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Source: Journal of Coastal Research, 32(4) : 840-852
Published By: Coastal Education and Research Foundation
URL: https://doi.org/10.2112/JCOASTRES-D-14-00178.1
Tectonic Processes along the South America Coastline
Derived from Quaternary Marine Terraces

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ABSTRACT

South America is overriding the Nazca, Antarctic, and Cocos plates, and at the same time is moving along the Caribbean and Scotia plates. Quaternary sea-level highstands are ideal benchmarks to estimate tectonic uplifts considering altitude differences along the coast. The Sangamonian highstand, corresponding to the Marine Isotopic Stage 5, is the most helpful indicator for these purposes as it is more easily preserved and spanning a record of 120,000 years. The Mid-Holocene highstand leads to errors assigned to tidal-range variations, estuarine floods, and meteorological effects; however, its maximum altitudes could confirm faster uplifting rates. The major uplifting trends were estimated in relation to the subduction of seismic or aseismic ridge systems along the Pacific Ocean coast. The Quaternary uplifted terraces of the Atlantic coast at Patagonia were explained by the decreasing uplift induced by the subduction of the Chile Ridge, and related to a very modern volcanic field.

ADDITIONAL INDEX WORDS: Quaternary highstands, Holocene highstand, Tectonics, South America.

INTRODUCTION
Present rates of climate change seem unique in terms of historic scale. However, the geologic scale contains records that permit discrimination of the man-made rates from the natural ones. The last Interglacial—spanning between 140 and 80 ka—has different names in Europe (Eemian, Tyrrenian) and North America (Sangamonian), but there is consensus to refer to it as Marine Isotopic Stage 5 (MIS5), accepting a maximum sea-level highstand between 5 and 8 m higher than present (Hearty and Neumann, 2001; Hearty et al., 2007). In many coastal locations these MIS5 sequences are sedimentary condensed, but in uplifting coasts it is possible to solve with detail minor scale variations, recognizing the maximum 5c (120 ka) and the secondary highstands known as 5c and 5a (Coyne, Jones, and Ford, 2007; Hearty et al., 2007). Assuming that sea level and the oxygen isotopic ratio contents from benthic organism are related, climate and sea-level changes can be modeled (Siddall et al., 2010; Waelbroeck et al., 2002). In this sense, there is a modern concern to study comparatively these MIS5 coastal sequences from different continents, e.g., North America (Blum and Aslan, 2006), Europe (Andreucci et al., 2009; Antonioli et al., 2006; Bardaji et al., 2009; Federici and Pappalardo, 2006), Africa (Carr et al., 2010), and Oceania (Murray-Wallace, 1995). However, these comparative studies need to discern the effects of tectonic behaviors.

South America presents coasts of diverse tectonic settings: to the west, they are dominated by active plate collision; to the east, they are assumed to be more stable (Figure 1). As a result of both tectonic settings, different Quaternary coastal sequences have been preserved. Several papers have reported these deposits to discern uplifting rates (Cantalamessa and Di Cimla, 2004; Goy et al., 1992; Marquardt et al., 2004; Ortlieb et al., 1996; Pedoja et al., 2006; Saillard et al., 2009). However, a continental approach has never been stated, comparing different uplifting trends, sediment availability, and oceanic and climate conditionings. In some cases, minimum radiocarbon ages led to erroneous interpretations; in other cases, erroneous assumptions also led to mistaken conclusions.

The aim of this paper is to report the locations of these highstands in South America, comparing and analyzing critically the different tectonic behaviors calculated or estimated along the coastline (Figure 2), considering the interaction between plates. To achieve this goal, the most trustable, modern, and accurate information was handled. MIS 5 deposits were considered useful as this highstand is recognized worldwide and quite common along the South American coastline. Instead, the Holocene highstand introduces some controversy as it reached a maximum level in the Southern Hemisphere, whereas it is still rising in the Northern Hemisphere. In this sense, the Holocene records along the coastal plains of South America were here handled to confirm or contradict the long-term tectonic trends.

Sea-Level Highstands
The sea-level highstand that occurred during the MIS5 is very recognizable in the Quaternary record because it is relatively modern but also for its maximum elevation higher than 6 m over present mean sea level (Coyne, Jones, and Ford,
As was already mentioned, the maximum 5e highstand did not occur alone but associated with other high sea-level positions, known as 5c and 5a (Coyne, Jones, and Ford, 2007; Schellmann et al., 2004). The maximum 5e highstand has been recorded with altitudinal variations from 6 to 20 m at different places at the Northern Hemisphere and west coast of Australia (Hearty and Neumann, 2001), and between 20 and 40 m at the uplifting Barbados islands (Schellmann et al., 2004). Although the information of these highstands has been analyzed worldwide, there are some doubts about the post-Sangamonian regression: modern models applied to Upper Pleistocene variations propose to tune information derived from sea-level indicators to deep-sea oxygen isotopic ratios (Siddall et al., 2003), long ice cores (Dahl-Jensen, Gogineni, and White, 2013), or speleothem records (Genty, Verheyden, and Wainer, 2013).

Considering the Holocene highstand, data from the Northern Hemisphere reported that sea level is still rising, whereas information from the Southern Hemisphere indicates that a maximum highstand occurred during the middle Holocene (Angulo, Lessa, and de Souza, 2006; Isla, 1989). Regarding the tidal-range effects on eustatic curves of South America, it should be considered that they increase at the northern Brazil coast and at the Atlantic coast of Patagonia. On the Pacific coast, small tidal ranges dominate from Colombia to southern Chile. Microtidal regimes also dominate at the coasts of the Caribbean Sea and Drake Passage.

Modern sea-level trends can be rescued from the last 50 years of tidal measurements in South America (Emery and Aubrey, 1991). Sea-level trends indicate submergence at Cartagena and Maracaibo. The subsidence at Maracaibo Lake has been explained by the compaction of sediments due to the intense oil extraction at the Bolivar fields. The tide gauges of Pacific

Figure 1. Location of coastal sites and major tectonic features.

Figure 2. Potential preservation of Quaternary highstand sequences in relation to tectonic trends (modified after Isla and Bujalesky, 2008).
Colombia and Ecuador (from Buenaventura to Talara) indicate a differential subduction rate causing either coastal submergence or uplift (Emery and Aubrey, 1991). Similar situations were reported from the coasts of Peru and Chile where three tidal gauges indicate land emergence, whereas four suggest submergence. For the Atlantic coast, most of the tidal-gauge records indicate submergence between 0.7 and 4.2 mm/y (Emery and Aubrey, 1991), although uplifting trends were assumed for the Atlantic continental shelf of Patagonia (Guilderson et al., 2000; Isla, 2013).

South American Tectonic Setting

South America has at first sight a simple tectonic setting, with trailing-edge margins toward the east (Atlantic Ocean) and active margins toward the west (Pacific Ocean) colliding against the Antarctic, Nazca, and Cocos plates (Figure 3). However, tectonics is not as simple for the northern and southern extremes of the continent. The interaction with the Caribbean microplate is complex, affecting the Colombian coast with modern faults and mud diapirism onshore and offshore (Restrepo et al., 2007; Restrepo-Correa and Ojeda, 2010; Shepard, Dill, and Heezen, 1968; Vernet et al., 1992). On the other extreme, Tierra del Fuego is splitting because of the interaction with the Scotia microplate (Diraison et al., 2000; Figure 1). Two volcanic arcs and trenches are associated with these interactions of the South American plate with other plates: the Lesser Antilles arc is related to the Caribbean microplate, the South Sandwich Islands arc to the Scotia microplate (Figure 3).

At the northeastern limit of the plate, and related to the movement of a transform-fault system, some blocks are being uplifted. The Sao Pedro and Sao Paulo archipelago conforms a block where an uplift of 13 m was estimated for the last 6000 years (Angulo et al., 2013a).

The tectonic behaviors along the South American coast were also related to the composition of the beach sands. At least for modern beaches, active and passive margins have been discriminated in regard to their mineralogical composition, although climate, relief, and continental geography also merge as important factors (Potter, 1984, 1986, 1994). One of the most surprising conclusions is that the Atlantic Patagonian coast has a mineral composition corresponding to an active margin although it is lying on a trailing-edge margin; this fact will be explained below.

METHODS

Quaternary marine terraces are usually dated by several methods: uranium–thorium decay (U/Th; Potter et al., 2004), optical-stimulated luminescence, Infrared stimulated luminescence (IRSL), thermal luminescence (TL; Murray et al., 2010), amino acid racemization (Carr et al., 2010; Murray et al., 2010), and electron spin resonance (ESR; Blunt, Kvenvolden, and Sims, 1981; Kvenvolden, Blunt, and Clifton, 1979; Schellmann and Radtke, 2000; Schwarz, 1989; Watanabe et al., 1997). Some of these methods have been correlated in their accuracies and errors (Durand et al., 2013; Murray et al., 2010), although they have different levels of reliability (Rutter, Brigham-Grette, and Catto, 1989; Rutter et al., 1989). For the Holocene highstand, conventional radiocarbon dating is the better option. As the atmosphere of the Southern Hemisphere is assumed to have a greater preindustrial latitude-dependent 14C offset than the Northern Hemisphere’s, there is another correction recommended for the Southern Hemisphere (Hogg et al., 2013). As marine radiocarbon dates are particularly sensitive to a time lag due to the differential C uptake between the atmosphere and the sea at different places (Durand et al., 2013), another correction commonly referred to as reservoir effect is recommended for Holocene coastal sequences. Different regional reservoir effects have been calculated for different coastal areas, although these effects are known to vary in time (Spennemann and Head, 1996; Ulm, 2006), and in relation to local upwelling effects (Turney and Palmer, 2007; Ulm, 2006). As these upwelling effects particularly characterise western South American (Ortlieb, Vargas, and Salie˘ge, 2011) it was considered as a better choice to use conventional radiocarbon data.

For the Upper Pleistocene, the U/Th decay method was recommended during many years for marine shells. However, if these remains are not placed in a closed system, a decomposition of organic matter due to humic or fulvic acids may occur (Van der Wijk et al., 1986), or if there was a supply of detrital carbonate, younger dates can be obtained from Pleistocene shells (Schwarz, 1989). Dealing with amino acid racemization, it is necessary to analyze the temperature history of each specimen (Kvenvolden, Blunt, and Clifton, 1979) and the diagenetic adsorption and hydrolysis processes (Blunt, Kvenvolden, and Sims, 1981). TL has been largely applied for dating of eolian sands with a significant discussion about the determination of the equivalent dose, although some efforts were performed to correlate with 14C determinations (Dijkmans and Wintle, 1991).
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Table 1. Altitude and vertical uplifting rates related to the Sangamonian highstand (considering +6 m the maximum eustatic altitude). Tectonic contexts are specified in each case.

<table>
<thead>
<tr>
<th>Location</th>
<th>Geologic Unit Site</th>
<th>Latitude (N)</th>
<th>Altitude (m)</th>
<th>Uplift (m/ky)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caribbean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grand Cayman, Cayman Islands</td>
<td>Unit D, Ironshore Formation</td>
<td>19°20’ N</td>
<td>6</td>
<td>0</td>
<td>Coyne, Jones, and Ford, 2007</td>
</tr>
<tr>
<td>Marie Galante, Guadeloupe, France</td>
<td>Pointe des Colibris</td>
<td>16°19’ N</td>
<td>4–5</td>
<td>0</td>
<td>Battistini et al., 1986</td>
</tr>
<tr>
<td>La Desirade, Guadeloupe, France</td>
<td>Barbados III</td>
<td>13°02’ N</td>
<td>20–40</td>
<td>0.276</td>
<td>Schellmann et al., 2004</td>
</tr>
<tr>
<td>Barbados</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlantic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pernambuco, Brazil</td>
<td></td>
<td>8° S</td>
<td>7–11</td>
<td>0</td>
<td>Dominguez et al., 1990</td>
</tr>
<tr>
<td>Bahia, Brazil</td>
<td>Penultimate transgression</td>
<td>13–14° S</td>
<td>6–10</td>
<td>0</td>
<td>Martin, Flexor, and Suguo, 1998</td>
</tr>
<tr>
<td>Rio de Janeiro State, Brazil</td>
<td></td>
<td></td>
<td>6–10</td>
<td>0</td>
<td>Martin, Flexor, and Suguo, 1998</td>
</tr>
<tr>
<td>São Paulo State, Brazil</td>
<td>Cananéia Formation</td>
<td>23–25° S</td>
<td>9–10</td>
<td>0</td>
<td>Watnabe et al., 1997</td>
</tr>
<tr>
<td>Paraná and Santa Catarina, Brazil</td>
<td>Barbados III</td>
<td>25–29° S</td>
<td>6–10</td>
<td>0</td>
<td>Martin et al., 1988</td>
</tr>
<tr>
<td>Rio Grande do Sul, Brazil</td>
<td>Barrier III</td>
<td>29–33° S</td>
<td>5–7</td>
<td>0</td>
<td>Tomazelli and Dillenburg, 2007</td>
</tr>
<tr>
<td>Buenos Aires Province, Argentina</td>
<td>Belgranoa Interacial</td>
<td>38° S</td>
<td>7</td>
<td>0</td>
<td>Isha et al., 2000</td>
</tr>
<tr>
<td>Buenos Aires Province, Argentina</td>
<td>Faro Segundo Barranca</td>
<td>40°45° S</td>
<td>10</td>
<td>0</td>
<td>Radtke, 1989</td>
</tr>
<tr>
<td>Gustamante Bay, Chubut, Argentina</td>
<td>Caleta Malaspina</td>
<td>45°05° S</td>
<td>12</td>
<td>0</td>
<td>Schellmann, 1998b</td>
</tr>
<tr>
<td>Marazredo Harbour, Argentina</td>
<td>N1</td>
<td>47°03° S</td>
<td>16–19</td>
<td>0</td>
<td>Schellmann, 1998a</td>
</tr>
<tr>
<td>San Julián Bay, Santa Cruz, Argentina</td>
<td>SI</td>
<td>49°17° S</td>
<td>14–15</td>
<td>0</td>
<td>Schellmann, 1998a</td>
</tr>
<tr>
<td>Tierra del Fuego, Argentina</td>
<td>La Sana Formation</td>
<td>53º31” S</td>
<td>14</td>
<td>0</td>
<td>Bujaedly, Coronato, and Isha, 2001</td>
</tr>
<tr>
<td>Navarino Island, T. del Fuego, Chile</td>
<td>Unit 5</td>
<td>54º56” S</td>
<td>&gt;10</td>
<td>0</td>
<td>Rahbasa et al., 2008</td>
</tr>
<tr>
<td>Pacific</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galera, Ecuador</td>
<td>T1</td>
<td>00º50’ N</td>
<td>46</td>
<td>0.34</td>
<td>Peda et al., 2006</td>
</tr>
<tr>
<td>Manta, Ecuador</td>
<td>T1</td>
<td>00º58’ S</td>
<td>43</td>
<td>0.31</td>
<td>Peda et al., 2006</td>
</tr>
<tr>
<td>La Plata Island, Ecuador</td>
<td>T1</td>
<td>01º17’ S</td>
<td>43</td>
<td>0.31</td>
<td>Peda et al., 2006</td>
</tr>
<tr>
<td>Santa Elena Headland, Ecuador</td>
<td>T1</td>
<td>02º12’ S</td>
<td>18</td>
<td>0.10</td>
<td>Peda et al., 2006</td>
</tr>
<tr>
<td>Cancas, Ecuador</td>
<td>T1</td>
<td>03º30–4” S</td>
<td>30</td>
<td>0.20</td>
<td>Peda et al., 2006</td>
</tr>
<tr>
<td>Ilecsas Headland, Bayobay Bay, Peru</td>
<td>T2</td>
<td>05º40’ S</td>
<td>18</td>
<td>0.12</td>
<td>Peda et al., 2006</td>
</tr>
<tr>
<td>Pampa del Polo, Peru</td>
<td>T10</td>
<td>17º42’ S</td>
<td>25</td>
<td>0.16</td>
<td>Orlihe et al., 1996</td>
</tr>
<tr>
<td>Chala, Peru</td>
<td>Tabelazos</td>
<td>15º51’ S</td>
<td>64–64</td>
<td>0.46</td>
<td>Goy et al., 1992</td>
</tr>
<tr>
<td>Antofagasta, Chile</td>
<td>Caleta Playa de los Hornos</td>
<td>22º54’ S</td>
<td>30</td>
<td>0.2</td>
<td>Radtke, 1989</td>
</tr>
<tr>
<td>Mejillones, El Rincon, Antofagasta, Chile</td>
<td>23º05’ S</td>
<td>9–10</td>
<td>0</td>
<td>Radtke, 1989</td>
<td></td>
</tr>
<tr>
<td>Caleta Obispo, Copiapó, Chile</td>
<td>24º46’ S</td>
<td>29–34</td>
<td>0.25</td>
<td>Radtke, 1989</td>
<td></td>
</tr>
<tr>
<td>Bahia Inglesa, Copiapó, Chile</td>
<td>b</td>
<td>27º03’ S</td>
<td>40</td>
<td>0.28</td>
<td>Quezada et al., 2007</td>
</tr>
<tr>
<td>Caldera, Copiapó, Chile</td>
<td>27º07’ S</td>
<td>44</td>
<td>0.28</td>
<td>Quezada et al., 2007</td>
<td></td>
</tr>
<tr>
<td>Herradura Bay, Coquimbo, Chile</td>
<td>29º57’ S</td>
<td>31–36</td>
<td>0.2</td>
<td>Radtke, 1989</td>
<td></td>
</tr>
<tr>
<td>Santa María Island, Arauco, Chile</td>
<td>Santa Maria Formation</td>
<td>37º03’ S</td>
<td>60–80</td>
<td>0.68</td>
<td>Modified from Melnick et al., 2006</td>
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<td>Caniote, Arauco</td>
<td>Canete Formation</td>
<td>37º40’ S</td>
<td>50–61</td>
<td>1.8</td>
<td>Melnick et al., 2009</td>
</tr>
</tbody>
</table>

RESULTS

The MIS 5 highstand was detected at several locations of the South American coast and they were therefore handled to establish altitude differences and tectonic changes (Table 1).

Caribbean Coast

At the Guadeloupe islands, the Eemian highstand has been dated at the Marie Galante and La Désirade islands (Battistini et al., 1986). At the southeastern coast of Marie Galante (15°53’45” N), corals were dated by U/Th in 122 ± 8 ka at an altitude of 4–5 m. At the southwestern point of the La Désirade island, the Pointe des Colibris (16°17’27” N) was dated in 119 ± 9 ka at approximately the same altitude (Battistini et al., 1986).

Three marine terraces have been discriminated at the western coast of Barbados Island (13°10’ N). Barbados III was the name given to the highstand assigned to M5S6e (125 ka), Barbados II for the highstand that occurred between 111 and 104 ka, and Barbados I for the stage spanning between 79 and 84 ka (Mesolella et al., 1969). U/Th datings performed at two profiles located at Clermont and Christ Church confirmed this scheme (Radtke, 1989). Considering an average uplifting rate of 276 mm/ka at South Point, the former depths of the Last Interglacial highstand were estimated in 13 to −25 m (below present mean sea level) for the highstand 5c (approximately 105 ka) and −21 to −19 m for the 5a highstand (74–85 ka; Schellmann et al., 2004).

Several U/Th datings were performed from cores at the northwestern coast of Grand Cayman Island (19°20’ N), northern Caribbean Sea. The Ironshore Formation includes three units, the first one being of Sangamonian age (Coyne, Jones, and Ford, 2007). Most of those dates were performed on remains of Montastrea annularis, Acropora palmata, and A. cervicornis. This sequence of Grand Cayman Island permits us to propose the variations of the sea level for stage 5e (+6 m), 5c (+5 to +2 m), and 5a (+3 to +6 m; Coyne, Jones, and Ford, 2007).

Pacific Coast

Three marine terraces have been discriminated along the Ecuador coast; from north to south, the Manta Peninsula–La Plata Island, the Esmeraldas, and the Santa Elena Peninsula (Peda et al., 2006). The marine terraces of Manta Peninsula and La Plata Island have been dated by IRSL and the U/Th decay method. Shells of Strombus galeatus from La Plata Island gave a U/Th age of 104 ± 2 ka. This terrace has been mapped at the southern coast of the island (Cantalamessa and Di Celma, 2004). Two sites close to Manta Peninsula confirmed Sangamonian ages: Anoda grandis shells (Manta 6 sample) yielded an age of 85 ± 1.2 ka, whereas Ostrea iridescens shells (Manta 10 sample) gave a U/Th age of 187 ± 4 ka (Peda et al., 2006).
2006). Using Quaternary marine terraces of older age, it was possible to reconstruct the differential uplifting rates along this coast in relation to the subduction of the Carnegie Ridge beneath the South American Plate (Pedoja et al., 2006), a movement that was estimated at 58 mm/yr (Bethoux et al., 2011). Some of these Quaternary marine terraces were correlated to others occurring in Puná Island, Gulf of Guayquil (Dumont et al., 2005).

In Bayovar Bay, close to the Illescas Peninsula, northern Peru, an IRSL dating performed in feldspar minerals from a marine terrace gave an age of 111 ± 6 ka (Pedoja et al., 2006); this age would signify an uplifting rate of 0.12 m/ka. Pampa de Palo is one of the lowermost of the three marine terraces of southern Peru. Six marine units were recognised; shoreface and lagoon facies were discriminated, summing 9 m of the Sangamonian sequence. Racemization ratios (allo/isoleucine) between 0.57 and 0.67 were attributed to the highstand 5e (Ortlieb et al., 1996). The altitude of +25 m of this terrace originated about 120 ka ago and permits us to estimate an uplifting rate of 0.16 m/ka. At Chala, southern Peru, 27 remnants of Quaternary highstands, locally known as Tablas, were discriminated. At about 64–68 m height over mean sea level, there is a 25-m-tall paleo-cliff that was assigned to the uplift caused by the subduction of the Juan Fernández Ridge (Figure 3), although this uplift was not considered uniform. Three periods of rapid uplift were detected: one very rapid between the MIS17 and MIS15, another between MIS9 and MIS7 (1.16 mm/yr), and an uplifting rate of 2 m/ka (Melnick et al., 2006). However, considering these ages as minimum and close to the limit of the radiocarbon method, they could be assigned to the Sangamonian highstand (120 ka BP). In this sense, the uplifting rate of the island should be lower than estimated. This highstand was reported as the Valdivia Interglacial, characterized by volcanic sands (“canagua”), interbedded with silt-sized volcanic ash partially weathered to clay. In particular, at Mancera Island (39°56′ S), three peat layers contain logs, plants, and insect remains (Astorga and Pino, 2011).

Atlantic Coast

In the State of Bahia, Brazil, aragonitic corals of the genus *Siderastrea* were obtained from a clay layer. Five samples gave U/Th ages pointing to the Sangamonian highstand: 122 ± 6.1, 116 ± 6.9, 132 ± 9.0, 124 ± 8.7, and 142 ± 9.7 ka, the last one being suspect of contamination (Martin, Bittencourt, and Vilas-Boas, 1982; Martin, Flexor, and Suguoio, 1998).

TL datings performed in sands from the Cananéia Island confirmed ages between 0 and 120 ka for the Cananéia Formation.

In Rio Grande do Sul State, southern Brazil, the so-called Barrier III is the best Pleistocene barrier preserved, responsible for the emplacement of the coastal lagoons of Lagoa dos Patos and Lagoa Mirim (Tomazelli, Dillenburg, and Vilwock, 2000). The main body of this barrier is composed of quartzose, well-stratified (with tabular, asymptotic, and hummocky cross-bedding) fine sand belonging to beach facies, and overlain by aeolian facies composed of quartzose and reddish sand, without sedimentary structures, with abundant roots (Tomazelli and Dillenburg, 2007; Tomazelli and Vilwock, 2005). At Farol da Conceição, Rio Grande do Sul, a foreshore deposit gave a TL age of 109 ± 7.5 ka (Buchmann and Tomazelli, 2003).

Along the Buenos Aires coastline, Argentina, there are several references to the Sangamonian highstand, locally called Belgranense stage. At Claromecó (38°51′23″ S; 60°01′16″ W), shells of the gastropod *Teugala patagonica* scattered at a beach deposit were dated by the U/Th method at 93.5 ± 3.5 ka (Isla et al., 2000). Several Quaternary coastal terraces, with beach deposits overlying, are scattered at eastern Patagonia (Rodtke, 1989, Rutter, Brigham-Grette, and Catto, 1989; Rutter et al., 1989; Schellmann, 1998a). At Faro Segunda Barranca (40°46′ S), mollusk shells in a coarse sand deposit gave ESR ages spanning between 72.7 and 108 ka (Rodtke, 1989). Further west, at an ancient shoreline of a bay, a marine gravelly sand has been sampled below the San Matías lighthouse (40°49′ S); mollusk shells gave ESR ages between 83.2 and 107 ka (Rodtke, 1989). At Caleta Valdés (42°30′ S), paired mollusk shells sampled between coastal lagoon deposits were dated either by U/Th or ESR; both methods gave ages spanning from 92 ± 5 to 136 ± 16 ka (Schellmann, 1998a). At Bahía Bustamante (45° S), some of these barriers have been
related to the Sangamonian highstand (Schellmann, 1998a), although barriers related to MIS5 and 7 are here confused. However, in some locations such as Cañadón de las Mercedes and Caleta Malaspina, the MIS5e is clearly defined by ESR datings (Schellmann, 1998b). Richness and diversity of the mollusk assemblages from this 5e highstand indicate bay conditions slightly warmer than present (Aguirre, Negro Sirch, and Richiano, 2005). However, colder sea-surface temperatures are suggested for the mollusk assemblages of the Late Pleistocene terraces located to the west of the gulf (Aguirre, 2003). Although similar datings confirmed the presence of the 5e highstand along the San Jorge Gulf, at the northern portion (Camarones and Bustamante) this stage is a bit higher, 16–19 m above present sea level (Martin and Aguirre, 2005). However, colder sea-surface temperatures are suggested for the mollusk assemblages of the Late Pleistocene terraces located to the west of the gulf (Aguirre, 2003). Although similar datings confirmed the presence of the 5e highstand along the San Jorge Gulf, at the northern portion (Camarones and Bustamante) this stage is a bit higher, 16–19 m above present sea level (Martin and Speciosa, 2006). As it is considered a minimum age, the deposit is assumed to belong to the 5e highstand (Rabassa et al., 2008).

**Table 2. Maximum and minimum ages of the Holocene coastal sequences of South America.**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Coastal plain</th>
<th>Max. agea</th>
<th>Min. agea</th>
<th>Max. height (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>09° N</td>
<td>Sinú Delta</td>
<td>2650</td>
<td>2450</td>
<td>2</td>
<td>Martinez and Robertson, 1997</td>
</tr>
<tr>
<td>10° N</td>
<td>Cartagena</td>
<td>3409</td>
<td>1600</td>
<td>6</td>
<td>Martinez et al., 2010</td>
</tr>
<tr>
<td>06° N</td>
<td>Surinam Estuary</td>
<td>5620</td>
<td>2950</td>
<td></td>
<td>Groen, Velstrab, and Meesters, 2000</td>
</tr>
<tr>
<td>10° N</td>
<td>Maracas Bay</td>
<td>5880</td>
<td>2930</td>
<td></td>
<td>Ramcharan and McAndrews, 2006</td>
</tr>
<tr>
<td>05° N</td>
<td>Gallinas Barrier</td>
<td>6520</td>
<td>2180</td>
<td>1.2</td>
<td>Stattege, Cahals, and Vital, 2004</td>
</tr>
<tr>
<td>19° S</td>
<td>Dece Delta</td>
<td>7150</td>
<td>4250</td>
<td>5</td>
<td>Martin and Speciosa, 1992</td>
</tr>
<tr>
<td>25° S</td>
<td>Ilha Comprida</td>
<td>5308</td>
<td>1004</td>
<td></td>
<td>Sawukuchi et al., 2008</td>
</tr>
<tr>
<td>29.6° S</td>
<td>Curumin</td>
<td>6750</td>
<td>3450</td>
<td>5</td>
<td>Dillenburg et al., 2004</td>
</tr>
<tr>
<td>30° S</td>
<td>Tramandai</td>
<td>9620</td>
<td>4620</td>
<td></td>
<td>Travessas et al., 2005</td>
</tr>
<tr>
<td>30° S</td>
<td>Tongoy</td>
<td>6380</td>
<td>910</td>
<td>5.1</td>
<td>Ota and Paskoff, 1993</td>
</tr>
<tr>
<td>33° S</td>
<td>Paraná Delta</td>
<td>6440</td>
<td>1770</td>
<td>5</td>
<td>Codignotto, Kokot, and Marcomini, 1992; Cavalletto, Violante, and Colombo, 2005</td>
</tr>
<tr>
<td>33° S</td>
<td>Arroyo Chui</td>
<td>5150</td>
<td>3530</td>
<td>3</td>
<td>Martinez et al., 2006</td>
</tr>
<tr>
<td>34° S</td>
<td>La Plata</td>
<td>8620</td>
<td>1770</td>
<td>6.5</td>
<td>Cavaletto, Violante, and Parker, 2004</td>
</tr>
<tr>
<td>36° S</td>
<td>Samborombón Bay</td>
<td>5810</td>
<td>1610</td>
<td></td>
<td>Codignotto and Aguirre, 1993</td>
</tr>
<tr>
<td>37° S</td>
<td>Mar Chiquita</td>
<td>3840</td>
<td>1340</td>
<td>2.5</td>
<td>Codignotto, Kokot, and Marcomini, 1992; Schnack, Fasano, and Isla 1982</td>
</tr>
<tr>
<td>38° S</td>
<td>Las Brusquitas Estuary</td>
<td>6380</td>
<td>2040</td>
<td>4</td>
<td>Isla et al., 1986; Vilanova, Prieto, and Speciosa, 2006</td>
</tr>
<tr>
<td>38° S</td>
<td>Bahía Blanca</td>
<td>7500</td>
<td>3560</td>
<td></td>
<td>Farinati, 1985; Grill and Quatrocchio, 1996</td>
</tr>
<tr>
<td>38° S</td>
<td>Coronel Plain</td>
<td></td>
<td></td>
<td></td>
<td>Isla et al., 2012</td>
</tr>
<tr>
<td>39° S</td>
<td>Colorado Delta</td>
<td>6750</td>
<td>407</td>
<td>7.5</td>
<td>Codignotto, Kokot, and Marcomini, 1992; Weiler, 2000</td>
</tr>
<tr>
<td>40° S</td>
<td>San Blas</td>
<td>5370</td>
<td>2170</td>
<td>8</td>
<td>Rutter, Brigham-Grette, and Catto, 1989; Rutter et al., 1989; Trebits, 1987</td>
</tr>
<tr>
<td>42° S</td>
<td>Puerto Lobos</td>
<td>3370</td>
<td>1030</td>
<td>8</td>
<td>Codignotto, Kokot, and Marcomini, 1992</td>
</tr>
<tr>
<td>42° S</td>
<td>Caleta Valdés</td>
<td>5720</td>
<td>1330</td>
<td>6</td>
<td>Codignotto, Kokot, and Marcomini, 1992; Rutter, Brigham-Grette, and Catto, 1989; Rutter et al., 1989</td>
</tr>
<tr>
<td>42° S</td>
<td>Ancud</td>
<td>2050</td>
<td>750</td>
<td>10</td>
<td>Hervé and Ota, 1993</td>
</tr>
<tr>
<td>43° S</td>
<td>Chubut</td>
<td>4987</td>
<td>1009</td>
<td></td>
<td>Monti, 2000</td>
</tr>
<tr>
<td>45° S</td>
<td>Bustamante Bay</td>
<td>5424</td>
<td>4220</td>
<td>12</td>
<td>Codignotto, Kokot, and Marcomini, 1992; Schellmann, 1998</td>
</tr>
<tr>
<td>45° S</td>
<td>Solano Bay</td>
<td>6310</td>
<td>2040</td>
<td>1.85</td>
<td>Codignotto, Kokot, and Marcomini, 1992</td>
</tr>
<tr>
<td>49° S</td>
<td>San Julián Bay</td>
<td>1779</td>
<td>570</td>
<td>4.5</td>
<td>Schellmann, 2003; Schellmann and Radtke, 2003</td>
</tr>
<tr>
<td>53° S</td>
<td>San Sebastián Bay</td>
<td>5616</td>
<td>509</td>
<td>7.5</td>
<td>Vilas et al., 1999</td>
</tr>
<tr>
<td>53.6° S</td>
<td>Río Chico</td>
<td>4620</td>
<td>2890</td>
<td>9</td>
<td>Isla and Bujalesky, 2000</td>
</tr>
<tr>
<td>54° S</td>
<td>Punta María</td>
<td>3820</td>
<td>1310</td>
<td>8</td>
<td>Codignotto, Kokot, and Marcomini, 1992</td>
</tr>
<tr>
<td>55° S</td>
<td>Oliva River delta, Beagle Channel</td>
<td>5615</td>
<td>405</td>
<td>10</td>
<td>Gordillo et al., 1992</td>
</tr>
</tbody>
</table>

*a* Noncalibrated radiocarbon years before present.

Navarino Island, Chile, a marine bed composed of broken shells interfingered with laminated beds with wood fragments was dated by 14C at 41.7 ± 1.5 ka (Rabassa et al., 2008). Mollusk assemblages resemble those living today in the Beagle Channel (Gordillo et al., 2010). As it is considered a minimum age, the deposit is assumed to belong to the 5e highstand (Rabassa et al., 2008).

**Holocene Sea-Level Fluctuation**

The Atlantic trailing-edge coast of South America contains extended beach-ridge plains related to the regressive phase of the Holocene sea-level fluctuation containing deltas and coastal-lagoon sequences. These regressive plains are so extended that they were subject to several lists of radiocarbon datings (Schellmann, 1998b). Although similar datings confirmed the presence of the 5e highstand along the San Jorge Gulf, at the northern portion (Camarones and Bustamante) the altitude is about 12 m above mean high tide level (MHTL), whereas at the southern portion (Caleta Olivia and Mazaroedo) this stage is a bit higher, 16–19 m above MHTL (Schellmann, 1998b). Farther south, at Bahía San Julián (Santa Cruz Province), beach facies related to the 5e highstand was also dated by ESR (Schellmann, 1998a).

In Northern Tierra del Fuego, the Upper Pleistocene marine terrace composed of a sandy gravel ridge with shells was called La Sara Formation (Codignotto and Malumina, 1981). At a geoidal height of 14 m (measured by a geodetic GPS), mollusk shells were dated by U/Th at 82 ± 2.5 ka (Bujalesky, Coronato, and Isla, 2001). Farther south, at the northern coast of

(Martínez and Robertson, 1997). Between Punta Canoas and Cartagena, there are several outcrops where mollusk shells were dated between 4070 and 2020 YBP; the height of these outcrops depends on the tectonic effects induced by diapirism (Martínez et al., 2010). Much of the behavior of the Caribbean coast of Colombia is conditioned to this kind of local uplift that used to finish with the sudden explosion of mud volcanoes (Correa, Alcántara Carriño, and González, 2005).

At the north of Trinidad Island, in Maracas Bay, a 980-cm-long core collected from a mangrove permitted us to determine the building of a beach-ridge system between 5880 and 2930 14C YBP (Ramcharan and McAndrews, 2006).

At the coastal plain of the Suriname River, Suriname, shells collected from drills close to present mean sea level permit us to reconstruct a Holocene coastal progradation between 5620 and 2950 14C YBP (Groen, Velstrab, and Meesters, 2000).

At the coastal plain surrounding the Galinhos coastal lagoon, Rio Grande do Norte (Brazil), well-preserved shells from beach rocks permit us to reconstruct a sea-level curve, spanning between 6520 and 2180 14C YBP (Stattegge, Caldas, and Vital, 2004). Similar conditions were confirmed at the Fernando de Noronha Island, where calcareous algae and forams were dated in a sequence spanning from 3590 and 110 14C YBP (Angulo et al., 2013b). At this island, eolianites formed during the postglacial transgression between (10,700 and 5700 YBP), before the Mid-Holocene maximum between 7000 and 5000 YBP (Angulo et al., 2013b).

At the Doce Delta, north of Rio de Janeiro, a beach-ridge plain at a maximum altitude of 5 m gave ages between 7150 and 4250 radiocarbon years (Martin et al., 1997). The barrier of Ilha Comprida, Sao Paulo State, grew between 5308 and 1004 14C YBP; this long barrier has been prograding until recent years (Sawakuchi et al., 2008). At Guarapuava River (north of Matinhos), Paraná State, a beach-ridge plain extends between ages of 7580 and 2750 14C YBP. Within this barrier sequence there are age-sequence reversals explained by differences between in situ remains and those (vegetal debris, wood fragments) that would have been transported onshore by coastal processes (Angulo et al., 2008).

At the northern coast of Rio Grande do Sul, a beach-ridge plain is overlain by a dune field. Radiocarbon datings from shells obtained from drills were handled to reconstruct the progradation of this plain between 6750 and 3450 14C YBP (Dillenburg et al., 2004). Organic-rich silts (peats) bored farther south, at the Tramandai coastal plain, helped to determine a transgressive phase of this sea-level fluctuation. According to this data set, the plain would have prograded rapidly between 9620 and 4620 14C YBP (Traversas, Dillenburg, and Clerot, 2005).

At the Uruguay coast, the Arruyu Chuí coastal plain extends from Los Rodriguez site to the inlet of the creek. Several radiocarbon datings were performed on shells spanning from 5150 to 3530 14C YBP (Martinez et al., 2006). Along the inlet of the Uruguay River into the La Plata River there is another regressive sequence between 5243 years at Tabaré to 3620 years at Carmelo (Martinez and Rojas, 2013).

In the northern Argentina coastline, several sea-level curves were proposed for different coastal plains: Paraná Delta (Cavalotto, Violante, and Colombo, 2005), La Plata (Cavalotto, Parker, and Violante, 1995), Samborombón Bay (Aguirre and Whatley, 1995), Mar Chiquita (Isla, 1989), and Bahía Blanca (Gómez and Perillo, 1995). However, new datings produced new interpretations (Cavalotto, Violante, and Parker, 2004; Cavalotto, Violante, and Colombo, 2005; Spagnuolo, 2004; Weiler, 2000). The more extended progradation occurred at the Paraná Delta (140 km), where beach-ridge systems extended between 6440 and 1770 14C YBP (Cavalotto, Violante, and Colombo, 2005). South of Mar del Plata, several estuaries became infilled because of this Holocene fluctuation of about 4 m (Isla et al., 1986); the most complete vertical sequence was dated at Las Brusquitas Creek spanning between 6380 and 2040 14C YBP (Vilanova, Prieto, and Espinosa, 2006).

South of the Colorado River delta, at the northern coast of Patagonia, several beach-ridge systems were recognised and mapped at San Blas Bay (Witte, 1918). Holocene beach ridges spanned between 5370 to 2170 14C YBP (Isla, 1998; Rutter, Brigham-Grette, and Catto, 1989; Rutter et al., 1989; Trebino, 1987).

Farther south, several gravel-composed beach-ridge plains were surveyed. In the Chubut Province, Holocene beach plains were dated in Puerto Lobos (Codignotto, Kokot, and Marcomini, 1992), Caleta Valdés (Codignotto, 1983; Rutter et al., 1989), Chubut River estuary (Monti, 2000), Bustamante Bay (Codignotto, Kokot, and Marcomini, 1992; Schellmann, 1998a,b), and Solano Bay (Codignotto, Kokot, and Marcomini, 1992). At the Deseado River estuary, gravel ridges indicate a sea-level drop since 6300 YBP of about 4–7 m (Zanchetta et al., 2014). Along the Santa Cruz Province similar highstands were recorded at San Julián Bay (Schellmann and Radtke, 2003) and Rio Gallegos (González Bonorino et al., 1999).

At the northwest of the Malvinas Islands and at Port Howard (San Carlos Strait) there are beach deposits over present sea level. Peat layers between pebbles, with dunes overlying, gave ages between 4950 ± 35 and 225 ± 30 ka (Regnauld, Planchon, and Goff, 2008). Although these deposits are quite similar to the obliterate-dominated pebble beaches of Patagonia, they were assigned to a tsunami.

In Tierra del Fuego, extended beach-ridge and chenier plains were dated at the northern coast: San Sebastián Bay (Vilas et al., 1999), Río Chico coastal plain (Isla and Bujalesky, 2000) and Punta María (Codignotto, Kokot, and Marcomini, 1992). The extended chenier plain of Bahía San Sebastián presents the best representation with radiocarbon ages spanning between 5616 and 509 14C YBP. Within the Beagle Channel, several beach-ridge plains occur, most of them associated with shell middens of Yamana Indians. Close to the Olivia River delta, the sequence of Playa Larga is the most complete. Several beach ridges between 5615 and 405 14C YBP are located according to steps dropping to the Beagle Channel (Gordillo et al., 1992); the more recent deposits have been reworked by the original inhabitants of the channel (shell middens).

At the region between the Bio Bio Delta and the Arauco Gulf, Chile, several coastal plains were located attached to the coastal mountains. Mollusk shells gave ages spanning between 8010 and 3330 YBP at a maximum altitude of 5 m (Isla et al., 2012). At the bays of Herradura and Tongoy, mollusks from coastal ridges between 2- and 5-m altitude gave ages between...
6310 and 910 YBP (Ota and Paskoff, 1993). At this coast of Chile and Perú, significant variations of the C reservoir effect were assigned to the yearly upwelling dynamics (Ortlieb, Vargas, and Saliège, 2011).

Across the coastal plain of the Santa embayment, Peru, several beach ridges were dated between 6250 and 5160 YBP; this sequence was analyzed in relation to the El Niño–Southern Oscillation (ENSO) events (Wells and Noller, 1999). The subduction of the aseismic Nazca Ridge caused similarly the marine terraces between Pisco and San Juan de Marcona (Folguera and Ramos, 2002). Some of these ridges are not active today but there are evidences of the uplift that caused their subduction below the South American plate. The subduction of the Carnegie Ridge is uplifting the Manta Peninsula and La Plata Island (Bethoux et al., 2011; Cantalamessa and Di Celma, 2004; Pedoja et al., 2006). The subduction of the active Chile Ridge (47°S) caused basaltic lava deposits scattered at the Patagonian plateaus; some were assigned to Miocene or Pliocene, whereas others were dated Pleistocene and even Holocene (Figure 5). The uplifting rates of Atlantic terraces of southern Patagonia were calculated between 0.11 and 0.20 mm a⁻¹, and distinguished from the tectonic behavior of northern Patagonia (Pedoja et al., 2010). The higher and therefore older (Upper Pliocene) marine terraces are lying on the coast of Santa Cruz Province (Cabo Buen Tiempo and Cerro Laciar). These latitudinal variations (Pedoja et al., 2006) are considered related to the subduction of the Chile Ridge below the South American plate that caused the basaltic deposits and also reversals in the river drainage directions (Isa et al., 2015). As this ridge has an asymmetric growth, the different uplifting responses of the Pleistocene marine terraces are hard to discern.

Modern studies are also considering tectonic processes affecting the trailing-edge coast of Brazil. In the State of Rio Grande do Norte, some faults oriented ENE–WSW are indicating faults of Late Pleistocene age (Bezerra et al., 2008). On the other hand, intraplate tectonics was mentioned affecting Holocene deposits in NE Brazil (Bezerra et al., 1998).

In relation to the increase or decrease in the uplifting rates, they should be interpreted in regard to the alongshore differences caused by the subduction rates of volcanic ridges. These differential uplifts were discriminated into flat and steep subduction processes, and used to explain differences between Middle and Upper Pleistocene–Holocene uplifting rates of Altos de Talinay (Saillard et al., 2009). On the other hand, the subduction of the Chile ridge would have caused a progressive diminution of the uplift of the Atlantic marine terraces of Southern Patagonia (Isa et al., 2015).

Although the Mid-Holocene sequences are evident from satellite images, it is difficult to use them to discern tectonic trends, as there is no consensus about the maximum height of this highstand. Global analyses assure that sea level is still...
rising, whereas the Middle Holocene records of the Southern Hemisphere accepted a highstand of 3–5 m (Angulo, Lessa, and de Souza, 2006; Isla, 1989). However, as this highstand was not considered for the Pacific coast of Colombia (González, Shen, and Mauz, 2014), uplifting trends have been overestimated.

Sangamonian highstands are more useful to calculate long-term tectonic trends. However, caution should be considered in relation to regional uplifting trends. In the Argentine continental shelf a long-term uplifting rate of 0.08 mm/y (Guilderson et al., 2000) has been estimated and considered to explain the

Figure 5. Quaternary marine terraces of the Atlantic coast of Patagonia related to the subduction of the Chile Ridge (modified after Isla, Espinosa, and Iantanos, 2015).
Holocene sea-level rise at the Argentine trailing-edge margin (Isla, 2013).

CONCLUSIONS
At the Atlantic coast, between latitude 6° N and 39° S, the Sangamonian terrace altitudes are close to the worldwide-accepted eustatic highstand of +6 m above present sea level. The altitudinal differences along this coast should be explained by low gradients of the plains generating little accommodation space.

This pattern does not apply to Atlantic Patagonia where there is a considerable uplift decreasing during the Quaternary.

Regarding the Pacific coast, rapid tectonic uplifting rates prevail over the eustatic sea-level changes related to highstands. Assuming a global eustatic height of +6 m for the 5e highstand, different uplifting trends were calculated. Maximum uplifting rates are in coincidence with the subduction of oceanic ridges beneath the South American plate: Carnegie (Ecuador coast), Nazca (southern Peru), and Juan Fernández (Chile). The subduction of the active Chile ridge explains the uplifting rates of the Atlantic terraces of Southern Patagonia. At the Caribbean coast, there is not enough data about both highstands. At the northern coast of Colombia, tectonics is not easily distinguished and is a matter of discussion: the diapirism of mud volcanoes introduces modern processes difficult to analyze in terms of space and time effects. Uplifted blocks have also been recognized related to modern transform faults.

At the Sao Pedro and Sao Paulo Archipelago (Mid-Atlantic Ridge), and at the Beagle Channel, Holocene sea-level remains are uplifted over the maximum level assumed for the Middle Holocene. However, the glacioisostatic rebound of Tierra del Fuego was not yet precisely estimated.

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