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Middle- to late-Holocene relative sea-level changes at Puerto Deseado (Patagonia, Argentina)

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Abstract

Stratigraphic, morphologic and radiocarbon data from Puerto Deseado coastal area (Santa Cruz Province, Argentina) indicate that the Holocene coastline formed in response to the discontinuous aggradation of coarse gravely beaches since *c.* 6300 cal. yr BP related to a progressive falling of relative sea level. Beach ridge crests crudely approximate to the sea level showing at least three steps of aggradation and relative sea-level lowering. Two inactive abrasive notches at *c.* 7.9 and 3.4 m a.s.l. have recorded this sea-level trend, suggesting two important phases when sea level was stationary. This allows the estimation of a rate of relative sea-level fall in the last *c.* 3500 years of *c.* 1.8 mm/yr. Moreover, notches and morphological data indicate that the crest of the beach ridges exceeded the sea-level height by *c.* 2 ± 0.5 m. This value provides a reasonable regional estimate to be applied to produce comparable relative sea-level curve for Atlantic Patagonia coast.

Keywords

abrasive notches, Argentina, beach ridges, middle to late Holocene, Patagonia, relative sea level

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Introduction

The eustatic sea-level rise predicted for the 21st century represents one of the greatest potential threats from climate change, yet its magnitude remains a subject of considerable debate (Oppenheimer et al., 2007; Solomon et al., 2008). However, determining the local impacts of sea-level changes relies on detailed knowledge of local uplift/subsidence rates and sedimentary supply or other natural or anthropogenically induced factors (Blum and Roberts, 2009). To assemble these data, detailed local reconstructions of relative sea-level history are necessary (Blum and Roberts, 2009; Gehrels, 2010).

Since the 19th century, the Atlantic Patagonian coast of Argentina has attracted several studies in view of the spectacular succession of Quaternary raised beach deposits and their rich and significant palaeontological content (Aguirre, 2003; Aguirre et al., 2006; Darwin, 1846; D'Orbigny, 1834–1847, 1842–1844; Feruglio, 1950). In the last decades, these deposits have given rise to new interest in their use in reconstructing the local relative seal-level curve and potentially testing current glacioeustatic models (e.g. Codignotto et al., 1992; Isola et al., 2011; Pedoja et al., 2011; Ribolini et al., 2011; Rostami et al., 2000; Rutter et al., 1989; Schellmann and Radtke, 2000, 2003, 2010; Zanchetta et al., 2012). Being located in a 'passive margin', this area should be particularly suitable for testing geophysically based models (Guilderson et al., 2000; Rostami et al., 2000) given low tectonic disturbance and slow uplift rate, even if it is located close to the ice-caps in the Andes (the 'Hielo patagonico'; e.g. Rabassa, 2008), and the Antarctic ice sheet makes coastal Patagonia to be potentially affected by glacioisostatic adjustment during the final part of Pleistocene and Holocene. Indeed, models predict that coastal Patagonia was characterised by a prominent relative high stand during middle Holocene, *c.* 6 kyr, and since then subject to a progressive fall of the relative sea level (Clark et al., 1978; Milne and Mitrovica, 2008; Milne et al., 2005). This prediction has been corroborated by observations in many records of the area (Codignotto et al., 1992; Ribolini et al., 2011; Schellmann and Radtke, 2010; Zanchetta et al., 2012), even if correct estimations of sea-level trends have given controversial results principally for the difficulty to establish accurate sea-level markers in deposits formed in an environment characterised by macrotidal ranges and by high storm energy (e.g. Codignotto et al., 1992; Isola et al., 2011; Ribolini et al., 2011; Rostami et al., 2000; Schellmann and Radtke, 2000, 2003, 2010; Zanchetta et al., 2012). In addition, most landforms and related deposits are

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Figure 1. Location map of the studied area, with the three sectors discussed in the text (see Figure 2 for the detailed geology and geomorphology): (a) Puerto Deseado village, (b) Punta Cavendish–Punta Foca sector and (c) the north area. Regional tectonic setting is also reported in the upper inset.

difficult to date because of the absence of suitable material or the large uncertainty in available dates (e.g. Rutter et al., 1989, 1990). It is probably for such a reason that Milne et al. (2005) in their modelling of the relative sea-level change during the Holocene along the South America Atlantic coast did not include the Patagonian coast data. Moreover, the presence of the Nazca and the Antarctic plates subducting under South America and southern Patagonia, respectively (Ramos and Ghiglione, 2008, and references therein), may have produced a long-wavelength tectonic effect, onto which the glacioisostatic signal is overprinted (e.g. Pedoja et al., 2011), and for some authors, different Patagonian coastal sectors are affected by different tectonic-induced uplift rates (e.g. Codignotto et al., 1992).

For instance, according to Codignotto et al. (1992), the uplift rate during the Holocene can vary locally between *c.* 0.12 and 1.63 mm/yr, with the highest rates located in the southern sector. According to Rostami et al. (2000), the uplift rate is much lower, with an average value of *c.* 0.09 mm/yr during the late Quaternary. However, Pedoja et al. (2011) found an interesting south–north uplift gradient, with values of Patagonian coast ranging from 0.08 to 0.14 mm/yr during the Quaternary.

Therefore, it is of paramount importance to provide a local relative sea-level curve for Patagonia, which can also have relevant implication for exploring the potential impact of future sea-level variation (e.g. Gehrels, 2010; Milne et al., 2009). Recently, a significant synthesis of the Holocene coastal evolution of Patagonia has been provided by Schellmann and Radtke (2010) – the result of many years of fieldwork in the area. However, this synthesis points out that areas characterised by macrotidal ranges and coarse storm–dominated beaches (coarse beach ridges or 'swash built ridges'; sensu Tanner, 1995) can give a substantial overestimation of the relative sea levels, according to the type of marker selected.

In this paper, we present new data for reconstructing relative sea level of the Atlantic Patagonian coast during the Holocene from the analyses of the Holocene deposits in the area of Puerto Deseado (Santa Cruz Province, Argentina; Figure 1). In the Puerto Deseado area, the association of shore platforms, abrasive notches and beach ridges gives the opportunity to attempt the comparison of different sea-level markers for reconstructing the Holocene sea-level evolution of the area and coastal aggradation.

The study area

The study area is located in the left bank of the mouth of the Deseado River (Figure 1). Local climate is dominated by the southern

Westerlies (Garreaud et al., 2009) with yearly precipitation around *c.* 250 mm (Isla et al., 2004) and an average temperature of 10°C, with a macrotidal regime (>4 m; Isla and Bujalesky, 2008; Isla et al., 2004). According to Isla et al. (2004), average tidal amplitude ranges between *c.* 2 and 4 m. Geologically, the Puerto Deseado area is located on the so-called Deseado Massif (Ramos and Ghiglione, 2008), a structural high, the outcrops of which is formed by Jurassic volcanic rocks (Bahía Laura Group). This rocky substratum dominates the area of Puerto Deseado settlement, with part of the Deseado River mouth being shaped with several fluvial rocky terraces and shore platforms, patchily covered by Quaternary marine and continental deposits. At the northern edge of the Puerto Deseado village, a rocky promontory (Punta Cavendish–Punta Foca) with an indentation with gravely pocket beach divides the Puerto Deseado area from the northern coast, which is aligned N-S. There, the coast is dominated by littoral Quaternary deposits of different ages (Codignotto et al., 1988; Feruglio, 1950). The most recent (Holocene) coastal deposit comprises high-energy, wave-dominated elongated coarse gravely ridges. According to Schellmann (1998) and Schellmann and Radtke (2010), the youngest part of the Holocene beach successions of this sector was formed during the latest part of the late Holocene.

For the area, Feruglio (1950) distinguished at least seven terraces, mostly marine in origin, developing from *c.* 8 to 10 m up to *c.* 180 m a.s.l. (above sea level). Later on, Codignotto et al. (1988) complemented this study with additional morphological information supported by some topographic profiles, attempting to correlate the lower marine terrace orders at regional scale. Rutter et al. (1989, 1990) reported some chorological data for the lower terraced units using electron spin resonance (ESR) dating and aminostratigraphy. According to Rutter et al. (1989), the lower terrace (*c.* 8–10 m a.s.l.) was Holocene in age. In agreement with aminostratigraphy, the terrace at *c.* 20–25 m a.s.l. was initially related to marine isotope stage 5e (MIS5e; Rutter et al., 1989). Later on, ESR data did not confirm this interpretation, yielding ages older than MIS5e (two ESR determinations yielded both ages ≥400 kyr). Similarly, the ESR dating of the terrace comprised between *c.* 30 and 35 m a.s.l. yielded ages ≥242 kyr (Rutter et al., 1990).

Schellmann (1998) and Schellmann and Radtke (2010) reported some stratigraphic and morphological information on sections located *c.* 8–10 km inland on the left bank of Deseado River. They recognised three different marine terrace units ranging from *c.* 2 to 5 m a.h.T. (above high tide level), with the lower two units chronologically ranging from *c.* 4400 to 2400 BP. The upper marine unit, with the top at *c.* 5–5.5 m a.h.T., was considered still Holocene, although in the absence of direct radiometric dating, this attribution cannot be considered secure.

Material and methods

A preliminary remote-sensing analysis was undertaken, based on LANDSAT7 images (acquisition dates 1999–2001), and Quick Bird images (acquisition dates 2003–2008–2009 Sensor QBO2 Band info Pan MS1) supported by a digital elevation model Shuttle Radar Topography Mission (SRTM; http://www.jpl.nasa.gov/srtm). Remote sensed data were then improved by means of field surveys carried out in January 2009 and February 2010–2011. Elevation data were inferred from topographic maps of the Geographic Military Institute (IGM) of Argentina (scale from 1:100,000), local topographic quoted points and from dedicated elevation measurements carried out with a barometric altimeter associated with a global positioning system (GPS) device. For comparison with previous works in the area, the altitudinal measurements were first referred to the high tide level. Operatively, high-tide morphological step used for calibration during the day was supported by tide tables available for the area. Several points were selected for a continuously monitored control during the day and for instrument calibration. Topographic profiles were undertaken using both tracks recorded by the digital altimeter associated with a GPS device and graduated bars equipped with a spirit level. The level of precision of the graduated bars is assumed to be ±0.50 m or less, based on our trials performed using local ground points as reference. Elevation measurements of geological and geomorphological significant points were obtained from replicate measurements during different days with barometric altimeter (estimated precision for these measurements, ±1.5 m). Finally, the sea-level indicators were reported to the local geoid using tidal table and ground points and reported in metres above sea level. The final total error for the point used for the reconstruction of the relative sea-level curve can be then estimated between *c.* ±1 and 0.5 m. However, most of the data used in this paper were obtained using graduate bar profiles with the highest precision (±0.5 m or better). However, other points and profiles for the area based only on few measurements with barometric altimeter can have higher errors up to ±3 m. These points are not considered for the reconstruction of relative sea level proposed in this paper.

For radiocarbon dating, well-preserved marine shells with articulated valves were preferentially selected to reduce the possibility of reworking from older levels (Schellmann and Radtke, 2010). It is important to remember that shells found on beach ridges mainly represent parautoctonous assemblage resulting from storm accumulation (e.g. Zanchetta et al., 2012), partly reworked later by normal wave action. The samples for radiocarbon dating were first cleaned in an ultrasonic bath with addition of oxygen peroxide and then gently etched with dilute HCl. Radiocarbon measurement was carried out at the CIRCE laboratory of Caserta, Italy (Terrasi et al., 2007, 2008). Radiocarbon ages were calibrated using Marine09 curve in CALIB 6 (Reimer et al., 2009). However, the reservoir effect values for Southern Atlantic Ocean and, in particular, Patagonia, are not well constrained (Schellmann and Radtke, 2010). Cordero et al. (2003) have reported reservoir effect from different localities of the Patagonian coast between *c.* 42°S and 50°S ranging between *c.* 180 and 530 years. Modelling reported by Butzin et al. (2005) yielded for the area a reservoir effect of *c.* 500 years for the Holocene.

Results

Figure 2 shows a simplified geological and geomorphological map of the area studied, while selected geological sections are reported in Figure 3. The radiocarbon results are reported in Table 1 along with the altitude of the top of the morphostratigraphic units.

The two main groups of morphostratigraphic units are discussed here, which are important for the focus of our work: (1) Holocene marine deposits and related forms (e.g. H1, H2 and H3) and (2) the first marine terrace after the Holocene (Tp5). Tp5 can be probably correlated with MIS5e even if the definition of the age is problematic (Rutter et al., 1989, 1990). There is more than one unit of Pleistocene age in the area higher than Tp5 (Figure 2), but for this work, this unit is useful for constraining the Holocene transgression and its extension (Figures 2 and 3).

Generally, the Holocene deposits show poorly developed or almost absent soil cover, and the most prominent landforms are related to the seaward prograding succession of beach ridges. The Holocene littoral units show a maximum altitude of *c.* 10 m a.s.l. The top of Tp5 unit is better vegetated (Figure 4b), and soil development is often highlighted by the presence of a maximum 20- to 30-cm-thick A horizon. Tp5 mostly consists of well-sorted and well-rounded gravels, alternating with sandy beds with highly fragmented marine shells (Figure 4a). The top of Tp5 ranges from *c.* 11 to 13 m a.s.l. Characteristic of the top of Tp5 is also the presence of *c.* 1- to 2-m-thick succession of aeolian (loess) and colluvial deposits alternating with truncated palaeosols (usually

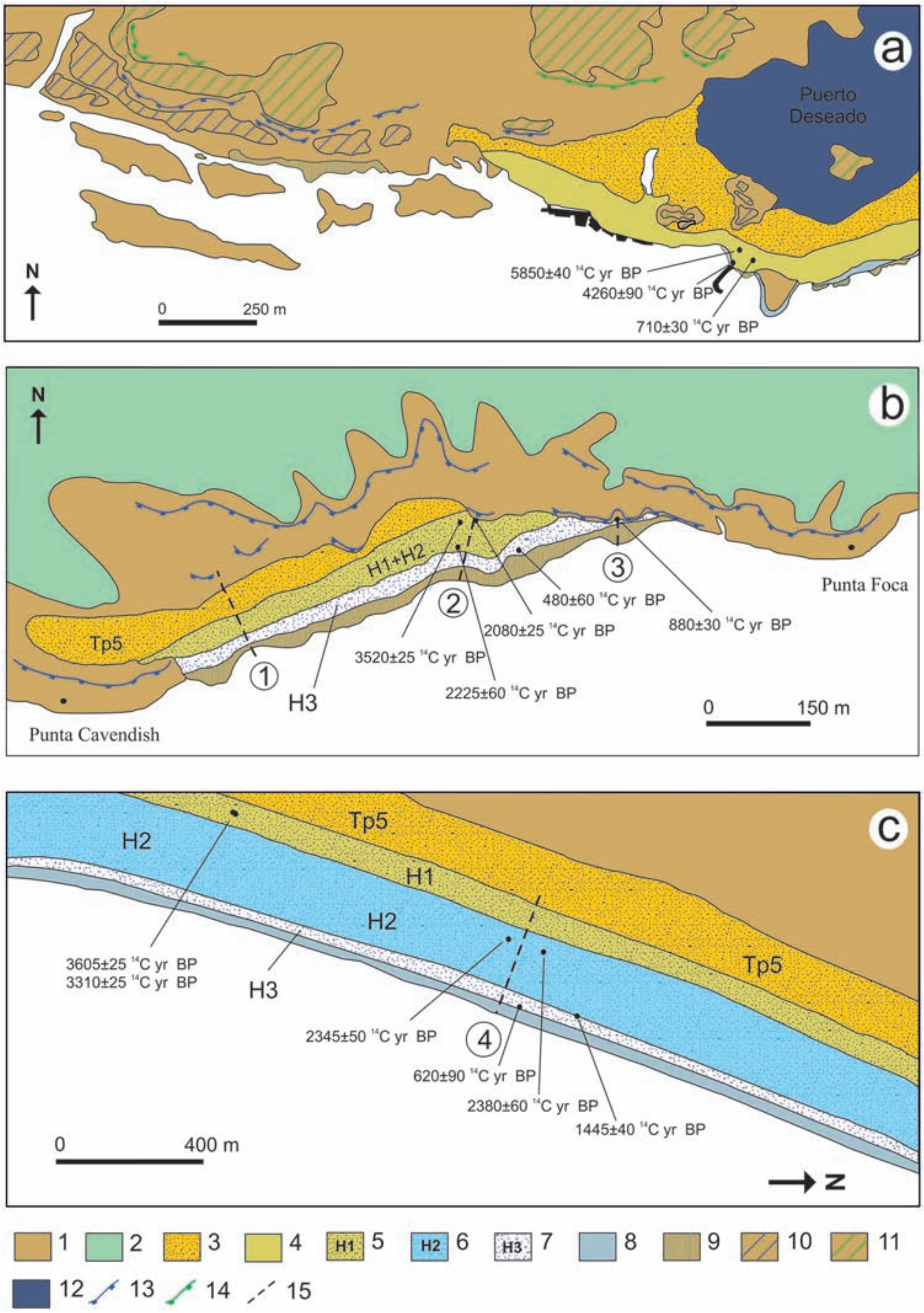

Figure 2. Simplified geomorphological map of the three different sectors discussed in the text: (a) the terminal left side of the Deseado River and Puerto Deseado village, (b) the Punta Cavendish–Punta Foca area and (c) the north area. 1: bedrock, 2: fluvial deposits, 3: Pleistocene marine deposits (MIS5e), 4: Holocene marine deposits (undifferentiated), 5: Holocene beach ridge (morphostratigraphic unit H1), 6: Holocene beach ridge (morphostratigraphic unit H2), 7: Holocene beach ridge (morphostratigraphic unit H3), 8: active beach deposits, 9: shore platform, 10: relict shore platform, 11: fluvial rock terrace, 12: urban area, 13: edge of marine cliff, 14: edge of fluvial scarp and 15: trace of geological section. The position of radiocarbon ages is reported.
MIS5e: marine isotope stage 5e.

easily identified for the presence of Bk or By horizons). On topmost part, there is the presence of relict sand wedges (Ribolini et al., in press), which ensure that the marine unit is older than the Last Glacial Maximum (i.e. the cold period responsible for the formation of the cryogenic sand wedges) and that the unit cannot be confused with the Holocene succession.

Puerto Deseado village

In the Puerto Deseado village, the urbanisation does not allow detailed observations, and the definition of the limits of Holocene littoral deposits may be locally problematic. No clear distinction of different sub-units is possible here (Figure 2a). The currently active intertidal zone is mainly characterised by a shore platform covered by coarse (partially active) beach ridges. Older Holocene deposits, showing a more developed soil horizon, are present on land. A good exposure is present in the western part close to the harbour showing two littoral units with a prograding seaward stratification separated by a clear unconformity. The stratigraphically older unit is made by an alternation of coarse sands and gravels with some lenses of shell accumulation. A sample of *Mytilus edulis* yielded a radiocarbon age of 5850 ± 40 BP (Figure 2a

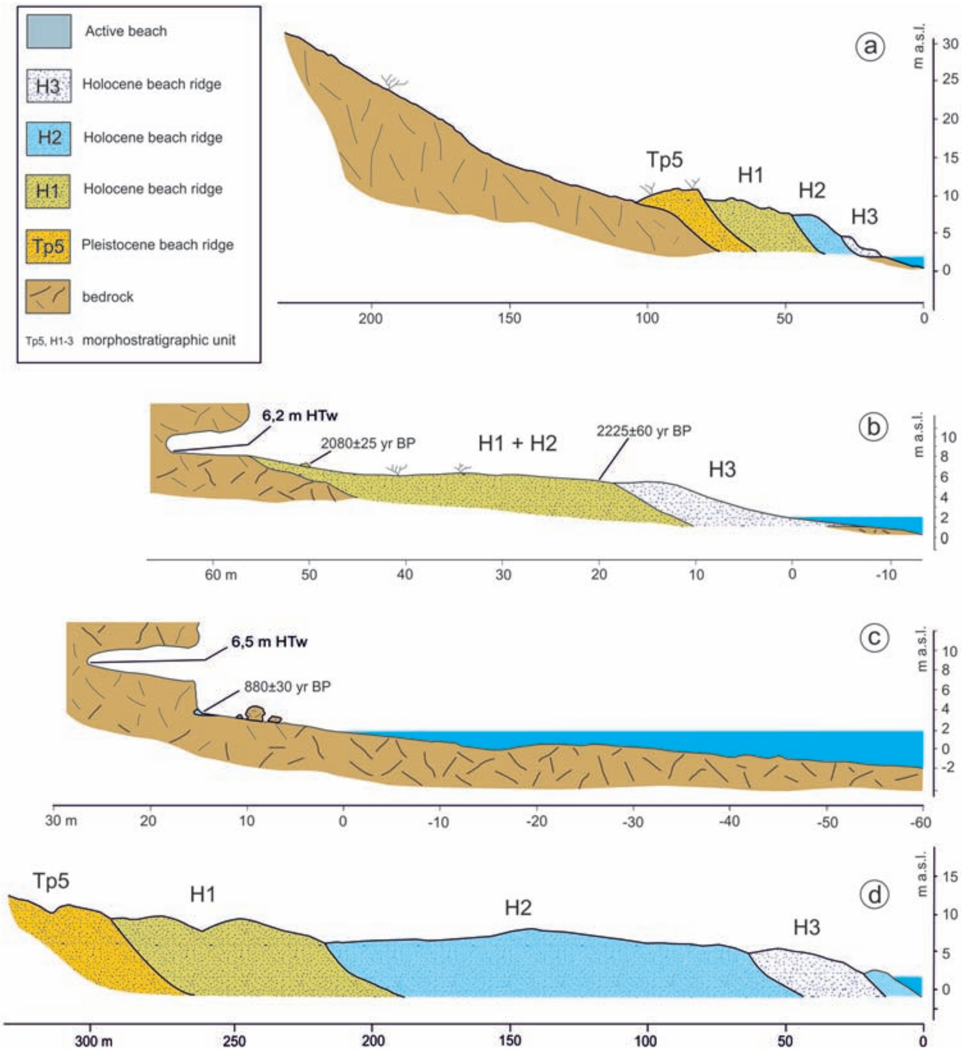

Figure 3. Selected geological sections based on elevation data acquired by means of graduated bars (see Figure 2 for the location).

and Table 1). The second unit visible in the outcrop is made by coarse and well-rounded gravels and pebbles, with local lenses of fragmented shells. A whole valve of *M. edulis* was used for radiocarbon dating yielding an age of 4260 ± 90 BP. A sample of *Aulacomya atra* collected at the base of a dark upper soil horizon in a molluscs accumulation (shell midden) yielded an age of 710 ± 30 BP (Figure 2a and Table 1). Shell middens are quite common in this area (e.g. Castro, 2008), and their radiocarbon age then represents a minimum age for the marine deposit below and can be useful for constraining the sea level.

The Punta Cavendish–Punta Foca area

The rocky coast to the north-east of Puerto Deseado village is characterised by two small promontories (Punta Cavendish and Punta Foca), embracing a pocket gravely beach. The topmost part of the promontory is shaped as a flat rocky surface ranging between *c.* 25 and 30 m a.s.l. and partly covered by a thin veneer of gravel (Figure 2b). The pocket beach, *c.* 600 m long and *c.* 150 m wide, is particularly interesting for the presence of several abrasive notches (Figures 5 and 6c–f). The most evident feature of this area is the presence of three well-defined steps of coastal aggradation (Figures 2b, 3a and 5). The older morphostratigraphic unit is characterised by a small terrace at *c.* 12–13 m a.s.l. related to Tp5. Moving seaward and after a small degraded scarp 1–2 m high, there are a number of Holocene partially vegetated coarse ridges, with a top part showing clasts with reddish patina. These crests can be separated into two groups displaying a small difference in the altitude (Figures 3a and 5; H1 and H2). The H1 and H2 cover a palaeoshore platform well distinct from the active shore platform (Figure 5), and they lap on the exterior of a small cave (Cueva del Indio) characterised by the presence of a well-preserved abrasive notch (Figure 6e), the retreat point of which is located at an altitude of *c.* 8 m a.s.l. (Figure 3b). The exterior of the cave and partially the beach ridge deposit in front of it are covered by a shell midden, mostly formed by an accumulation of *Nacella (Patinigera) deaurata*, and minor disarticulated bone and lithic artefact remains. A sample from this shell midden yielded an age of 2080 ± 25 BP (Table 1). We have excavated a beach ridge related to H1 unit as close as possible to the inner margin of the Holocene deposits, collecting two samples of *N. (Patinigera) deaurata* at *c.* 10 m a.s.l., which have yielded an age of 3520 ± 25 BP and 3530 ± 40 BP (Figure 2b and Table 1). H2 beach ridge was dug close to the scarp limiting seaward to this unit, and an *A. atra* yielded a radiocarbon age of 2225 ± 50 BP (Figures 2b and 5). A further cave with abrasive notch (Cueva del Leon) is preserved at the east edge of the pocket beach (close to Punta Foca; Figure 3). The elevation of its retreat point at *c.* 8 m a.s.l. allows a confident correlation of this notch with that of the nearby Cueva del Indio (Figure 3c).

A third phase of local littoral aggradation is characterised by a lower set of coarse beach ridges, with very fresh aspect and no evidence of soil development (Figure 5). This set of beach ridges has a maximum altitude of *c.* 5 m a.s.l. (H3; Figures 2b and 3a). Locally, the inner part of this set of beach ridges buries an abrasive notch (Figure 6f), which is positioned at *c.* 3.70–3.40 m a.s.l.

Table 1. Radiocarbon data obtained from different samples, their morphological units and altitude of the top of the unit. Calibration has been performed using Marine09 curve in CALIB 6 (Reimer et al., 2009).

Sample	Field code	^{14}C yr BP (±1σ)	^{14}C cal. yr BP (±1σ)	Species or material	Morphological unit	Altitude[a] (a.s.l.)
DSH1960	WP307-1	3605 ± 25	3456–3543	*Adelomelon ferussacii*	H1	10–9
DSH1965	WP307-2	3310 ± 25	3112–3215	*A. ferussacii*	H1	10–9
DSH2153	WP312	2380 ± 60	1930–2090	*A. ferussacii*	H2	8–7
DSH2163	WP313	1445 ± 40	942–1038	*A. ferussacii*	H3	6–4
DSH2162	WP315	2345 ± 50	1894–2030	*Nacella (Patinigera) deaurata*	H2	6–5
DSH1963	WP323	710 ± 30	306–395	*Aulacomya atra*	Shell midden	6–5
DSH1959	WP344	880 ± 30	476–521	*N. (Patinigera) deaurata*	H3	3.8
DSH1968	WP381	2080 ± 25	1609–1697	*N. (Patinigera) deaurata*	Shell midden	7
DSH1961	WP383(1)	3520 ± 25	3367–3434	*N. (Patinigera) deaurata*	H1	10–9
DSH2161	WP383(2)	3530 ± 40	3361–3457	*A. atra*	H1	10–9
DSH2732	WPi038	2225 ± 60	1681–1981	*A. atra*	H2	7–6
DSH2735	WPi039	480 ± 60	0–236	*A. atra*	Shell midden	3.5
DSH4028	PDP1	5850 ± 40	6220–6305	*M. edulis*	–	9
DSH4031	PDP2	4260 ± 90	4085–4625	*Mytilus edulis*	–	8
DSH4035	PDN1	620 ± 90	136–362	*N. (Patinigera) deaurata*	H3	4.5

[a]This altitude refers to the position of the top of the morphological unit.

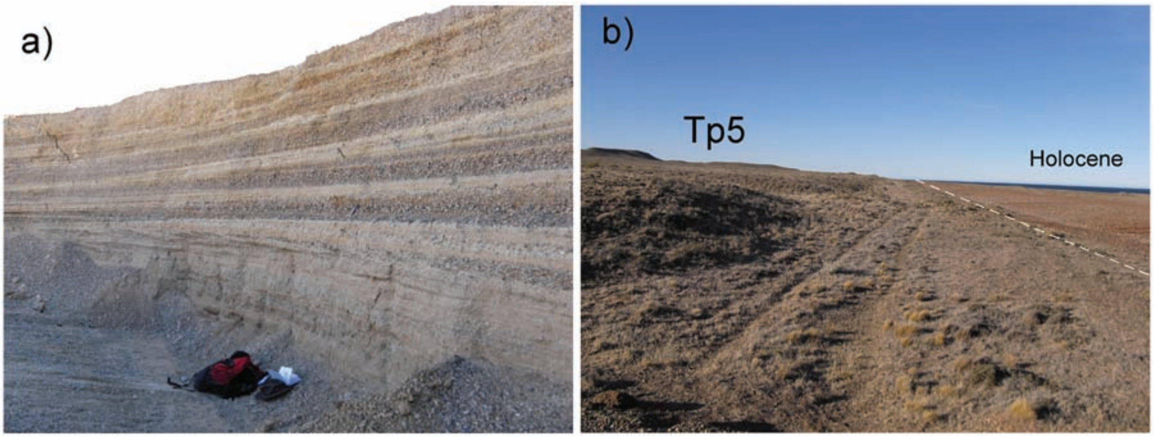

Figure 4. (a) The general view of the stratigraphy of the deposits forming the Tp5 terrace (north of Puerto Deseado) and (b) north of Puerto Deseado: note the scarp present between the Tp5 morphostratigraphic unit and the Holocene succession. Note that the Tp5 top surface is well vegetated, whereas Holocene deposits are mostly free of vegetation and soil.

This buried notch was excavated just below the 'Cueva del Leon', where the sediment thickness was reduced, and one individual of *N. (Patinigera) deaurata* was collected below a boulder to reduce the possible effect of reworking due to exceptional recent storm activity, which could have occasionally interested these littoral sediments. This sample yielded a ^{14}C age of 880 ± 30 BP (Table 1 and Figure 3c). A further sample was excavated in sediments covering a notch close to the 'Cueva del Indio'. On top of the burying material, there are some centimetres of colluvial materials which rest on a dark horizon rich in shell, bones and flintstone remains, which, in turn, cover the littoral deposits. A sample from the dark horizon, representing an archaeological deposit, of *A. atra* yielded an age of 480 ± 60 BP (Table 1). Also in this case, the radiocarbon age is the minimum age of the deposits and indicates that H3 and the buried notch are substantially inactive, in agreement with tidal data, which indicate that it is above the present tidal limit and not currently affected by sea activity (Bini et al., 2013). Instead, an active notch is associated with the current high-tide activity and shore platform (Figure 6c and d). All of these notches are carved into massive Jurassic ignimbrite deposits and show no evidence of lithological or structural control.

The north area

In the North area, the Holocene deposits form a well-defined succession of prograding coarse gravely ridges. There is a clear colour transition from the active and most recent, which have a greyish colour and fresh aspect compared with the inner ridge crests which appear reddened by superficial oxidative processes (Figure 6a and b). Superficially, the deposits do not contain matrix being particularly coarse and the fine-grained matrix (often carried by wind) percolating at a certain depth. When deposits are deeply dissected in quarries, they show an alternation of well-sorted and well-rounded gravel beds and pebbles (sometime reversed graded) with few or no matrix and coarse sands sometime with lenses of shell accumulations.

The Holocene succession is bounded in its inner part by a scarp from the Tp5 unit (Figure 4b). Tp5 top in the area ranges

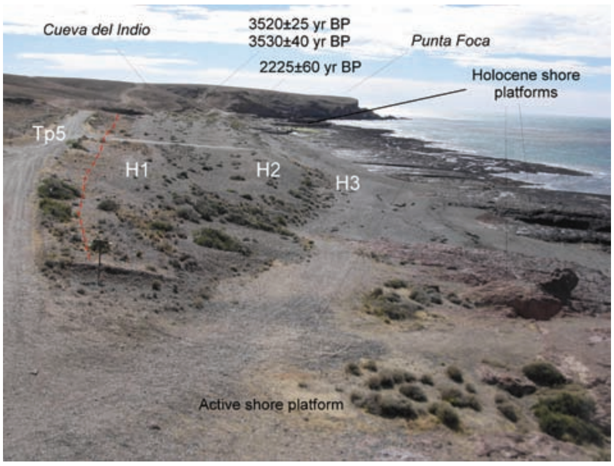

Figure 5. Punta Cavendish–Cueva del Indio pocket beach. Note partially degraded scarps between Tp5 and Holocene deposits, and between the Holocene deposits (H1–H2) and H3 beach ridges. A well-exposed active platform is visible. A second discontinuous strongly eroded platform is visible locally, and it is covered by the Holocene sediments.

between *c.* 11 and 13 m a.s.l. (Figure 3d). Two individuals of *Adelomelon ferussacii* were collected in a section of *c.* 1.50 cm depth close to the innermost part of the Holocene beach ridge (H1 unit; Figures 2c, 3d and 6b). Radiocarbon dating yielded a coherent age of 3605 ± 25 BP and 3310 ± 25 BP (Table 1). H1 unit shows a maximum crest altitude ranging from *c.* 9 to 10 m a.s.l. In the second set of beach ridges (H2 unit; Figure 2c), two samples of *A. ferussacii* and *N. (Patinigera) deaurata* were collected in two different quarries yielding ages of 2380 ±6 0 BP and 2345 ± 50 BP, respectively. H2 has an elevation ranging from *c.* 6 to 8 m a.s.l. (Figure 3d). A further unit can be defined and corresponds to the inner set of beach ridges showing a fresher aspect, positioned at the back of an active storm berm and indicated here as H3. This unit shows an elevation up to 5 m a.s.l. A sample of *A. ferussacii* collected in the inner part of this unit yielded a radiocarbon age of 1445 ± 45 BP, consistent with the ages reported by Schellmann (1998). A further sample was obtained from the outer part of H3 unit, yielding a radiocarbon age of 619 ± 90 BP.

Discussion

Relative sea level from beach ridges

Figure 7a shows the relative sea-level points for the area obtained using different sea-level markers. These data are not corrected for present tidal influence, and strictly speaking, they crudely approximate the relative sea level from the high tide level. In Figure 7a, the radiocarbon data from shell midden are also reported representing an upper level constraint for the relative sea level.

Because the coarse gravely beach ridges represent the accumulation of surf and high-energy events (e.g. Otvos, 2000; Taylor and Stone, 1996), the top of the deposits cannot be considered indicative of the average high tide level (Isla et al., 2005; Schellmann and Radtke, 2010). The data then should be corrected for the surf and storm effect, which are both difficult to evaluate with accuracy because they can vary locally according to tidal rage, storminess, coast exposure and so on. For a final correction, we must also assume that tidal range was the same in the past (e.g. Horton et al., 2009). An attempt to correct these effects is to use the present range of altitudes reached by active storm berm in the area and in similar contexts of the Atlantic coast of Patagonia. In the Puerto Deseado area, current-forming storm berm is of *c.* 1.5–2.5 m above the average high tide. Other observations for the coast comprised between *c.* 42°S and 50°S indicate that on average, the crest of current beach ridge deposits can have a higher altitude of *c.* 2.0 ± 0.5 m above the average high tide (Ribolini et al., 2011; Schellmann and Radtke, 2010; Zanchetta et al., 2012). Although we are aware of the poor precision of the correction, to remove the surf/storm effect, a correction of about −2 m should be considered to our data, which is represented with error bars in Figure 7a.

Using the data from the top of the beach ridges, a general decreasing trend is observed, with an average rate of relative sea level decreasing by *c.* 1.2 mm/yr; however, with only two points between *c.* 6300 and 4500 cal. yr BP, no conclusions can be drawn for this period. Using only the data from *c.* 3500 cal. yr BP, which shows a more consistent trend, a rate of 2.1 mm/yr is obtained.

Interestingly, 1.2 mm/yr is close to the rate that can be calculated with littoral terraces described by Schellmann and Radtke (2010) *c.* 10 km inland the Deseado River (Figure 7a; *c.* 1.1 mm/yr) for the last *c.* 4500 cal. yr BP. According to Isla et al. (2004), no particular tidal dissipation is recorded inland of the Deseado River, but for these deposits, storm and surf action is considered minor compared with beach ridges at the mouth of the Deseado River, and a minor correction can be considered appropriate (*c.* 1 m, Schellmann and Radtke, 2010).

Despite the beach ridges and littoral terraces having similar general trend for the overlapping period of time, they show substantial differences (*c.* 2 m) in the altitudinal values of relative sea level. It is difficult to say whether this depends on different impacts of glacioisostatic adjustment between coastal and inland sites or a noticeable decrease of tidal range inland of the Deseado River.

Figure 7b shows the radiocarbon measurements available for the coastal area comprised between *c.* 42°S and 50°S characterised by macrotidal regime (Isla and Bujalesky, 2008) and obtained from records on which detailed information on geomorphological characteristic of the deposits, precise location and altitudinal data are available. Data are organised according to the type of morphological sea-level marker employed (i.e. littoral terraces and beach ridges, see Schellmann and Radtke, 2010). To compare the data from different sources, they are reported with respect to the average high tide instead of above sea level. Puerto Deseado beach ridges show a pattern consistent with other data, which indicate that although poorly accurate and quite scattered, a general trend of decrease in relative sea level since *c.* 5000–4000 cal. yr BP can be confidently defined using these indicators. A less clear trend seems to be present between *c.* 8 and 6 cal. kyr BP. In Figure 7b, it is also evident that a similar (but lower in altitude) trend is depicted by littoral terraces. The latter show a more consistent decrease of the elevation of the unit top than observable for beach ridges from *c.* 8 to 6 cal. kyr BP. According to Schellmann and Radtke (2010), littoral terraces form in more protected area instead of beach ridges; therefore, the period between *c.* 8 and 6 cal. kyr BP may have been characterised by more storm activities and significant different coast exposures and conformations.

The general trend described for Puerto Deseado is similar to that observed in other southern America Atlantic coast data sets of relative sea-level indicators (e.g. Milne et al., 2005, and references therein). Also models predict a substantial high stand during middle Holocene and since then a progressive relative sea-level decrease. In particular, Milne et al. (2005) model indicates a relative sea-level high stand between *c.* 8000 and 6000 cal. yr BP, which is consistent with data in Figure 7b. However, at this stage, it is difficult to suggest an accurate elevation for the high stand phase at Puerto Deseado. The notch at *c.* 8 m a.s.l. could be an indicator of this point. This altitudinal value could be consistent with an inner margin of rocky terrace at Cabo Raso (*c.* 400 km northward) possibly of Holocene age reported with an altitude of *c.* 7 m a.s.l. by Ribolini et al. (2011). The inner Holocene beach ridge of the area has been dated at *c.* 6450 cal. yr BP, even if the

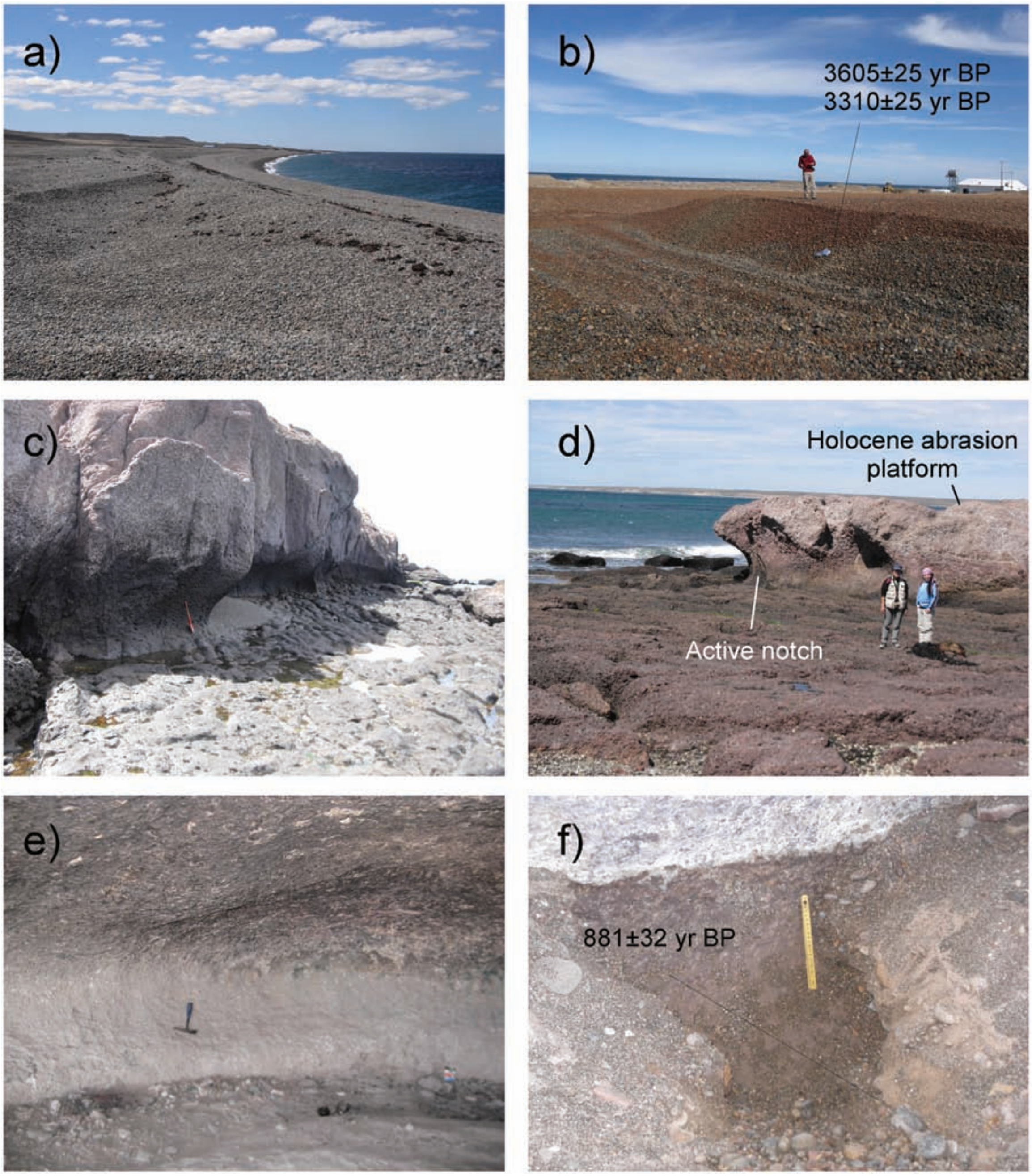

Figure 6. Holocene Puerto Deseado: (a) active and recent beach ridges north of Puerto Deseado. On the background, it is possible to see at least two order of older terraces and (b) the inner Holocene beach ridge north of Puerto Deseado. Note the reddish colour of the gravels. In the point marked by the field notebook, two collected samples of *Adelomelon* were radiocarbon dated, (c) active high-tide abrasive notch in the area of Punta Cavendish and (d) active shore platform and related high-tide notch. Note the higher shore platform related to Holocene (Cueva de l'Indio area); (e) abrasive notch tentatively related to beach ridges formed about 3500 cal. yr BP and (f) buried abrasive notch and radiocarbon dating of the shell found within the sediments.

correlation with the inner margin of the terrace was not certain. At Camarones (*c.* 300 km northward), Zanchetta et al. (2012) indicated an elevation for the maximum ingression of the Holocene at *c.* 6.8 cal. kyr BP of *c.* 4 m a.s.l. Considering these points as the best available, a general high stand at *c.* 4–7 m a.s.l. seems to be present.

Sea level from abrasive notches

Abrasive notches are commonly found at a level of highest tide in the upper part of the midlittoral zone (Kelletat, 2005; Kershaw and Guo, 2001; Pirazzoli, 1986, 1996). Although only tidal notches are first-quality sea-level markers, abrasive notches associated with shore platform, indicating shallow sea conditions should be a marker decisively superior to beach ridges crest deposits. According to Trenhaile et al. (1998), in the Canadian coast, abrasive notches have been considered good marker of medium high tide. This seems to be confirmed for Puerto Deseado area according to our preliminary observations (Bini et al., 2013). The three notch levels found in the Cueva del Indio and at Cueva del Leon area are indicative of three phases of stationary sea level long enough to produce notches, with the lowest indicating the current high tide level.

However, dating notches can be difficult because it is difficult to relate the age of a notch to the age of possibly related deposit. Excluding the lowest, which is still active, those at *c.* 3.4 m a.s.l. are older than *c.* 400 cal. yr BP and stratigraphically younger than H2 (i.e. 1900 cal. yr BP; Table 1). If this notch is related to H3

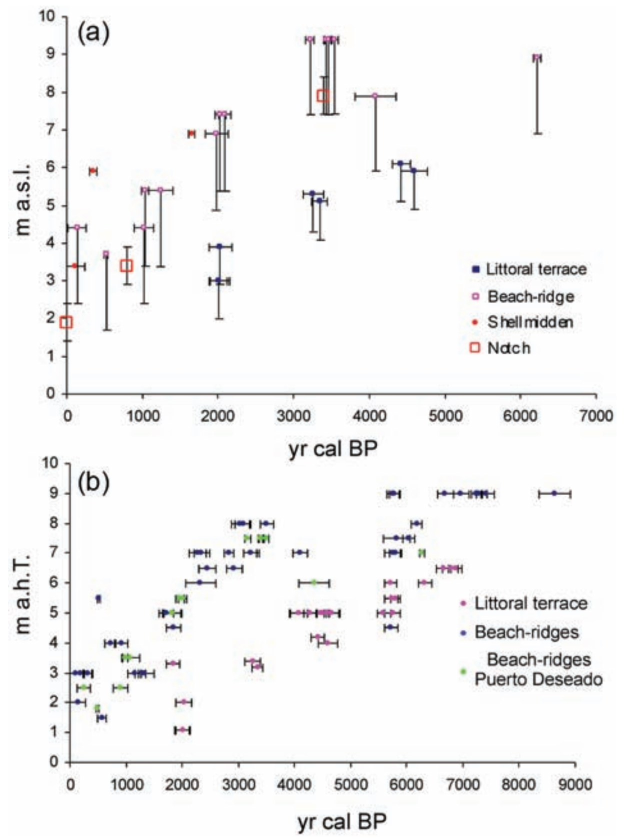

Figure 7. (a) Relative sea-level points for Puerto Deseado. Data for littoral terraces are from Schellmann and Radtke (2010). Note the significant differences between the relative sea-level data from littoral terraces and beach ridges. Ages of notches were assumed by the radiocarbon ages of the associated deposits. (b) Altitudinal data from different sea-level markers (littoral terraces and beach ridges) for Patagonia (data principally from Codignotto et al., 1992; Ribolini et al., 2011; Schellmann and Radtke, 2010; Zanchetta et al., 2012), compared with the data obtained in this work. Correction as for Figure 7a. Data set calibrated using Marine09 curve in CALIB 6 (Reimer et al., 2009). Note that these are reported as above to high tide level.

beach ridges (as seems reasonable), this should have an age not older than *c.* 1000 cal. yr BP.

The definition of the age of the upper notch is probably more complex. A correlation with H2 can be ruled out, being the notch located at higher altitude, and because of the presence of shell midden dated at *c.* 1600 cal. yr BP, just at the entrance of the Cueva de lo Indio. This notch is more likely to be associated with H1 units, even if the H1 did not cover it directly (Figures 2a and 3b). Locally, there is no older Holocene deposits than H1 to constrain the age of this notch, and a correlation with the older deposit described in the village is not directly possible. Moreover, the shape of the notch does not suggest possible reshaping of an older/existing abrasive notch.

If the association with H1 is correct, then, we will have the indication that the maximum height of H1 is actually *c.* 2 m higher than the point of maximum convexity in the notch profile, the so-called retreat point or vertex (Table 1 and Figure 3), which will confirm basically the correction to be made to beach ridge altitude for estimating the sea level. This can also be applied for the second notch at *c.* 3.4 m a.s.l. If it is correctly assigned to the first phase of deposition of H3 unit, the difference in altitude varies from *c.* 1 to 2.5 m (Table 1).

Figure 7a also shows the notch positions with their assigned age. If our data are basically correct, we should have three very accurate points for defining the general trends of relative oscillations in the area. Notches indicate an average rate of relative

Table 2. Relative sea-level falling rate reported by different authors for the Atlantic Patagonian Coast.

Author	Marker type used	Uplift rate (mm/yr)
Codignotto et al. (1992)	Beach ridges	0.65
Schellmann and Radtke (2003)	Beach ridges	0.93–1.15
Rostami et al. (2000)	Littoral terrace	0.87
Schellmann and Radtke (2010)	Littoral terrace	0.3–0.4
Pedoja et al. (2011)	Various	0.12–0.15
Ribolini et al. (2012)	Terrace inner margin	0.4[a]
Zanchetta et al. (2012)	Inter-ridge swale top and beach ridges	0.3

[a]The value is *c.* 1.1 mm/yr if the inner margin at 7 m a.s.l. is considered (see discussion in Ribolini et al., 2012; Zanchetta et al., 2012). However, the age of inner margin is not obtained from sediment covering it but from correlation with dated beaches ridges.

sea-level fall of *c.* 1.8 mm/yr for the last *c.* 3500 cal. yr BP. Notches data also support the notion that once the beach ridge crests are corrected for surf action their top indicates reasonably well the average high tide level. In Figure 7a, an accuracy of ±0.50 m is associated with the sea-level estimation of the notches.

Relative sea-level falling rate: comparison with regional data

Rate of sea-level fall from the Atlantic Patagonian coast has been obtained essentially using a similar approach followed in this paper (hence, with similar associated altitudinal errors) by several authors but giving substantially different results. Table 2 shows the data for the region spanning the Holocene and considering also the uplift rate obtained from Pleistocene units as well. Regarding the Holocene, calculated values are rather scattered. The reason for this variability is mostly related to the employment of different sea-level markers and, when the same marker is employed, the different ways of inferring sea-level elevation from the marker. For instance, Schellmann and Radtke (2010), based on surface elevations from valley-mouth and littoral terraces, suggested that the middle and southern Patagonian Atlantic coast is likely to be undergoing a slow glacioisostatic uplift of the order of 0.3–0.4 mm/yr. However, littoral terraces from the Deseado River, dated by Schellmann and Radtke (2010), indicate (see Figure 7a and the previous section) a value of *c.* 1.1 mm/yr, which is significantly higher than the average suggested by Schellmann and Radtke (2010). For the northern part of the Deseado massif, the structural high that includes the Puerto Deseado area (Ramos and Ghiglione, 2008), values of sea-level fall of *c.* 1.6 mm/yr have been obtained (Codignotto et al., 1992), in agreement with the data reported in this work (according to the marker used), which range from *c.* 2.1 to 1.8 mm/yr for the last *c.* 3500 years. If only the data of the last 3500 cal. yr BP are considered (Figure 7b) from the data set of Schellmann and Radtke (2010), a clear trend is visible, and it yields an average rate of sea-level fall of *c.* 1.7 mm/yr, again in close agreement with our data. Therefore, in the last 3500 years, there is a clear convergence towards a high rate of relative sea-level fall. High rates of relative sea-level fall (although minor) are also reported by Rostami et al. (2000) for the Holocene (*c.* 0.8 mm/yr; Table 2). Data reported in Table 2 suggest a tendency of slower uplift rate in the north, but data from Ribolini et al. (2011) and Zanchetta et al. (2012), for instance, are poorly constrained, and overall the data from Schellmann and Radtke (2010) do not support this view.

A significant difference can be found in rates calculated by different authors for the Holocene and those calculated for the

Pleistocene. These are one order of magnitude lower for the Pleistocene (e.g. 0.09 mm/yr for Rostami et al., 2000; 0.12–0.15 mm/yr for Pedoja et al., 2011) for the area of the Deseado massif. The higher uplift rates found for the southern part of the Atlantic Patagonia by Pedoja et al. (2011), about twice the uplift of the rest of South American margin, has been associated with subduction of the Chile ridge and associated dynamic uplift (Pedoja et al., 2011). Using the values proposed by Pedoja et al. (2011) for correcting from the tectonic uplift the last 6000 years, less than a metre can be attributed to tectonic uplift. Considering this effect for the data of the last 3500 years, we obtain an uplift rate of *c.* 1.5 mm/yr, which should be due mostly to glacioisostatic adjustment. It is important to note that using the ICE-4G (VM2) model of Peltier (1996), Rostami et al. (2000) predicted a rate of relative sea-level fall for the middle to late Holocene of *c.* 0.8 mm/yr, substantially lower than that calculated in this paper.

Are there evidences for a transgression during middle- to late-Holocene transition?

Beach ridges are usually considered regressive landforms, which mark phases of standstill and growing when local conditions are favourable, for example, when supply of material is sufficient (e.g. Otvos, 2000; Tanner, 1995; Taylor and Stone, 1996). The truncation of beach ridges and successive formation of different sets of ridges are then related to changes in the drift amount, coastal erosion, sediment availability and/or sea-level changes (e.g. Taylor and Stone, 1996). During phases of change, beach ridges can be then subjected to cannibalisation (Carter and Orford, 1984; Isla and Bujalesky, 2000).

In Figure 7b, there is an evident age gap between *c.* 5500 and 4500 cal. yr BP, as previously noted by Zanchetta et al. (2012) for a more restricted area of the Atlantic coast. The fact that the inner beach ridges at the Punta Foca–Punta Cavendish and in the north area (Figure 2b) rest directly on the scarp modelled on the older Pleistocene unit unequivocally indicates that H1 deposition is related to a phase of transgression responsible for the scarp formation. Both in the North sector and at Punta Foca, the inner ridges were consistently dated at *c.* 3500 cal. yr BP. The main phase of transgression may have possibly eroded previous littoral Holocene deposits, which instead seem locally preserved in the Puerto Deseado village. This geological evidence is consistent with a hypothesis that the age gap visible in Figure 7b could have been formed by partial erosion of deposits during a phase of transgression. Although the data reported in the Figure 7b are too scattered to be conclusive, they leave the possibility that there is a trend of decreasing sea level at *c.* 6 kyr and then followed by a recovery since 4 cal. kyr BP. This may explain the lower altitudinal values at *c.* 4500 and 6300 cal. yr BP at Puerto Deseado.

Concluding remarks

Stratigraphic, morphologic and radiocarbon data from Puerto Deseado coastal area indicate that Holocene littoral deposits represent the result of a discontinuous aggradation of coarse gravely beach ridges, with accumulation starting from *c.* 6000 cal. yr BP and recording a progressive fall in relative sea level, which is particularly very clear since *c.* 4000 cal. yr BP. Beach ridge crests crudely approximate the story of the relative sea-level curve with at least three steps of aggradation (H1, H2 and H3 beach ridges systems) and sea level lowering to the current position of active beach. Two abrasive notches at *c.* 8 and 3.7 m a.s.l. have recorded this sea-level trend, suggesting at least two phases of important standstill. Using different sea-level markers (littoral deposits, beach ridges, notches), an average sea-level drop can be estimated to be within *c.* 1.1–2.1 mm/yr for the last *c.* 3500 years. These data are consistent with Codignotto et al. (1992) and by analyses of the data of Schellmann and Radtke (2010) for the last 3500 cal. yr BP using beach ridges but show inconsistencies with data proposed by Rostami et al. (2000), which calculated values of *c.* 0.8 mm/yr.

Chronological, stratigraphic and geomorphological data seem to be consistent at regional scale, indicating a phase of transgression that occurred between *c.* 5000 and 4000 cal. yr BP eroding Holocene deposits and causing an age gap in many costal records. Whether this transgression is due to changes in relative sea level or in drift and/or sediment availability is still unclear.

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