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The flooding of the San Matías Gulf: The Northern Patagonia sea-level curve

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ABSTRACT

Northern Patagonia is characterised by tectonic depressions below present sea level. Some of them are today flooded by the sea; others remain emerged although they are at altitudes of −50 m (Bajo del Gualicho), −35 m (Salinas Grandes) and −7 m (Salina La Piedra). San Matías Gulf also was such an emerged depression below contemporary mean sea level during the Late Pleistocene. It flooded between 11,500 and 11,000 years ago, when the sea level surpassed the sill of the gulf (today 50 m below mean sea level) during postglacial sea-level rise. In those days, shrublands extended on the slopes of the tectonic depression. In-situ pieces of woods dredged from the bottom of the gulf at depths of 70 m gave a conventional age of 11,310 ± 150 years BP. We used the wood, together with dated shells from the continental shelf, and shells and organic matter dated from the San Blas, Negro and Chubut coastal plains to construct a sea-level curve. Sea level rise surpassed the present level somewhat before 6000 years BP, reaching a maximum stand of +6 m. It has since gently diminished towards present sea level.

1. Introduction

As Patagonia is located on a passive continental margin, sea-level high stands play a significant role in estimating uplift rate. They have been subject of recent research in order to relate marine terraces or beach-ridge plains to uplift. While some authors believed that in Patagonia tectonics affect only localized areas (Schellmann and Radtke, 2010), others propose uniform uplifting trends of 0.12 mm/yr at least for the last 120,000 years (Pedoja et al., 2011), and others identify different areas of block uplift (Codignotto et al., 1992).

In this short paper, a radiocarbon dating performed on Late Pleistocene wood fragments extracted from the bottom of the San Matías Gulf, is reported. Considering the paleogeographic and biogeographical significances of this date, a sea-level curve is here proposed for Northern Patagonia, including compiled dates from Holocene mollusc shells and peat deposits collected onshore in the region. For the emergent sediment sequences, it became clear that a distinction should be made between storm deposits, estuarine sequences and indicators of mean sea level (Schellmann and Radtke, 2010).

2. Setting

The San Matías Gulf is about 18,000 km^2 (Gagliardini and Rivas, 2004). It is a deep depression where 55% of the floor is below the 100 m isobath (Fig. 1), with a sill of 60 m depth (Gagliardini et al., 2005). The gulf has two maximum depths below 160 m in the middle (Pierce et al., 1969). In contrast, the San José Gulf is shallower (80 m at maximum) and linked with the San Matías Gulf by an outlet of only 9 m depth (Amoroso and Gagliardini, 2010). To the south, the Nuevo Gulf has a mean depth over 160 m, with a maximum depth recorded of 184 m. Its bottom is composed of silty clay while the slopes are covered by sandy silt. This gulf is separated from the open ocean by a sill, where water depth is less than 50 m, composed of a rocky platform covered by shingle. In the middle of this sill there is a 20 km long, 4-km wide canyon (Mouzo et al., 1978). The San Matías Gulf originates as an enclosed tectonic depression that was inundated by the shelf sea during interglacial transgressions. In Northern Patagonia, non-inundated other examples of such enclosed tectonic depressions exist onshore (Bajo del Gualicho, Gran Bajo Valdés), with bottoms that lie below present-day sea level and lacking river outlets. Salt pans occur in these depressions (Marchionni et al., 2009). Northern Patagonia's geomorphology is otherwise characterised by several plateaus crowned by the Patagonian Shingle Formation (Darwin, 1842). The more extended plateaus or "pampas" are Somuncurá, Montemayor, Salamanca and Pampa del Castillo (Martínez and Coronato, 2008). The San Matías Gulf depression is surrounded by such plateaus, with elevations of 50 to 300 m above MSL.

The region has a semiarid to arid climate with mean temperatures of 13 °C and yearly precipitation below 400 mm (Coronato et al., 2008). Two vegetation zones dominate: a dry forest ("Espinal") dominated by several species of the genus *Prosopis*, *Schinus longifolia*, *Condalia lineata* and *Celtis spinosa*, and a xerophytic shrubland (called "Monte") is not only dominated by shrubs of *Larrea divaricata* and *Larrea cuneata* but also containing trees of *Prosopis* (Schäbitz, 1994; Mancini et al., 2008). Soils are dominated by aridisols (Coronato et al., 2008).

The gulf has a macrotidal semidiurnal regime (tidal range: more than 7 m during spring tides), with maximum flood and ebb currents

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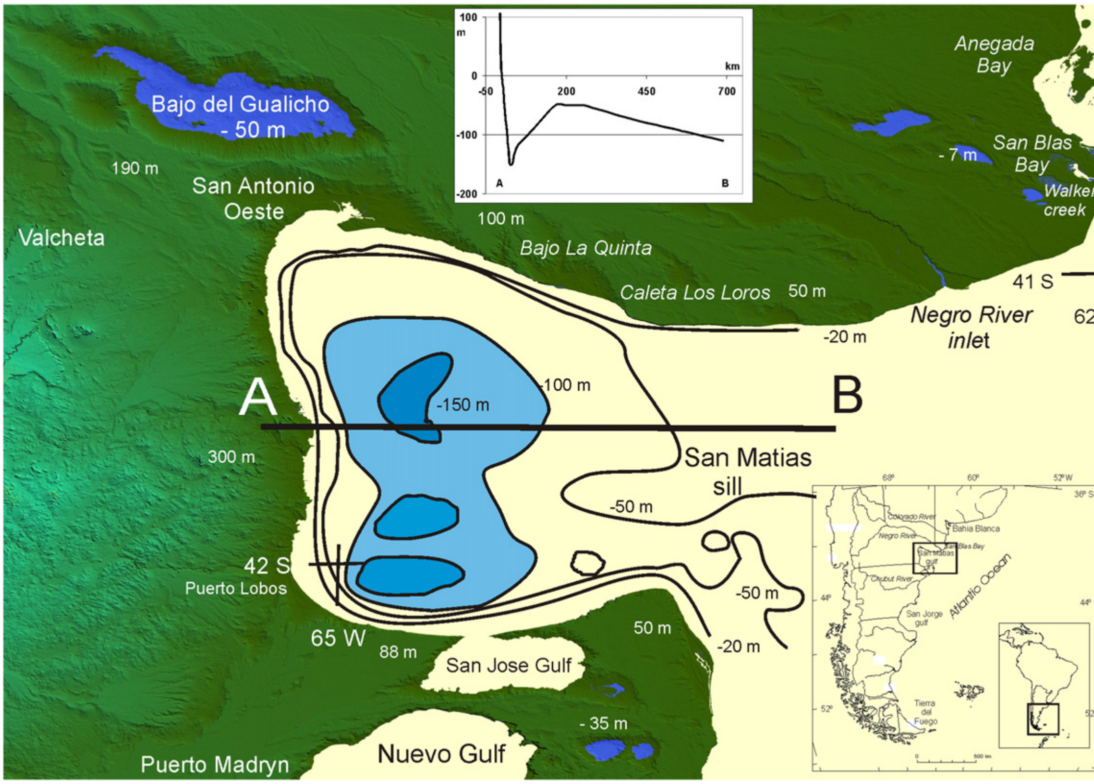

Fig. 1. Digital elevation model of northern Patagonia highlighting depressions below mean sea level with the simplified bathymetry of San Matías Gulf. Inset is the profile of the gulf and the sill.

located in the southern portion of the entrance to the gulf with maximum values of 2 m/s (Gagliardini et al., 2005). These currents are responsible for a bedform field composed mostly of gravel waves. They have heights of 10 m and wavelengths of 600 m (Gagliardini et al., 2005). A microtidal regime occurs immediately to the north of the inlet and a mesotidal regime to the south (Isla and Bujalesky, 2008). Strong tidal currents have explained the asymmetric pattern of sand waves migrating towards the E and NE at the southern portion of the sill, and recorded from the European radar ERS (Gagliardini et al., 2005). The sill is composed mostly by gravel and coarse sand (Gelós et al., 1988).

The gulf is surrounded by cliffs of shallow marine deposits related to two Miocene transgressions (Uliana and Biddle, 1988), although there are small outcrops of a Paleocene marine formation called El Fuerte formation. The Colorado Basin opened during the Jurassic and since the Paleocene has been subject to marine passive-margin deposition (Gerster et al., 2011). The flanks of the tectonic depressions are composed of older Miocene transgressive sediments, while the northern portion of the San Matías Gulf is composed of Upper Miocene transgressive sediments (Farinati and Zavala, 2005). Upper Miocene eolian sandstones crown the top of the northern cliffs (Folguera and Zárate, 2009). The Patagonian Shingle Formation is deposited on top of these deposits and is assigned to piedmont processes although there are deposits related to fluvial, glaciofluvial, littoral and more modern piedmont processes (Fidalgo and Riggi, 1970; Martínez and Coronato, 2008). The water table is very difficult to predict. After rains, water can be found at the bottom of small creeks, but seepage and evaporation limit these flows to a few days. An artificial channel cut to transport water from the Negro river to San Antonio Oeste has significant losses during the summer time.

The Colorado and Negro rivers (Fig. 1) are aligned in relation to the Payunia-Colorado (WNW–ESE) fracture systems (Perucca and Bastías, 2008). Previous papers have proposed a regional tectonic uplift of 0.8 mm/yr for the continental shelf (Guilderson et al., 2000) and about 0.12 mm/yr for the coastline (Pedoja et al., 2011). Regarding the tectonics of the trailing-edge coast of Patagonia, there is a controversy between those that argue that it has persisted for the last 7000 years (Schellmann and Radtke, 2010), those that believe in the differential behaviour of blocks (Codignotto et al., 1992), and those believing uplift has taken place ever since the Pleistocene (Pedoja et al., 2011) peaking to a maximum of 1.2 mm/yr in Tierra del Fuego (Isla and Bujalesky, 2008).

3. Methods

A Digital Elevation Model (DEM) was downloaded from the SRTM web site (Shuttle Radar Terrain Model; http://srtm.csi.cgiar.com). This model has a ground spatial resolution of 90 m and helped to recognise some depressions from the plateau region. The DEM was handled with the Global Mapper v.7.04 (www.globalmapper.com). Bathymetric data were obtained from chart H4 of the Argentine Hydrographic Survey (Servicio de Hidrografía Naval). The bathymetric data from the San Matías Gulf have been periodically updated over the last hundreds of years.

Wood fragments collected from 70 m depth were radiocarbon dated at the LATYR lab (University of La Plata). Other radiocarbon dates were performed on mollusc shells, but due to spatial and temporal uncertainties on the reservoir effect on coastal molluscs (Schellmann and Radtke, 2010), no corrections were considered. Some sequences were obtained from estuarine deposits while some samples were collected from storm deposits and therefore they were related to the altitude reached by storms (Guilderson et al., 2000; Schellmann and Radtke, 2010). Some radiocarbon dates were based on mollusc shells; other dates were performed on organic matter from estuarine deposits.

4. Results

The Colorado River is the northern limit of Patagonia. To the south, there is an estuarine complex (Anegada and San Blas embayments; Fig. 1) located between Upper-Pleistocene and Mid-Holocene beach ridge systems (Weiler, 1998, 2000). A barrier island system, composed of several islands (Olga, de los Césares, de los Riachos, Flamenco and Gama), has been eroded in historic times as the outlet of the Colorado delta changed and oriented northwards (Spalletti and Isla, 2003). San Blas Bay is enclosed between Gama and Jabalí islands, where gravel beaches of the Last Interglacial (Sangamonian) high stand were dated by Electron Spin Resonance (Rutter et al., 1989). Estuarine deposits of the Holocene sea-level fluctuation lie between the gravel beach ridges. They have been sampled for their mollusc content (Trebino, 1987; Codignotto et al., 1992) and for their organic matter layers (Espinosa and Isla, 2011; Table 1). The Walker Creek became obstructed during the XIX century (Espinosa and Isla, 2011).

The estuary of the Negro River became infilled mostly after the sea level dropped in the Middle Holocene. Auer (1974) obtained a radiocarbon date of 7300 ± 100 years BP from a peat close to the limit of the transgression at an altitude of 6 m, about 20 km from the present coastline (Table 1). He correlated this high stand of 6 m with evidences that surround Puerto Lobos. New dates from organic matter close to the inlet gave ages of 2027 ± 34 years BP about 15 km from the inlet, and 1373 ± 37 years BP very close to the outlet (Escandell et al., 2009; Isla et al., 2010).

Similar deposits related to the Holocene sea-level fluctuation are present at the northern coast of San Matías Gulf: Caleta Los Loros, Bajo La Quinta and San Antonio Bay. At Bajo La Quinta, a coastal lagoon became infilled between 6821 ± 58 and 2767 ± 93 (Favier-Dubois and Kokot, 2011).

Between the gravel spits that encompassed Puerto Lobos, mollusc shells gave radiocarbon ages of 3310 ± 90 and 750 ± 75 years BP (Bayarsky and Codignotto, 1982). Another complex gravel spit is attached to the Valdés Peninsula. It grew from north to south enclosing the Valdés Sound (Caleta Valdés). Five mollusc samples were collected in life position and dated. They gave ages between 1330 ± 80 and 5725 ± 105 years BP (Codignotto and Kokot, 1988; Table 1).

The estuary of the Chubut River shows a pattern of infilling that differs from that of the Negro River (Fig. 1). Its outlet has become enclosed by the southward migration of spit complex composed of gravel and sand during the last 5000 years (Monti, 2000; Table 1). Much of the sedimentation at the headlands increased by this blocking, and caused an avulsion that can be distinguished on satellite images.

Wood collected at approximately 70 m depth in the flooded tectonic depressions of the San Matías Gulf, was radiocarbon dated to 11,310 ± 150 years BP (Table 1) with a measured $^{12}C/^{13}C$ ratio of −24‰ ± 2 (LP 2384). The trunk was 4.5 cm in diameter and in very well preserved condition (Fig. 2). This dating confirms that the San Matías Gulf was emergent, but at the time, was below the contemporary sea level. At that time, the sill should have been inundated.

A sea-level curve of Northern Patagonia has been drafted (Fig. 3) compiling the radiocarbon dates from the region discussed above. The data were collected from emergent areas and combined with the radiocarbon datings performed on shells collected from the continental shelf (Guilderson et al., 2000). The data show a maximum sea-level high stand occurring about 6000 years ago, and a sea level fall at approximately 2600 years BP. This fall confirms that proposed for Middle and Southern Patagonia (Schellmann and Radtke, 2010).

5. Discussion

The postglacial transgression flooded restricted seas or gulfs in relation to the vertical position of their sills. Two significant accelerations ("jumps") of sea-level rise took place about 14,300 and

Table 1
Location and altitudes of the radiocarbon dates from the region. M: mollusc; B: bryozoans; O: organic matter. BA: Buenos Aires Province; RN: Río Negro Province; CH: Chubut Province.

Location	Lat. S	Long. W	Conventional age	Material	Marine correction	Lab. number	Altitude (m)	Reference
San Blas BA	40° 34′ 30″	62° 13′17″	4100 ± 95	M	3888–4407	Ac-266	6.5	Trebino (1987); Codignotto et al. (1992)
	40° 35′35″	62° 12′35″	5370 ± 110	M	5510–5981	Ac-255	8.0	Trebino (1987); Codignotto et al. (1992)
	40° 33′35″	62° 23′47″	2320 ± 80	M	1732–2138	Ac-261	3	Trebino (1987); Codignotto et al. (1992)
	40° 35′58″	62° 26′09″	3450 ± 110	M	3027–3596	Ac-260	4.5	Trebino (1987); Codignotto et al. (1992)
	40° 34′ 09″	62° 15′10″	4720 ± 110	M	4704–5286	Beta-203524	−1.40	Espinosa and Isla (2011)
Paso Seco BA	40° 38′ 28″	62° 14′49″	4904 ± 70	O	5005–5430	AA-79991	2	Espinosa and Isla (2011)
	40° 38′28″	62° 14′49″	987 ± 43	B	508–644	AA-69684	2.1	Espinosa and Isla (2011)
Pérez García RN	40°43′48″	63° 09′49″	7120 ± 70	O	7460–7733	Y-196		Auer (1974)
	40° 43′48″	63° 09′49″	6570 ± 110	O	6803–7313	Y-197		Auer (1974)
	40° 43′48″	63° 09′49″	6555 ± 130	O	6743–7333	Y-198		Auer (1974)
Ya Verán RN	40° 51′ 50″	62° 55′02″	7300 ± 100	O	7576–7949	Y-137		Auer (1974)
Criadero RN	40° 55′ 27″	62° 51′33″	2027 ± 34	O	1506–1693	AA-77055	1.40	Escandell et al. (2009)
	40° 55′ 27″	62° 51′33″	1636 ± 35	O	1108–1277	AA-77054	0.40	Escandell et al. (2009)
Villarino RN	41° 01′ 07″	62° 48′08″	628 ± 34	O	173–372	AA-87713	1.3	Isla et al. (2010)
	41° 01′07″	62° 48′08″	1373 ± 37	O	812–1015	AA-85520	0	Isla et al. (2010)
Puerto Lobos CH	41° 59′57″	65° 04′11″	750 ± 75	M	262–506		6.00	Bayarsky and Codignotto (1982)
	41° 59′59″	65° 04′23″	3310 ± 90	M	2906–3371		8.00	Bayarsky and Codignotto (1982)
Caleta Valdés CH	42° 48′	63° 26′	2160 ± 85	M	1534–1945	Ac-2063	1.0	Codignotto and Kokot (1988)
	42° 36′	63° 44′	5725 ± 105	M	5898–6341	Ac-2061	6.0	Codignotto and Kokot (1988)
	42° 21′	63° 44′	5100 ± 100	M	5239–5674	Ac-2035	5.0	Codignotto and Kokot (1988)
	42° 20′	63º44′	1330 ± 80	M	702–1044	Ac-2060	1.0	Codignotto and Kokot (1988)
	42° 15′	63° 44′30″	4180 ± 100	M	3966–4520	Ac-2034	5.0	Codignotto and Kokot (1988)
Ba. Engaño CH	43° 17′19″	65° 01′	1009 ± 88	M	464–730	Ac-3818	5.50	Monti (2000)
	43° 17′36″	65° 02′33″	2770 ± 81	M	2319–2705	Ac-3819	6.50	Monti (2000)
	43° 18′	65° 04′32″	3929 ± 97	M	3643–4186	Ac-3891	8.00	Monti (2000)
	43° 18′37″	65° 06′43″	4.987 ± 106	M	5029–5572	Ac-3892	9.00	Monti (2000)
Magagna CH	43° 19′54″	65° 04′04″	4376 ± 69	O	4357–4775	AA-90823	4.0	Escandell (2012)
	43° 19′54″	65° 04′04″	672 ± 39	O	253–421	AA-92986	5.4	Escandell (2012)
Arenas Doradas CH	41° 36′	64° 52′	11,310 ± 150	w		LP-2384	−70.0	This paper

Fig. 2. Transverse section of the wood dredged from the bottom of the San Matías Gulf.

11,000 years BP, respectively (Bard et al., 1996: MWP-1A and MWP-1B). The wood dated at the bottom of the San Matías Gulf indicated that it was not yet submerged 11,300 years ago. Considering that the sill of this gulf is today 60 m depth, it should have been flooded about 11,000 years BP during the MWP-1B (Fig. 4). In this sense, this gulf was flooded in a similar way to the Red Sea that was inundated when the Bab el Mandab strait (Hanish sill) was surpassed by the rising Indian Ocean sea level, and the Black and Marmara seas about 8400 years BP when the Bosporus Strait was flooded from the rising Mediterranean Sea (Siddall et al., 2004).

It is assumed that the two depressions, today flooded as the San Matías gulf, had some water content during the Late Pleistocene.

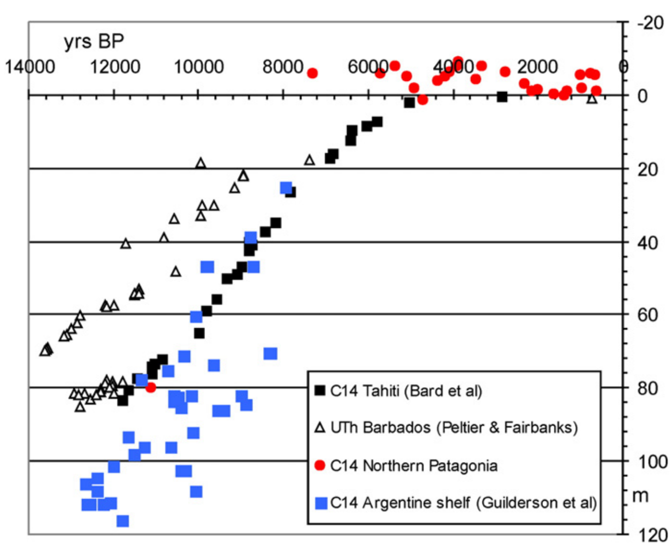

Fig. 3. Postglacial sea-level curves from Tahiti (Bard et al., 1996), Barbados (sensu Peltier and Fairbanks, 2006) and composed from the Argentine continental shelf (sensu Guilderson et al., 2000). Circles correspond to references cited in the text and the dating of this paper.

Woods grew in small valleys that occasionally transport water to these depressions, as occurs today in Valcheta (Fig. 1). At this locality there are woods at the bottom of a valley that ends in a salt pan. In this sense, it is speculated that the woods were related to a former valley that contributed to the southern depressions prior to their marine inundation.

In the San Matías Gulf, the tidal ranges increase from the inlet to the northernmost corner of the gulf (San Antonio Bay). Spatial variations in tidal ranges can be modelled in relation to the sea-level rise as the coast takes a different configuration (Leorri et al., 2011). The Late Pleistocene flooding of the San Matías Gulf would have been associated by an increase in tidal range from a microtidal to a macrotidal regime. These spatial and temporal changes in the tidal regime should have increased the transport of sand and gravel from the continental shelf towards the centre of the gulf, with a significant tidal transport induced by flood currents from the south.

Dealing with Holocene sequences obtained from salt lakes, Schäbitz (1994) recorded a short duration rise in the level of the Anzoátegui salt lake (39°00′23″S; 63º46′30″W) immediately after the Mid-Holocene. During the Late Holocene and until today, these depressions have been continuously increasing their water levels (Schäbitz, 1994). A 2.30 m core obtained from the bottom of Nuevo Gulf (143 m depth) was studied for its foraminifer content, and indicated that marginal marine conditions prevailed 450 years ago (Bernasconi et al., 2009).

Regarding the noise that can be introduced by carbon reservoir correction, it was considered prudent not to subscribe to the two sea-level falls (6200–6000 and 2600–2400 ^{14}C years BP) proposed for Middle and Southern Patagonia by Schellmann and Radtke (2010). Only the second drop in sea level can be accepted by the data collected, and it would be relatively gentle. Sea level falls are not recorded in the storminess record of San Sebastián Bay (Vilas et al., 1999), nor in the estuarine record of the Beagle Channel (Gordillo et al., 1992).

Differential uplift is accepted for Eastern Patagonia. However, elevation differences of storm deposits at the entrance and headlands of bays and gulfs with different tidal ranges do not permit a tectonic component to be discerned from data from the last 6000 years. Differential tectonic components are better discerned by measuring elevations of older coastal features, i.e. Pleistocene high stands such as that from the Last Interglacial. Such features in Northern Patagonia show that area to have experienced less uplift than areas to the south towards the plains of Tierra del Fuego.

6. Conclusions

1. The dating of wood fragments of 11,130 years BP relates to the flooding of the San Matías Gulf in coincidence with the suggested jump in the sea level rise.
2. During the postglacial minimum sea-level stand, the gulf had been occupied by a steppe in a depression below the sea level. In this sense, water balances during the Upper Pleistocene were similar to present conditions in emergent areas (evapotranspiration exceeding precipitation).
3. While some tectonic depressions became flooded by the postglacial transgression (San Matías, San José, Nuevo gulfs), others remain emergent, but below present mean sea level (Bajo del Gualicho, Gran Bajo Valdés, Salina La Piedra). As the Holocene high stands have much noise, introduced by spatial-related tidal ranges and storm setup, they are not particularly useful for indicating uplift rates. Uplift rates are best considered over the longer timescales of the Quaternary.
4. Radiocarbon dates performed on different materials from Northern Patagonia coastal plains confirm a constant sea-level fall over the last 2600 years.

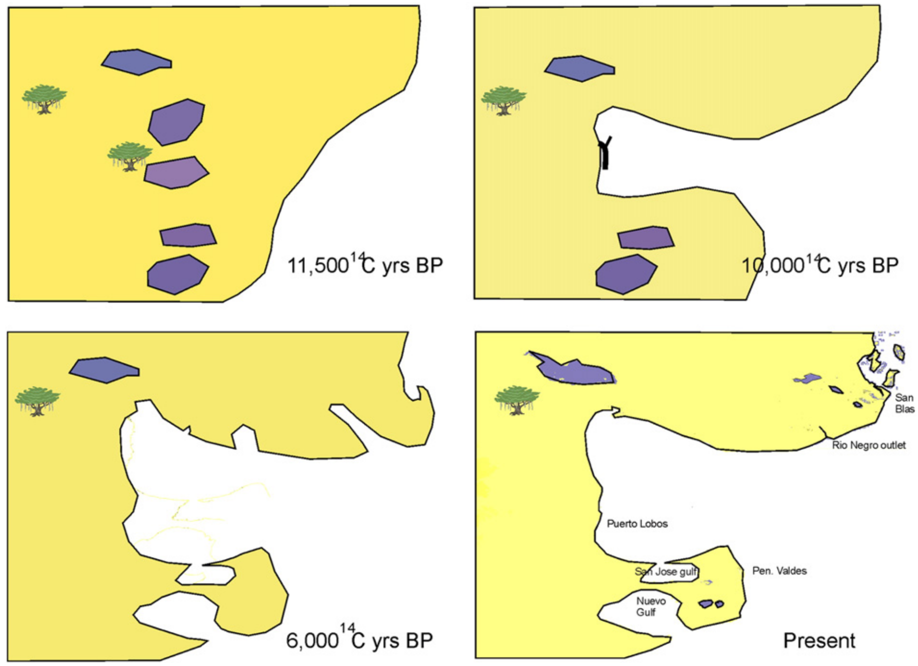

Fig. 4. Schematic evolution of the sea level at San Matías Gulf. The gulf was flooded about 10,000 years when the sea level had surpassed the sill.

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