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DIATOM AND SEDIMENTARY RECORD DURING THE MID-HOLOCENE EVOLUTION OF THE SAN BLAS ESTUARINE COMPLEX, NORTHERN PATAGONIA, ARGENTINA

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Abstract. Diatom and sedimentological analyses of two cores from San Blas Bay and the analysis of historical charts provide information about the environmental evolution of this estuarine complex during the last 5000 yr BP. The Holocene sea-level regression is recorded in San Blas Bay by infilling of a tidal channel. Two sediment cores were drilled at Arroyo Jabalí (San Blas Bridge) and at the former inlet of Arroyo Walker and Arroyo Jabalí (Paso Seco). The diatom record of the San Blas Bridge sequence is dominated by marine and brackish/freshwater plankton and tychoplankton and composed by fine to very fine sand and mud characterizing the infilling of a tidal channel. The Paso Seco sequence is more abundant in sand. Textural and diatom facies are interpreted as the infilling of a tidal channel very similar to the one at San Blas Bridge, that evolved towards the top into a sandflat characterized by the dominance of marine and marine-brackish epipsammon accompanied by marine tychoplankton. Arroyo Walker and Arroyo Jabalí were flowing eastward across a tidal channel during the Holocene. Because of obstruction of the channel, the tidal channel assemblages were replaced by sandflat assemblages. According to historical charts, as late as 1833 a tidal inlet still existed in this sector, which was later obstructed completely according to Twentieth Century charts. At this timescale, eustasy is considered to be a minor environmental control on the dynamics of the system. Instead, control is forced by other factors, such as inlet instability due to morphological changes of the sand barrier whether emergent or submerged.

Key words. Diatoms. Holocene. Coastal environments. Tidal paleoinlet. Argentina

Resumen. REGISTRO DIATÓMICO Y SEDIMENTARIO DE LA EVOLUCIÓN DEL COMPLEJO ESTUARINO SAN BLAS DURANTE EL HOLOCENO MEDIO, PATAGONIA NORTE, ARGENTINA. El análisis de las diatomeas y la sedimentología de dos testigos obtenidos en la Bahía San Blas, y la comparación de cartas náuticas, han aportado información sobre la evolución ambiental de este complejo estuarino durante los últimos 5000 años AP. El relleno de canales de mareas representa la regresión marina del Holoceno en la Bahía San Blas. Se obtuvieron dos testigos, en el arroyo Jabalí (Puente San Blas) y en la antigua desembocadura de los arroyos Walker y Jabalí (Paso Seco). El registro diatómico de la secuencia Puente San Blas está dominado por plancton y ticoplancton marino y salobre/dulceacuícola y compuesto por arena fina a muy fina y fango, caracterizando el relleno de un canal de mareas. Los registros diatómicos y sedimentarios de la secuencia Paso Seco se interpretan como la colmatación de un canal de mareas muy similar a la secuencia de Puente San Blas, que evolucionó hacia una planicie arenosa en el tope, caracterizada por epipsammon marino y marino-salobre acompañado por ticoplancton marino. Durante el Holoceno, los arroyos Walker y Jabalí desaguaban hacia el este, a través de un canal de mareas. El proceso de obstrucción del canal (en Paso Seco) hizo que las asociaciones características de canales de mareas fueran reemplazadas por las típicas de planicies arenosas. De acuerdo a cartas antiguas, en 1833 aún existía una desembocadura de mareas en este sector, que se obstruyó completamente según cartas del Siglo XX. En ese momento, la eustasia habría sido un factor de control ambiental menor en este sistema. Un factor importante es la inestabilidad de la desembocadura debida a cambios morfológicos de la barrera medanosa emergida o sumergida.

Palabras clave. Diatomeas. Holoceno. Ambientes costeros. Paleocanal. Argentina

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STUDIES on coastal evolution and Holocene sea level are based on the investigation of stratigraphic records preserved in coastal environments. Along the microtidal coast of Buenos Aires (Pampean domain), postglacial sea-level fluctuation deposited sediments related to the highest sea-level and represented by the infilling of muddy environments (Espinosa *et al.*, 2003). Coastal plains formed during the regressive phase include barriers, coastal lagoons, tidal flats, marshes and chenier plains (Isla and Espinosa, 1995). Sea-level fluctuation along the meso-macrotidal coast of Patagonia also deposited gravel barriers or infilled estuaries, subject to different dynamic and tectonic conditions (Schellmann and Radtke, 2003; Isla and Bujalesky, 2008). The importance of San Blas Bay lies in its location at the boundary between two tectonically, geomorphologically and climatically different areas, *i.e.*, the Pampean and Patagonian domains.

Witte (1916) published a geologic map of Jabalí Island (San Blas Bay) based on morphological expression and elevations. He defined five development stages for gravel ridges related to sea-level fluctuations during the Quaternary: Pleistocene Stages I, II and III followed by Holocene Stages IV and V. Trebino (1987) reported Holocene beach ridges of

2170±110 and 3450±110 yr BP at heights of 3 m. Rutter *et al.* (1989) reviewed the area but their Electron Spin Resonance (ESR) age datings focused only on the Pleistocene highstands.

Diatoms are useful tools to interpret paleoenvironmental changes in coastal zones because of their sensitivity to salinity, substrate and tidal range changes. According to Denys and De Wolf (1999), the species composition of marine littoral diatom communities is fairly similar throughout the world enabling spatial and temporal correlations. Hassan *et al.* (2006, 2007) studied the distribution of modern diatom assemblages in three estuaries from Buenos Aires Province with the purpose of gathering quantitative ecological information useful for diatom-based paleoecological reconstructions in the region. They concluded that the observed distribution of diatom assemblages was consistent with the salinity classifications proposed for other geographical regions.

Frenguelli (1938) studied the diatom composition of plankton samples and surface sediments collected from the area. Samples were dominated by a mixture of brackish and coastal-marine taxa, constituting an estuarine assemblage under a strong tidal influence. The assemblages always showed relatively high proportions of freshwater diatoms transported from the headwaters of the creek.

The purposes of this paper are (1) to study the paleoenvironmental evolution of this estuarine complex using cores obtained from two different areas, *i.e.*, Jabalí Island (San Blas Bridge) and Paso Seco, and (2) to analyse historical charts and maps of the region in relation to the obstruction of the tidal inlet. In the sense of Witte, the cores studied in this manuscript belong to stages IV and V (Holocene). Results were analysed in relation to Holocene sea-level curves proposed for the Pampas and Patagonia regions and provide information on the dataset for diatom-based paleoenvironmental interpretation of the sedimentary record along the northern Patagonian coast.

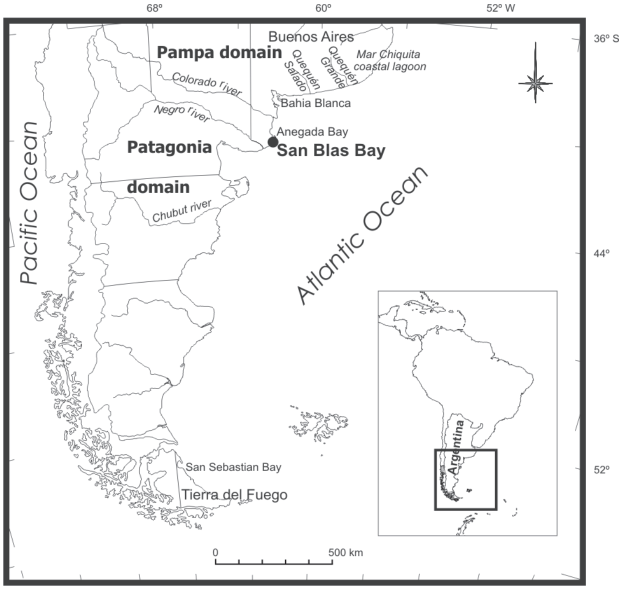


Figure 1. Location map/ *Mapa de ubicación*

REGIONAL SETTING

The coastline of eastern Buenos Aires Province (Fig. 1) is dominated by storms while the Patagonian coast is dominated by tidal effects. Tidal ranges increase towards the Bahía Blanca embayment (Cuadrado *et al.*, 2002) but remain microtidal (1.52–1.76 m) south of San Blas Bay (Isla and Bértola, 2003). Beach drift is from south to north, while tidal effects dominate in Anegada Bay. According to hydrographic charts, the tide slows from 4 to 3 knots within the bay (outside the sampled channel).

San Blas Bay is located on a plateau composed of Lower Pliocene sandstones but close to the southern margin of non-operative delta lobes of the Colorado River (Trebino, 1987; Spalletti and Isla, 2003). Jabalí Island records the complex relationships between the Upper Quaternary beach deposits (Upper Pleistocene and Holocene) composed of gravel (described originally by Witte, 1916) and Holocene sand dunes. The Holocene sea-level drop is recorded by dunes moving landwards and channels becoming obstructed. Present dynamics is also controlled by gravel spits growing northwards (and towards the NW within San Blas Bay) and dunes moving westwards on Jabalí Island.

Considering Holocene sea level variations, San Blas Bay is at the boundary between two different tectonic domains, with evidence of a maximum sea-level higher than 8 m above present average sea-level (Patagonian model in the curve of Schellmann and Radtke, 2003). At the same time, the most ancient evidence of a sea-level highstand is not older than 6000 years ago (Buenos Aires model in the curve of Isla and Espinosa, 1998).

1. *Pampa domain*: Buenos Aires Province (to the north) is assumed to be rather stable, and the low-lying microtidal coastline recorded the glacioeustatic fluctuation assigned to a Mid-Holocene highstand (Isla, 1989; Angulo *et al.*, 2006). Considering the beach deposits produced by storms, a maximum rise of +6 m was proposed (Isla, 1998); however, considering the variations of the MSL recorded from several proxy data, a maximum rise of +3.5 m was accepted (Isla and Espinosa, 1998).

2. *Patagonia domain*: the Patagonia meso-macrotidal coastline has been subject to tectonic uplift induced by the interaction between the South American and Nazca plates. This tectonic effect increases towards the south, where the intermixed glacioeustatic and glacioisostatic effects increased the uplifting trends (Porter *et al.*, 1984; Rutter *et al.*, 1989; Vilas *et al.*, 1999; Rabassa *et al.*, 2000; Schellmann and Radtke, 2003).

MATERIALS AND METHODS

Two sediment cores were drilled with a 7 cm diameter vibracore. One of them was drilled at Arroyo Jabalí (179 cm long), in the access bridge to San Blas Harbour (SB: San Blas Bridge, 40°34′09″S–62°15′10″W). The other (176 cm long) was drilled at the common inlet formerly shared by Arroyo Walker and Arroyo Jabalí (PS: Paso Seco, 40°38′28″S–62°12′49″W) (Fig. 2.2). As the cores were obtained between high and low tides, they could be related approximately to the fluctuation of present mean sea level (MSL). Surface sediments were collected by triplicate with a 20 mm diameter and 100 mm length plastic tube, and some basic water parameters such as pH, temperature, turbidity and salinity were measured using a Horiba U-10 quality checker (Horiba, 1991).

Once cores were split, subsamples were selected for diatom, radiocarbon and grain size analyses. Geochronology is provided using radiocarbon (^{14}C) dating of shells of *Heleobia australis* (d'Orbigny), organic matter and bryozoans. All ^{14}C measurements were taken using Accelerator Mass Spectrometry (AMS) at Beta Analytic Lab, Florida and Arizona AMS Laboratory. Radiocarbon ages were calibrated to calendar years by INTCAL98 (Stuiver *et al.*, 1998). Conventional ages (^{14}C yr BP) and calibrated ages (cal. yr BP±2δ) are presented in Table 1.

Subsamples (one each 10–20 cm) were prepared for diatom analysis by oxidation in hot 30% H_2O_2 and 35% HCl –to remove organic matter and carbonates– and then rinsed with distilled water. Diluted aliquots of cleaned slurries were evaporated onto coverslips, and mounted onto slides with Naphrax®. From each diatom-bearing interval in the cores, a minimum of 300 diatom valves was counted in transects including coverslip edges. All counts were performed under oil immersion (1000x), using a Zeiss microscope equipped with phase contrast optics.

Diatom taxonomy followed Hustedt (1930, 1937–1938, 1959–1966), Germain (1981), Archibald (1983), Krammer and Lange-Bertalot (1986, 1991, 1997), Hartley (1996),

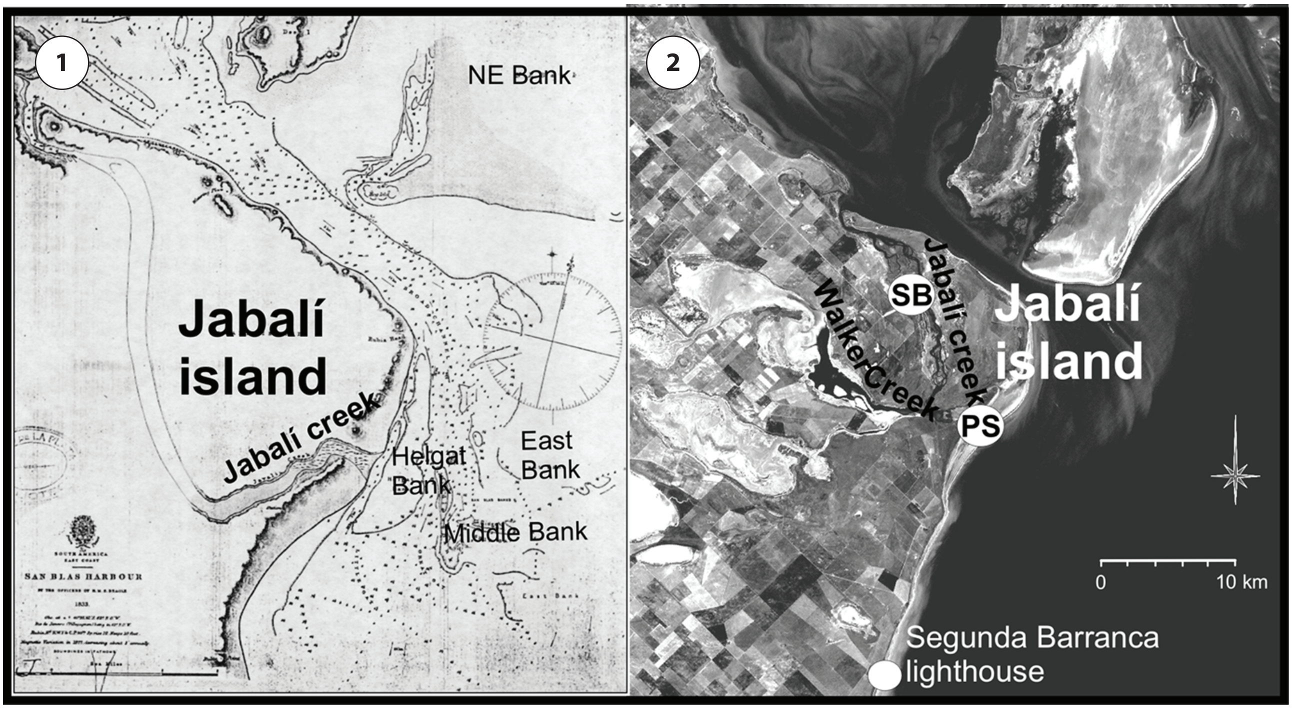


Figure 2. 1, Nautical chart of HMS Beagle's expedition of 1833 (Modified from Isla, 2002). **2,** Location of the coring sites: San Blas Bridge (SB) and Paso Seco (PS)/ ***1,*** *Carta náutica de la expedición HMS Beagle realizada en 1833 (Modificada de Isla, 2002).* ***2,*** *Ubicación de los sitios de muestreo: Puente San Blas (SB) y Paso Seco (PS).*

Rumrich *et al.* (2000) and Lange-Bertalot (2001). Diatom species were grouped in relation to salinity tolerances and life form, following the ecological classification of De Wolf (1982), Vos and De Wolf (1988, 1993) and Denys (1991–1992).

Sediment subsamples (each one 10 cm) were taken for grain-size analysis. Sediment grain-size was analyzed using the dry-sieving technique of Folk (1968). Categories of grain-size included gravel (> 2 mm), coarse sand (> 500 µm), medium sand (250–499 µm), fine sand (125–249 µm), very fine sand (62–124 µm), and mud (silt and clay, < 62 µm).

Cluster analyses were performed on both the sediment grain-size and diatom abundance data matrices using TILIA and TILIAGRAPH software (Grimm, 1991) with the purpose of defining (1) lithological units and (2) diatom assemblage zones. Both were established on the basis of clusters generated by a stratigraphically constrained classification (minimum variance, Euclidean distance). For diatom analyses, all taxa were included in the similarity matrixes. Cluster analysis was not used for the definition of diatom assemblage zones at Paso Seco because of the hiatus in the core. Differences in diatom assemblages are clear enough for defining zones, rendering cluster analysis unnecessary.

Differences among samples considering diatom composition were assessed by means of NMDS (*non-metric multidimensional scaling*). NMDS is a robust ordination technique for community analysis (Minchin, 1987) and was used to create similarity matrixes using Euclidean distance. A simple concept underlies NMDS, leading to a sample map in which inter-sample distances have the same rank order as the corresponding dissimilarities or similarities between samples (Clarke and Warwick, 2001 in Tomasovych, 2006). A numerical measure of the closeness between the similarities in the lower dimensional space is called stress. Stress values range from 0 to 1, with 0 indicating perfect fit and 1 indicating worst possible fit. The NMDS plot was based on similarity matrixes using PAST software (Hammer *et al.*, 2001). Solutions were obtained for one, two and three dimensions. The best solution –in terms of trade-off between complexity associated with increased dimensionality and reduction of stress– was chosen for interpretation.

Old charts drawn by De la Peña (1798; in Isla, 2002) and the crew of HMS Beagle (1833; in Isla, 2002), and modern charts by the *Servicio de Hidrografía Naval* (National Hydrographic Survey, Argentina) were used to recognize morphological changes occurred at the ebb tidal delta of the joint inlet of Arroyo Walker and Arroyo Jabalí (Isla and Espinosa, 2005).

RESULTS

The Walker-Jabalí system (Fig. 2.2), that includes both studied sections (SB and PS), records high salinities (40‰) due to evaporation. In summer 2004 (February-March) three replicate measurements of environmental parameters were taken at low and high tide in each sampling station and mean values were used in this study. At Arroyo Jabalí inlet (into San Blas Bay) 38‰ salinity was measured. Water pH and temperature are higher in the obstructed paleoinlet at Paso Seco (PS) than at San Blas Bridge (SB); turbidity is lower. Environmental parameters measured during the study (estimated summer averages) from both study sites are shown in Table 2.

HISTORICAL CHARTS

Some of the islands mapped in the Eighteenth Century (De la Peña, 1798 in Isla, 2002) evolved into banks forming an ebb-tidal delta complex. In 1833, three banks clearly remained: Helgat, Middle and East, the inlet remaining open as depicted on the nautical chart of the HMS Beagle Expedition (Fig. 2.1). The obstruction of the inlet induced the

Table 1 - AMS radiocarbon dates from the study sites/ **Dataciones radiocarbónicas AMS de los sitios estudiados**

Core	*Depth interval (cm)*	*Conventional ^{14}C yrs BP*	*Calibrated age (cal yrs BP±2δ)*	*Material*	*Lab #*
SB	*17-18*	*Post bomb*	*~ 1957- last 4 years AD**	*Gastropods:* **Heleobia australis**	*AA66207*
SB	*85-86*	*4960±170*	*6176-5316*	*Bulk organic matter*	*AA79992*
SB	*143-146*	*4720 ± 40*	*4820 – 4530*	*Gastropods:* **Heleobia australis**	*Beta 203524*
PS	*160-162*	*987± 43*	*965-792*	*Bryozoans*	*AA69684*
PS	*176-178*	*4904± 70*	*5887-5475*	*Bulk organic matter*	*AA79991*

(*) Calibrated age in years AD/ Edad calibrada en años AD

deposition of sand, as a barrier began to grow. Fine sand progressively covered the gravel ridges (at Eastern San Blas); foredunes overgrew former cliffs (Segunda Barranca lighthouse).

SEDIMENT STRATIGRAPHY

The San Blas Bridge (SB) core is composed mostly of mud (usually more than 50%) and fine sand. It contains three lithological units defined by cluster analyses and described below in chronological sequence from oldest to youngest (Fig. 3.1).

Unit I (170 to 128 cm). Basal sediments comprise fine and very fine sand with well preserved (articulated/whole) shells of *Corbula patagonica* and *Heleobia australis* (dated horizon) and mud (Group I, Fig. 3.1).

Unit II (128 to 78 cm). This interval is composed of mud with very fine sand (Group II, Fig. 3.1).

Unit III (78 to the top). Fine sand percentages increase to the top indicating the effects of eolian activity on the intertidal muds (Group III, Fig. 3.1).

The core from Paso Seco (PS) contains more sand than the core drilled at the bridge (Fig. 3.2). Cluster analysis divided the sequence in three zones with the dominance of fine and very fine sand.

Unit a (176 to 118 cm). Fine and very fine sands are accompanied by medium sand and mud (Group a, Fig. 3.2).

Unit b (118 to 35 cm). The medium sand content increases (Group b, Fig. 3.2).

Unit c (35 to the top). Fine and very fine sand dominate, but are accompanied by black mud with shells (Group c, Fig. 3.2).

DIATOMS

The diatom record of the SB core was represented by 63 taxa. The relative frequencies of the 38 diatom taxa (over 1%), representing no less than 80% at least assemblage, are illustrated on Figure 4. Three diatom zones were defined according to Q-mode cluster analysis:

Zone 1 (between 160 and 130 cm). Diatom assemblages were dominated by *Cymatosira belgica* Grunow, *Paralia sulcata* (Ehr.) Cleve, *Podosira stelligera* Bailey (Mann), *Rhaphoneis amphiceros* Ehr., *Thalassiosira* spp. and *Cyclotella ocellata* Pantocsek.

Zone 2 (between 130 and 10 cm). *Cymatosira belgica* is the most frequent taxon (usually more than 50%) accompanied by *Rhaphoneis amphiceros* and *Thalassiosira* spp.

Zone 3 (between 10 cm to the top). A peak of epipsammic diatoms as *Planothidium delicatulum* (Kützing) Round and Bukht and *Auliscus sculptus* (Smith) Ralfs, the epiphyte *Cocconeis* cf. *costata* var. *pacifica* (Grunow) Grunow accompanied by *Cymatosira belgica* and *Paralia sulcata* in low percentages was observed to the top.

Marine tychoplankton and plankton dominate the sequence (Fig. 5). The base is dominated by marine plankton and tychoplankton accompanied by brackish-freshwater tychoplankton. Marine tychoplankton increases towards the middle of the sequence. Marine brackish epipsammon and epiphyte diatoms also increase further up the sequence.

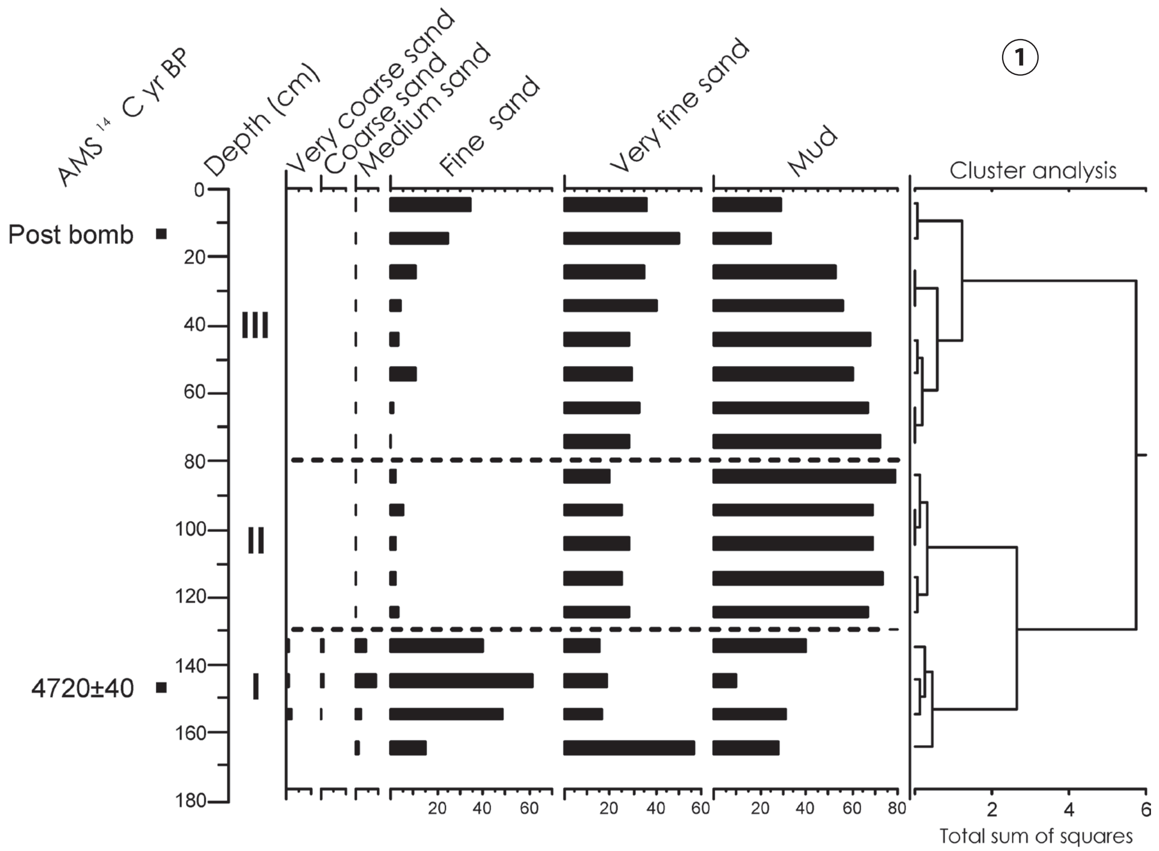
A total of 51 diatom species were identified at Paso Seco, of which 35 taxa occurred in percentages over 1% in at least two samples (Fig. 6). Marine tychoplankton and plankton dominate the basal section (20 cm), the same ecological groups dominating the SB core. The middle section contains no diatoms. At the top (between 15 and 0 cm), diatom assemblages change to marine and marine/brackish epipsammon accompanied by marine tychoplankton (Figure 7). The most abundant taxa are *Opephora pacifica* (Grunow) Petit, *Petroneis granulata* (Bailey) D.G. Mann and *Paralia sulcata*.

COMPARISON BETWEEN SAN BLAS BRIDGE AND PASO SECO

The variation within –and overlap between– groups obtained by cluster analysis was best explored using the ordination method NMDS (Figure 8). The two methods jointly provided a complete analysis of the diatom data. NMDS arranged diatom samples in a specified dimensional space according to the rank order of their ecological similarities. A stress value of 0.085 was obtained. This low stress value indi-

Table 2 - Environmental parameters (summer estimated averages) from the study sites/ **Parámetros ambientales (medias estimadas de verano) de los sitios de estudio**

	San Blas Bridge (SB)	***Paso Seco (PS)***
pH	*7.72±0.01*	*8.36±0.01*
Temperature (ºC)	*20.1±0.1*	*21.0±0.1*
Turbidity (NTU)	*20.0±1.0*	*8.0±1.0*
Salinity (‰)	*40.0±1.0*	*40.0±1.0*


①
AMS 14 C yr BP
Depth (cm)
Very coarse sand
Coarse sand
Medium sand
Fine sand
Very fine sand
Mud
Cluster analysis
Post bomb
4720±40
III
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I
0
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20 40 60
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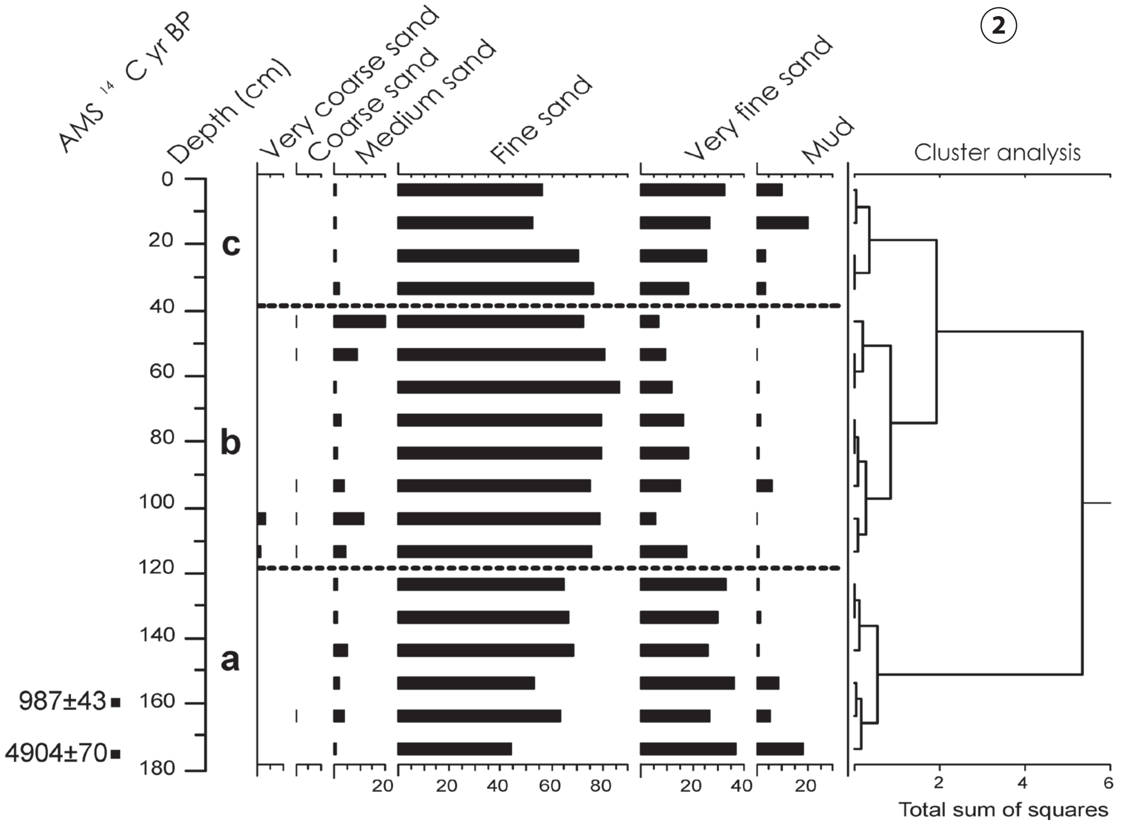
Total sum of squares


②
AMS 14 C yr BP
Depth (cm)
Very coarse sand
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Medium sand
Fine sand
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Total sum of squares

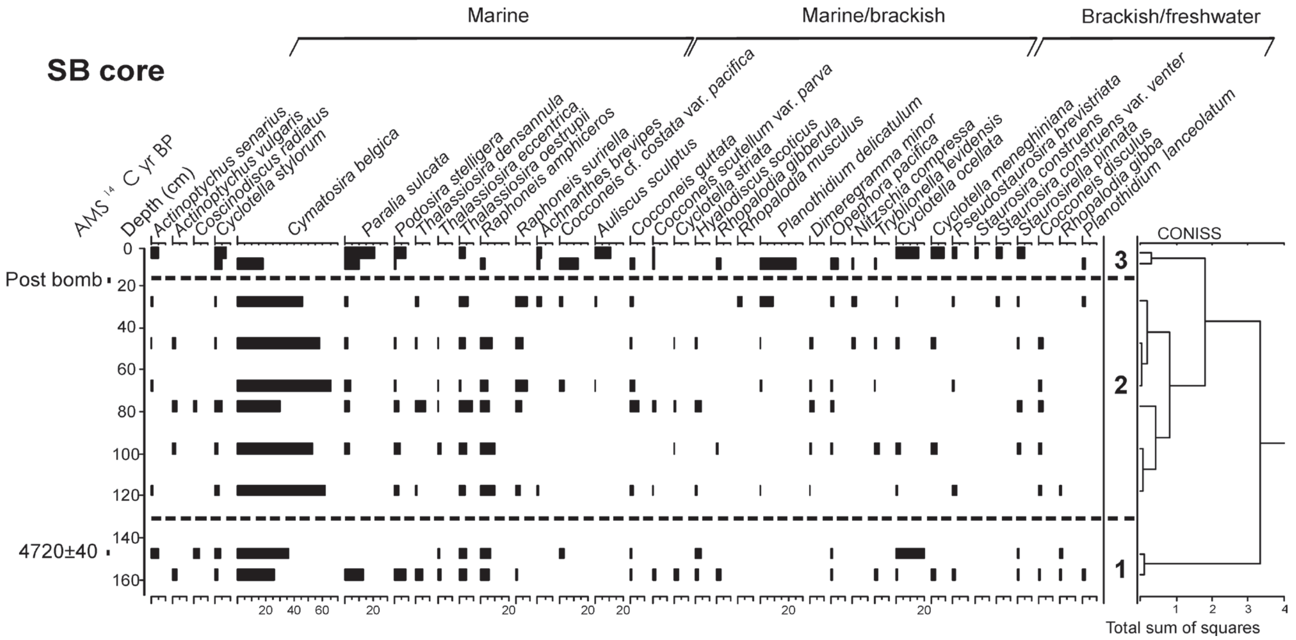

Figure 4. Diatom diagram from San Blas Bridge/ *Diagrama de diatomeas de Puente San Blas.*

cates that the data indeed remained in the two dimensional space. The NMDS ordination plot revealed differences in the structure of the assemblages. Samples showed a distributional pattern clearly related to environment type. Figure 8 shows that samples belonging in groups 1 and 2 of SB diagram (Fig. 4) remained together with the samples from the base of PS (Fig. 6). All of them are characterized by the dominance of marine plankton and tychoplankton diatoms and represent a tidal channel environment. The samples from the top of PS suggest sand-flat conditions.

GEOCHRONOLOGY

Shells of *Heleobia australis,* bulk organic matter and bryozoan samples were dated by AMS ^{14}C (Tab. 1). All ages are reported in uncalibrated radiocarbon yr. BP and calibrated ages (cal. yr. BP ± 2δ). An exact 2σ calibration of the top of SB sequence (post-bomb) was not possible because the fraction modern value for this sample (1.0612±0.0044) crosses over two points of the calibration curve. An approximate age for this sample, based on a rough reading of the calibration curve, is (1) ~1957 AD or (2) approximately within the last four years. Both of these values are very rough estimations.

Radiocarbon dates indicate that the studied sections were deposited since *ca*. 5000 years BP to present. Marine radiocarbon dating is particularly sensitive to time lag because of differencial uptake between the atmosphere and the sea at different places. Several Regional Reservoir Effects (RRE) have been calculated for different seas (Hughen *et al*., 2004); however, this effect is known to vary in time too (Spennemann and Head, 1996; Ulm, 2006). Regarding estuarine environments, the reservoir effect (RE) surely has varied in time in relation to the size (shape and depth) of the estuary/coastal lagoon, ground water influx, temperature, light effects, tidal action (Spennemann and Head, 1996; Ulm, 2006). Moreover, shells of different mollusk species should have their own signature in relation to C uptake, particular location and behavior (Spennemann and Head, 1996). Particular correction factors (ΔR) are the deviations between calculated RE and the RRE. For the Western South Atlantic, Angulo *et al.* (2005) postulated a regional marine reservoir correction (ΔR) of 33±24 ^{14}C yr. and Gómez *et al.* (2008) postulated a ΔR of -40±46 to 50±46 ^{14}C yr. for the Bahía Blanca estuary (200 km north of San Blas Bay).

Dating of gastropod shells from the base (143–146 cm) of SB sequence (4720±40 ^{14}C yr BP; 4820–4530 cal. yr. BP) yielded an age younger than the dating of organic matter from the level located above at 85–86 cm (4960± 170 ^{14}C yr BP; 6176–5316 cal. yr. BP) as shown in Table 1. The discrep-

Figure 3. 1, Grain-size diagram of the San Blas Bridge core. **2,** Grain-size diagram of the Paso Seco core/ ***1****, Diagrama de tamaño de grano del testigo Puente San Blas.* ***2****, Diagrama de tamaño de grano del testigo Paso Seco.*

ancy of ^{14}C dates between gastropod shells and organic matter has been interpreted as the result of reservoir effect, but it can not be the case because the mollusk shell would be older instead of younger. Dated organic matter from the middle of the sequence may have been reworked from the marshes surrounding the estuarine complex. Lateral migration of the channel and consequent erosion of levees may produce concentrations of peat (*gyttja*) in the sequence. Therefore, datings performed on shells of the epifaunal gastropod *Heleobia australis* are considered more reliable (Tab. 1).

DISCUSSION

The San Blas Bay estuarine complex exhibited similar salinity conditions during the last *ca*. 5000 years BP. Paleoenvironmental interpretations are based on major trends in the relative abundance of diatom ecological groups. Marine plankton and tychoplankton, and marine brackish epipsammon are the dominant ecological groups in both cores and modern sediment samples. These can be used to characterize different tidal subenvironments. Tide transported planktonic diatoms are often found in tidal-channel and tidal-inlet sediments (Vos and De Wolf, 1993). In these environments the conditions of high current velocities and poor light were unfavorable for the development of a diatom population on the sediments (benthic and/or epiphytic groups) (Anderson and Vos, 1992). The most abundant taxon, *Cymatosira belgica*, lives in the littoral zone at a water depths of 3–10 m characterizing tidal inlets and large tidal channels (Vos and De Wolf, 1988). *Paralia sulcata* is very abundant, especially in the PS sediment core. The tychoplanktonic nature of *Paralia sulcata* must be considered when interpreting its usefulness as a paleoindicator. This cosmopolitan species is more resistant to dissolution than other diatom species (Ryu *et al*., 2005) and especially abundant in fine-grained, organic-rich sediments (Zong, 1997). It occurs at the base of the PS sequence, between 4904 ± 70 ^{14}C yr BP (5887–5475 cal. yr. BP) and 987 ± 43 ^{14}C yr BP (965–792 cal. yr. BP) and at the top. *Paralia sulcata* is considered an indicator of coastal conditions (Mc Quoid and Nordberg, 2003).

Assemblages dominated by *Cymatosira belgica*, accompanied by *Paralia sulcata, Rhaphoneis amphiceros* and *Thalassiosira* spp. were recorded in modern sediment samples from the

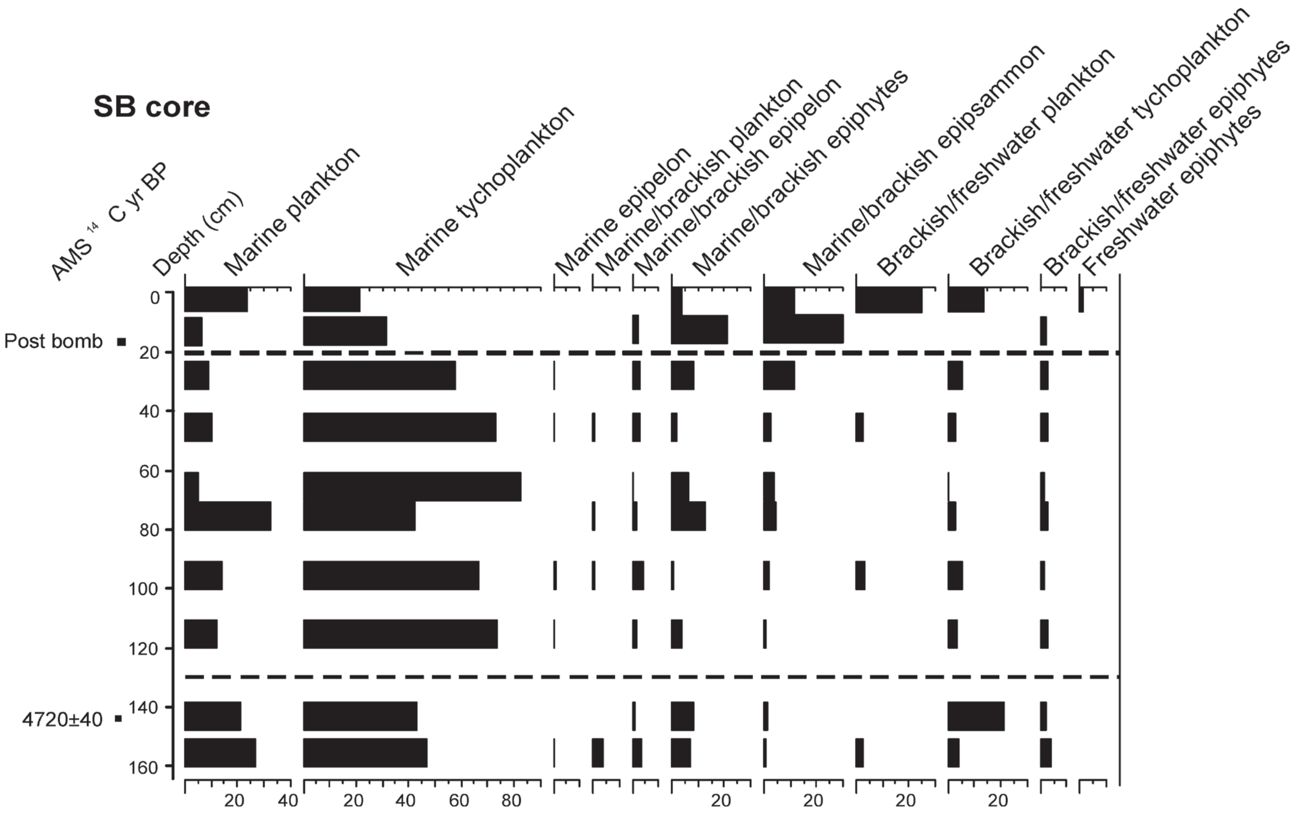

Figure 5. Distribution of the main diatom ecological groups in San Blas Bridge/ *Distribución de los principales grupos ecológicos en Puente San Blas.*

outer part of the Quequén Salado estuary (350 kms north of San Blas Bay) in salinities ranging from 15 to 37‰ (Hassan *et al.*, 2007) and in modern sediment samples at the mouth of the Río Negro estuary (69 kms south of San Blas Bay) in salinities of 23‰. In addition, this assemblage was reported by Escandell *et al.* (2009) dominating late Holocene coastal sediments of the Río Negro estuary. This marine/brackish assemblage constitutes a useful analog for marine-brackish tidal environments along the Argentinean coast (Hassan *et al.*, 2007), and it is well represented in SB core and in basal sediments of PS core. Assemblages of sediment cores are rather similar to those described by Frenguelli (1938) from plankton and sediment samples of San Blas Bay. This author described the dominance of marine taxa accompanied by some brackish and freshwater species as typical of tide-influenced channels. The dominance of marine and marine/brackish plankton and tychoplankton in SB core indicates the infilling of a tidal channel (Isla and Espinosa, 2005).

Marine/brackish epiphytes and epipsammon taxa are important towards the top of SB core; accompanied by marine plankton, these assemblages are characteristic of mudflats. In these sediments, the relative abundance of autochthonous marine/brackish groups generally fluctuates between 15–40% and the allochthonous component is generally very large (Vos and De Wolf, 1993). Changes among the three diatom zones (Fig. 4) indicate a freshwater input into the channel by 4720±40 ^{14}C yr BP (4820–4530 cal yr BP), as indicated by a peak of brackish/freshwater tychoplankton (Fig.5). The typical tidal channel assemblages were developed between 4700 ^{14}C yr BP and recent time. Today, a shallower environment such as a mudflat is evidenced by the increase of marine/brackish epiphytes and epipsammon, accompanied by brackish/freshwater plankton and tychoplankton.

In the fossil record of intertidal sand flats, the autochthonous benthic community is generally well represented (Vos and De Wolf, 1993). Most of the benthic community consists of small epipsammic diatoms (Vos *et al.*, 1988). *Opephora pacifica* is an epipsammic taxon which is dominant at the top of the PS sequence. It appears in high proportions within the tidal inlet of Mar Chiquita Lagoon in salinities of 7–19‰ and in Quequén Grande River (1.7 to 9 km from the mouth) in salinities of 8–25‰ (Hassan *et al.*, 2006).

The PS core is interpreted as the infilling of a tidal channel, very similar to SB in terms of diatom assemblages, that evolved into a sandflat towards the top characterized by the dominance of marine and marine-brackish epipsammon accompanied by marine tychoplankton species. The base was dated at 4904±70 ^{14}C yr BP (5887–5475 cal yr BP). Taking into account that the inlet was operative in 1833 (Fig. 2) and it was closed in 1912 (Witte, 1916), it would have evolved rapidly, closing in less than 80 years. The sterile middle section (after 987 ±43 ^{14}C yr BP, 965–792 cal yr BP) can be related to the formation of the sandy spit.

The infilling of tidal channels was common during the Late Holocene at the delta of the Colorado River (Weiler, 2001) and at the northern shore of Bahía Blanca complex estuary (Farinati *et al.*, 1992; Grill and Quatrocchio, 1996; Spagnuolo, 2004). Erosion of the sand banks has been recog-

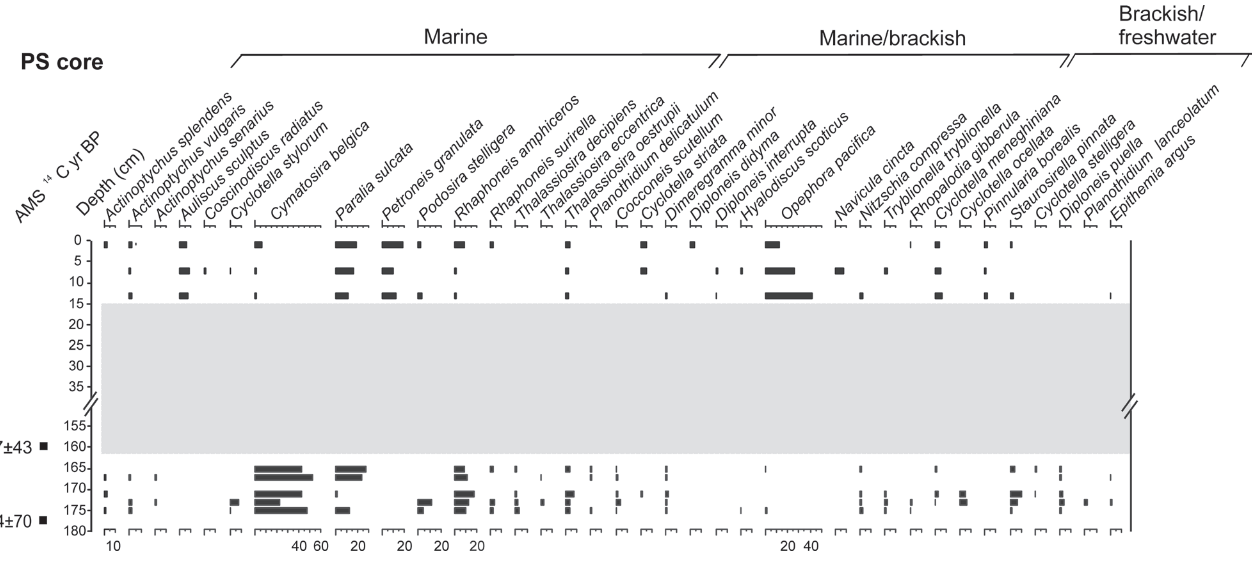

Figure 6. Diatom diagram from Paso Seco. Grey-shaded area is representing the sterile samples/ *Diagrama de diatomeas de Paso Seco. El área gris sombreada representa las muestras estériles.*

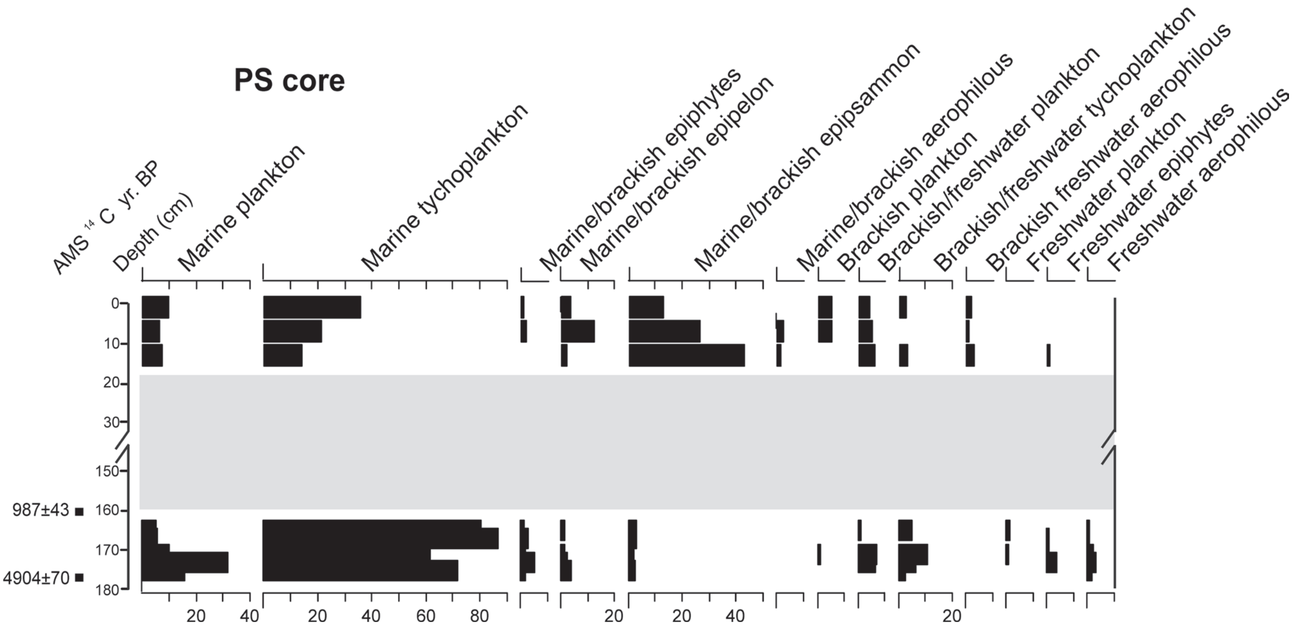

Figure 7. Distribution of the main diatom ecological groups in Paso Seco. Grey-shaded area is representing the sterile samples/ *Distribución de los principales grupos ecológicos en Paso Seco. El área gris sombreada representa las muestras estériles.*

nized in the northern part of Anegada bay due to the abandonment of the Colorado River (Spalletti and Isla, 2003). Here, at the inlet of San Blas Bay, an ebb-tidal delta became non-operative, and therefore, the outer sand banks were eroded.

The SB sequence extends –without any sedimentary evidence of significant unconformities– from 4720±40 ^{14}C yr BP (4820–4530 cal yr BP) close to the bottom, to a post-bomb dating, in a manner similar to that of many Holocene estuarine sequences over the MSL of Buenos Aires Province (see Espinosa, 2001; Espinosa *et al.*, 2003; Vilanova *et al.*, 2006). In the area, Trebino (1987) sampled beach-ridge sequences dated between 3450±110 and 2170±110 ^{14}C yr BP, with no evidence of unconformities.

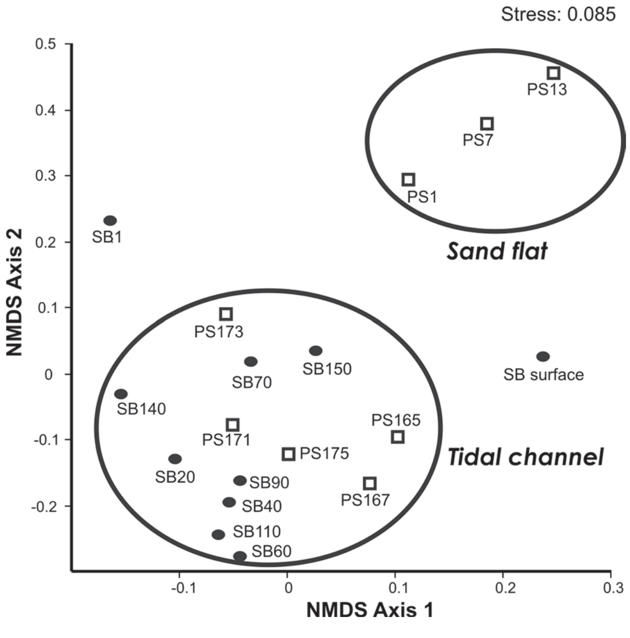

Figure 8. NMDS ordination plot of samples from San Blas Bridge (full circles) and Paso Seco (empty squares)/ *Gráfico de ordenación NMDS de las muestras de Puente San Blas (círculos rellenos) y Paso Seco (cuadrados vacíos).*

Several estuarine areas of Patagonia were subject to progradation due to the Holocene regression (Isla and Bujalesky, 2008) and SB sequence confirms the relative stability of the region during last 5000 years. Within this bay, Jabali Island has prograded about 6 km towards the northeast. The inlet of the Chubut River was subject to a southward migration during the Mid-Holocene regression, and a progradation of about 1.12 m/yr between 4987±106 and 1009±88 ^{14}C yr BP (Monti, 2000). The sand flat of San Sebastián Bay (Tierra del Fuego) prograded between 0.6 and 2.1 m/yr in the last 5600 yr BP; this progradation also fluctuates from 2.35 m/yr at the early stages of the regression, to 0.6 m/yr when approaching the present sea level (Vilas *et al.*, 1999). The gravel spit that caused the migration of the Río Chico in Tierra del Fuego induced a progradation (transverse to coast) of 0.43 m/yr in the vicinities of Laguna Arcillosa (Bujalesky *et al.*, 2001).

In the Southern Hemisphere there are several examples of estuaries that became enclosed since mid Holocene. At Lagoa dos Patos (Southern Brazil), sedimentation began *ca.*

8,000 years ago (Toldo *et al.*, 2000) and geophysical methods evidenced that a paleoinlet remained operative at 2450–2080 ^{14}C yr BP (Toldo *et al.*, 1991; Weschenfelder *et al.*, 2005). However, this Holocene paleoinlet was related to the Pleistocene valley of the present Camaquá River (Weschenfelder *et al.*, 2008). Historical inlets of ages equivalent to the closed inlet of Paso Seco have been recorded by vibracores and Ground Penetrating Radar (GPR) surveys along the Massachusetts coast (USA) (Buynevich and Donnelly, 2004). In the coast of Queensland (Australia), Louisa Creek has been infilling over the past 8500 years (Lessa and Masselink, 1995). In the same way that tidal channels naturally evolve towards their infilling, the opposite could also have happened. On the Belgian coastline, a tidal channel that became inactive during early to mid-Holocene was activated again during the late Holocene sea-level rise. Baeteman (2005) suggested that the accumulation of water in the lowlands induced incision and "cleaning" of the former tidal channels.

For the Argentine shelf, an uplifting trend of 8–9 cm/kyr has been proposed for the postglacial transgression (Guilderson *et al.*, 2000). In the Río Negro estuary (69 km south of San Blas) a maximum sea-level of of +9 to10 m was originally proposed for the Holocene transgression (Auer, 1959). More recently, and dealing with different localities in Patagonia, two sea-level curves were reconstructed, *i.e.* the beach-ridge curve, with maximum levels (storm deposits) at +10 m asl about 7–8 kyr ago, dropping to altitudes of 2.5 m (present storm berms). The curve based on terraces from valley mouths indicated a maximum of 5 m approximately 6000 years ago, dropping to 3±1 m about 5500 years ago (Schellmann and Radtke, 2003). The differences between the "storm" curves and the "estuarine" curves should be assigned to the different dynamics of the Buenos Aires (microtidal, storm-dominated) and Patagonian (meso-macrotidal) coasts. San Blas Bay is located at the boundary between these two regions, and sea-level indicators confirm the infilling of tidal channels and the progradation of a beach-ridge plain (Jabalí Island) during the Late Holocene regression.

CONCLUSIONS

1. The Holocene sea-level regression is recorded in San Blas Bay by a beach-ridge plain along Jabalí Island and by the infilling of the tidal channel of an estuarine complex.
2. Walker and Jabalí creeks flowed to the Atlantic Ocean (east) during the Holocene, across a tidal channel characterized by marine and marine-brackish plankton and tychoplankton diatoms.
3. The assemblage dominated by *Cymatosira belgica*, accompanied by *Paralia sulcata, Rhaphoneis amphiceros* and *Thalassiosira* spp. is a marine/brackish group that constitutes a useful proxy for tidal environments in Holocene sedimentary records of the Patagonian coast. This assemblage is dominant in the SB core and is present in modern sediments in Jabalí Creek, while in PS core it is recorded only at the base.
4. According to old charts, a tidal inlet was closed between 1833 and 1912. As a consequence of the channel obstruction, marine-brackish plankton and tychoplankton diatoms were replaced by marine-brackish epipsammon taxa living on sand flats.

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