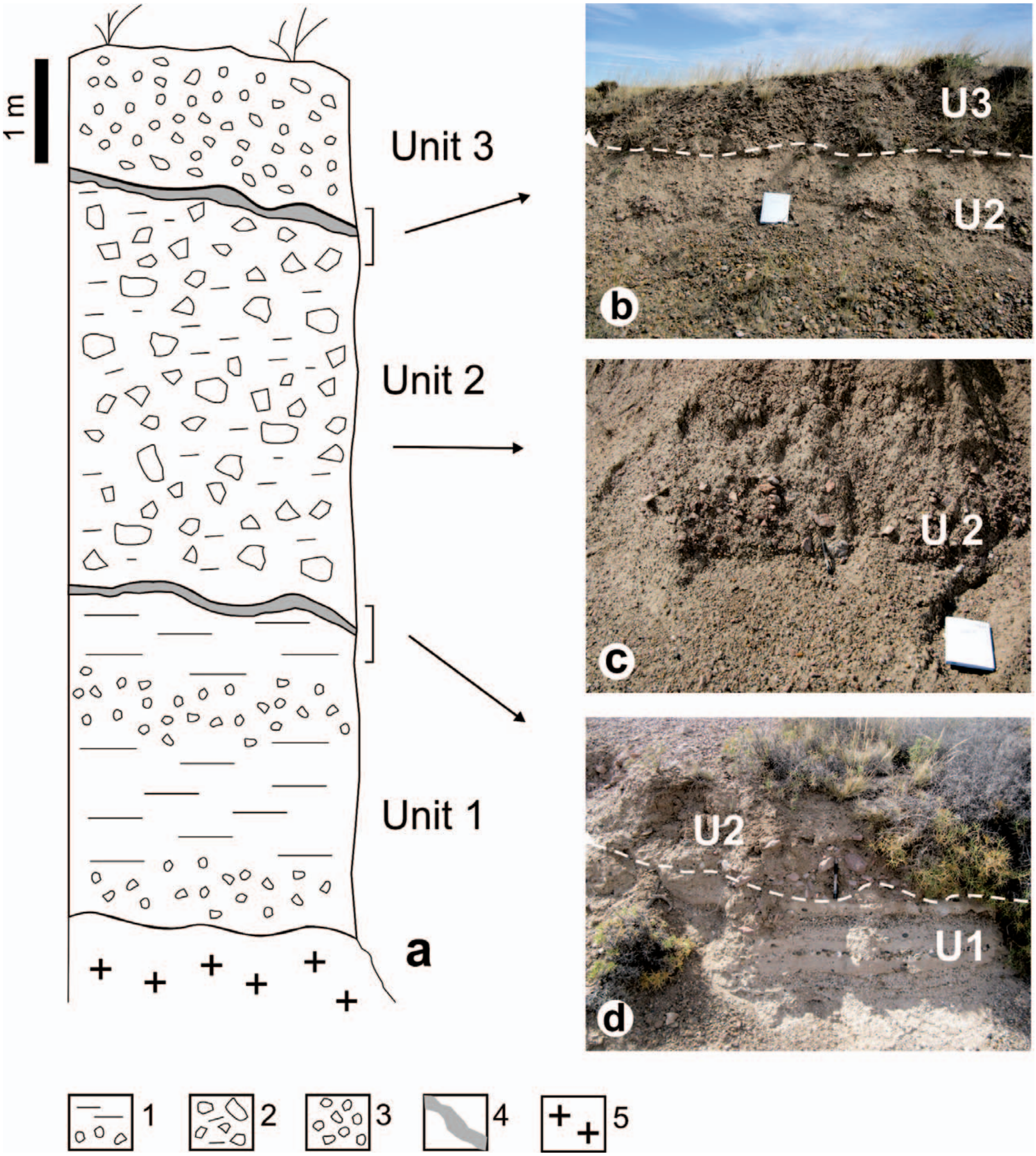

Figure 5. Reconstructed stratigraphic section of the Cabo Raso *cantera*. 1 = sorted sand and gravel, 2 = poorly sorted angular gravel, 3 = sorted rounded gravel (beach ridge deposit), 4 = palaeosoil, 5 = bedrock. Layers of thickness are laterally variable.

This is also indicated by the presence of shells with joined valves, which are also observable on current storm accumulation along the Cabo Raso coast and elsewhere in Patagonia.

In general, the shells are well preserved. Bivalves like oysters, Mytilidae, and Veneridae and gastropods like Patellacea, Trochacea, Muricidae, Volutidae, and Bucinidae are amongst the most outstanding taxa in terms of abundance, shell size and thickness, and preservation. Of all the molluscan taxa identified (31 gastropods and 17 bivalves) (Table 1), bivalves are in general better preserved, in some cases even as complete shells in living position *(i.e., Protothaca antiqua, Aulacomya atra, Brachidontes* spp., *Mytilus edulis).* Gastropod shells show in general more

Figure 6. Beach ridges sampled (a and b), *Aulacomya atra* (c), and *Brachidontes purpuratus* (d).

abraded surfaces with loss of their original colour and lustre, except for the big shells of *Tegula atra,* which characterise the middle and exterior Pleistocene ridges, and those of mytilids and patellids, which characterise the Holocene ridges.

The most common gastropod taxa in the Holocene beach ridges are *Nacella, Tegula, Crepidula, Trophon, Buccinanops, Odontocymbiola,* and *Siphonaria.* Amongst the bivalves, the most common taxa are *Protothaca, Brachidontes,* and *Aulacomya*. Oysters associated with the scarce *Mactra* sp. characterise the innermost (oldest) Pleistocene ridges. Abundant shells of associated *T. atra–P. antiqua* characterise Upper Pleistocene (middle and exterior) ridges. *Brachidontes cf. purpuratus, Nacella (Patinigera) magellanica, Nacella (P.) deaurata, Trophon geversianus,* and *A. atra* characterise the Holocene ridges. *Natica isabelleana, Aequipecten tehuelchus, Buccinanops,* and *Odontocymbiola* characterise the modern nearshore.

A synthesis of the most characteristic and relevant gastropod and bivalve taxa recovered is shown in Table 1. Comprehensive systematic references are available elsewhere (Aguirre and Farinati, 2000; Aguirre, Hlebzsebitch, and Delatorre, 2008).

Radiocarbon Dating

The radiocarbon ages of two specimens of *A. atra* and *B. purpuratus* were determined. The molluscs collected presented valves that were stuck together, and the sample positions are reported in Figure 6. The results are illustrated in Table 2. Radiocarbon ages are reported in years before present. Conventional radiocarbon age is always reported without adjustment for differences in ^{14}C-specific activity of reservoirs, *i.e.,* the difference between the atmospheric ^{14}C content and the local ^{14}C content of ocean surface water. Reservoir effect values for the southern Atlantic ocean and, in particular, Patagonia are few and are spread over large range. Data from Gomez *et al.* (2008) for the Argentine coast from Buenos Aires to the La Plata range from 90 to 2802 years. Estimates from Butzin, Prange, and Lohmann (2005) and Cordero *et al.* (2003) are 450 years for Comodoro Rivadavia, Rada Tilly, Caleta Olivia (370 ± 65 years, according to Cordero *et al.,* 2003), Bahía Laura (185 years, according to Cordero *et al.,* 2003), and Puerto San Julian and 215 years (Butzin, Prange, and Lohmann, 2005) or 529 years (according to

Cordero *et al.,* 2003) for Bustamante. This constitutes a large uncertainty for the reservoir effect (which probably varies over time); therefore, we only discuss uncertained ages.

Table 1. *Fossil contents collected in this work compared with those described by Feruglio 1950.*

Molluscs	B. Vera–C. Raso (this contribution)	Cabo Raso (Feruglio, 1950)
Gastropoda		
Fissurella picta (Gm.)*†	PL-HO	
Fissurella radiosa Lesson*	PL-HO	HO
Fissurella oriens Sowerby	PL-HO	
Nacella (P.) magellanica (Gmelin)*†	PL-HO	HO-PLv
Nacella (P.) deaurata (Gmelin)	PL-HO	
Nacella (P.) cf. deaurata (Gmelin)	PL-HO	
Nacella mytilina (Helbling)*†	HO	
Tegula (C.) atra (Lesson)*†	PL	PL
Tegula patagonica (d'Orbigny)	HO	PLv
Ataxocerithium pullum (Philippi)*	PL	HO
Crepidula protea d'Orbigny	PL-HO	
Crepidula dilatata Lamarck	PL-HO	HO-PLv
Crepidula cf. dilatata Lamarck	HO	
Crepidula aculeata (Gmelin)*†	HO	
Crepidula onyx Sowerby*†	PL	
Natica isabelleana d'Orbigny†*	PL-HO	
Trophon varians (d'Orbigny)	PL-HO	HO
Trophon geversianus (Pallas)	PL-HO	HO
Trophon laciniatus (Martin)*	HO	HO
Acanthina monodon (Pallas)*†	PL-HO	
Adelomelon ferussaci (Donovan)	PL	PLv
Adelomelon sp.*†	HO	
Odontocymbiola magellanica (Gmelin)*	PL-HO	PLv
Olivancillaria cf. carcellesi Klapp.†	PL	
Pareuthria plumbea (Philippi)†	PL-HO	
Dorsanum moniliferum (Valenciennes)†	PL	
Buccinanops globulosus (Kiener)*	PL-HO	PLv
Buccinanops cochlidium (Dilwynr)*	PL-HO	PLv
Buccinanops sp.*	PL	
Siphonaria lessoni (Blainville)*†	PL-HO	
Volutidae indet.*†	PL-HO	
Bivalvia		
Glycymeris longior (Sowerby)	HO	PLv
Mytilus edulis Linné*†	PL-HO	
Brachidontes (B.) rodriguezi (d'Orbigny)*†	PL-HO	
Brachidontes (B.) purpuratus (Lam.)*†	PL-HO	
Aulacomya atra (Molina)*†	PL-HO	
Aequipecten tehuelchus (d'Orbigny)*†	PL-HO	
Pectinidae indet.†	PL	
Ostrea equestris Say	PL	
Ostrea tehuelcha Feruglio	PL	PLv
Ostrea cf. tehuelcha Feruglio	PL	
Ostrea sp.	PL-HO	
Mactra cf. isabellenaa	HO	PL-PLv
Mactra cf. patagonica (d'Orbigny)†	PL	
Solen sp.†	PL-HO-Rec	
Eurhomalea exalbida (Dilwyn)	PL-HO	PLv
Protothaca antiqua (King)*	PL-HO	HO-PL
Clausinella gayi (Hupé)	PL-HO	HO

* Taxa not mentioned in the area of Cabo Raso (Aguirre, Richiano, and Negro Sirch, 2006).

† Taxa not mentioned before in the area of this study.

HO = Holocene, PL = Pleistocene, PLv = oldest Pleistocene ridges ("Marine Terraces" sensu Feruglio, 1950), Rec = modern records.

DISCUSSION

Beach Ridges in Caleta Cabo Raso

On a geomorphological basis, the limit between Pleistocene and Holocene beach ridges can be qualitatively determined, observing the surface weathering, grade of channelling, soil development, and top-of-crest elevations. Accordingly, the first beach ridge system (8–9 m asl) and the associated depression can be considered a Holocene unit. Looking at the crest elevation, this unit can also include the second beach ridge (10–11 m asl), bordering the depression internally and preserved only in southern Caleta Cabo Raso (Figures 1 and 4). The rapid increase in elevation recorded moving towards the third beach ridge (15–16 m asl) suggests a Pleistocene age, which is in agreement with the age reported by some authors for beach ridges with similar crest elevations (*e.g.,* Rostami, Peltier, and Mangini, 2000; Schellman and Radtke, 2003).

The palaeontological inspection of all beach ridges in the area revealed typical macrofaunal associations for Holocene (first and second beach ridges) and Pleistocene (third through sixth beach ridges). Moreover, compared with the faunal lists of late Quaternary terraces mentioned by Feruglio (1950) and in recent papers (Aguirre, Hlebzsebitch, and Delatorre, 2008, and references therein) our results document the first records of the following taxa: *Fissurella radiosa, Ataxocerithium pullum, Natica isabelleana* (in the Pleistocene), *Fissurella picta, Fissurella oriens, Tegula patagonica, Acanthina monodon, Buccinanops cochlidium* (in the Holocene), and *Dorsanum moniliferum* (in the Pleistocene) (Table 1). We lack, however, *T. patagonica* in the Pleistocene and *A. pullum* in the Holocene.

The area of the *cantera* intercepts the passage from the first beach ridge system and the onset of the second, giving us the opportunity to reconstruct the last phases of the Holocene evolution in Caleta Cabo Raso (Figure 4). The age of *A. atra* at 6055 ± 20 YBP confirms that the second beach ridge can be ascribed to Holocene marine phases. Because the fossil content of the third beach ridge is consistent with a Pleistocene age, the dated beach ridge corresponds to the maximum preserved Holocene phase in the area. Moreover, the outcrop of the bedrock at the base of the *cantera* allows us to associate the age of the sample collected near the top of the beach ridge with the elevation of the (basal) marine transgression surface (about 2 m asl) on which the entire deposit rests.

The elevation of the base of the beach ridge deposit should be equal to or slightly lower than the maximum sea-level stationing, *i.e.,* the inner margin of the corresponding marine terrace. Consequently, the beach ridge dated at 6055 ± 20 YBP can be reasonably correlated with the inner margin of 2 to 3 m asl of the marine terrace individuated along the Cabo Raso lighthouse dorsal.

Because of the stratigraphic position, the two lower continental units described in the *cantera* section (units 1 and 2) probably represent different phases of the last glacial period (after marine isotope substage 5e). The lowermost unit

Table 2. *Radiocarbon data measured for shells of* Aulacomya atra *and* Brachidontes purpuratus*, reported as fraction modern and radiocarbon age without correction or calibration.*

UCIAMS Sample Code	Sample Name	Sample Altitude (m asl)	Fraction Modern	^{14}C Age, YBP (±y)	Species
65208	WP39(1)	4	0.4707 ± 0.0010	6055 ± 20	*A. atra*
65209	WP41(2)	7	0.5710 ± 0.0012	4500 ± 20	*B. purpuratus*

UCIAMS = University of California, Irvine, accelerator mass spectrometry.

corresponds to a dismantling phase of some older marine deposit, followed by a phase of local erosion and a production of debris flows triggered along local small channels during intense storm events. The detritical supply coming from the slope dominant in the *cantera* today appears insufficient to support such processes. However, the terminations of Pleistocene beach ridges covering the slope can be invoked as a debris source, even though they are now dismantled. This hypothesis is confirmed by the finding in the fossil content of *T. atra,* which is absent in the Atlantic Holocene beach deposits, correcting what was erroneously reported by Aguirre, Hlebzsebitch, and Delatorre (2008) about its presence in the Holocene deposits of this area.

The poorly developed soil on the sequence top is probably Holocene in age, just predating the Holocene transgression. The age of *B. purpuratus* documents that at 4500 ± 20 YBP the coastal palaeogeomorphology was shaped similarly to its present shape, with a lagoonal depression separated from the sea by a beach ridge system.

The lack of stratigraphic sections does not allow dating of the first beach ridge facing the sea, adding to the Holocene evolution the events after 4500 ± 20 YBP. An indirect solution could be retrieved by the analysis of human occupation, *i.e.,* studies of archaeological remnants and historical documentation about the Cabo Raso settlement (now abandoned).

The inner margins at 7 and 12 m asl along the Cabo Raso lighthouse dorsal can be attributed to Upper Pleistocene marine highstands and correlated with the third and fourth beach ridges, in agreement with fossil and geomorphological data (crests of 15–16 and 27–28 m asl, respectively). However, a more convincing attribution must be based on additional field data, such as the correlation between the inner margins and the basal surface of the third and fourth beach ridges, along with new radiocarbon ages. Furthermore, it cannot be excluded *a priori* that the inner margin at 7 m asl could have been formed during a Holocene marine phase of stationing older than 6000 YBP, representing the maximum relative sea level. In fact beach ridges are regressive forms and thus they do not necessarily mark the maximum transgression. However, our data do not strongly support this alternative interpretation.

Holocene Beach Ridges in Patagonia

Rutter, Radtke, and Schnack (1990) using electron spin resonance age estimates, in conjunction with amino acid data on marine invertebrates in paired mollusc shells, to demonstrate that beach ridges at elevations between 8 and 10 m asl along the coastline of Patagonia are Holocene in age.

Codignotto, Kokot, and Marcomini (1992) analysed the relationship between radiocarbon ages of marine invertebrates in littoral deposits and their corresponding present-day elevations (above mean sea level) for 172 samples from 15 sites along the coast of Patagonia. Their data are scattered and point to a maximum elevation of beach ridge crests of 12 m with respect to present-day mean sea level during the middle Holocene. This work represents the first attempt to use beach ridges as sea-level markers in Patagonia. It may be objected, anyway, that the elevation of the dated shells can be related to past sea level only with great approximation.

Schellmann and Radtke (2003) proposed a relative sea-level curve for the Holocene, plotting radiocarbon ages obtained from shells found in beach ridges along the Atlantic Patagonian coast against beach ridge crest elevations. Schellmann and Radtke's data highlight a general positive correlation of elevation with age: the relative sea level was as high as 10 m (with respect to the current high-tide water level) from 8000 to 6500 BP and decreased down to its present-day position, displaying a minor peak of 7 m at 2500 BP. Comparing this curve with those of sea-level elevation data obtained using valley mouth terraces as sea-level markers (available only for a few sites in the study area), the authors calculated that the latter underestimates sea-level values of 3.5 m during the middle Holocene. The beach ridge elevation (strongly depending on the local environmental conditions), in contrast to the elevation of the fluvial terrace at the estuary of a river with periodical runoff (the mouth terrace, according to Schellmann and Radke, 2003), is considered a better indicator of the high-tide water level.

Rostami, Peltier, and Mangini (2000) produced a relative sea-level curve for Atlantic Patagonia using as sea-level marker a marine terrace that they recognise all along the coast at different elevations, ranging from 3 to 7 m asl. This terrace is higher than Holocene beach ridges (which are regressive features and thus younger) but morphologically connected to them. The authors obtain an elevation of 6 to 7 m asl for the maximum Holocene transgression, which they dated to 7000 to 8000 YBP. However, a relevant thickness of the marine deposit resting onto the rocky platform beneath could result into an overestimation of the corresponding sea level.

CONCLUSIONS

The multiapproach method employed in this work allowed us to study the Holocene evolution of a tract of Patagonia coast (Caleta Cabo Raso), taking care to consider fossil contents, sampling procedure, stratigraphic interpretation, and morphological correlation amongst littoral landforms.

The beach ridge systems and the inner margin of corresponding marine terraces allowed us to individuate and chronologically constrain the maximum Holocene marine transgression. This was dated at 6055 ± 20 YBP and stands around 2 to 3 m asl.

The altimetric positioning of the maximum Holocene transgression is lower than indicated by previous data for the Patagonian coast (Rostami, Peltier, and Mangini, 2000; Schellmann and Radke, 2003), even though the comparison is difficult because of differences in the quoted features considered (beach ridge crest, marine terrace surface, and mouth terrace) and in the reference system adopted for elevation (mean high tide and mean sea level). However, we believe that the correlation between the base of the beach ridge deposit (*i.e.,* the basal marine transgression) and a rocky erosional landform (*i.e.,* an inner margin formed by the same marine transgression at its maximum stationing) represents an improvement in the determination of the sea-level highstand elevation, avoiding local effects of marine condition (*i.e.,* wave intensity affecting maximum surf and undetermined thickness of the marine deposit covering the platform beneath). The inner margin should be slightly higher than the base of the beach ridge and older than radiocarbon ages obtained from any part of the related deposits. For the case examined in this work, the use of the second beach ridge crest to mark the sea level should have caused an overestimation of about 7 to 8 m.

Overall, considering that a glacioesutatic sea level at 6000 YBP was about 0 m asl (Fleming *et al.,* 1998; Waelbroke *et al.,* 2002; and references therein), the quote of this level in Cabo Raso area appears elevated from 2 to 3 m asl, in agreement with the recent model estimate of Milne and Mitrovica (2008), which reports for this area a relative sea level of about 5 m. This crudely implies an average uplift of 0.3 to 0.5 mm/y, a departure from the eustatic value of sea level induced by a dominant glacioisostatic process.

In conclusion, we suggest that traditional geomorphological indicators of past sea level (*i.e.,* the inner margin of a marine terrace), chronologically anchored and accurately quoted, should be associated to beach ridge morphology and stratigraphy to reconstruct a relative sea-level curve, which, in turn, can be used to test the geophysical model and estimated rate of uplift.

ACKNOWLEDGMENTS

We thank G. Schellmann for the friendly critical review of the manuscript and two anonymous reviewers for their useful comments, which greatly improved the manuscript. This work has been funded by the projects Ateneo 2007—Reconstruction of sea-level, palaeoenvironments and climate during the last and present interglacials over the Patagonian coast (Argentina). An attempt to evaluate future climatic scenarios" (leader G. Zanchetta) and PRIN 2008—"The Patagonian coastal deposit as natural archives of the sea-level changes and palaeoclimate of the Southern Hemisphere during the Quaternary: a contribute to evaluate the future climatic scenario" (leader G. Zanchetta).

LITERATURE CITED

Aguirre, M.L. and Farinati, E.A., 2000. Moluscos del cuaternario marino de la Argentina. *Boletín de la Academia Nacional de Ciencias Exactas. Físicas y Naturales,* 64, 1–44 [in Spanish].

Aguirre, M.L.; Hlebzsebitch, J., and Delatorre, F., 2008. Late Cenozoic invertebrate paleontology, with emphasis on molluscs. *In:* Rabassa, J. (ed.), *Late Cenozoic of Patagonia and Tierra del Fuego*. Developments in Quaternary Sciences. Amsterdam: Elsevier, pp. 285–325.

Aguirre, M.L.; Richiano, S., and Negro Sirch, Y., 2006. Palaeoenvironments and palaeoclimates of the Quaternary molluscan faunas from the coastal area of Bahía Vera–Camarones (Chubut, Patagonia). *Palaeogeography, Palaeoclimatology, Palaeoecology,* 229, 51–286.

Butzin, M.; Prange, M., and Lohmann, M.G., 2005. Radiocarbon simulations for the glacial ocean: the effects of wind stress, Southern Ocean sea ice and Heinrich events. *Earth and Planetary Science Letters,* 235(1–2), 45–61.

Codignotto, J.O.; Kokot, R.R., and Marcomini, S.C., 1992. Neotectonism and sea level changes in the coastal zone of Argentina. *Journal of Coastal Research,* 8, 125–133.

Cordero, R.R.; Panarello, H.; Lanzelotti, S., and Favier Dubois, C.M., 2003. Radiocarbon age offsets between living organisms from the marine and continental reservoir in coastal localities of Patagonia (Argentina). *Radiocarbon,* 45, 9–15.

Coronato, M.J.; Coronato, F.; Mazzoni, E., and Vásquez, M., 2008. The physical geography of Patagonia and Tierra del Fuego *In:* Rabassa, J. (ed.), *Late Cenozoic of Patagonia and Tierra del Fuego*. Amsterdam: Elsevier, pp. 13–55.

Feruglio, E., 1950. Descripción Geológica de la Patagonia. Direción General de Y.P.F., T. 3, Buenos Aires, 431p [in Spanish].

Fleming, K.; Johnston, P.; Zwartz, D.; Yokoyama, Y.; Lambeck, K., and Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters,* 163(1–4), 327–342.

Gómez, E.A.; Borel, C.M.; Aguirre, M.L., and Martínez, D.E., 2008. Radiocarbon reservoir ages and hard-water effect for the northeastern coastal waters of Argentina. Radiocarbon, 50, 119–129.

Gordillo, S.; Bujalesky, G.G.; Pirazzoli, A.; Rabassa, J.O., and Saliège, J.F., 1992. Holocene raised beaches along the northern coast of the Beagle Channel, Tierra del Fuego, Argentina. *Palaeogeography, Palaeoclimatology and Palaeoecology,* 99, 41–54.

Guillaume, B.; Martinod, J.; Husson, L.; Roddaz, M., and Riquelme, R., 2009. Neogene uplift of central eastern Patagonia: Dynamic response to active spreading ridge subduction? *Tectonics,* 28, TC2009, doi: 10.1029/2008TC002324.

Isla, F.I. and Bujaleski, G.G., 2008. Coastal geology and morphology of Patagonia and the Fuegian Archipelago. *In:* Rabassa, J. (ed.), *Late Cenozoic of Patagonia and Tierra del Fuego*. Amsterdam: Elsevier, pp. 227–239.

Kidwell, S.M.; Fürsich, F.T., and Aigner, T., 1986. Conceptual framework for the analysis and classification of fossil concentrations. *Palaios,* 1, 228–238.

Lema, H.; Busteros, A., and Franchi, M., 2001. Hoja Geológica 4566-II y IV, Camarones (1: 250.000). Programa Nacional de Cartas Geológicas de la República Argentina. Boletin No 261, Buenos Aires, 53 [in Spanish].

Milne, G.A. and Mitrovica, J.X., 2008. Searching for eustasy in deglacial sea-level histories. *Quaternary Science Reviews,* 27, 2292–2302.

Milne, G.A.; Long, A.J., and Bassett, S.E., 2005. Modelling Holocene relative sea-level observations from the Caribbean and South America. *Quaternary Science Reviews,* 24, 1183–1202.

Pedoja, K.; Regard, V.; Husson, L.; Martinod, J.; Guillaume, B.; Fucks, E.; Iglesias, M., and Weill, P., 2010. Uplift of Quaternary shorelines in eastern Patagonia: Darwin revisited. *Geomorphology,* doi: 10.1016/j.geomorph.2010.08.003.

Peltier, W.R., 1988. Lithospheric thickness, Antarctic deglaciation history, and ocean basin discretization effects in a global model of postglacial sea level change: a summary of some sources of non-uniqueness. *Quaternary Research,* 229, 93–112.

Perucca, L. and Bastias, H., 2008. Neotectonics, seismology and paleoseismology. *In:* Rabassa, J. (ed.), *Late Cenozoic of Patagonia and Tierra del Fuego*. Amsterdam: Elsevier, pp. 73–94.

Porter, S.C.; Stuiver, M., and Heusser, C.J., 1984. Holocene sea-level changes along the Strait of Magellan and Beagle Channel, southernmost South America. *Quaternary Research,* 22, 59–67.

Radtke, U.; Rutter, N., and Schnack, E.J., 1989. Untersuchungen zum marinen Quartar Patagoniens (Argentinien). *Essener Geographische Arbeiten,* 17, 267–289 [in German].

Rostami, K.; Peltier, W.R., and Mangini, A., 2000. Quaternary marine terraces, sea-level changes and uplift history of Patagonia, Argentina: comparisons with predictions of the ICE-4G (VM2) model of the global process of glacial isostatic adjustment. *Quaternary Science Reviews,* 19, 1495–1525.

Rutter, N.; Radtke, U., and Schnack, E.J., 1990. Comparison of ESR and amino acid data in correlating and dating Quaternary shorelines along the Patagonian coast, Argentina. *Journal of Coastal Research,* 6, 391–411.

Rutter, N.; Schnack, E., and Del Río, L., 1989. Correlation and dating of Quaternary littoral zones along the Patagonian coast, Argentina. *Quaternary Science Reviews,* 8, 213–234.

Santos, G.M.; Southon, J.R.; Griffin, S.; Beaupre, S.R., and Druffel, E.R.M., 2007. Ultra small-mass AMS 14C sample preparation and analyses at KCCAMS/UCI Facility. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 259, I1, 293–302.

Schellmann, G., 1998. Jungkänozonische Landschaftsgeschichte patagoniens (Argentinien): Andine Vorlandvergletchenrungen, Talentwicklung und marine Terrassen. *Essener Geographische Arbeiten,* 29. Essen, Germany [in German].

Schellmann, G. and Radtke, U., 2003. Coastal terraces and Holocene sea-level changes along the Patagonian Atlantic coast. *Journal of Coastal Research,* 19(4), 983–996.

Schellmann, G. and Radtke, U., 2010. Timing and magnitude of Holocene sea-level changes along the middle and south Patagonian Atlantic coast derived from beach ridge systems. *Earth-Science Review,* doi: 10.1016/j.earscirev.2010.06.003.

Sylwan, C.A., 2001. Geology of the Golfo San Jorge Basin, Argentina. *Journal of Iberian Geology,* 27, 123–157.

Tanner, W.F., 1995. Origin of beach ridges and swales. *Marine Geology,* 129, 149–161.

Tassara, A.; Swain, C.; Hackney, R., and Kirby, J., 2007. Elastic thickness structure of South America estimated using wavelets and satellite-derived gravity data. *Earth and Planetary Science Letters,* 253, 17–36.

Taylor, M.T. and Stone, G.W., 1996. Beach-ridges: a review. *Journal of Coastal Research,* 12(3), 612–621.

Vilas, F.; Arche, A.; Ferrero, M., and Isla, F., 1999. Subantarctic macrotidal flats, cheniers and beaches in San Sebastian Bay, Tierra del Fuego, Argentina. *Marine Geology,* 160, 301–326.

Waelbroeck, C.; Labeyrie, L.; Michel, E.; Duplessy, J.C.; McManus, J.F.; Lambeck, K.; Balbon, E., and Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quaternary Science Reviews,* 21, 295–305.