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Tectonic Processes along the South America Coastline Derived from Quaternary Marine Terraces

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ABSTRACT

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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 ridges 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 rates. The last Interglacial—spanning between 140 and 80 ka—has different names in Europe (Eemian, Tyrrhenian) 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 5e (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; Bardají *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.

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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 Celma, 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,

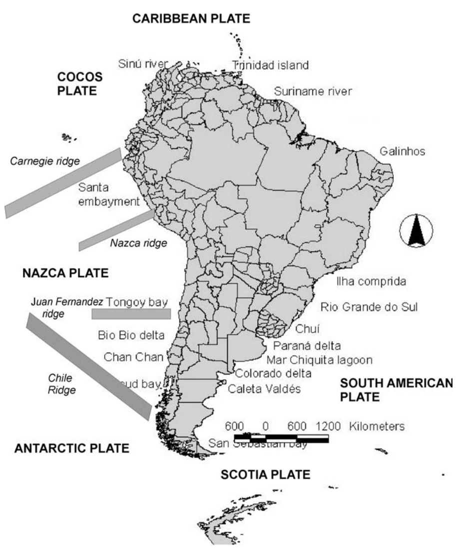

Figure 1. Location of coastal sites and major tectonic features.

2007; Hearty and Neumann, 2001). 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 Bolívar fields. The tide gauges of Pacific

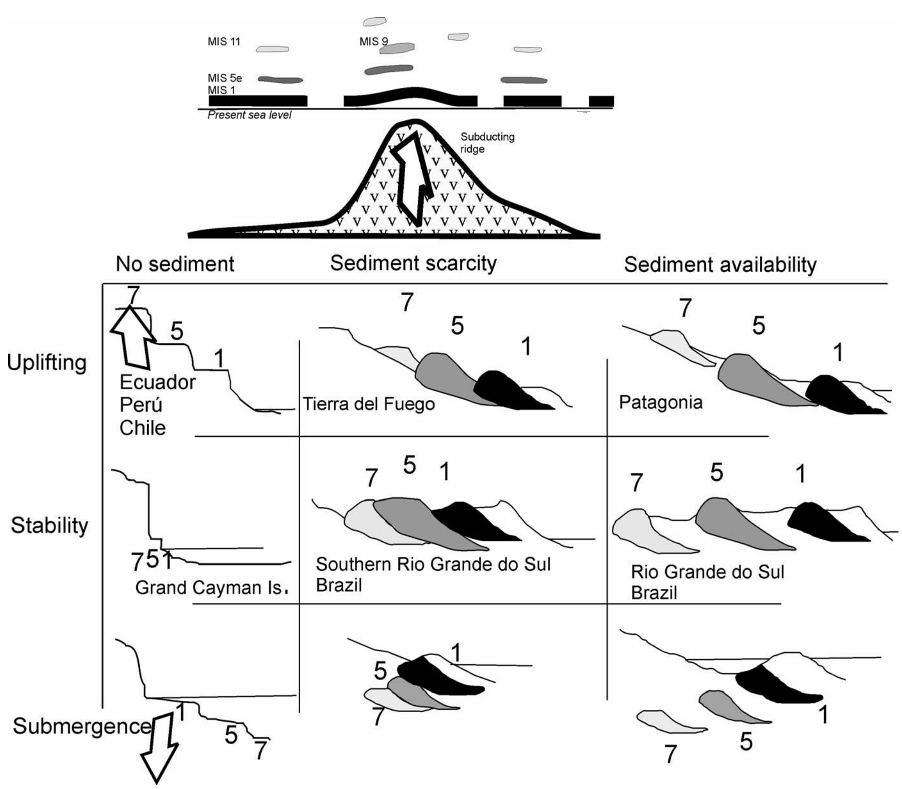

Figure 2. Potential preservation of Quaternary highstand sequences in relation to tectonic trends (modified after Isla and Bujalesky, 2008).

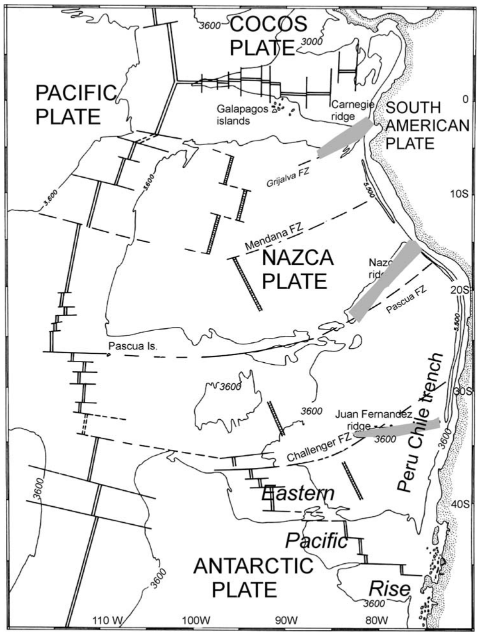

Figure 3. Interactions between different plates with South American plate.

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; Vernette *et al*., 1992). On the other extreme, Tierra del Fuego is splitting because of the interaction with the Scotia microplate (Diraisson *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; Schwarcz, 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 ^{14}C 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 Saliège, 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 (Schwarcz, 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 ^{14}C determinations (Dijkmans and Wintle, 1991).

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.*

Location	Geologic Unit Site	Latitude	Altitude (m)	Uplift (m/ky)	References
Caribe					
Grand Cayman, Cayman Islands	Unit D, Ironshore Formation	19°20′ N	6	0	Coyne, Jones, and Ford, 2007
Marie Galante, Guadeloupe, France		15°54′ N	4–5	0	Battistini *et al.,* 1986
La Desirade, Guadeloupe, France	Pointe des Colibris	16°19′ N	4–5	0	Battistini *et al.,* 1986
Barbados	Barbados III	13°02′ N	20–40	0.276	Schellmann *et al.*, 2004
Atlantic					
Pernambuco, Brazil		8° S	7–11	0	Dominguez *et al.*, 1990
Bahia, Brazil	Penultimate transgression	13–14° S	6–10	0	Martin, Flexor, and Suguio, 1998
Rio de Janeiro State, Brazil			6–10	0	Martin, Flexor, and Suguio, 1998
São Paulo State, Brazil	Cananéia Formation	23–25° S	9–10	0	Watanabe *et al.*, 1997
Paraná and Santa Catarina, Brazil		25–29° S	6–10	0	Martin *et al.,* 1988
Rio Grande do Sul, Brazil	Barrier III	29–33° S	5–7	0	Tomazelli and Dillenburg, 2007
Buenos Aires Province, Argentina	Belgranense Interglacial	38°	7	0	Isla *et al.*, 2000
Negro River mouth, Argentina	Faro Segunda Barranca	40°45′ S	10	0	Radtke, 1989
Bustamante Bay, Chubut, Argentina	Caleta Malaspina	45°05′ S	12		Schellmann, 1998b
Mazarredo Harbour, Argentina	N1	47°03′ S	16–19		Schellmann, 1998a
San Julián Bay, Santa Cruz, Argentina	SI	49°17′ S	14–15		Schellmann, 1998a
Tierra del Fuego, Argentina	La Sara Formation	53°31′ S	14		Bujalesky, Coronato, and Isla, 2001
Navarino Island, T. del Fuego, Chile	Unit 5	54°56′ S	>10		Rabassa *et al.*, 2008
Pacific					
Galera, Ecuador	T1	00°50′ N	46	0.34	Pedoja *et al.,* 2006
Manta, Ecuador	T1	00°58′ S	43	0.31	Pedoja *et al.,* 2006
La Plata Island, Ecuador	T1	01°17′ S	43	0.31	Pedoja *et al.,* 2006
Santa Elena Headland, Ecuador	T1	02°12′ S	18	0.10	Pedoja *et al.,* 2006
Cancas, Ecuador	T1	03°30′–4° S	30	0.20	Pedoja *et al.,* 2006
Illescas Headland, Bayobar Bay, Peru	T2	05°40′ S	18	0.12	Pedoja *et al.,* 2006
Pampa del Palo, Peru	T10	17°42′ S	25	0.16	Ortlieb *et al.*, 1996
Chala, Peru	Tablazos	15°51′ S	64–64	0.46	Goy *et al.*, 1992
Antofagasta, Chile	Caleta Playa de los Hornos	22°54′ S	30	0.2	Radtke, 1989
Mejillones, El Rincón, Antofagasta, Chile		23°05′ S	9–10	0	Radtke, 1989
Caleta Obispito, Copiapó, Chile		26°46′ S	29–34	0.25	Radtke, 1989
Bahia Inglesa, Copiapó, Chile	b	27°03′ S	40	0.28	Quezada *et al.,* 2007
Caldera, Copiapó, Chile	b	27°07′ S	44	0.28	Quezada *et al.,* 2007
Herradura Bay, Coquimbo, Chile		29°57′ S	31–36	0.2	Radtke, 1989
Santa María Island, Arauco, Chile	Santa María Formation	37°03′ S	60–90	0.68	Modified from Melnick *et al.,* 2006
Cañete, Arauco	Cañete Formation	37°40′ S	50–61	1.8	Melnick *et al.,* 2009

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 MIS5e (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 (+6m), 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 (Pedoja *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: *Anada 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 (Pedoja *et al.,* 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/y (Bethoux *et al.,* 2011). Some of these Quaternary marine terraces were correlated to others occurring in Puná Island, Gulf of Guayaquil (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 lagoonal 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 Tablazos, were discriminated. At about 64–68-m height over mean sea level, there is a 25-m-tall paleocliff that was assigned to the MIS5e highstand (Goy *et al.,* 1992). A mean uplifting rate of 0.46 m/ka was calculated for the last 500 ka, although less uplifting rates (0.27–0.35 m/ka) were established for the surroundings. The higher uplifting trend calculated at 0.7 m/ka has been stated for the segment between Pisco and San Juan de Marcona, where the Nazca Ridge (Figure 3) is subducting beneath the South American plate (Macharé and Ortlieb, 1992).

North of Antofagasta, Chile, there are several marine terraces easily distinguished because of the very arid climate. The 5e highstand has been dated at Mejillones (El Rincón; 23°05′ S), Caleta Playa de Los Hornos (22°54′ S), and Iquique (20°20′ S). ESR and U/Th datings were similar, although the altitude of the 5e highstand is positioned at 9–10 m at Mejillones, and 30 m at Los Hornos (Radtke, 1989). At the bays of Caldera and Bahía Inglesa (27°03′ S), several marine terraces have also been distinguished. The Sangamonian terrace has been dated at 125 ± 5 ka (Marquardt *et al.,* 2004); stages 5c and 5a have also been dated. In regard to these datings, uplifting rates of 0.31 and 0.28 m/ka were assigned to Caldera and Bahía Inglesa, respectively (Marquardt *et al.,* 2004). New analyses permitted the confirmation of the uplifting rate of Caldera Bay (Quezada *et al.,* 2007). Similar ESR and U/Th datings have been yielded at Caleta Obispito at 29–34-m altitude (26°46′ S; Radtke, 1989). Close to Coquimbo, at Herradura Bay (29°57′ S), coarse marine beds provided mollusks dated between 86 and 160 ka either by ESR or U/Th methods (Radtke, 1989).

Several Pleistocene marine terraces were also detected at Altos de Talinay (close to Tongoy). These terraces were 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/y), and an uplifting rate of 0.1 mm/y for the last 6000 years; each interval was separated by periods of low uplifting rates (Saillard *et al.,* 2009).

In southern Chile, at Santa María Island, a Late Pleistocene marine terrace is tilted. It has been dated by the accelerator mass spectrometry (AMS) radiocarbon method on samples performed on charcoal and large pieces of wood. The dates span between 27,380 and 52,750 YBP and led us to calculate 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 ("cancagua"*),* 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 Suguio, 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 *Tegula 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 (Radtke, 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 (Radtke, 1989). Farther 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 (Radtke, 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

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

Latitude	Costal plain	Max. age[a]	Min. age[a]	Max. height (m)	Reference
09° N	Sinú Delta	2650	2450	2	Martinez and Robertson, 1997
10° N	Cartagena	3409	1600	6	Martínez *et al*., 2010
06° N	Surinam Estuary	5620	2950		Groen, Velstrab, and Meesters, 2000
10° N	Maracas Bay	5880	2930		Ramcharan and McAndrews, 2006
05° N	Gallinas Barrier	6520	2180	1.2	Stattegge, Caldas, and Vital, 2004
19° S	Doce Delta	7150	4250	5	Martin and Suguio, 1992
25° S	Ilha Comprida	5308	1004		Sawakuchi *et al*., 2008
29.6° S	Curumin	6750	3450	5	Dillenburg *et al*., 2004
25–26° S	Paraná	6170	475	5	Angulo *et al*., 2002, 2008
30° S	Tramandaí	9620	4620		Travessas *et al.,* 2005
30° S	Tongoy	6380	910	5.1	Ota and Paskoff, 1993
33° S	Paraná Delta	6440	1770	5	Codignotto, Kokot, and Marcomini, 1992; Cavalotto, Violante, and Colombo, 2005
33° S	Arroyo Chuí	5150	3530	3	Martínez *et al*., 2006
34° S	La Plata	8620	1770	6.5	Cavalotto, Violante, and Parker, 2004
36° S	Samborombón Bay	5810	1610		Codignotto and Aguirre, 1993
37° S	Mar Chiquita	3840	1340	2.5	Codignotto, Kokot, and Marcomini, 1992; Schnack, Fasano, and Isla 1982
38° S	Las Brusquitas Estuary	6380	2040	4	Isla *et al*., 1986; Vilanova, Prieto, and Espinosa, 2006
38° S	Bahía Blanca	7500	3560		Farinati, 1985; Grill and Quatrrocchio, 1996
38° S	Coronel Plain				Isla *et al*., 2012
39° S	Colorado Delta	6750	407	7.5	Codignotto, Kokot, and Marcomini, 1992; Weiler, 2000
40° S	San Blas	5370	2170	8	Rutter, Brigham-Grette, and Catto, 1989; Rutter *et al*., 1989; Trebino, 1987
42° S	Puerto Lobos	3370	1030	8	Codignotto, Kokot, and Marcomini, 1992
42° S	Caleta Valdés	5720	1330	6	Codignotto, Kokot, and Marcomini, 1992; Rutter, Brigham-Grette, and Catto, 1989; Rutter *et al*., 1989
42° S	Ancud	2050	750	10	Hervé and Ota, 1993
43° S	Chubut	4987	1009		Monti, 2000
45° S	Bustamante Bay	5424	4220	12	Codignotto, Kokot, and Marcomini, 1992; Schellmann, 1998
46° S	Solano Bay	6310	2040	1.85	Codignotto, Kokot, and Marcomini, 1992
49° S	San Julián Bay	1779	570	4.5	Schellmann, 2003; Schellmann and Radtke, 2003
53° S	San Sebastián Bay	5616	509	7.5	Vilas *et al*., 1999
53.6° S	Río Chico	4620	2890	9	Isla and Bujalesky, 2000
54° S	Punta María	3820	1310	8	Codignotto, Kokot, and Marcomini, 1992
55° S	Olivia River delta, Beagle Channel	5615	405	10	Gordillo *et al*., 1992

[a] Noncalibrated radiocarbon years before present.

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) the altitude is about 12 m above mean high tide level (MHTL), whereas at the southern portion (Caleta Olivia and Mazarredo) 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 Malumián, 1981). At a geoidal height of 14 m (measured by a geodetic GPS), mollusk shells were dated by U/Th at 82 $\pm$ 2.5 ka (Bujalesky, Coronato, and Isla, 2001). Farther south, at the northern coast of Navarino Island, Chile, a marine bed composed of broken shells interfingered with laminated beds with wood fragments was dated by ^{14}C at 41.7 $\pm$ 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 (Angulo, Lessa, and de Souza, 2006; Codignotto, Kokot, and Marcomini, 1992; Isla, 1989, 1998; Martin *et al.,* 1997). The maximum altitude of these plains can confirm or deny long-term uplifting trends. At the Pacific collision coast, the Mid-Holocene regression is restricted to small and narrow bays related to grabens, and they are therefore suggesting local tectonic effects (Table 2).

At the Caribbean coast of Colombia, corals located within the coastal plain of the Sinú River delta permit reconstruction of a Holocene beach-ridge plain between 2650 and 2450 YBP

(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 Carrió, 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 ^{14}C 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 ^{14}C 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 ^{14}C 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 ^{14}C 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 ^{14}C YBP; this long barrier has being prograding until recent years (Sawakuchi *et al.,* 2008). At Guaraguaçu River (north of Matinhos), Paraná State, a beach-ridge plain extends between ages of 7580 and 2750 ^{14}C 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 ^{14}C YBP (Dillenburg *et al.,* 2004). Organic-rich silts (peats) bored farther south, at the Tramandaí 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 ^{14}C YBP (Travessas, Dillenburg, and Clerot, 2005).

At the Uruguay coast, the Arroyo 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 ^{14}C YBP (Martínez *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 (Martínez 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 ^{14}C 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 ^{14}C 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 ^{14}C 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 Río 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 oblate-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 ^{14}C 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 ^{14}C 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

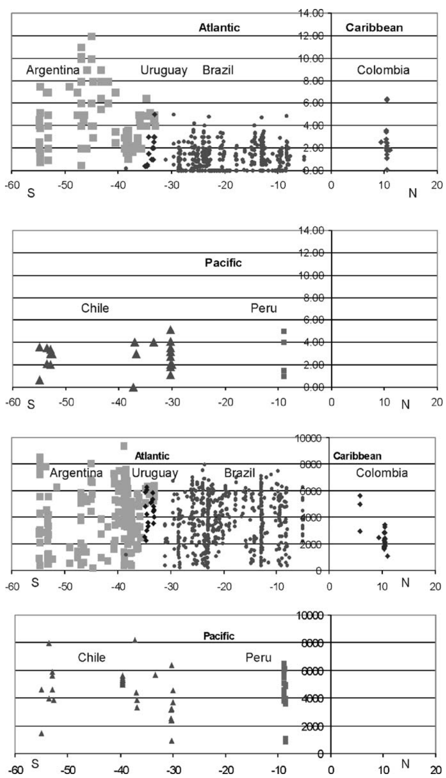

Figure 4. Plot of Holocene highstand data along the South American coast (radiocarbon ages were not corrected in regard to the errors that can be introduced without a proper knowledge of the reservoir effects and the resuspension of "old C" by marine currents).

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).

A Holocene uplifted beach was described at the Pacific coast of Colombia, attached to the Baudo Mountain Range. Considering that present backshore deposits reach levels of +5–5.5 m, these deposits dated between 2930 and 2770 YBP would have been representing uplifts of 0.7 mm/y for the Chocó Block microplate (González, Shen, and Mauz, 2014).

Although the Mid-Holocene highstand is well recorded along the Atlantic coast, its distribution along the Pacific coast needs more controls (Figure 4). The altitude controls depend on the tectonic effects but also on the different tidal ranges (Schellmann and Radtke, 2003), and storm or tsunami effects.

DISCUSSION

Trying to forecast the conditions of the end of the Present Interglacial, there are increasing interests about how the Last Interglacial ended. Information from the Northern Hemisphere is providing doubts about the instability that occurred between 130 and 75 ka ago (Bardají *et al.,* 2009). In this sense, there is a need for a worldwide scope of the processes involved during this period. For example, at the southern coast of South Africa, three barriers were built because of the availability of sand during the MIS5e highstand (Bateman *et al*., 2011), and similar Sangamonian barriers were described in Australia (Belperio, Murray-Wallace, and Cann, 1995), Argentina (Isla *et al.,* 2000), and Brazil (Giannini *et al.,* 2007).

At the active margin of South America, the plate is colliding against several volcanic ridges. These collisions occurred since at least 90 Ma when the ancient active ridge that separated Farallón and Alluk (Phoenix) plates subducted beneath South America (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 aseismic Nazca Ridge caused similarly the marine terraces between Pisco and San Juan de Marcona (Macharé and Ortlieb, 1992) and the Pliocene alluvial fan close to Lima (Le Roux, Tavares Correa, and Alayza, 2000). 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.,* 2010) 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 (Isla *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 (Isla *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

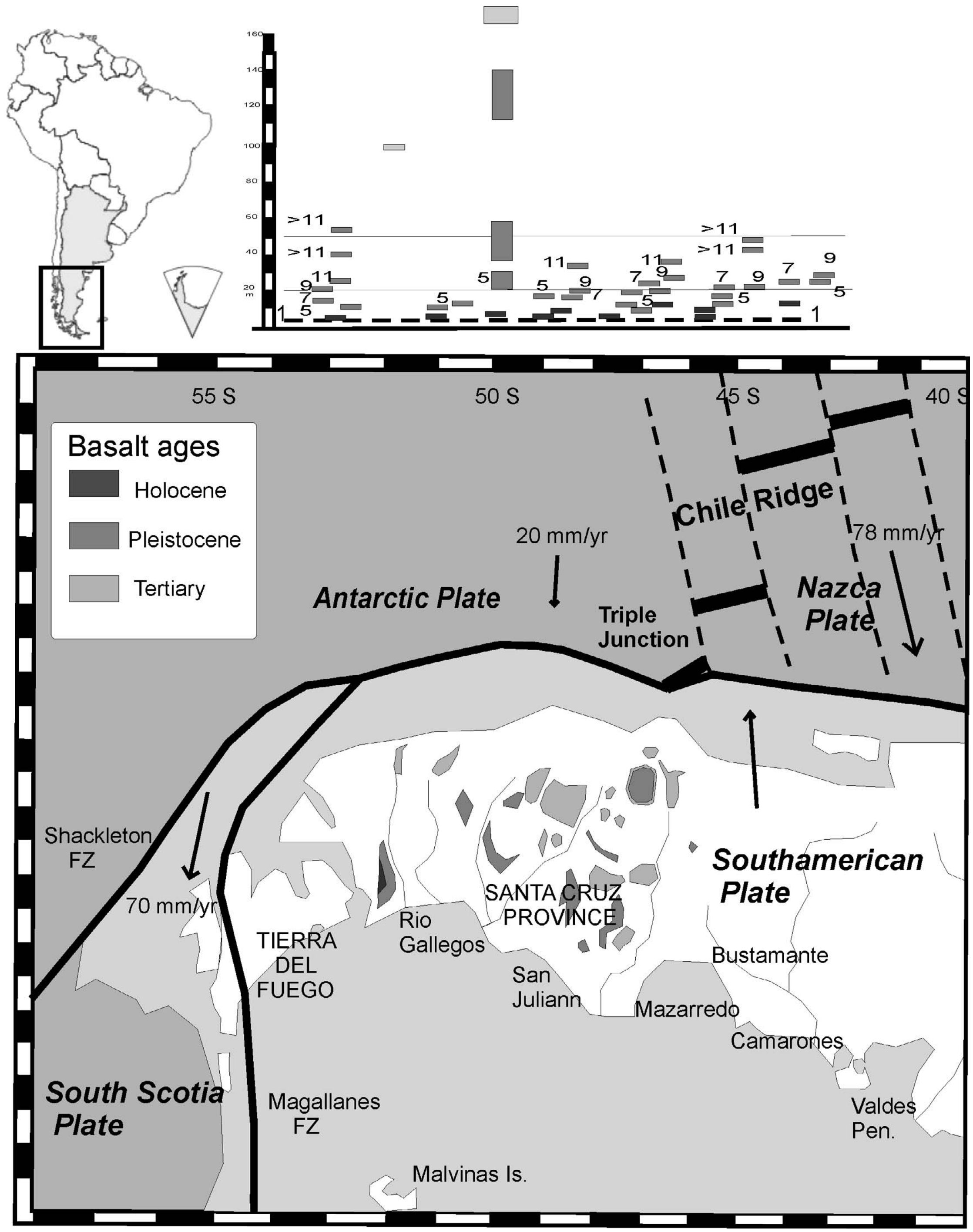

Figure 5. Quaternary marine terraces of the Atlantic coast of Patagonia related to the subduction of the Chile Ridge (modified after Isla, Espinosa, and Iantanos, 2015).

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

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 recognised 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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