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GEOSCIENCES

Holocene coastal evolution of Colorado River Delta based on diatom assemblages, Northern Patagonia, Argentina

ROCÍO FAYÓ, MARCELA ALCIRA ESPINOSA & FEDERICO IGNACIO ISLA

Abstract: Diatom assemblages and coastal sedimentary facies succession in the deltaic plain of the Colorado River (Argentina) were studied in order to reconstruct the environment conditions in response to Holocene eustatic sea-level changes and delta progradation. Samples were selected from a 200-cm core (39°35’52” S, 62°6’43” W). Chronology was based on radiocarbon datings in bulk samples and mollusk shells. Nine lithological units were recognized where fine and very fine sand predominate. The core sediments were dominated by tychoplanktonic coastal-marine diatoms. The accompanying flora included stable marine-coastal taxa and allochthonous fluvial fresh-brackish species. Three diatom zones (DZ) were established based on cluster analyses. The LCH site was significantly affected by Late Pleistocene and Holocene sea-level fluctuations, and the progradation of the deltaic lobe during the last *ca*. 7,000 ^{14}C yr. BP. Ancient tidal channels were flooded in the early Holocene postglacial transgression. Erosive and re-working processes associated with the formation of estuarine channels, affected valves preservation, yielding with barren sections. Tidal flats and marshes have developed in the area during the late Holocene regression phase. The comparison of the sedimentary sequence with deltaic facies evolution models, confirm the presence of a hiatus, which masks the Holocene Maximum and highstand.

Key words: deltaic facies, diatoms, Holocene, Northern Patagonia, progradation, sea-level change.

INTRODUCTION

The Colorado River Delta is one of the two active deltaic systems in Argentina. It is located at the south of Buenos Aires province and prograde into the open mesotidal coast of the Atlantic Ocean (Isla & Toldo 2013). Since the 1970s deltas have been classified as rivers-, waves- and tidal dominated (Li et al. 2011). The variation of natural forcing factors and anthropogenic pressure can affect the rate of progradation and deltaic growth. These include hydrological and climate changes in the fluvial basin (discharge factor), the tectonic activity (relief, slope and subsidence) and changes of the sedimentary balance (Chiocci & Normark 1992, Hori et al. 2011). The deltaic evolution shows complex and dynamic sedimentary processes over time and supposes continuous reworking events (Colombo et al. 2014). Different portions of the delta may be in the growth process, while other areas may be subject to destructive conditions by waves and tides due variations in water-sedimentary fluvial processes (Elliott 1986, Spalletti & Isla 2003). The sudden abandonment of sectors of the deltaic plain by avulsion processes, temporary migration of distributary channels, deactivation/activation of paleochannels in oxbow lakes and changes in depositational input by flow regulation by dams or irrigation channels, among others

(Frazier 1967, Stouthamer & Berendsen 2007, Makaske et al. 2012, Akter et al. 2015, Pierik et al. 2018). When these modifications of depositional factors are conjugated with changing eustatic environments, their effects on the deltaic architecture are accentuated (Spalletti & Isla 2003, Hori et al. 2004, Ta et al. 2005).

Most modern deltaic systems were formed during the later stages of the postglacial transgression of the mid-late Holocene (Ta et al. 2001, 2005, Zong et al. 2009, Colombo et al. 2014, Wei & Wu 2011, Jeong et al. 2018). Holocene eustatic sea level changes have modified coastlines, and baseline variations had effects over the fluvial sediment supply (Woodroffe et al. 1993). In the Northern Hemisphere, the Holocene sea-level-rise was persistent; however, during the last *ca.* 8,000-6,000 years BP, a relative slowdown of this rise favored deltaic progradation (Nguyen et al. 2000, Stanley & Warne 1994, Ta et al. 2002a, b, Wei & Wu 2011). In contrast, in the Southern Hemisphere the sea-level increased until a maximum level *ca*. 7,000-5,000 years BP and later it fell to the present level, which allowed the construction of deltaic lobes (Spalletti & Isla 2003, Cavallotto et al. 2004, Castro et al. 2013, Melo et al. 2013).

Evolutive analysis of the present deltaic conformations incorporates time as a variable and the fluctuations in Holocene sea level (Boyd et al. 1992, Dalrymple et al. 1992). According to Boyd et al. (1992) the regressive deltaic geoforms prograde to transgressive and regressive stages; however, if during the transgression the contribution of fluvial sediments was scarce, the ancient fluvial valley is flooded, dominating the erosive features and the formation of estuaries (Boyd et al. 1992). During the subsequent regressive phase, estuaries become clogged due to delta progradation, forming extensive tidal flats and salt marshes (Dalrymple et al. 2003, Dalrymple & Choi 2007). After that, different authors have documented the succession of transgressive and regressive facies in Holocene sequences extracted from the deltaic plains (Ta et al. 2002b, 2005, Hori et al. 2004, Castro et al. 2013, Jeong et al. 2018).

The reconstructions from sediment cores are characterized by high-resolution analysis of sedimentary facies supported by micropaleontological evidence (Wei & Wu 2011). Due to their sensitivity to salinity changes, the diatoms represent one of the most used proxies to reinforce the interpretation of sedimentary facies and deltaic evolution based on eustatic variations (Ta et al. 2001, Castro et al. 2013). These siliceous unicellular microalgae are excellent indicators due to its high ubiquity in aquatic or humid habitats, short generation times and sensitivity to environmental changes, high abundances and diversity (Round et al. 1990, Vos & De Wolf 1988, 1993, Flower 2005). Biogenic siliceous walls resist the diagenetic degradation and award them a high preservation capacity (Cooper et al. 2010). In consecuence, diatoms form abundants and representative fossil records of phytoplankton and microphytobenthos, and provide detailed archives of paleolimnological data (Taffs et al. 2017, Espinosa et al. 2020).

In Argentina, the diatoms have been successfully used as proxies for Holocene paleoenvironmental reconstructions in numerous studies. Qualitative and quantitative diatomological analysis of estuarine-coastal transitional environments have been usefull to infer variations in salinity, conductivity, turbidity, depth, sedimentation rates and changes of the coastline positions in the past. These inferences have allowed to reconstruct Holocene transgressive or regressive processes and their influence on the evolution of the coastal geoforms (Hassan et al. 2009, 2011, Espinosa & Isla 2011, Espinosa et al. 2012, Fayó & Espinosa 2014, Isla et al. 2015).

Most of the Quaternary estuarine-coastal reconstructions based on diatoms in Argentina were carried out in the last three decades, and were concentrated in the province of Buenos Aires (Espinosa 2008). Despite the fact that the Argentine deltaic systems are located in this province, studies of deltaic fossil floras and paleoenvironmental reconstructions are extremely scarce, generating an underestimation of real diatom diversity and biased and incomplete regional interpretations. Recently, Fayó et al. (2018, 2020a) performed the study of two sedimentary sequences in the deltaic plain of the Colorado River at 37 and 22 km inland from the present coastline. These studies together with the modern flora analyses of the middle-lower Colorado River basin (Vélez-Agudelo et al. 2017) allowed to identify a stable and diverse composition of Holocene diatom flora, distinguishing typical assemblages of delta. A classic autoecological approach with modern analogs, allowed to identify changes in salinity and water depth in response to variations in the position of the coastline.

In this contribution, diatom assemblages of a coastal sedimentary succession in the deltaic plain of the Colorado River (Argentina) were studied, in order to reconstruct the paleoenvironmental conditions of the delta in response to Holocene sea-level changes, the variation of the coastline position and the progradation processes. The specific objectives were: (1) to analyze the diversity of the Holocene diatomological flora in the region; (2) to identify paleoenvironments based on changes in salinity and depth, through the variation in the fossil assemblage's composition and autoecology data, and (3) to propose the succession of sedimentary facies in deltaic environments based on micropaleontological and sedimentological evidence.

Regional setting and study area

The Colorado is an allochthonous river that flows across central Argentina (Spalletti & Isla 2003). It is born in the Andean zone, from the confluence of the Barrancas and the Grande rivers, and runs E-SE for 923 km until its outlet, draining 34,100 km^2 (González Uriarte 1985, Alcalde 2014). Of all Patagonian rivers it carries the highest sediment load (mean annual solid 569,000 tons), which favors the formation of an extensive fluvial-deltaic system (Blasi 1986). According to the Galloway`s (1975) ternary classification scheme, the Colorado River form a regressive delta dominated by waves (Spalletti & Isla 2003). The Holocene delta extends from the "Peninsula Verde" (northern limit) to the "Otero" Island to the south, and includes ancient non-functional deltaic lobes, subject to destructive conditions by waves and tides, extending about 900 km^2 (Codignotto & Marcomini 1993, Spalletti & Isla 2003). The dating of ancient coastlines of its deltaic plain has allowed estimating a progradation rate of 5 m/year in the last 1,000 years (Fayó et al. 2020a).

In the delta plain, the river forms three active or intermittent meandering distributary channels and numerous afunctional courses and oxbow lakes (Weiler 1988, Fayó et al. 2018, 2020b). The active river courses include from north to south, the Colorado Nuevo, the Colorado and the Colorado Viejo arms, the last one discharging into the Anegada Bay (Figure 1).

The river is characterized by a pluvio-nival hydrological regime, without a significant current contribution of water by its tributaries (Butacó and Curacó streams). The lower basin has a mean annual flow of 140 m^{3}seg^{-1}, with maximum values in December (summer, 818 m^{3}seg^{-1}) and minimum values in August (winter-spring, 32 m^{3}seg^{-1}), and it has also registered extraordinary seasonal floods by rainfall effects of 650 m^{3}seg^{-1} (Cappannini & Lores 1966). Due to its great

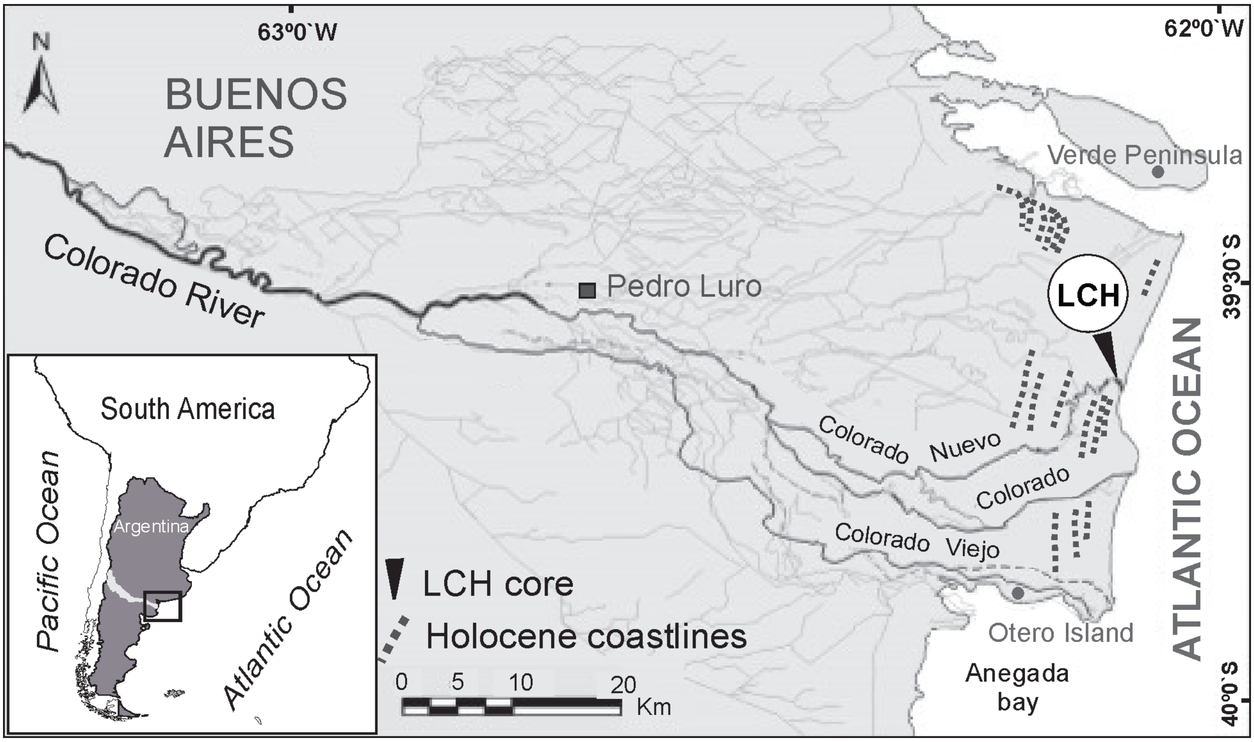

Figure 1. Location map of the Colorado River Basin, Argentina. The study site "La Chiquita" (LCH) is located at the deltaic plain (1.2 km from the coast). Dotted lines: Holocene's coastline positions (Modified from Codignotto & Weiler 1980).

extension, the Colorado River runs through a precipitation gradient that increases towards the east, passing through arid to semi-arid-temperate conditions and presents 384 mm of mean annual rainfall in the lower basin (Alcalde 2014). The Colorado River runs through old saline substrates with little drainage, because of this it has brackish-fresh waters (Spalletti & Isla 2003, Biasotti et al. 2014). Salinities are of 0.5±0.6‰ in summer and 0.84±0.13‰ in winter, and its concentration increases towards at the mouth due to the marine influence (6.4–29.7‰; Vélez-Agudelo et al. 2017). In historical times, the river occasionally received hypersaline waters from the Curacó River (Isla & Toldo 2013).

The Colorado River tectonic basin is one of the basins of the Atlantic margin that was originated as part of a Rift system during the mid-late Jurassic or late Jurassic-early Cretaceous, as a consequence of the Gondwana breakup (Fryklund et al. 1996, Juan et al. 1996). Its sedimentary fill would have a maximum thickness of 7,000 m and extends to the late Miocene-Late Pliocene, corresponding to the Fm. Río Negro (Visconti et al. 2003, Folguera et al. 2015). Over the tectonic basin can be distinguished an extensive fluvial agradational plain with a succession of staggered river levels (terraces); this plain decreases in a W-E direction, between 100 and 10 m and was formed by the Colorado and the Negro River (González Uriarte 1985). Traditionally the deltaic plain of Colorado River has been considered a tectonically stable region. Recently, Seitz et al. (2019) stated that the Andean orogeny during the Miocene reactivated pre-existing structures and produced neotectonic geomorphological changes during the Upper Pleistocene.

The geological and morphological evolution of the Colorado River delta plain has been mainly explained as a result of eustatic and climatic changes (Codignotto & Weiler 1980, Weiler 2000, Spalletti & Isla 2003, Melo et al. 2003, 2013, Martínez et al. 2019). Today, the Colorado River delta is the remnant of a deltaic system with greater extension during the Pleistocene-Early Holocene (Spalleti & Isla 2003, Melo et al. 2003, 2013). Most of these studies inicially outlined the influence of Holocene stages in the delta evolution, using the paleontological information as a complementary biochronological tool (Charó et al. 2015). However, in the last ten-years, regional palaeoenvironmental reconstructions based on different lines of evidence have started to be made it: malacological evidence (Fucks et al. 2012, Charó et al. 2013, 2015), diatoms (Fayó et al. 2018, 2020a), forams on the continental shelf of the basin (Caramés & Malumián 2000, Bernasconi & Cusminsky 2015), the palynological evidence (Fernández 2014), and the geoarchaeology studies (Martínez & Martínez 2011, Martínez et al. 2019).

MATERIALS AND METHODS

The vibracore was obtained in February 2014 at a site located 1.2 km inland from the Colorado Nuevo River mouth (39°35’52” S, 62°6’43” W, Figure 1). The LCH-core, was removed on the left margin of the river, sealed and stored for laboratory analyses. Once it was longitudinally opened, a visual lithological description was based on sediment colors, grain sizes, sedimentary structures, presence of mollusk shells, and lithological units were photographed. The core was subsampled at each 2 cm intervals. A total of 20 sub-samples were selected for the grain-size analysis, while 43 sub-samples were selected for diatom analysis. The diatom sub-samples were concentrated by serial decantations. Subsequently an aliquot of the concentrated sample (3 ml) was oxidized with 30 % H_2O_2 and 10 % HCl to remove organic matter and carbonates respectively, after diatom sub-samples were washed with destilled water until reaching neutral pH (Battarbee et al. 2001). 20-µl sample aliquots were transferred onto a coverslip, oven-dried (60°C) and then mounted in permanent diatom slides using Naphrax® resin (Brunel Laboratory, RI=1.75) for taxonomic identification and counting. In order to calculate the relative frequency of diatom species, a total of 300 valves were counted at 1,000X magnification with a Zeiss Axiostar *plus* light microscope -LM- (equipped with phase contrast optics). Those samples with abundance <10 valves/ slides were considered sterile. When the identification of taxa required a higher level of detail Scanning Electron Microscopy -SEM- (JEOL JSM-64000 LV, operated at 15 KV) photographs, were taken. The identification of species was based on local and standard diatom taxonomic literature. Diatom synonymy was updated by the Algaebase (Guiry & Guiry 2020) and Diatombase (Kociolek et al. 2018). The grain-size analysis consisted of processing 20 gr of dry sediment with hydrogen peroxide (H_2O_2, 30%) and hydrochloric acid (HCl, 10%) to remove organic matter and carbonates respectively and disaggregate the sample. The separation of granulometric categories was carried out by dry sieving with a Rotap sieve shaker and a column of ASTM sieves each half phi grade (Krumbein & Pettijohn 1938). The categories of grain size considered were medium sand (250-500 µm), fine sand (125-250 µm), very fine sand (63-125 µm) and mud (silt and clay <63 µm). The results were expressed as a percentage of each of the categories. The organic matter or total carbon content of the sediment was determined by weight loss on ignition (LOI) according to the methodology of Davies (1974). The measurement was carried out in duplicate and the results were expressed as a percentage. The pumicite content of the median sand fraction was determined by flotation in a dense aqueous medium. The total median sand fraction was separated by dry sieving using the ASTM 60 sieve (Phi 2). Due to its porosity, the pumicite was retained in the supernatant and recovered on a wet sieve, it was dried in an oven at 60ºC and the results were expressed as a percentage with respect to the initial weight.

Four sediment samples rich in organic matter were collected from the core for dating. Chronology of core was based on radiocarbon datings from bulk sediment in Accelerator Mass Spectrometry (DirectAMS *Laboratory*, Washington, EEUU). Radiocarbon ages (^{14}C yr. BP) were calibrated (cal yr. BP ± 2δ) by CALIB 5.0.1 using the SHCal13 calibration curve for the Southern Hemisphere. Malacological fossil remains, located at a distance of 300 m east of the LCH site, were also dated by traditional radiocarbon dating methods in LATYR-CIG/UNLP (Argentina). These shells of *Tagelus plebeius* (Lightfood 1786) were found emerged, articulated and in living/trophic position on a surface level of silty sediment.

Data analyses

Diatom species were classified in relation to salinity tolerance and life form, following the ecological classifications of Vos & de Wolf (1993) and Denys (1991/1992). Diatom counts were expressed as relative frequencies in percentages. Only those taxa with an occurrence >5% in at least one sample were included.

Diatom zones in the fossil sequence were defined using constrained hierarchical clustering (CONISS) based on Bray-Curtis distance and variables transformed in x^2. The analysis was carried out respecting the stratigraphic order of the samples.The statistically significance number of diatomological zones was assessed using the Broken-stick model (Bennett 1996). The diatomologyc analyses were conducted with the statistical R version 3.2.2 (R Development Core Team 2015), using the packages “rioja” version 0.9-5 (Juggins 2015) and “vegan” version 2.3-0 (Oksanen et al. 2015). The granulometrics analyses were performed with software Gradistat (Blott & Pye 2001).

RESULTS

Chronology and sedimentologic analyses

The sedimentary succession LCH presented 200 cm of length, 7 cm of diameter and it extended from the Late Pleistocene to Holocene. The basal age of the sedimentary succession, determined from bulk sediment to 168-170 cm depth, was 11,434 ± 63 ^{14}C yr. BP (13,091-13,374 cal. yr. BP). It was corroborated with a new dating of organic matter in sediments at 2 cm (164-166 cm depth) and it was 10,397 ± 53 ^{14}C yr. BP (11,994-12,417 cal. yr. BP). The third dating carried out at 106 cm of depth was 7,800 ± 45 ^{14}C yr. BP (6,660-6,474 cal. yr. BP). And the fourth dating made from a layer of organic matter at 62 cm depth gave an age of 1,279 ± 31 ^{14}C yr. BP (1,068-1,189 cal. yr. BP). Valves of *Tagelus plebeius* presented ages of *ca.* 350 ± 50 ^{14}C yr. BP.

Nine lithological units were recognized according to grain size and the presence of sedimentary structures (Figure 2). The succession is mainly composed of fine and very fine brown sand (abundances 70-90%), massive or laminated with levels of pumicite. The mud was scarce (with abundance <10%) except a peak at the central section. The section from the base at 87 cm depth is dominated by fine brown sand (41-63%), accompanied by very fine sand (45-27%) and to a lesser extent by mud (<15%) and medium sand (<11%). In this section, six lithological units are distinguished: the basal unit U1 (200-188 cm depth), horizontal sheets of light color with different thickness (3-10 mm) and broken shells of *Heleobia* sp. The layers are

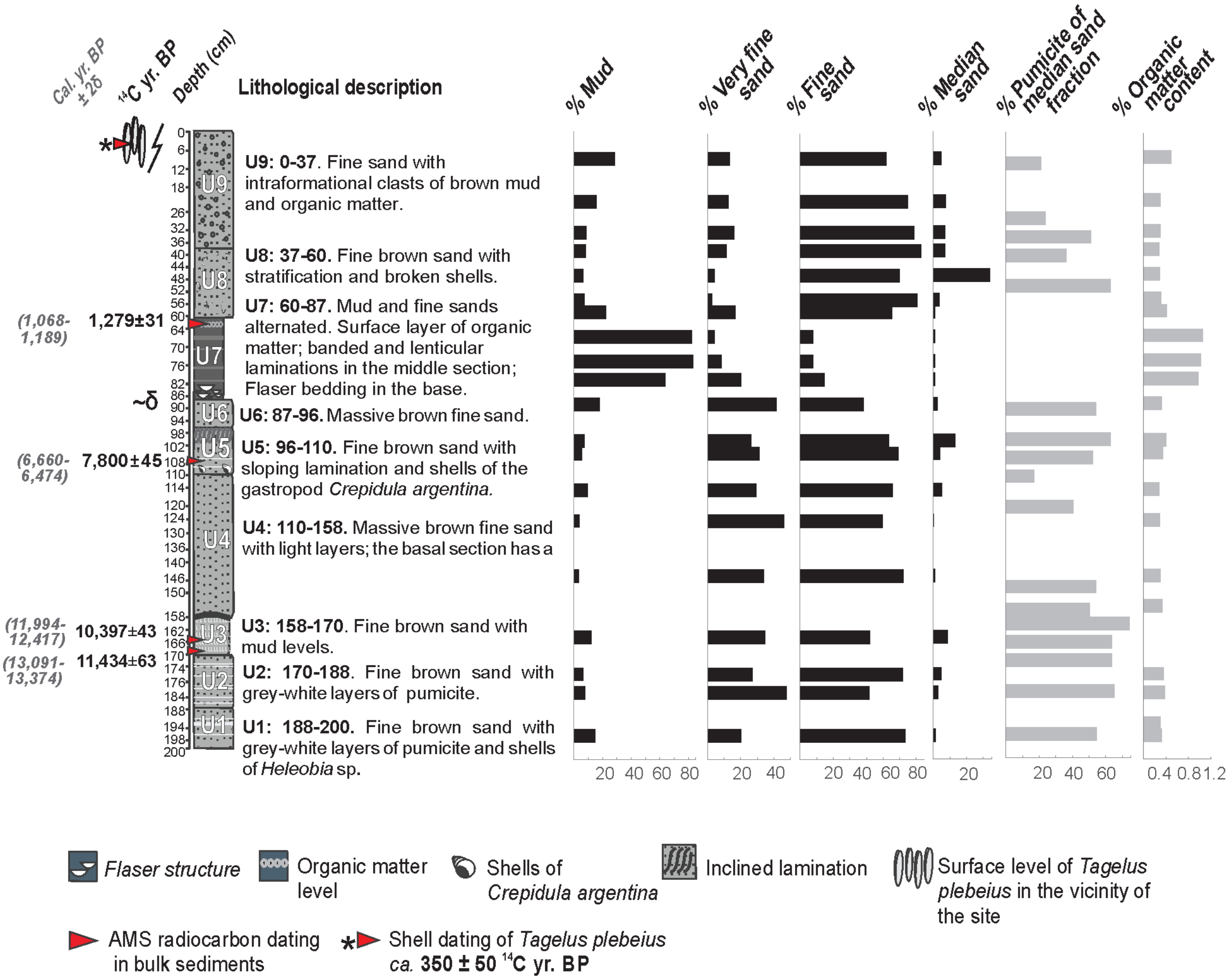

Figure 2. Lithological profile and granulometric analysis of LCH core. The grain size categories are: very fine, fine, median sand and mud (%). Additionally, it shows pumicite of median sand and organic matter in percentages (%).

mainly made up of pumicite clasts with medium sand (22-75%). Overlying U2 (170-188 cm), dominated by fine sand and whitish laminations of pumicite. In the ascending direction, the U3 (170-158 cm deep) is dominated by fine sand (43%) and presents mud levels (35%) from which radiocarbon dating was made. The top of the lithological unit U3 is defined by a 5 mm thick arched plate. U4 (158-110 cm) presents massive brown fine sand without sedimentary structures. Above this, the U5 (110-96 cm) is dominated by fine brown sand with light wavy laminations, broken shells and two entire valves from the gastropod (Calyptraeidae) *Crepidula argentina* (Simone 2000). The U6 (96-87 cm) is characterized by the dominance of massive brown fine sand without sedimentary structures. The U7 (87-60 cm depth), is the only lithological unit where mud dominates over the sands. The mud is found in a percentage of 63-86%, the fine sand 7-14% and the very fine sand 4-20%. At the same time, a maximum percentage of organic matter in sediment is recognized (1.0-1.2%, Figure 2). At the base and towards the top of the unit, different sedimentary structures are identified such as flasers (87-82 cm), banded and lenticular laminations. A 3 mm thick sheet of organic matter was also recognized at the top of it, from which one of the dating was made. The succession of the sedimentary structures refers to intertidal environments. The two superficial lithological units are again dominated by fine brown sand (58-83%), accompanied by very fine sand (3-17%) and mud (15-23%). In ascending order, U8 (60-37 cm) has stratification of fine brown sand (70%) and medium sand (35%) composed of 30-60% pumicite and has broken shells. Surface unit U9 (37-0 cm) is dominated by fine brown sand and presents intraformational clasts of mud and organic matter.

The LCH core has a wide temporal range, thus it is a condensed sequence. Due to the age difference between the dating of the lithological units U5 and U7, the existence of a hiatus between them is inferred.

Diatomological analysis

The diatomological analysis of the 43 subsamples allowed the identification of 256 taxa (including species and varieties). Seven of the analyzed samples presented scarce abundance (<10 valves/slide) and were considered sterile. One barren zone was found in the lower-middle section of the sedimentary succession, between 110-132 cm depth, and isolated barren subsamples were also recorded (22-24cm, 110-112cm, 114-116cm, 120-122cm, 124-126cm, 130-132cm, 178-180 cm).

The diatom analysis of the 36 remaining samples allowed the identification of 16 species of diatoms with abundance greater than 5% in at least one sample. Three statistically representative diatomological zones (DZI, II and III) were defined using the CONISS cluster analysis and the Broken-stick model. The relative proportions of the species in each subsample of the sedimentary succession and the diatomological zones were synthesized in the diagram of relative frequencies (Figure 3).

The whole sedimentary succession was dominated by marine-coastal species, most of which are tychoplanktonic. The two dominant species were *Paralia sulcata* (Ehrenberg) Cleve (tychoplankton) and *Cymatosira belgica* Grunow (tychoplankton) with maximum abundances close to 50% alternately. They were accompanied by a stable set of marine-coastal species whose proportion varied between 10-15%. This accompanying flora included the species as *Rhaphoneis amphiceros* (Ehrenberg) Ehrenberg (tychoplanktonic), *Delphineis minutissima* (Hustedt) Simonsen (tychoplanktonic), *Schionodiscus oestrupii* (Ostenfeld) Alverson, Kang and Theriot (planktonic), *Diploneis aestuarii* Hustedt (benthic), *Tryblionella granulata* (Grunow) Mann (benthic), and brackish-freshwater species such as *Luticola mutica* (Kütsing) Mann (aerophile) and small "fragilarioids" taxa. The presence of *Pseudopodosira boltovskoyi* (Sar, Lavigne, Wetzel, Ector and Sunesen) was identified as part of the accompanying marine flora and constitutes the first record of this species in holocene sediments from Argentina, however it was not represented in the frequency diagrams due its low abundance. LM photomicrographs (and one SEM) of the Holocene diatoms of the LCH-core in valvar and cingular view are shown in a Figure 4.

The basal diatom zone DZI (200-110 cm) represents the hydro-ecological conditions of the early Holocene (*ca.* 11,000 ^{14}C yr. BP) and integrates the lithological units U1-U4. It was characterized by the dominance of *Paralia sulcata* (47%) and secondly *Cymatosira belgica* (29%). Accompanying marine species were recorded with abundances ~10%. The freshwater species presented abundance ~5% and were composed of *Luticola* spp. and a set of small "fragilarioids": *Staurosira venter* (Ehrenberg) Cleve and Möller, *Punctastriata glubokoensis* Williams,

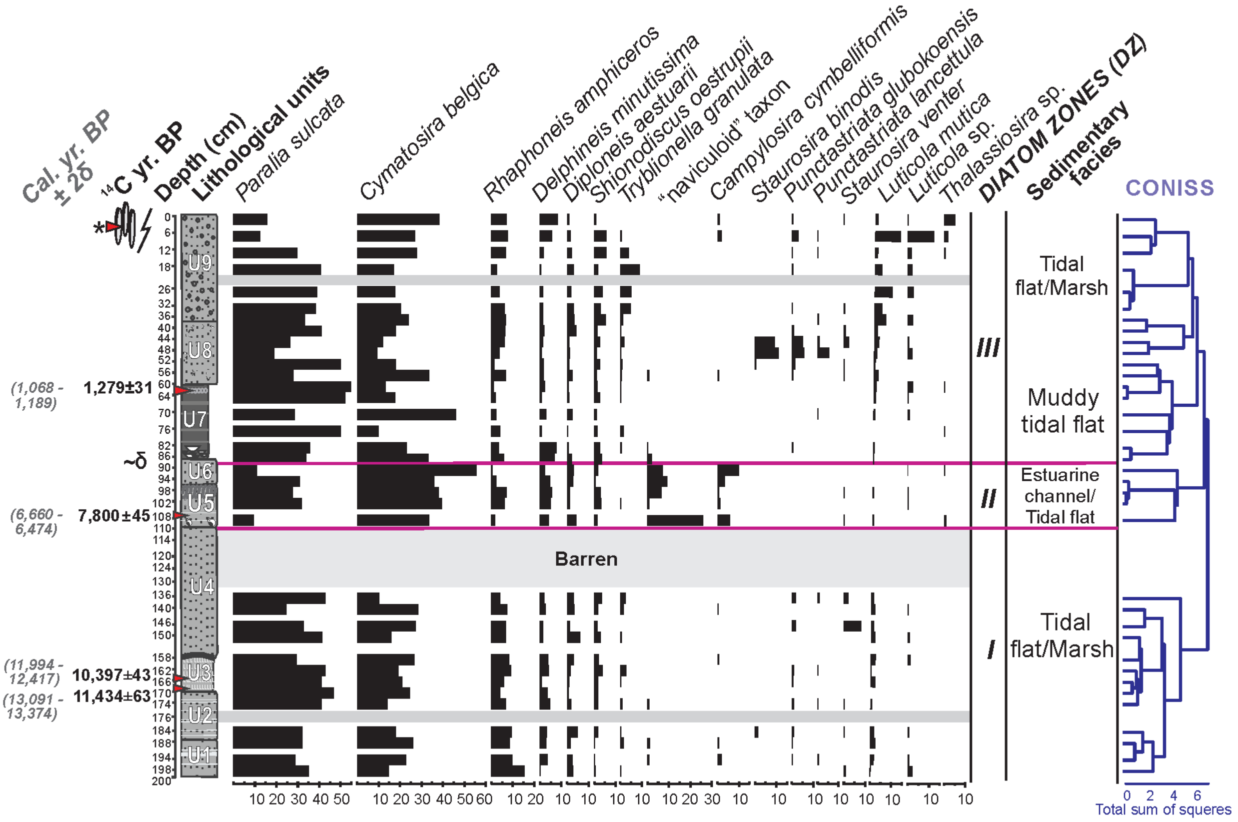

Figure 3. Relative frequencies diagram showing the most abundant diatoms taxa (> 5%) of the LCH-core and diatom zones (DZI to DZIII) obtained by CONISS (Bray Curtis distance). Sedimentary facies are based in the Ta et al. (2001) model.

Chudaev & Gololobova, *Punctastriata lancettula* (Schumann) Hamilton & Siver, and *Staurosira binodis* (Ehrenberg) Lange-Bertalot. At the top of the DZI was observed a 22 cm sterile section (110-132 cm depth). These five samples analyzed shown extremely low abundance (<10 valves / slide) for which they were not considered in the statistical analyzes. However, the presence of poorly preserved *Paralia sulcata* and *Cymatosira belgica* was recorded as fragments of valves.

The DZII include the U5-U6 (110-87 cm depth). The base was dated at 7,800±45 ^{14}C yr. BP (6,660-6,474 cal. yr. BP). It is dominated by *Cymatosira belgica* (55%) and *Paralia sulcata* (35%). The accompanying taxa are mainly marine and present abundances <10%. Only in this zone it is noted the presence of the epipsammitic diatom *Campylosira cymbelliformis* (Schimdt) Grunow ex Van Heurck (13%) and a peak of abundance of "naviculoid" taxon (25%) that could not be recognized at a specific level. Freshwater species are practically absent.

The DZIII (87 cm at the top) integrated three lithological units U7-U9 and the late Holocene, covered the last 1,279±31 ^{14}C yr. BP (1,068-1,189 cal. yr. BP). It is mainly dominated by *Paralia sulcata* and *Cymatosira belgica* too. The abundances of *C. cymbelliformis* and a "naviculoid" taxon decrease steeply and a significant increase in the brackish-freshwater accompanying flora is identified (<15%), represented by *Luticola mutica* and *Luticola* sp., *Punctastriata glubokoensis*, *Punctastriata lancettula*, *Staurosira binodis* and *Staurosira venter*.

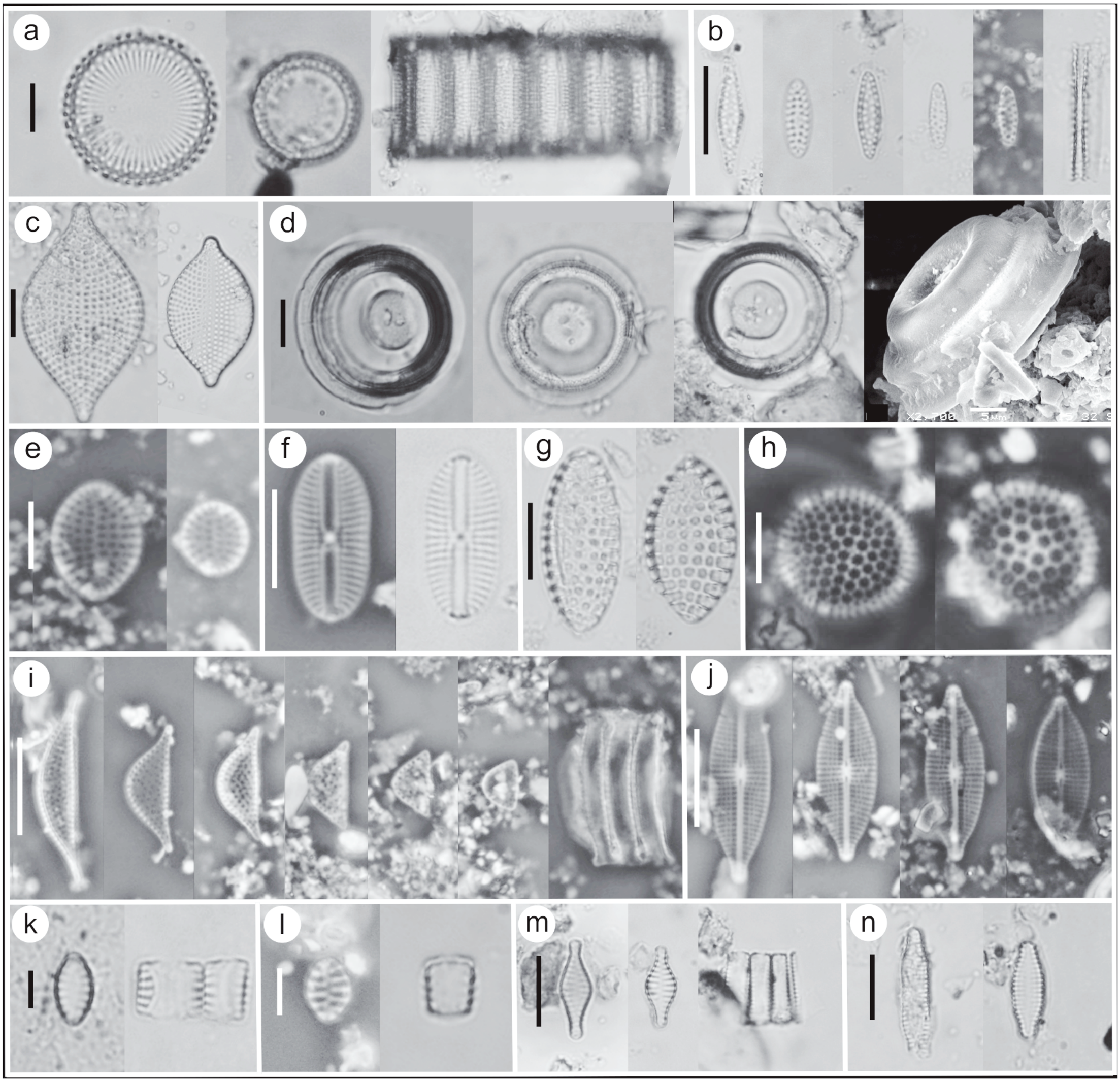

Figure 4. Light photomicrographs of Holocene diatoms taxa from the LCH core. a: *Paralia sulcata*; b: *Cymatosira belgica*; c: *Rhaphoneis amphiceros*; d: *Pseudopodosira boltovskoyi*; e: *Delphineis minutissima*; f: *Diploneis aestuarii*; g: *Tryblionella granulata*; h: *Schionodiscus oestrupii*; i: *Campylosira cymbelliformis*; j: "naviculoid" taxon; k: *Staurosira venter*; l: *Punctastriata glubokoensis*; m: *Punctastriata lancettula*; n: *Staurosira binodis*. Scalebar = 10µm (in c, h, k, l, scalebar = 5 µm).

DISCUSSION

Organic-matter and ash layers

Patagonian estuarine regressive sequences used to be crowned by marsh or peaty levels rich in organic matter (Isla et al. 2015). This is also the case for the organic-rich layer of the LCH sequence (U7).

The estuarine Holocene sequences of Patagonia can content ash or pumicite layers from the Andean volcanoes commonly derived by westerly winds (Hildreth & Drake 1992). During the Holocene, several eruptions have taken place and dated from the Hudson, Mentolat and Sollipulli volcanoes (Naranjo et al. 1993, Stern 2004, 2008, Lachowycz et al. 2015, Bendle et al. 2017) although other ash concentrations were described without precise reference to any known eruption. For example, at the Claromecó estuarine sequence (Buenos Aires Province) ash fragments layers were recorded between 1,310 and 640 yrs BP (Hassan et al. 2004).

Composition and autoecology of diatom assemblages

The totality of the LCH sedimentary succession is dominated by tychoplanktonic coastal-marine diatom assemblages indicating a marine-dominate influence. Tychoplanktonic diatoms are those capable of carrying out reproductive and metabolic processes in the water column, although they originate from other habitats such as benthos or periphyton, for which they are partially associated with the substrate (Denys 1991/1992). *Paralia sulcata* grow in the benthos of coastal environments, although they are abundantly recorded in plankton, transported under mixed conditions by winds and tides (Zong 1997, Santos-Fischer et al. 2016). It has been widely recorded in marginal coastal-marine environments of the planet, particularly abundant in those with fine sediments, rich in organic matter and with a wide range of salinity, such as marshes, tidal channels, bays, coastal lagoons and coral reefs (Weiss et al. 1978, Cooper 1995, 1999). Actually, *P. sulcata* is abundantly recorded along the entire Argentine coastline, living in different marginal coastal-marine environments and estuarine areas with tidal influence (Parodi & Barría de Cao 2003, Garibotti et al. 2011, Pucci et al. 1996, Santinelli & Esteves 1993, Espinosa & Isla 2015).

The codominant diatom of the LCH sedimentary succession *Cymatosira belgica* is a centric coastal-marine species with bipolar morphology (Hasle et al. 1983). The *C. belgica* has a cosmopolitan distribution and its life form is epipsammitic (associated with sands), although it can also be found in silty sediments and occasionally in plankton (Underwood 1994). *C. belgica* is abundant in sandy marginal coastal areas such as open beaches or bays and tidal channels at depths of 3-10 m (Vos & de Wolf 1988, García 2016). Currently, there is abundance of this species at the mouth of coastal lagoons such as the Patos Lagoon, southern Brazil (da Silva et al. 2010) and dominates the epipelitic community at the mouth of deltaic systems with significant tidal influence (Manoylov & Dominy 2013).

The marine-coastal accompanying flora of the LCH core is stable, as a whole these species present an abundance of ~30% and persist throughout the entire sedimentary sequence. It is composed mainly by *Rhaphoneis amphiceros*, *Delphineis minutissima*, *Diploneis aestuarii*, *Shionodiscus oestrupii* and *Tryblionella granulate* (Figures 4.c, e-h). These species have been found together with *Paralia sulcata* and *Cymatosira belgica* in plankton and the surface sediments of estuarine and coastal environments in the Buenos Aires province and Patagonia, Argentina (Sar et al. 2001, 2007, Ferrario et al. 2003, Hassan et al. 2007, Garibotti et al. 2011, Espinosa & Isla 2015). Currently, this assemblage is found abundant at meso-tidal estuaries such as Negro and Colorado Rivers, where salinity variations fluctuate from 0 to 26.9‰ and 6.5 to 29‰, respectively (Escandell et al. 2009, Vélez-Agudelo et al. 2017) and in tidal banks and marshes of macro-tidal estuaries of Patagonia (Espinosa & Isla 2015).

The composition of the fossil diatomological assemblages of the LCH core is the same as the modern assemblages of the lower course of the Colorado Nuevo River, where a tidal channel environment develops (Vélez-Agudelo et al. 2017). This result is congruent with the observations made by Vos & de Wolf (1993), who stated that the dominance of marine planktonic and tychoplanktonic species in estuarine sediments is an indicator of tidal channels; where the influence of tides and the speed of the current are maximum, conditioning the growth of epiphytic and benthic species.

The presence of *Pseudopodosira boltovskoyi* was identified as part of the accompanying marine flora en the LCH core (<5%, Figure 4.d). This specie was recently descripted by Sar et al. (2017) from phytoplankton samples from marine coastal waters and surface sediments of littoral environments in Buenos Aires Province (Bahia Anegada). This finding constitutes the first record of the *P. boltovskoyi* species in the Holocene sediments of Argentina.

In addition to coastal-marine taxa, the fossil samples of the core have few accompanying brackish-fresh diatoms represented by “small fragilarioids” taxa (*Punctastriata glubokoensis*, *Punctastriata lancettula*, *Staurosira binodis* and *Staurosira venter*; Figures 4.k-n), and two aerophilous species of the genus *Luticola,* capable of living in humid, temporarily dry sites or even outside water bodies (van Dam et al. 1994). They are present in the DZI and DZIII zones and absent in DZII. The term “small fragilarioids” is a generalization that refers to the araphid diatoms of the family Frafilariaceae whose valves sizes do not exceed 20 µm (Li et al. 2016). They are important components of the assemblages of planktonic and benthic microalgae from continental brackish-fresh and coastal-marine environments (Morales 2005, Witkowski et al. 2000, Metzeltin & Lange-Bertalot 2007). They generally form chains and are associated to fine sediments, sand, rocks, algae or submerged macrophytes (Morales et al. 2010, Cejudo-Figueiras et al. 2011, García et al. 2017); Frequently they are found in plankton, which is why they are considered facultative planktonic or tychoplanktonic species (Gell et al. 2007). Although the small representatives of the Fragilariaceae family are very abundant in aqueous environments and have been exhaustively studied during the last two decades, the taxonomic determination of the species and genera is still subject to discussions due to important change in the identification criteria. (Guerrero et al. 2019, Li et al. 2019).

In Argentina, ″small fragilarioids″ are abundant in surface sediments, periphyton and plankton of lakes, rivers, streams, wetlands, ponds and reservoirs (Maidana & Díaz-Villanueva 2001, Espinosa & Isla 2015, Vélez-Agudelo et al. 2017). They have also been recorded in sedimentary sequences of estuaries and freshwater environments of Buenos Aires and Patagonia (Espinosa 2008, Escandell et al. 2009, Hassan et al. 2009, 2011, Espinosa et al. 2012, Fayó & Espinosa 2014). Only the most recent contributions address the taxonomic identification of fossil diatoms with the new classification criteria and the combined use of LM and SEM analysis (*e.g.,* García & Maidana 2015, Grana et al. 2018, Fayó et al. 2018, 2020a). Along the Colorado River, Vélez-Agudelo et al. (2017) studied the composition and spatial distribution of modern diatomological flora in surface sediments of the middle and lower basin and identified *Staurosira venter* (Ehrenberg) Cleve & Möller, as the dominant species of the brackish-freshwater fluvial assemblages. Also, they established the first record in Argentina of *P. glubokoensis* and *P. lancettula* as part of the accompanying fluvial flora of the Colorado River. Later, from a diatomological study of two sedimentary sequences of the deltaic plain, Fayó et al. (2018, 2020a) corroborated the presence and persistence of “small fragilarioids” taxa mentioned as stable components of the fluvial-deltaic environment of the Colorado

River since *ca.* 7,300 years BP to the present. The new findings of ″small fragilarioids in the LCH core (DZI and DZIII), confirm the temporal range of the ubiquity of the genera *Punctastriata* and *Staurosira* in Northern Patagonia throughout the Late Pleistocene and Holocene.

Ecological studies and records of *Punctastriata* in general are very scarce in the literature and particularly in South America (Fayó et al. 2020a). According to Vélez-Agudelo et al. (2017), *Punctastriata glubokoensis* has a tolerance to salinity of 0 to 2.1‰, while *Punctastriata lancettula* tolerates even more restricted ranges (0 to 1.68‰). The low abundance and ecological incompatibility of these fresh-brackish species in a coastal-marine environment allows to infer that the "small fragilarioid" and the *Luticola* species found in DZI and DZIII, are allochthonous taxa, that were transported downstream from fluvial reaches without marine influence during the Holocene.

DZII zone lacks the brackish-freshwater species as accompanying flora. These taxa were replaced for *Campylosira cymbelliformis* and "naviculoid" species that could not be identified (Figures 4.i, j). *C. cymbelliformis* is a bipolar-centric marine and epipsammitic specie, common in shallow and dissipative open coasts (García-Baptista 1993) Generally, is found with *C. belgica* in sandy environments (García 2016); this is consistent with the grain sizes of the lithological units U5 and U6. Despite an extensive bibliographic review, this "naviculoid" species has not been consistently assigned to a generic or specific taxonomic category. Its dimensions and valve morphology were obtained by LM analysis (n = 40) but require a further MB study for valve ultrastructure details.

Along the LCH core, the dominance of tychoplanktonic forms have been recorded in previous investigations carried out in this coastal plain (Vélez-Agudelo et al. 2017, Fayó et al. 2020a) and other deltaic environments. In the Ebro River delta (Spain), Benito et al. (2015) interpreted the dominance of tychoplanktonic diatoms as indications of habitats with a shallow water column and environmental conditions with a certain degree of physical instability (scarce light availability and significant turbulence due to winds and tides). Shallow environments present inherent processes of sedimentary resuspension caused by the action of waves, tides and/or winds, and constitute physical variables that influence on the composition of diatom assemblages since they favor the detachment of benthic diatoms and epiphytes from macrophytes and their incorporation into the water column (Schweizer 1997). However, in the estuary of the Severn River estuary (England), the dominance of the tychoplanktonic forms could represent a survival strategy to avoid burial in waters with significant load sedimentary (Underwood & Paterson 1993). The partial relationships between tychoplanktonic diatoms with the substrate and the continuous resuspension in the water column, would allow the development of benthic diatoms that are incapable of moving and to escape from burial (as is the case of the araphids), allowing their burial in estuarine or deltaic context.

Palaeoenvironmental reconstruction of the LCH site and Holocene eustatic variations.

Numerous palaeoenvironmental reconstructions reflect that the South American Atlantic coast has been extensively affected by the Holocene sea level fluctuations. Therefore, the inferred paleoenvironmental conditions in each of the evolutionary phases of the LCH core were interpreted in a changing eustatic context. On the basis of diatom analysis of LCH sedimentary succession, the integration of the chronological and lithological results, and the analysis of the autoecology of the most abundant species, it has been possible to reconstruct three phases in the evolution in the coastal sector of the deltaic plain from the Late Pleistocene-Early Holocene transition to the present.

The abundance and persistence of marine-coastal tychoplanktonic in LCH core indicates that the marine influence prevailed at the site during the last 11,000 years, with important bedload and resuspension processes. According to the Holocene sea-level fluctuations recorded in Argentina (Isla 1989, Isla & Espinosa 1998, Cavallotto et al. 2004, Spagnuolo 2005, Isla 2013, Prieto et al. 2017), evolutionary phase I and II (DZI-II, early and middle Holocene, respectively) occurred during sea level rise, while the most recent phase (DZ III) occurred under regressive conditions (Late Holocene).

The dominance of *Paralia sulcata* in Holocene sediments from different parts of the world has been related to sea levels higher than the modern one and the evolution of various eustatically dependent littoral environments (Mc Quoid & Nordberg 2003, Weschenfelder et al. 2008, Medeanic et al. 2009, Santos-Fischer et al. 2016, 2018). On the micro-tidal coast of Buenos Aires Province, its dominance was indicated in sedimentary sequences extracted from the coastal plain of the Mar Chiquita lagoon at *ca.* 6,020–4,170 ^{14}C yr. BP (Espinosa & Isla 2011, Fayó & Espinosa 2014), indicating marginal coastal-marine paleoenvironments during periods immediately to the maximum transgressive and prior to the restriction of the coastal lagoon, while during its establishment the presence of *P. sulcata* was persistent only in tidal channels (Hassan et al. 2011). It is also abundant in the Holocene sediments of the Quequén Grande River estuary (7,040 ± 50 ^{14}C yr. BP), where the development of an extensive estuarine lagoon was inferred by the transgressive flooding of ancient river valley (Espinosa et al. 2012).

In contrast, in the meso-tidal coast at the south of Buenos Aires province and northern Patagonia, *Paralia sulcata* and *Cymatosira belgica* are frequent in Holocene and modern sediments, so they are considered good proxies of tidal environments of the patagonian coasts (Espinosa & Isla 2011). Coastal-marine assemblages similar to those found in LCH-core are identified in Holocene sediments of two sites of Negro River estuary, 170 km to the south of LCH core (Escandell et al. 2009, Escandell & Espinosa 2012). Its dominance was associated with the clogging of tidal channels in a regressive context. The codominance of these species was also recorded in Holocene sedimentary successions from San Blas Bay (115 km south of LCH site) in a full-length core at the Puente San Blas site from 4,904 ± 70 ^{14}C yr. BP to the present, and at the base of the Paso Seco core from 4,904 ± 70 and 987 ± 43 ^{14}C yr. BP. Its abundance was also interpreted as the clogging of tidal channels during Late Holocene (Espinosa & Isla 2011). In Chubut River marsh, the dominance of *P. sulcata* in a Holocene succession (Magagna site), was interpreted as a coastal-marine paleoenvironment dominated by tides *ca*. 4,376 ± 69 ^{14}C yr. BP (Escandell & Espinosa 2012, Isla et al. 2015). In the same way, its dominance in Holocene sediments at the mouth of the Negro River and in the Sauce Grande lagoon, was interpreted as the development of paleoenvironments of tidal flats associated with sea levels higher than today (Gutierrez-Tellez & Schillizzi 2002, Schillizzi et al. 2012).

Recently, 22 km upstream from LCH, Fayó et al. (2020a) performed a diatomological analysis of a core from the deltaic plain of the Colorado river (Las Isletas, LI) and registered a maximum abundance of *P. sulcata* and *C. belgica* (25%) in the basal section of the sequence (DZI: *ca.* 7,315 ± 64 ^{14}C yr. BP) and its decrease towards the middle section of the core (DZII). Both species are considered allochthonous by the authors due to the scarcity and poor preservation valves. However, their presence allowed them to infer that the LI site was affected by the Holocene fluctuations of sea level. So, during the transgressive periods of maximum marine influence, the tide was the transport agent in LI site, depositing marine-coastal species upstream, while the gradual decrease of allochthonous marine-coastal species between 7,315 ± 64 and 2,218 ± 29 ^{14}C yr. BP it was associated with an increase in fluvial influence due to the development of the deltaic lobe and the progradation of the coastline towards the East.

The abundance of *Paralia sulcata* in Argentina is consistent with records from Uruguay and Brazil that also indicate the regional trend of sea level rise. In Brazil, they were identified in Holocene sediments of the Barra Falsa channel (Weschenfelder et al. 2008, Santos-Fischer et al. 2018), on Cassino Beach (Medeanic et al. 2009), in the coastal lagoon Peixe (Santos 2015), on Hermenegildo beach (Lima 2008) and in the Patos Lagoon (Santos-Fischer et al. 2016), among others. In the southeast of Uruguay *P. sulcata* dominates the transgressive Holocene sediments of different coastal lagoons (García-Rodríguez & Witkowski 2003, García-Rodríguez et al. 2004, García-Rodríguez 2012).

Based on previous paleoenvironmental reconstructions from northern Patagonia and the similarity between the fossil and current assemblages, it could infer the evolutionary phase I of the LCH site (DZI: U1–U4), as a sandy marginal coastal-marine environment with high deposition energy, similar to the current tidal channel that develops at the mouth of the Colorado Nuevo River. These it would have been established since the late Pleistocene/Early Holocene *ca.* from 11,434 ± 63 ^{14}C yr. BP (13,091–13,374 cal. yr. BP, DZI) to 7,800 ± 45 ^{14}C yr. BP. During the early Holocene (*ca.* 11,000 ^{14}C yr. BP), different lines of evidence indicate a low and rising sea level, which would have favored the development of marginal coastal environments in what currently makes up the continental marine platform of the Colorado River basin (Ponce et al. 2011, Bernasconi & Cusminsky 2015). Despite a position of the coastline shifted to the East in response to a low sea level, the presence and persistence of the coastal-marine tychoplanktonic assemblage at the LCH site, indicates that an important marine influence and tidal action reached the site early during the Holocene (Figure 5).

In the upper section of the DZI (U4: 132–110 cm depth), the abundance of diatoms declines abruptly, as well as the state of preservation of the valves, indicating the occurrence of drastic changes in environmental conditions or a period of instability of the system *ca.* 7,800 ^{14}C yr. BP. The absence of diatoms in sandy sedimentary successions has been previously recorded in littoral areas, as being attributed to a low resistance of the valves to high-energy deposition conditions, and/or their washing due to the porosity of the sandy deposits. (Espinosa 1998, Castro et al. 2013). In this sense, the poor preservation stage and the lack of diatoms in the sterile section of the LCH-core are associated with high-energy coastal environments deposited in the marine transgression during the early-mid Holocene. During this period, intrinsic marine transgressive characteristics such as the reworking of coastal sediments and erosive features represented unfavorable conditions for the development and preservation of diatoms in the LCH registry (DZI).

According to the new diatomological evidence during the transgressive period, the coastline would have moved west from the early Holocene to the Middle Holocene, favoring the clogging of pre-existing tidal channels in the

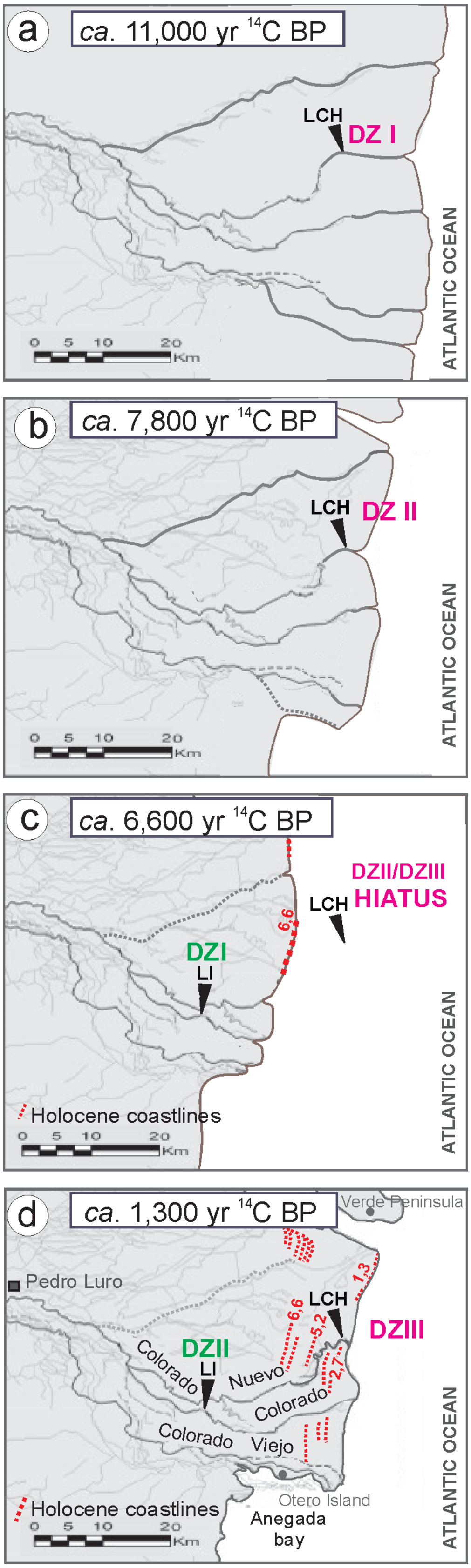

Figure 5. a-d. Conceptual model of the three phases in the hydrological evolution of the LCH site based on diatom zones (pink) and its integration with others evidence from the area (Holocene's coastline positions and LI-core diatom assemblages' interpretation). a- Late Pleistocene-Early Holocene. Tidal flats developed in the sea level rising and tidal channels from the LCH site were clogged (DZI). b- Early-Middle Holocene. After 7,800 ^{14}C yrs. BP, the coastline was close to the LCH site and estuarine channels were clogging in the coastal deltaic plain (DZII). c- Holocene Sea-level Maximum. *ca.* 6,600 ^{14}C yr. BP the coastline was located 16 km inland (red dotted lines: modified from Codignotto & Weiler 1980) and allochthonous coastal marine diatom assemblages were transported to the LI site (DZI in green, Fayó et al. 2020a). The ocean surpasses the LCH site and the transgressive reworking sediment and erosive features produce a gap in the LCH sedimentary record (pink DZII/DZIII boundary) which masks the transgressive signal. d- Last *ca.* 1,300 years BP. A progressive decrease in sea level and deltaic progradation during the regressive phase, formed parallel littoral ridges located at 16.5 km to 400 m from the present coastline (red dotted lines: modified from Alberó et al. 1980; Codignotto & Weiler 1980). Stable Fluvial diatom assemblages are established on the site LI (DZII in green, Fayó et al. 2020a). In the LCH site the fluvial influence is accentuated (DZIII): the tidal channels that crossed the coastal delta plain and marshes were clogging towards the present.

delta plain (DZI, Figure 5.a). In this context of rising sea level, the tides and waves reworked the littoral sediments of the deltaic plain (Spalletti & Isla 2003), which could affect the preservation of fossil remains contained and generate sterile areas of siliceous microfossils.

Paleoenvironmental conditions inferred during phase II (DZII: U5 and U6) were similar to those of the early Holocene (DZI) and analogous to a tidal channel. However, the lack of small allochthonous "fragilarioid" species in DZII and the presence of *Campylosira cymbelliformis*, give indications of a greater marine influence and/or a less fluvial influence than the remaining phases. Additionally, the lithological units of this phase present horizontal and inclined sandy laminations and the presence of *Crepidula argentina* shells. *C. argentina* is an epifaunal gastropod that integrates currently beach associations and Quaternary beach deposits in the Colorado River delta and Anegada Bay (Charó et al. 2015). The lithological and malacological evidences support the interpretation of greater marine influence at the LCH site *ca*. of the 7,800 ± 45 ^{14}C yr. BP (6,660-6,474 cal. yr. BP). Thus, during the middle Holocene (phase II) a coastline position similar to the current one (and near to LCH site), would have allowed the growth of coastal-marine diatoms, indicating reestablishment of stable littoral conditions, similar to current tidal channels with significant marine influence (estuarine channel, Figure 5.b). In addition to the diatomological evidence, the deltaic plain of the Colorado River presents diverse geomorphological and malacological records of the transgression during the middle Holocene and the subsequent regression process (Spalletti & Isla 2003, Melo et al. 2013). Among the remarkable evidences, it presents a series of parallel littoral ridges, oriented N-S and successively, located from 16.5 km to 400 m from the current coast that represent old coastlines (Codignotto & Weiler 1980, Figure 5). Radiocarbon dating of the malacological contents confirmed ages decreasing towards the east from *ca*. 6,630 ± 120 to 407 ± 100 ^{14}C yr. BP, indicating the progradation of the coast in the regressive stage (Alberó et al. 1980, Codignotto & Weiler 1980, Fucks et al. 2012). The interpretations based on diatoms agree with Codignotto & Weiler (1980) hypothesis, who claim that the coastline was located 16 km upstream *ca*. 6,600 years ^{14}C BP (Figure 5.c). According to the new evidence during the maximum transgressive event, the coastline would have been located past the LCH site to the west near Las Isletas site, as indicated by the transport of *P. sulcata* and *C. belgica* at the base of the LI core *ca*. 7,315 ± 64 ^{14}C yr. BP (Fayó et al. 2020a, Figure 5.c).

Phase III (DZIII: U7-U9) occurs during the late Holocene *ca*. 1,279 ± ^{14}C yr. BP (1,068-1,189 years cal BP) and continues to the present. The coastal-marine assemblage is similar to that of the previous phases and to that found in the current tidal channel of the Colorado Nuevo distributary channel. Geomorphological studies of the Colorado River delta plain and surrounding areas indicate that tidal channel clogging was a widespread process during the Late Holocene (Weiler 2000). The increase in the abundance of the accompanying brackish-fresh diatom flora (*Punctastriata*, *Staurosira* and *Luticola*), refers to an increase in fluvial influence during this period. As mentioned above, the presence of fragilarioids taxa in the LCH sequence can be associated with the post-mortem transport of valves in the direction of river flow and their deposition during periods with greater fluvial influence associated to delta progradation (Figure 5.d). According to a previous diatomological research, fragilarioids species have a vast ubiquity in the region and constitute the main component of fluvial assemblages without marine influence of the Colorado River since the Holocene to the present (Fayó et al. 2020a, b, Vélez-Agudelo et al. 2017). The abundance peaks of continental freshwater taxa of the DZIII (such as those obtained in 48 and 44 cm depth), can be associated to sporadic pulses or extraordinary floods of fresh water that occurred during the last *ca*. 1,279 ± 31 ^{14}C yr. BP (1,068-1,189 cal. yr. BP). The flaser bedding and lenticular laminations of the basal section of this phase (U7) indicate intertidal marine-coastal conditions, while the levels of organic matter and the increase of mud towards the surface section (U9) support a greater fluvial influence towards the surface.

Although the accompanying assemblages do not change abruptly at the limit of phase (DZ II/III), there is a wide temporal range between the lithological units dated U5: 7,800 ± 45, and U7: 1,279 ± 31 ^{14}C yr. BP. This difference between the dates allows us to infer the occurrence of a hiatus in the record at the limit between U6 and U7 (DZII/DZIII boundary; Figure 5.c).

Located in the vicinity of the LCH site, a level of articulated valves of *Tagelus plebeius* in living / trophic position was identified with ages of 350 ± 50 ^{14}C yr. BP. The shells of estuarine mollusks are widely used as reliable samples for radiocarbon dating (Gómez et al. 2008). *T. plebeius* is a euryhaline infaunal organism that is distributed from North America to San Matías Gulf (41°S, Argentina, Morris & Rosenberg 2005). This species lives gregariously in shallow environments in sub-coastal areas, where it digs caves up to 50 cm deep (Golfieri et al. 1998). Buenos Aires province has a lot of Holocene deposits with a high density of articulated *T. plebeius* in living position (Charó et al. 2013). Their abundance has been interpreted as mass die-offs due to changes in sea level, sediment burial, or overlapping of temporally different populations (Schnack et al. 1982, Golfieri et al. 1998). In the area of the Colorado Nuevo River, three grayish sandy-silt deposits with these malacological evidences, were interpreted as past tidal flats, formed when the sea level was higher than today (Charó et al. 2013). Similar malacofaunas were also identified at the base of a Holocene sedimentary succession from the Estancia San Antonio archaeological site, 4 km from the current coastline, indicating greater marine influence in the vicinity of the study area *ca.* 1,500 ^{14}C yr. BP (Martínez & Martínez 2011). Both interpretations are consistent with the dates obtained by Codignotto & Weiler (1980) and represent evidence of the regressive phase during the late Holocene. In contrast, the level of *T. plebeius* dated close to the LCH-core indicates the development of intertidal marine conditions during historical times. Later and in a context of regressive coast, the meso-tidal flat was vegetated forming a marsh while other parts of the deposit were eroded by the river channel, exposing the valves on the surface.

Deltaic sedimentary facies based on diatoms

Consistent with the sedimentary evolutionary models of deltas (Boyd et al. 1992) and Dalrymple et al. (1992), the regressive deltaic reconstructions based on diatoms, indicate the succession of estuarine-transgressive stages to progradational-regressive stages, during the middle and late Holocene respectively (Ta et al. 2001, Castro et al. 2013). The transgressive stage is associated with the flooding of the river valleys and the consequent formation of estuaries and bays with significant marine influence, which is inferred by the increase in marine and marine-brackish planktonic diatoms (Ta et al. 2021, 2002a, b, Santos-Fischer et al. 2018). When the estuary occupies the ancient valley and the process of flocculation of clays at the interface of fresh-salty water occurs, generating muddy depocentres inland (Cavallotto et al. 2004). In consequence, the increasing number of planktonic diatoms is accompanied by pelitic sedimentary textures as a signal to maximum transgressive events. In subsequent regressive-prograding stages, paleoestuaries gradually fill up and fluvial or continental influence increases due to delta progradation. Thus, marine planktonic assemblages are replaced by brackish-marine and freshwater diatoms, and sand grain sizes interfingered with silts, typical of regressive facies (Ta et al. 2001, 2002a, 2005).

Ta et al. (2001) used a combination of diatoms, foraminifera and lithological units from a 71-m core from the coastal delta plain of the Mekong River (Southeast Asia), to investigate the succession of deltaic sedimentary facies in relation to changes in sea level during the last *ca*. 13,000 cal yr BP. The authors identified nine depositional facies and described the assemblages of fossil diatoms and ecological groups associated to them, based on the transgressive and regressive phases of sea level (Ta et al. 2001, 2005). Like the Colorado River, the Mekong River delta is another regressive system, without significant tectonic activity, and dominated by a mesotidal regime. This deltaic system has progradated for the last *ca*. 6,000 yr. BP at different speeds and presents a greater influence of waves for the last *ca*. 3,000 yr. BP (Ta et al. 2002b). It has an important fluvial contribution due to the tropical climate and monsoonal regime, which favors the construction of a delta of extended areal and depths. In contrast, the Colorado River delta is a more restricted and shallow system, built with minor and discontinuous fluvial inputs, due to the semi-arid Patagonian climate. This causes that the development of the lithological units of both deltaic systems different. Even so, it is possible to recognize similar deltaic facies in the sedimentary successions of both deltas in base to dominant ecological groups of diatoms. According to Ta et al. (2001), the transgressive stages in the sedimentary succession of the Mekong River are represented by the following biofacies in ascending order: *Estuarine channel/ Tidal river sandy silt, Salt marsh / Mudy tidal flat, Estuary marine sand, Transition sandy silt and Open bay mud*. The mudy facies represent the maximum marine influence of the Holocene transgression in the ancient fluvial valley *ca*. 5,300 cal yr BP. The succession of diatom assemblages described from the *Estuarine channel facies* to the *Open bay mud facies* (see A-D in Ta et al. 2001), shows the gradual replacement of a mixture of freshwater and brackish euryhaline species (characteristic of tidal environments) by marine planktonic ecologycal groups of diatoms, and where brackish and freshwater taxa are subordinate. This floristic replacement is also accompanied by an abrupt increase in open-sea foraminifers and by lithological replacing the silt-sandy sediments with parallel laminations and flaser, with massive pelitic sediments. In the overlying section of the Mekong River sedimentary succession, four regressive biofacies were identified, in ascending order: *Prodelta mud*, *Delta front Sandy silt*, *Sub-to Inter-tidal flat Sandy silt*, *Subaerial delta plain channel* (*marsh and beach ridge*). During this succession of facies, the marine planktonic diatoms gradually decrease and the abundance of brackish and freshwater diatoms increases due to the progradation of the delta (Ta et al. 2001).

On the other hand, in Brazil, Castro et al. (2013) analyzed the succession of sedimentary facies and the diatomological evidence of an 11-m core extracted from the deltaic system of the Doce River, as a function of transgressive and regressive Holocene events. Like the Colorado River, the Doce River delta is a regressive system that was built in a mesotidal environment during the mid-late Holocene and was affected by fluctuations in sea level of the same order of magnitude. However, the delta of this River presents a greater sedimentary contribution due to the tropical climate of the region. In its delta plain a succession of four association facies was identified, where the continental influence increases over time: *Estuarine channel, Estuarine central basin, Lake / Ria and Fluvial channel / Marsh*. As in the Mekong River, the Doce River has clay estuarine deposits *ca*. 7,000-5,000 ^{14}C yr. BP (in *Estuarine central basin* facies), where planktonic and marine taxa are dominant and freshwater diatoms are subordinate. According to the authors, *Tryblionella punctata*, *Paralia sulcata*, *Tryblionella granulata* and *Diploneis* *gruendleri* dominate. This association of coastal-marine diatoms is similar to the assemblage that currently grows in the Rio de la Plata (Argentina) and constitutes an indicator of estuarine paleoenvironments with significant marine influence (Pérez et al. 2017). The upper section of the Doce River core shows a gradual floristic replacement associated to regressive phases and deltaic progradation, where brackish-fresh water diatoms become dominant.

The sedimentological and diatomological evidence of the basal and middle section of the LCH core (DZI and DZII, 200-87 cm depth) was interpreted as a tidal channel between *ca.* 11,434 ± 63 ^{14}C yr. BP and 7,800 ± 45 ^{14}C yr. BP, similar to that exist today. This interpretation is consistent with the transgressive facies of the *sandy Estuarine channel / Tidal river sandy silt / salt marsh* and *Estuarine channel,* (Ta et al. 2001, Castro et al. 2013), respectively. However, the overlying section of the LCH core (DZIII) does not present the massive muddy sedimentary facies associated to assemblages of marine planktonic diatoms typical of the paleoestuary facies (*Open bay mud /Estuarine central basin*) as recorded in both deltaic evolutionary models. The absence of massive muddy facies, the lack of marine planktonic diatoms and the time difference between the dating of the lithological units U5 and U7, allow to corroborate the occurrence of a hiatus in the sedimentary record of LCH core at the U7/U6 limit.

According to the regional reconstructions carried out in the Mekong River, the muddy facies are produced due to the flocculation of estuaric clays as the ancient's valley became flooded (*Estuarine channel* facies), at the maximum flood level (*Open bay mud* facies) and also during the initial regressive stages (*Prodelta mud* facies, Ta et al. 2001). In this sense, Ta et al. (2002a, 2005) and Wei & Wu (2011) indicate that the regressive *Delta front Sandy silt* facies represent high energy palaeoenvironmental conditions with significant tidal currents, high sedimentation rates and erosion surfaces. Sometimes, these features in regressive facies might impact on the record and cause the alteration or absence of muddy transgressive facies. Based on this background, it is inferred that the hiatus in the LCH sedimentary succession could have occurred during high-energy stages in incipient regressive or transgressive phases, masking the signals of the Colorado River paleoestuary/bay and prodelta facies. The inference of high energy deposition conditions during the regressive stage is also supported by the shelly ridges found in the deltaic plain *ca*. 6,000-400 ^{14}C yr. BP (Codignotto & Weiler 1980). These littoral geoforms represent ancient coastlines, formed during the progradation of the delta; their formation involves the reworking by storms.

The upper section of the LCH sequence (DZIII) presents lithological units with defined sedimentary structures, similar to those described in regressive deltaic facies of the Mekong River. The *Inter-tidal flat Sandy silt* (U7) and *Subaerial delta plain facies* (tidal channel/marsh) in U8 and U9 are identified in ascending order (Figure 3). Regarding the diatomological evidence, section (DZIII) is dominated by marine-coastal euryhaline species; planktonic species are scarce and an increase in brackish-freshwater diatoms is observed towards the top, indicating an increase in continental influence associated to the progradation of the deltaic lobe. The succession of regressive facies at the LCH site allowed to infer the establishment of a shallow coastal-marine prograding environment with significant tidal action, in which the fluvial/continental influence gradually increased, favoring its colonization by halophilic plants. The paleoenvironments of the tidal flats and the marsh would then have been established sequentially from the late Holocene *ca.* 1.279 ± 31 ^{14}C yr. BP to the present.

CONCLUSIONS

These results and interpretations represent the first paleolimnological study based on diatoms in a deltaic system in Argentina. Increasing worldwide research indicates that diatoms related to sediments are very valuable information for paleoenvironmental reconstructions involving eustatic changes.

Three evolutionary stages were identified at the site during the last *ca.* 11,000 years BP in response to sea level fluctuations, delta progradation and fluvial dynamics.

a) The dominance and persistence of coastal-marine tychoplanktonic diatoms in the core, indicate that marine and tidal influence dominated during the Late Pleistocene and Holocene, significantly affected by the coastal advances and retreats associated with eustatic variations.

b) The coastal LCH sequence represents the clogging of tidal channels in a mesotidal environment of the Patagonia coast. During the Late Pleistocene-Early Holocene (DZI: *ca.* 11,000 ^{14}C yr. BP) a tidal channel was flooded when the transgression occupied this area. The pumicite were transported and deposited forming sandy layers at the high-tide levels. The resuspension and erosion processes associated with the marine influence and the transgressive context affected the preservation of the diatom valves and generated barren sections in the record. About 7,800 ± 45 ^{14}C yr. BP (DZII), a higher proportion of coastal-marine epipsammic diatoms and the absence of fresh water species, indicates the higher marine influence. Stable palaeoenvironmental conditions, similar to a tidal channel with significant marine influence, are re-established due to a coastline position. In the regressive stages of the late Holocene (DZIII, the last 1,300 ^{14}C yr. BP), the increase in the abundance of allochthonous fluvial fresh-brackish taxa (mainly "small fragilarioids") indicates a greater fluvial influence with respect to the previous phases. These environmental conditions are consistent with the re-establishment of tidal plains and marshes crossed by tidal channels (similar to those exist today) and deltaic progradation.

c) This new micropaleontological evidences constitutes the first record of *Pseudopodosira boltovkoyi* in Holocene sediments from Argentina, and temporarily extends the ubiquity of small fragilarioids in the Colorado River delta since the Late Pleistocene.

d) The ccomparison of the LCH sedimentary succession with different deltaic evolutionary models based in sedimentary facies and diatomological evidence allowed to confirm the absence of transgressive paleoestuary facies (massive muddy facies associated to assemblages of marine planktonic diatoms -*Open bay mud*/*Estuarine central basin*) as a consequence of a sedimentary hiatus at the U6 / U7 boundary. This masks the Holocene Maximum and Highstand sea level. In addition, the succession of tidal-flat to marshes (regressive facies) was identified as proofs of delta progradation during the Late Holocene.

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ROCÍO FAYÓ [1,2]
https://orcid.org/0000-0002-7420-2460

MARCELA ALCIRA ESPINOSA[1,2]
https://orcid.org/0000-0001-8947-9502

FEDERICO IGNACIO ISLA[1,2]
https://orcid.org/0000-0002-4930-0907

[1]Instituto de Investigaciones Marinas y Costeras
(IIMyC, CONICET/UNMdP), Rodríguez Peña 4046,
(7600) Mar del Plata, Buenos Aires, Argentina

[2]Instituto de Geología de Costas y del Cuaternario
(IGCyC, UNMdP/CIC), Funes 3350, (7600), Mar
del Plata, Buenos Aires, Argentina

Correspondence to: **Rocío Fayó**
E-mail: rociofayo@gmail.com

Author contributions

Rocío Fayó: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing-original draft, Writing-review & editing. Marcela Espinosa: Funding acquisition, Project administration, Conceptualization, Supervision, Visualization, Investigation, Writing-review & editing. Federico I. Isla: Conceptualization, Visualization, Field work, Investigation, Supervision, Writing-review & editing.