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MEANDERING TIDAL-FLUVIAL CHANNELS AND LAG CONCENTRATION OF TERRESTRIAL VERTEBRATES IN THE FLUVIAL-TIDAL TRANSITION OF AN ANCIENT ESTUARY IN PATAGONIA

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Abstract: The La Pastosa beds constitute a nice example of sediments deposited in the highly meandering reach of the fluvial-tidal transition within an estuary, developed at the top of the "Rionegrense" stage, a marine-estuarine sequence of late Miocene age from Patagonia. Sedimentary facies include channel lags rich in mud intraclasts; cross-bedded sandstones with mud drapes and "set-climber" ripples; heterolithic and herringbone bedding; and inclined heterolithic stratification (IHS), and suggest a strong tidal influence. Tidal facies together with paucity of bioturbation and marine fossils indicate that sedimentation took place mainly in brackish tidal-fluvial channels, bounded by deposits formed in transgressive conditions at the base and at the top of the succession. Channel lag intraformational conglomerates are product of collapse of the cutbank due to erosion in the active margin of lateral migrating meandering channels that eroded adjacent muddy tidal flats and salt marshes. Cross-bedded sandstones were accumulated above the conglomerates, forming subtidal sand dunes in the deeper parts of the channels and IHS was formed in point bars. Discontinuities at the base of the channels are the result of the entire channel-system lateral migration, whereas discontinuities capped by small mud pebbles at the base of large IHS sets are the result of seasonally increased run-off and widening of the channels. Alternation of sandy and muddy IHS suggests periodical changes in the position of the turbidity maximum due to seasonal variation of fluvial discharge, in good agreement with the seasonal climate in Patagonia during the late Miocene. IHS sets dipping alternatively to the north and south indicate lateral migration of the east-west running, high-sinuosity channels in the tightly meandering reach of the tidal-fluvial transition. The well preserved vertebrate fauna of Huayquerian mammal age is dominated by the hydrocherid *Cardiatherium patagonicum* together with whistling ducks and loricariid fishes. This fauna inhabited out-of-channel, freshwater, low-energy restricted environments, like marshes and ponds where the carcasses accumulated and underwent diagenetic fossilization. Repeated lateral migration of meandering channels caused erosion of these deposits and the bones were exhumed and incorporated into the channels, and finally concentrated in channel lags after short transport. Combination of fossilization in a low-energy environment and concentration after short transport in meandering channels make the fluvial-tidal transition "first class" deposits for prospecting vertebrate fossils. In

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spite of exhumation and transport, vertebrate fossil association closely reflects the environments adjacent to the channels. Excellent preservation is more related to rapid burial than to the energy level of the environment of final accumulation.

Resumen: Los estratos de La Pastosa constituyen un buen ejemplo de sedimentos depositados en la porción meandriforme de alta sinuosidad de un sistema de transición fluvial/mareal en un estuario. Estos representan el tope del "Rionegrense", una sucesión marino marginal del Mioceno tardío de Patagonia. Facies sedimentarias tales como residuos de canal con abundantes intraclastos pelíticos; areniscas con estratificación entrecruzada, cortinas de fango y ondulitas ascendentes en caras de avalancha; estratificación heterolítica horizontal; estratificación tipo "hueso de arenque" (*herringbone*); y estratificación heterolítica inclinada (*IHS*) indican una importante influencia mareal. Todo ello, sumado a la escasez de bioturbación y fósiles marinos, indican que la sedimentación ocurrió principalmente en canales de marea-fluviales, limitados por depósitos transgresivos tanto en la base como en el tope de la sucesión. Los conglomerados residuales intraformacionales son producto del colapso de la pared erosiva (*cutbank*) por la migración lateral de canales meandrosos que erodaron las planicies de mareas fangosas y marismas adyacentes. Las areniscas con estratificación entrecruzada se acumularon por encima de los conglomerados, en forma de dunas arenosas submareales dentro del canal y las *IHS* se formaron por migración de barras en espolón. Las discontinuidades de la base de los canales son el resultado de la migración del sistema canalizado en su totalidad mientras que las discontinuidades en la base de los grandes sets de IHS se deben al incremento estacional de la descarga fluvial con el consecuente ensanchamiento del canal. La alternancia de porciones fangosas y arenosas en las IHS sugiere cambios periódicos en la posición del máximo de turbidez causados por variaciones estacionales en la descarga fluvial, en concordancia con el clima marcadamente estacional que se registra en la Patagonia durante el Mioceno tardío. Los sets de IHS que inclinan al N y al S indican la recurrencia de la migración lateral de canales meandrosos de alta sinuosidad orientados en sentido E-O. La fauna de vertebrados muy bien preservados de edad mamífero Huayqueriense, está dominada por el hidroquérido *Cardiatherium patagonicum* junto con patos silbadores y peces loricárdidos. Estos organismos vivían fuera de los canales, en ambientes restringidos de agua dulce y baja energía como marismas y lagunas, en donde los esqueletos se acumularon y fosilizaron durante la diagénesis temprana. La repetida migración lateral de los canales produjo erosión de estos depósitos y los huesos fueron exhumados e incorporados a los canales, para finalmente ser concentrados en los depósitos residuales luego de un corto transporte. La combinación de la fosilización en ambientes de baja energía y la posterior concentración luego de un breve transporte en canales meandrosos hacen a los depósitos de la transición fluvial/mareal un objetivo de primera clase en la búsqueda de vertebrados fósiles. Pese a la exhumación y al transporte sufrido, la asociación de vertebrados fósiles refleja fielmente el ambiente adyacente al canal. La excelente preservación depende en mayor medida del rápido sepultamiento antes que de la energía del ambiente de acumulación final.

Keywords: Fluvial-tidal transition, Miocene, Sedimentology, Taphonomy, Patagonia.
Palabras clave: Transición fluvial/mareal, Mioceno, Sedimentología, Tafonomía, Patagonia.

INTRODUCTION

The fluvial-tidal transition in an estuary is a complex zone located between the point where tidal action is just sufficient to leave a recognizable record in the deposits and the end of the fluvial dominated portion (Dalrymple and Choi, 2007; van den Berg *et al.*, 2007). These authors stated that hydraulic and morphologic characteristics make the transition zone different from the 'pure' fluvial and tidal environments and make it distinguishable on the basis of sedimentary structures and textures as a separate environment, where the tightly meandering reach in the middle of the "straight"-meandering-"straight" succession of channel shapes, at the bedload convergence zone, is located. Excellent exposures of the "Rionegrense" beds (late Miocene) along the eastward trending cliff-lined coastline in Estancia (Ranch) La Pastosa (Península de Valdés), allowed recognition of several diagnostic features of the fluvial-tidal transition by means of a detailed facies analysis. Besides, the remains of a typical terrestrial fauna (Dozo *et al.*, 2010) concentrated in intraformational conglomerates interbedded with large-scale sets of inclined heterolithic strata (IHS) provided important paleoecological information to support the paleoenvironmental interpretation. These conglomerates overlie erosional surfaces and minor scours within tidally influenced meandering channels, which typically yield vertebrate lags that can be even richer than "upland" fluvial deposits (Rogers and Kidwell, 2000). The aim of this paper is twofold: on one hand to prove that La Pastosa deposits are good examples of meandering tidal-fluvial channels, developed within estuarine environments at the top of a marine-estuarine sequence (Scasso and del Río, 1987) and to characterize the fluvial-tidal regime for the "Rionegrense" times; on the other hand, to highlight the mechanisms of concentration of well-preserved vertebrate fossils and to show how close can vertebrate fossil associations reflect the environments around the tidal-fluvial channels.

AGE, GEOLOGICAL SETTING AND EVOLUTION

The studied sediments belong to the "Rionegrense" of Feruglio (1949), which is a chronostratigraphic unit composed of sandstones, shales and coquinas in the upper part of the stratigraphic column of the Valdés Peninsula region (Fig. 1). Feruglio (1949:199) stated that the transition between the underlying fully marine "Entrerriense" beds and the "Rionegrense" beds is gradual. Haller (1979) and Haller *et al.* (2001) grouped the "Entrerriense" and "Rionegrense" beds under the lithostratigraphic unit delineated as the Puerto Madryn Formation. Thus, the stratigraphic section in figure 1 represents the Puerto Madryn Formation or, what is equivalent, the "Entrerriense" transitionally covered by the "Rionegrense". Scasso and del Río (1987) considered the "Rionegrense" beds as deposited in a tide-dominated sedimentary environment, which comprises the regressive component of a transgressive-regressive cycle (del Río *et al.*, 2001).

Although the foraminifera association of the "Entrerriense" was considered of middle Miocene age (Malumián and Masiuk, 1973; Masiuk *et al.*, 1976; Malumián, 1999), the age of the Puerto Madryn Formation is currently assigned to the late Miocene on the basis of isotopic ages. ^{87}Sr/^{86}Sr datings from Pectinidae and oyster shells from "Entrerriense" beds yielded a mean age of 10 ± 0.3 Ma (Tortonian) (Scasso *et al.*, 2001). Also ^{40}K/^{39}Ar datings on three glass concentrates from a tuff in the upper part of the marine "Rionegrense" beds yielded an average Tortonian age of around 9.4 Ma (Zinsmeister *et al.*, 1981). The "Entrerriense" malacofauna was recently assigned to the late Miocene (Martínez and del Río, 2002; del Río, 2004) and a palynological study also assigned the sediments of the Puerto Madryn Formation to the late Miocene (Palazzesi and Barreda, 2004) in agreement with the Huayquerian Age of the fossil mammals (Dozo *et al.*, 2010).

The "Rionegrense" beds make up the regressive part of a transgressive-regressive cycle in which the combined Transgressive and Maximum Highstand Phases (del Río *et al.*, 2001) record dynamic to complete sediment bypassing conditions in tide- to wave-dominated, mid- and inner-shelf environments open to the Atlantic Ocean. Fossil marine invertebrate assemblages (del Río *et al.*, 2001) inhabited firm-gravel or sandy substrata in areas swept by strong currents, probably situated laterally or distally to the mouth of large tidal channels, above the storm-wave base. Sand ridges and shoals reworked during a transgression by tidal currents or waves can be modern environmental analogues for the accumulation of the lower part of the column (Fig. 1c). High rates of transgression with rapid water deepening and/or reworking of shelf deposits into

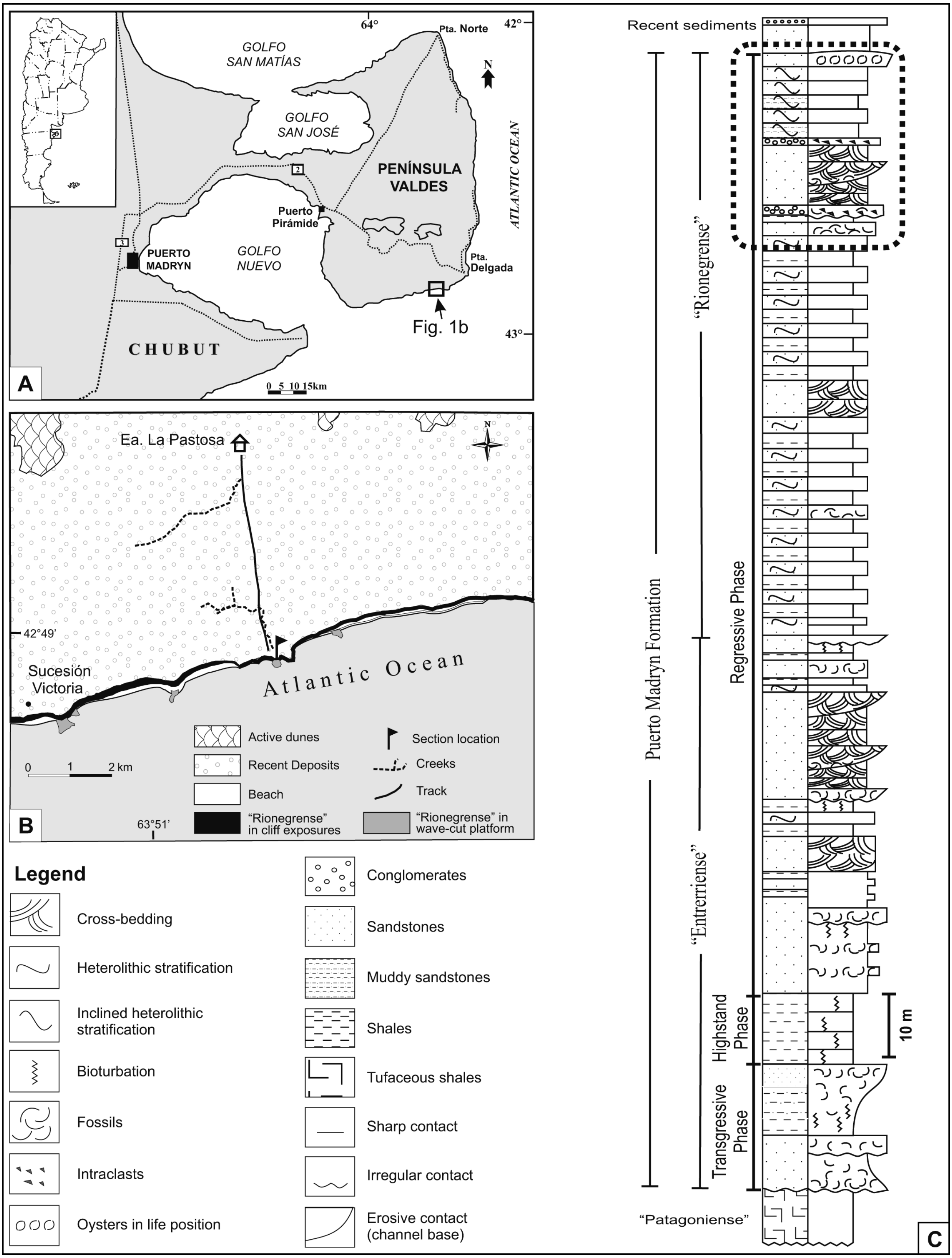

Figure 1. a) Regional location map. b) Geological map of La Pastosa area. c) Composite section of the "Entrerriense"-"Rionegrense" beds (Puerto Madryn Formation) in Peninsula Valdés area (after del Río *et al.*, 2001). Highlighted area corresponds to the part of the section exposed at La Pastosa cliff and represented in figure 2.

sand ridges reflect an accommodation/supply ratio > 1 (e.g. Swift *et al.*, 1991).

The overlying Regressive Phase (Fig. 1c), which contains the transition from the "Entrerriense" to the "Rionegrense", is best exposed eastwards from the Puerto Pirámide area in the Valdés Peninsula (Fig. 1a). The Regressive Phase is characterized by cycles formed by tidal channel-bar deposits interbedded with environmentally condensed shell-beds. Abundant volcaniclastic materials sourced by the rivers to the tidal channels (Scasso and del Río, 1987) contributed to the general regressive trend by shifting the depocenters to the east and northeast.

Deposition of the Regressive Phase was strongly influenced by tidal regimes and it reflects a more restricted environment. According to paleocurrent data (Scasso and del Río, 1987), sediment transport was mainly along a large embayment oriented NE-SW. Heterolithic deposits intercalated with mud-draped cross-bedded sands and shell-beds constitute several cycles in the lower part of the Regressive Phase (Fig. 1c). These deposits were interpreted to represent tidal bars and "sand tongues" (fan-shaped sandbars that run parallel to tidal channels) deposited in environments alternately dominated by tidal currents or waves, often capped by shell-rich beds that record a change from positive values of net sedimentation towards dominant omissional conditions, with the *Skolithos* ichnofacies (del Río *et al.*, 2001). When subsequent deepening and non-depositional conditions occurred, pecten assemblages colonized sandy or gravelly bottoms close to fair-weather wave base and swept by weak currents or waves (del Río *et al.*, 2001). Each of the cycles records an upward deepening from restricted upper shoreface (sandbars) to inner-shelf environments. The complex Type IV-I shells (Kidwell, 1986) that cap each cycle appear to be environmentally condensed accumulations that represent prolonged non-deposition and comprise the flooding surface. It is not certain if these water-depth fluctuations were caused by autocyclic (channel and sand tongue lateral shifting) or allocyclic (relative sea level rise) factors, but they do show that the regression of the "Entrerriense" sea was punctuated by short-term, high-order relative sea level rises, although the general style of accumulation is regressive-progradational, probably with expanded offlaping parasequences (*sensu* Embry, 1995) reflecting accommodation/supply ratio <<1. Overall decreasing marine influence is evidenced by gradual decrease in the abundance and variety of marine fossil molluscs and trace fossils (Fig. 1c). La Pastosa beds, in the uppermost part of the succession, show an impoverished mollusc association and sparse trace fossils together with a vertebrate fauna including capybaras and freshwater fishes (Dozo *et al.*, 2010). Marine to brackish or fresh water conditions are suggested by the faunal-ichnological association.

FACIES ANALYSIS IN LA PASTOSA SECTION

The cliffs along the southern coast of Península Valdés show excellent exposures of the "Rionegrense" deposits (Figs. 1, 2, 3). The trace of the coast is irregular near Estancia La Pastosa and shorter N-S cliffs interrupt the general E-W trend of the coastline, making it ideal for 3-D observations. Facies analysis on a fully exposed area 2.5 km long (E-W) and 1 km wide (N-S) reveals several diagnostic characters of estuarine deposits.

Facies 1

It is composed of laterally continuous, cemented hard beds of parallel-bedded bioclastic deposits, rich in oysters, pectens (*Aequipecten paranensis*), balanids and sand dollars (*Monophoraster darwini*), together with some bryozoan colonies with sandy to silty matrix (Fig. 3). Fossils are larger and more abundant towards the top of the three, 0.8 m-thick beds of coquinas that constitute the deposits of Facies 1. Well-preserved, disarticulated shells are oriented parallel to the bedding planes with their convex side either up or down. Large, pervasive burrows partially obliterated the original bedding. However, it is still possible to note that fossils were originally concentrated in 0.1 - 0.2 m-thick levels. The base contact of the coquina interval is sharp and strongly bioturbated with passively-filled *Thalassinoides* isp. and *Ophiomorpha* isp. burrows (*Glossifungites* ichnofacies) developed on a firm substrate on the top of a wavy-and flaser-bedded stratum. The top of the coquina interval is sharp and erosively cut by the conglomerate of Facies 2.

Interpretation. "Entrerriense" and "Rionegrense" coquinas contain silty to fine-sandy matrix and

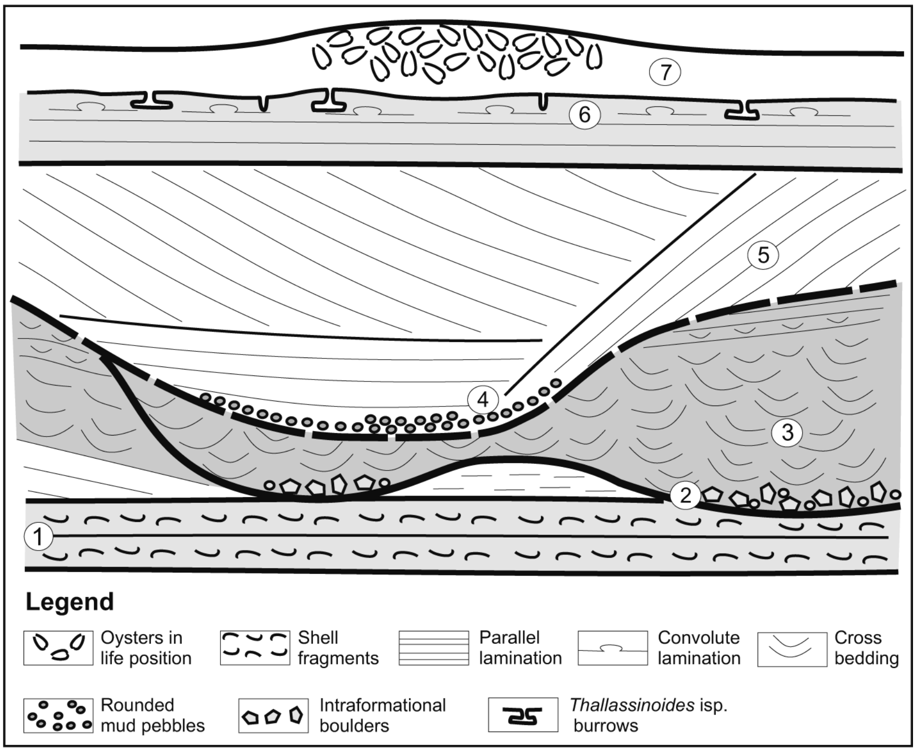

Figure 2. Sketch of facies distribution in La Pastosa. 1 = coquinas; 2 = intraformational conglomerates; 3 = cross-bedded sandstones; 4 = pebbly intraclast conglomerate; 5 = inclined heterolithic bedding; 6 = parallel laminated and convoluted sandstones; 7 = monospecific oyster reef. Thick full line marks the main discontinuity interpreted as the result of migration of the whole tidal-fluvial channel-system. Thick dashed line marks a second type of discontinuity, probably resulting of seasonally increased run-off and channel widening followed by migration of the point-bar (see text for more details). Not to scale.

well-preserved, disarticulated fossils accumulated in shoreface subtidal environments under the influence of storm waves (Scasso and del Río, 1987). The fossil association corresponds to the OMA (*Oyster*, *Monophoraster*, *Aequipecten*) Assemblage of del Río *et al.* (2001), typical of high-energy, shoreface environment with normal marine salinity. The characteristics of the coquinas match with the Type I shell beds of Kidwell (1986), which show an upward increase of shell concentration suggesting a gradual change from aggradation to non-deposition with consequent reworking and winnowing on the top of the beds by storm waves.

Facies 2

It is composed of lenticular, poorly-sorted intraformational conglomerate with large boulders and irregular, sharp erosive base (Fig. 4a) and internal, erosive discontinuities separating the main conglomerate from other lens-shaped conglomerate bodies of diverse composition. Pebbles and boulders are formed essentially of fragments of indurate muddy layers. Disarticulated and transported oysters and pectens as well as terrestrial vertebrate bones (Fig. 4b) are concentrated in some levels. Facies 2 is found above a strongly erosive surface that cuts into several different deposits, such as heterolithic beds, shales and the coquinas of Facies 1.

Interpretation. The intraformational boulder conglomerate was created by collapse of the cutbank due to erosion in the active margin of a meandering channel. The channel underwent multistage filling and this is revealed by the common occurrence of small conglomerate lensoid bodies separated by internal discontinuities. This suggests several episodes of erosion and accumulation due to changing flow regime within the channel. Mud pebbles record frequent and repeated scouring in contemporaneous or slightly older deposits containing semiconsolidated muds. Mixing of marine and terrestrial fauna might suggest alternating marine and fresh water conditions (see paleoecological analysis below). However, those evidences should be carefully analyzed because lateral migration of meanders incorporated skeletal remains from older deposits.

Facies 3

This facies makes up lenticular bodies up to 8 m thick and 100 m wide composed of large scale, cross-bedded grey sandstones (Fig. 5a-b). Large-scale, cross-bedded sets exhibit mud drapes and ripples upon reactivation surfaces. Herringbone cross-bedding also occurs. The larger sets were deposited by southward oriented paleocurrents (Fig. 5b). Smaller-scale cross-beds exhibit either north or south paleoflow indicators. Subcritical climbing ripples, current ripples and combined-flow ripples are intermingled and commonly exhibit alternatively opposite paleocurrent directions together with mud drapes and flaser bedding. Foresets and reactivation surfaces are frequently wrinkled by ripples moving up high on them ('setclimbers' of van den Berg *et al.*, 2007). Directions of ripple movement parallel to foreset-strike are also found. The scale of the cross-bedded sets decreases toward the upper part of the interval, where herringbone bedding can be observed, and it finally changes into parallel bedding and wave ripples at the top. The sand bodies often pinch out laterally (Fig. 2) because they lack the upper part, cut by a deep erosive surface overlaid by muddy IHS (Fig. 5b).

Interpretation. Cross-bedded sands are the product of dune migration (Ashley, 1990) in the subtidal part of tidal-fluvial channels (Choi *et al.*, 2004). Unidirectional cross-bedding is developed into mutually evasive flood-and ebb-dominated channels. Fining upward trends and heterolithic facies reflect gradual decrease in current speed from deeper parts of the channel to the channel bank (Mossop and Flach, 1983). Abundance of mud drapes suggests slack water periods during high- or low-tide stillstands. This, together with opposingly directed ripples, setclimber ripples and herringbone cross-bedding reflect a strong degree of tidal influence, typical of the fluvial-tidal transition (Dalrymple and Choi, 2007; van den Berg *et al.*, 2007). Combined-flow and wave ripples are the result of combined current and wave or wave action respectively, common in shallow subtidal and intertidal parts of the bank in large channels.

Facies 4

It is composed of intraclast conglomerates of pebble-sized, muddy rip-up clasts. Beds are commonly well sorted, from centimeters to few decimeters thick, locally reaching up to 1 m in thickness and dies out laterally in a few meters. Clasts are rounded, platy in shape, rarely reach boulder size and are sometimes imbricated (Fig. 6). Small-sized, well-preserved, disarticulated oysters are occasionally found within these conglomerates. Platy clasts and oysters are often imbricated and exhibit eastward or southeastward directed paleocurrents (Fig. 6). Conglomerates of Facies 4 are found at the base of Facies 5, on top of an erosional surface cut into Facies 3.

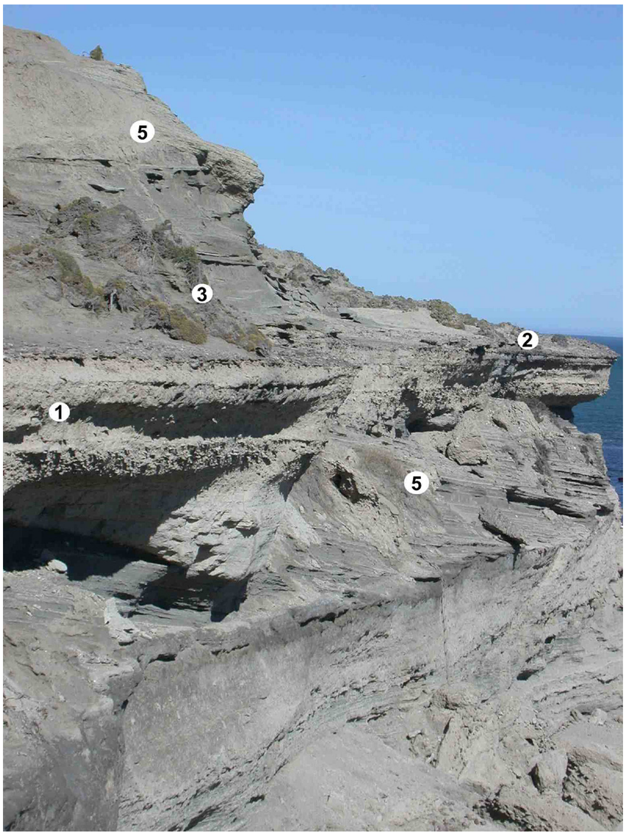

Figure 3. Shelly sandstones and coquinas of Facies 1 separated by an erosive surface from the overlying conglomerates of Facies 2, in turn covered by grey, cross-bedded sandstones of Facies 3. Muddy IHS (5, up) erosively covers the grey sandstones of Facies 3 (see also Fig. 7). Sandy IHS (5, down) underlying Facies 1 can be distinguished in the inaccessible part of the cliff. For scale regard the three coquina hard beds of Facies 1, that are altogether about 2.5 m thick.

Interpretation. The platy shape and rounded outlines of mud pebbles indicate the mud was still soft when eroded, which is typical of erosion of penecontemporaneous mud drapes and mud laminae (Dalrymple and Choi, 2007). Erosion surfaces are common in IHS and, in most cases, they are caused by widening of the channel or by seasonally-increased runoff when the channel thalweg locally cuts into the depositional bank (Bridges and Leeder, 1976; de Mowbray, 1983; Dalrymple and Zaitlin, 1994), or can be caused by retreating erosional scarps in the lower intertidal zone of the tidal channel bank (Choi

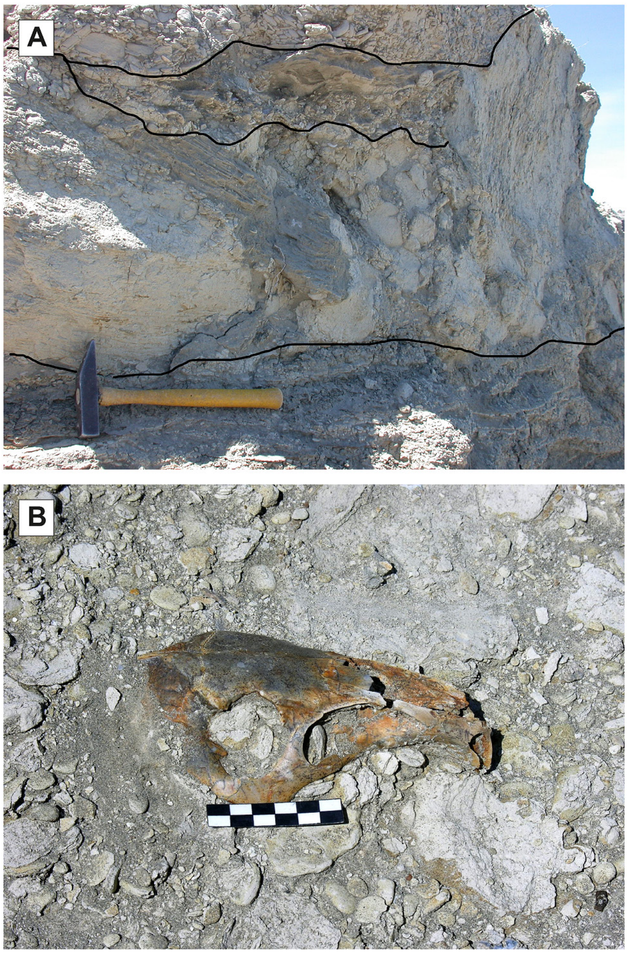

Figure 4. a) Intraformational conglomerates of Facies 2. The base is formed by large, intraformational boulders of shales and sandstones originated by collapse of the cutbank side in a meandering tidal-fluvial channel. The main discontinuity at the base of the channel, cut into the whitish shale is marked with the lower full line. Other lines point several internal discontinuities that often bear lags containing vertebrate bones. b) Well-preserved Capybara skull within an intraformational conglomerate of Facies 2. Scale units = 1 cm.

et al., 2004). However, rounded outlines of the mud clasts suggest they were originated by intra-channel erosion. Scattered small-sized oysters suggest selective transport by flood currents.

Facies 5

This facies is composed of inclined heterolithic stratification (IHS) forming large, up-to-10 m thick sets (Fig. 7). Sandy or muddy layers alternatively dominate in the different sets, sometimes making up decimeter thick tidal rhythmites (Cuitiño *et al.*, 2012). Sandy layers are composed of very fine sand, varying in thickness from few millimeters to up-to-5 cm, and show upper flow regime parallel lamination or current ripple lamination with opposite directions of migration (E and W; Fig. 6). Mud drapes are commonly around 1 cm thick and can be laterally continuous or be preserved only within the ripple troughs (Cuitiño *et al.*, 2012). Pebbly conglomerates with rip-up mud clasts of Facies 4 are commonly interbedded, but they are thicker at the base of the sets. The sets dip to the south or to the north along the east-trending cliff-bordered coastline, with angles from near the horizontal to a maximum of 12º.

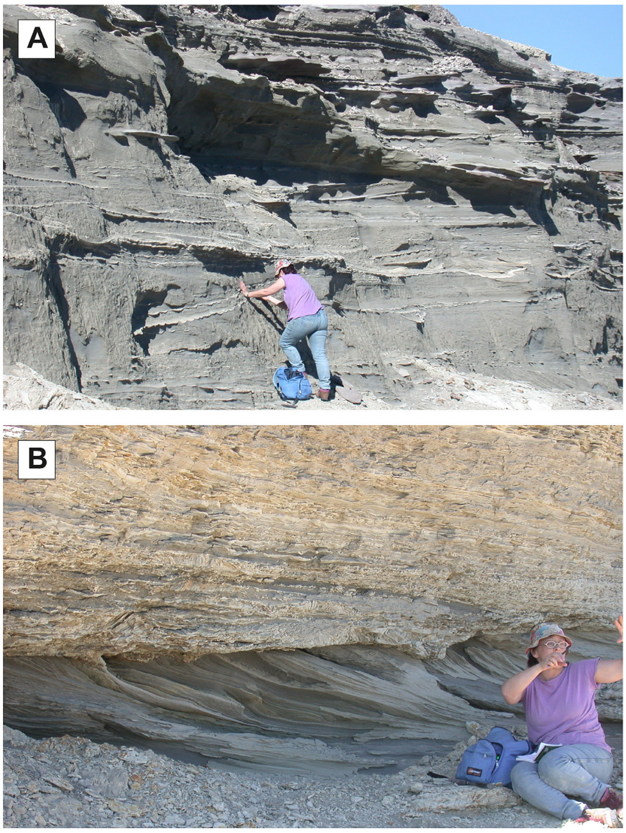

Figure 5. a) Thick bodies of grey, cross-bedded sandstones with white mud drapes typical of Facies 3. b) Large-scale set of cross-bedded sandstones formed by ebb currents. Large–scale, unidirectional sets are typical of tidal-fluvial channels in which mutually evasive ebb and flood currents are developed. Grey sandstones are separated from the overlying IHS beds by a marked erosional discontinuity suppressing most of the upper part of the sandstone body.

Interpretation. The IHS is particularly abundant in tide-influenced settings (Smith 1987; 1988; Thomas *et al.*, 1987; Eberth, 1996; Dalrymple *et al.*, 2003; Choi *et al.*, 2004) as a result of lateral meander migration. Point bars may develop IHS in the inner bends of meandering channels, especially

Figure 6. Intraformational conglomerates of Facies 4 within sandy heterolithic bedding. Note the minor erosive discontinuity at the base of the pebbly conglomerate and imbrication of the abundant platy intraclasts. Note the frequent change in current direction, marked by current ripples and ripple cross-lamination with ebb currents to the right and flood currents to the left. Ripples with wavy, discontinuous bundles and undulatory contacts suggest wave influence in the uppermost-arrowed bed (de Raaf *et al.*, 1977).

within small intertidal channels in areas with high suspended-sediment concentrations (Bridges and Leeder, 1976; de Mowbray, 1983). The abundant occurrence of lenticular and flaser bedding, or the rhythmic alternation of sand-mud interbedding and indications of the reversal of flow, as well as the preserved neap-spring tidal cycles, certify the formation in the fluvial-tidal transition (van den Berg *et al.*, 2007). Large-scale (up to 25 m thick) IHS was described by Mossop and Flach (1983) and assigned to meandering fluvial channels about 250 m wide. Similar IHS sets were found by Choi *et al.* (2004) in the 1000-1500 m wide and up to 50 m deep Sukmo tidal channel in Korea.

Facies 6

This facies consists of tabular beds of about 2 m thick composed of parallel laminated and convolute laminated fine sandstones (Fig. 8), with other evidences of syndepositional deformation such as load casts and flame structures. The upper part is profusely bioturbated by passively filled *Thalassinoides* isp. burrows.

Interpretation. These sandstones are interpreted as deposited in the middle intertidal zone whose deposits typically show parallel lamination and convolute synsedimentary deformation (Choi *et al.*, 2004). Bioturbation at the top of these deposits is related to the subsequent marine flooding represented by Facies 7.

Facies 7

This facies is composed mainly of monospecific oyster buildups with articulated "in situ" or slightly remobilized oysters of medium-size (10 to 15 cm long) with a fine-grained sand-rich matrix. They lie on top of a 1-m thick coarsening-upward bed of sandy-coquina, with disperse and broken shell fragments which in turn is separated from the underlying Facies 6 by a slightly erosive, irregular and profusely bioturbated surface (Fig. 8).

Interpretation. Oysters can occur both, in shallow-marine and estuarine environments (e.g. Kirby, 2001). However, monospecific oyster buildups today only develop in brackish settings (Stenzel,

	A	B	C	D	E	F	G	H	Total
skull		1			10				**11**
incisors-canines					8				**8**
lower teeth					10				**10**
upper teeth					15				**15**
vertebraes	1		1		22	5		7	**36**
metapodial elements							3		**3**
phalanges	1								**1**
humerus			2		2				**4**
femur					4	1			**5**
tarsus elements					2				**2**
carpus elements						5			**5**
ulna						1			**1**
tibia						2			**2**
fibula						2			**2**
scapula							5		**5**
pelvis					2	2	2		**6**
osteoderms				2					**2**
Total	**2**	**1**	**3**	**2**	**75**	**18**	**10**	**7**	**118**

Table 1. Terrestrial vertebrate fauna in La Pastosa. Number of elements identified by taxon: A) Psilopterinae indet.; B) Accipitridae indet.; C) Dendrocygninae indet.; D) *Scirrotherium* sp.; E) *Cardiatherium patagonicum*; F) Macraucheniidae indet.; G) Mammalia indet.; H) Osteichthyes indet. The fauna is composed by Birds (5% - columns A, B, C); Mammals (89% - columns D, E, F, G) and fishes (6% - column H).

1971; Puckett, 1994). Environmental conditions such as high turbidity within the water column, mesotrophic nutrient levels, low terrigenous input and disturbed seafloor conditions controlled the formation of oyster-rich bioherms in the past (Pufahl and James, 2006). These environmental factors, together with high spatial homogeneity of oyster buildups prevented recruitment of specialized, stenohaline organisms. Accordingly, oysters in La Pastosa section are interpreted as developed in an estuary with reduced clastic input formed on top of the channel overbank of Facies 6. These conditions are thought to be the cause of a low-amplitude relative sea-level rise.

FOSSIL VERTEBRATES IN THE LA PASTOSA DEPOSITS

About 120 well-preserved, unweathered, unabraded and disarticulated vertebrate bones (Table 1) were found in Facies 2, 3 and 4, forming part of the coarse-grained channel-fill deposits. The bone association in La Pastosa includes fishes, birds and mammals (Dozo *et al.*, 2010).

Osteichthyan fishes (6%) are represented by vertebrae, fragmented spines and one cleithrum; Gruiformes, Falconiformes and Anseriformes birds (5%) by one skull, one vertebrae, two humerus, one phalanx and one sinsacrum; while mammals (89%) by several complete skulls, several skull fragments with different quality of preservation, isolated osteoderms, many isolated teeth, and postcranial elements (including vertebrae, pelvis, tibia-fibula fragments, humerus, femur, metapodial, carpus and tarsus elements, and phalanges).

The majority (71%) of the mammal remains correspond to *Cardiatherium patagonicum* (Rodentia-Hydrochoeridae); 17% to Macraucheniidae (Liptoterna); 2% to Pampatheriidae (Xenarthra) and 10% to undetermined Mammalia. The remains can be included in the Groups I, II and III from Voorhies (1969) according to their potential for hydraulic transport. Vertebrae, scapulas and phalanges are easily transported by current water and belong to the Group I. The long bones, metapodial and pelvis belong to the Group II and have an intermediate

Figure 7. Inclined heterolithic stratifications (IHS) of Facies 5 on top of a marked discontinuity. The thickness and frequency of sand and mud layers is similar. The IHS dips to the S and are part of the point bar of a meander in a ENE-WSW running tidal-fluvial channel.

potential for transport. The skulls fall in the Group III, which includes bones that are not easily transported by the currents.

DISCUSSION

La Pastosa: Channels in the Fluvial-Tidal Transition Zone

Feruglio (1949) suggested that the "Rionegrense" accumulated in a very shallow sea subjected to the flux and reflux of tides and waves whereas Windhausen (in Feruglio, 1949: pp. 202) envisaged a sedimentary environment comparable to the "Watten" of the Northern Sea. The marine fauna and ichnofauna of the "Rionegrense" is poor in comparison to the underlying "Entrerriense" indicating stressed environmental conditions during the accumulation of the upper part of the sequence. The area of La Pastosa was part of a major, low gradient, NE-SW embayment (Scasso and del Río, 1987) at least several tens of kilometers long. Scasso and del Río (1987) defined a paleoenvironment similar to the recent sedimentary environment in the Nordergründe area to the south of the mouth of the Elbe river (Reineck and Singh, 1980) for the Upper "Entrerriense" and "Rionegrense" (see figures 5 and 6 of Scasso and del Río, 1987), in which tidal channels with complex filling are associated with "sand tongues", large bars elongated perpendicular to the coast, formed in subtidal environment at the mouth of tidal channels.

Paucity of bioturbation and lack of typical marine molluscs in Facies 2 to 6 suggest sedimentation in brackish or fresh water environment for most La Pastosa beds. The interval of the succession is bounded by typical marine deposits of the Facies 1 at the base and outer estuary deposits of Facies 7 at the top which both represent relative higher sea-levels.

The erosive base and general fining-upwards trend of the succession of Facies 2 to 6 (Fig. 2) point to sedimentation within a channel. The deeper and stratigraphically lowermost part of the channel was filled with coarse intraformational conglomerates product of the collapse of the cutbank due to erosion in the active margin of a meandering channel. Complex, multiepisodic filling is represented by many conglomerate lenses product of several episodes of scouring and accumulation due to changing flow regime inside the channel.

Cross-bedded sands are the deposits of subaqueous dunes migrating in the subtidal part of the tidal-fluvial channel. Large, unidirectional cross-bedding was originated by flood currents into mutually evasive, flood- and ebb-dominated systems, typical in meandering channels (Choi *et al.*, 2004). Fining upward trend and transition to heterolithic facies reflect gradual decrease in current speed from deeper parts of the channel to the channel bank. Lamina/bed thickness is expected to decrease upward in the channel bank (Choi *et al.*, 2004), together with an overall upward-fining trend, from medium sand at the base to fine silt and clay at the high-tide level. Abundance of mud drapes, opposing-directed ripples, setclimber ripples and herringbone cross-bedding reflect marked tidal influence with reversing flows (Dalrymple and Choi, 2007; van den Berg *et al.*, 2007).

The top of cross-bedded sandstones is sharp and erosive everywhere in the studied zone, pointing to deep scouring and remobilization of a considerable volume of sand, preceding the accumulation of IHS (Figs. 2, 5b, 7). Point bars in meandering channels may develop IHS, especially in areas with high suspended-sediment concentrations inside an estuary (Dalrymple and Choi, 2007). Large-scale (up to 25 m thick) IHS sets were described by Choi *et al.* (2004) in the Sukmo channel in Korea, a meander-like, “S” shaped tidal channel that reaches 1000-1500 m wide and 50 m deep during spring high tides. IHS sets in La Pastosa are about half in thickness and together with the 8 m thick, underlying cross-bedded sands, suggest 15-20 m deep tidal-fluvial channels more similar to the 25 m deep and 250 m wide tidal channels reconstructed by Mossop and Flach (1983). Abundant occurrence of lenticular and flaser bedding, or the rhythmic alternation of sand-mud interbedding and indications of the reversal of flow certify the accumulation in the fluvial-tidal transition (van den Berg *et al.*, 2007). Current tidal ranges in Puerto Madryn are about 6 m during spring tides (compared with the 7.8 m spring tidal range of Sukmo channel area). Miocene beds were accumulated in similar geographic conditions within large embayments and therefore similar tidal ranges as well as tidal amplification were surely present.

Erosion surfaces within the channel deposits and in the channel bank might be caused by seasonally-increased runoff producing more intense currents in the deeper parts of the channel and widening of the channel in the shallower parts (de Mowbray, 1983). Retreating erosional scarps product of wave action are also found in the lower intertidal zone of the tidal channel bank (Choi *et al.*, 2004). Lateral migration of large channels is expected to remove large amounts of materials from older deposits when the thalweg locally cuts into the depositional bank (Bridges and Leeder, 1976; Dalrymple and Zaitlin, 1994). Very large surfaces could be the product of slope failure and may remove the entire upper part of the channel succession (Choi *et al.*, 2004) causing the heterolithic stratification to show poor continuity in the dip direction. Main discontinuities in La Pastosa beds are at the base of the channels and at the base of large IHS sets. The first type is the result of migration of the whole channel-system (Mossop and Flach, 1983) and it might even be the result of a low amplitude sea-level drop (Eberth, 1996; Plink-Björklund and Steel, 2010). The second are probably the result of seasonally increased run-off and widening of the channel followed by migration of the point-bar (Figs. 2, 3, 4, 7).

Mud pebbles within channel deposits are common in the fluvial-tidal transition in the middle portion of estuaries (Dalrymple and Choi, 2007) in the vicinity of the turbidity maximum, where the high suspended-sediment concentration permits the deposition of thick mud drapes. There, the peak currents are sufficiently strong to re-erode these drapes, and lateral migration of the channels erodes the adjacent muddy tidal flats and salt marshes. Regarding the eastern-northeastern position of the open sea (Scasso and del Río, 1987), the presence of oysters in the mud-pebble conglomerates and eastward-directed paleocurrents suggest erosive flood tidal currents and some marine influence.

Mud-rich IHS is also expected to be formed in the zone of high concentration of suspended sediments (Dalrymple and Choi, 2007) and therefore it is associated with thin, mud pebble conglomerates. When IHS is formed in the inner part of the tidal-fluvial transition, it is more likely to contain coarse-grained layers formed by river floods. In the case of La Pastosa IHS, imbrication in the conglomerates indicates flood-directed currents intense enough to rework mud drapes from former deposits. However, sand-rich IHS also occurs in La Pastosa area, in close association with the muddy IHS. This suggest a periodical change in the position of the turbidity maximum, as IHS character is sand-dominated in the upper reach because of the seaward flux, fine-grained in the middle reach because of the convergent flux, and sand-dominated in the lower reach because of the landward flux (Lettley and Pemberton, 2004). Sandy IHS and sand dunes often have reverse-flow indicators which become common as the flood-tidal currents become stronger in the more seaward part of the fluvial-tidal transition. Dalrymple and Choi

Figure 8. Parallel- and convolute-laminated sandstones of Facies 6 covered by monospecific oyster reef with "in situ" or slightly remobilized, articulated oysters of Facies 7.

(2007) suggest that indicators of current reversals should begin to appear slightly further seaward than evidence of slack-water periods. These authors place the outer end of the fluvial-tidal transition at the bedload convergence in estuaries, which is also the location of the tightly meandering reach in the middle of the "straight"-meandering-"straight" succession of channel shapes (Fig. 9). Abundant IHS sets dipping in opposite directions in La Pastosa beds indicate recurrent migration of high-sinuosity channels. This, together with muddy IHS with reactivation surfaces, pebbly mud conglomerates, common reverse flow indicators and mud drapes in cross-bedded sandstones point to sedimentation in the tightly meandering reach, probably in the outer, seaward part of the fluvial-tidal transition. In this area bioturbation is expected to be minimal and includes fresh-water or low-diversity and small-size marine trace fossils typical of brackish water formed during times of low river flow (Dalrymple and Choi, 2007).

According to the paleoclimatic indicators in the late Miocene of Patagonia the paleoclimate was strongly seasonal (Barreda and Palazzesi, 2007). Location and character of the turbidity maximum may change due to seasonal variation of fluvial discharge (Allen *et al.*, 1980). During high fluvial influx the dilution of saline water by low density fresh water leads to a convergence of bottom water current, resulting in the concentration of suspended load near the limit of salt water intrusion. During periods of low fluvial influx, the concentration of fines takes place near the landward limit of flow reversal and the turbidity maximum is located in a landward position, and exhibits a transient tidal character. During high flow, the turbidity maximum is located in a relatively stable seaward position, and is maintained through density circulation. The seasonal excursion of the turbidity maximum can reach several tens of km (Allen, 1991). For example, the variation in the sand-mud content in different sets of the IHS has been attributed to differing position within the estuarine channel system, which would lead to differing influence of saltwater intrusion and suspended load deposition (Ranger and Pemberton, 1992). Changes in river discharge will not only change the character of the IHS but also the development of mud drapes in cross-bedded sandstones: during periods of high river flow, the turbidity maximum is pushed further seaward, thereby inhibiting the accumulation of mud drapes, whereas mud drapes may be formed more readily during periods of low river discharge when peak current speeds are less intense (Lettley *et al.*, 2005). Therefore the change between sandy and muddy IHS in La Pastosa might have been the consequence of the seasonal migration of fluvial influx and change in the position of the turbidity maximum in the fluvial-tidal transition. Dominant ebb currents run E-NE, during periods of high river discharge and dominant flood currents, run W-SW, during periods of low river discharge. Accumulation took place in a low-gradient and at least tens-of-kilometers-long embayment (Scasso and del Río, 1987). Renewed transgressive conditions towards the top of the sequence are evidenced by a monospecific oyster bioherm on top of a coquina overlying a burrowed discontinuity. The latter is interpreted as a ravinement surface covered by strandline deposits. Monospecific oyster bioherms typically formed in paleoestuaries with low terrigenous clastic input, brackish water conditions, a turbid water column, mesotrophic nutrient levels, during early transgressive stages (Pufahl and James, 2006).

Paleogeographic significance and the paleoecology of the Vertebrate Association

The mollusk fauna typical of the "Entrerriense" is mostly composed of tropical-subtropical Caribbean-Indo-Pacific taxa (del Río, 2000). Dozo *et al.* (2010) mentioned cysts of marine palynomorphs currently abundant in warm-temperate to tropical environments with high summer sea-surface temperatures (around 27°C) and water depths less than 60 m. According to Scasso *et al.* (2000) the Brazil Current reached central Patagonia in the early-late Miocene due to a southward displacement of the subtropical gyre that obliterated the northward-directed, cold Malvinas current.

Beds of La Pastosa were palynologically barren but records in the underlying "Entrerriense" provide some significant insights into the floristic context and paleoclimate during late Miocene times. Terrestrial palynomorphs (mostly pollen grains) suggest the presence of low xerophytic open forests similar to those present in northeastern Argentina today (Barreda and Palazzesi, 2007). In some cases, halophytic shrubs dominate the assemblages, indicating tidal salt-marshes (Palazzesi and Barreda, 2004). The palynological record might also indicate ponds or permanently saturated soils containing freshwater algae and aquatic ferns (Palazzesi and Barreda, 2004; Palazzesi, 2008). Seasonal swamps and ponds may have developed nearby the coast without any marine influence under warm and calm conditions, according to the abundance of floating plants like Azolla.

Aridization during the late Miocene caused the progressive replacement of forest types typical of the early Miocene by more open and xerophytic types in northeastern Patagonia (Barreda and Palazzesi, 2007). Major turnovers appear to reflect mainly the effects of Andean uplift and step-wise decrease of sea-surface temperatures (SST) associated with the establishment of the circum-Antarctic current and Antarctic ice cap.

The dominant hydrocherid *Cardiatherium patagonicum*, points to an autochthonous association (Behrensmeyer, 1975, Cladera *et al.*, 2004, Bergovist *et al.*, 2010). Modern hydrocherids like *Hydrochoerus hydrochaeris* are territorial animals living in groups of 7 to 20 individuals close to rivers and lakes, mainly in mangroves and marshes in temperate and tropical areas of South America (Woods and Kilpatrick, 2005; Herrera *et al.*, 2011). They feed on grasses and aquatic plants and spend most of the day in the water, or in water-saturated muds, but need bushy dry lands to sleep. Eagles (Accipitridae), whistling ducks (Dendrocygninae) and phorusrhacid Psilopterinae are recorded there. Whistling ducks (Dendrocygninae) materials show considerable similarities with the living Dendrocygna (Dozo *et al.*, 2010), which include herbivorous aquatic birds inhabiting lentic environments with dense surface vegetation. Psilopterinae are smallest and most gracile phorusrhacids that are, together with the eagles, the only carnivorous elements of these environments. Dendrocygninae records are consistent with the presence of freshwater environments. Large birds, such as Psilopterinae or Accipitridae, are in agreement with the occurrence of open forest and shrubs (Tambussi, 2011) and the occurrence of loricariid fishes (Cione *et al.*, 2005) suggests fresh water and a climate warmer than today. Therefore, autoecological comparisons are in good agreement with the palynological record and the facies analysis, pointing to a landscape of fresh-water lakes, ponds and swamps around the main channels, and open xerophytic forests in the mainland. Levees along channels probably provided dry and vegetated lands optimal for capybaras

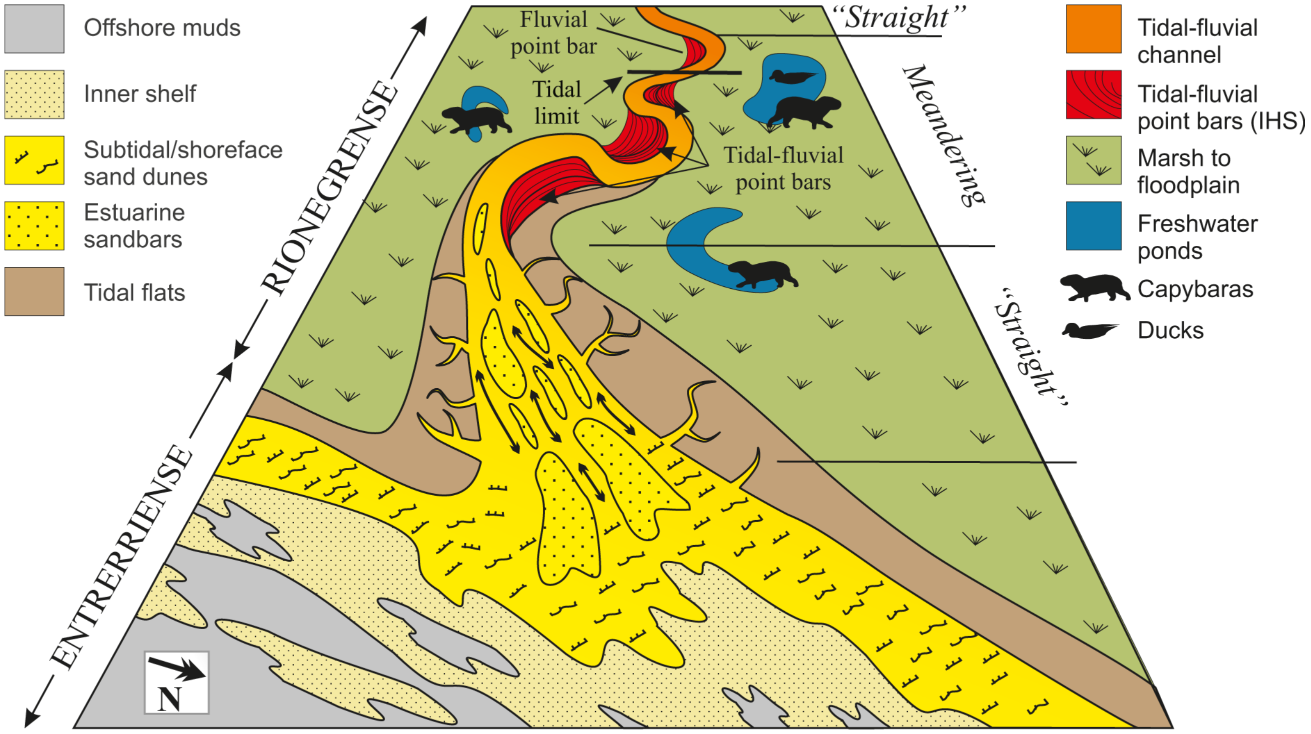

Figure 9. Tide-dominated estuarine model of the "Entrerriense" and "Rionegrense" deposits, showing the changes in tidal-fluvial channel geometry ("straight"-meandering-"straight"), and lateral migrating point bars in the fluvial-tidal transition (after del Río *et al*., 2001; Dalrymple and Choi, 2007 and Musial *et al*., in press).

development, which were probably predated by eagles and Psilopterinae (modern "harpías" predate on young capybaras nowaday).

Fossil Concentration in Tidal-Fluvial Channels

Tidally-influenced fluvial deposits are known to be rich in terrestrial vertebrate remains, which are mostly found in lags associated with erosional bases of channels and minor scours within channels (Eberth, 1996; Rogers and Kidwell, 2000). Most La Pastosa beds were deposited in tidal-fluvial channels in the fluvial-tidal transition of an estuary under variable marine influence, but the vertebrate fauna suggest that areas surrounding the channels were fresh-water marshes and ponds.

Therefore, alternation of levels with marine fossils or mixing of their remains in a single bed, as occur in the channel deposits of Facies 2 to 5, are in accordance with the paleoenvironmental characteristics. Moreover, single beds bearing fossils from very different environments and with different degree of reworking are not rare in similar environments. This fossil mixing is caused by seasonal or millennial scale shift of the coastline leading to rapid changes from shallow marine to terrestrial environments, and/or transport of the organic remains seaward or landward due to reversing tidal currents typical of an estuary (Rogers and Kidwell, 2000).

In the La Pastosa beds most of the fauna is contemporaneous (Huayquerian mammal age, see Dozo *et al*., 2010). The presence of well-preserved dense skull elements from Group III of Voorhies (1969) in La Pastosa conglomerates indicates short transport before concentration. Even though other bones from Groups I and II could undergo longer transport, they never show evidence of major weathering or moderate abrasion, pointing to rapid burial. Therefore, the vertebrate remains must belong to a fauna living within or close to the paleoenvironment of their final accumulation. Most probably well preserved, fragile and delicate parts of organisms in La Pastosa beds accumulated in low-energy restricted environments with rapid sedimentation, like fresh-water ponds and marshes along the floodplains of the meandering channel system of the fluvial-tidal transition (Fig. 9). These suboxic or anoxic environments are ideal for preservation of fossils. Lack of scavengers and other organisms led to burial and rapid fossilization by early diagenetic processes. Phosphate precipitation into the bones or development of carbonate concretions nucleated by fossils gave them enough strength to undergo later erosion, transport and accumulation in the channel lags. Repeated lateral migration of meandering channels caused erosion of the deposits of levees, swamps and ponds along the fluvial-tidal transition and the bones were incorporated into the channels individually or articulated in blocks of semiconsolidated, fine-grained sediments. The heavy bones were later concentrated in channel lags by reworking and winnowing of fine sediment within the channels. On the other hand, "marine fossils" are mostly restricted to small-sized oysters, which are also able to thrive in brackish water, also suggesting that most of the marine fauna came from contemporaneous deposits. Stenohaline organisms are rarely found in the channel deposits proving that fully marine conditions were not established within the channel, but also that channel incision did not fully reach the underlying "Entrerriense" coquinas.

La Pastosa meandering channels in the fluvial-tidal transition did not cut deep in the underlying sediments and most of the fossils belong to organisms that live adjacent to the channels and accumulated there after dying. Later concentration in lags associated to discontinuities suggests these are short- time averaged mixtures of ecologically related skeletal material. This confirms the proposal of Roger and Kidwell (2000) in the sense that vertebrate lag development depends strongly on preexisting local sources of skeletal materials rather than on the magnitude of the erosional vacuity or the duration of the hiatus. In spite of transport and exhumation fossils can closely reflect the environmental conditions adjacent to the channels. Good preservation seems to be more related to rapid burial than to the energy of the environment.

CONCLUSIONS

Sedimentary facies like channel lags rich in mud intraclasts, cross-bedded sands with mud drapes and "set-climber" ripples, IHS, heterolithic and herringbone bedding together with paucity of bioturbation and marine fossils indicate that sedimentation of the late Miocene La Pastosa beds took place mainly in large tidal-fluvial channels subjected to strong tidal influence in the fluvial-tidal transition.

Intraformational conglomerates are product of collapse of the cutbank due to erosion in the active margin of a meandering channel about 25 m deep and a 200 m wide and multiepisodic filling reveals repeated scouring and accumulation due to changing flow regime inside the channel. Discontinuities at the base of the channels and at the base of large IHS sets are the result of the migration of the whole channel-system and seasonally increased run-off and widening of the channel respectively, and mud pebbles within channel deposits point to high suspended-sediment concentration. Alternation of sand-rich and muddy IHS suggests periodical changes in the position of the turbidity maximum due to seasonal variation of fluvial discharge, in good agreement with the seasonal climate in Patagonia during the late Miocene. Dominant ebb currents run E-NE during periods of high river discharge and dominant flood currents. IHS sets dipping in N-S opposite directions indicate recurrent migration of high-sinuosity channels in the tightly meandering reach.

The vertebrate fauna in the tidal-fluvial channels is dominated by the hydrocherid *Cardiatherium patagonicum* that, together with whistling ducks and loricariid fishes suggest freshwater environments like marshes and ponds. Alternating levels with marine and terrestrial fossils or mixing in the channel deposits of Facies 2 to 5 are the product of seasonal reverse tidal current transport within the estuary or of millennial scale shift of the coastline leading to rapid changes from shallow marine to terrestrial environments. Monospecific fauna of small-sized oysters indicate that marine fauna is contemporary with the sediments and that fully marine conditions were not established within the channel, but also that channel incision did not fully reach the underlying transgressive coquinas.

Well-preserved, fragile and delicate parts of terrestrial vertebrate organisms in La Pastosa beds first accumulated in low-energy restricted environments out of the channels in tidal flats, ponds or marshes and there underwent diagenetic fossilization. The bones were later exhumed and incorporated into the channels, and finally concentrated in channel lags by lateral migration of the channel meanders. Combination of fossilization in a low energy environment and concentration after short transport in meandering channels make the fluvial-tidal transition "first class" deposits for prospecting vertebrate fossils. Lag-associated discontinuities suggests these are short- time averaged mixtures of ecologically related skeletal material and confirms the proposal of Roger and Kidwell (2000) in the sense that vertebrate lag development depends strongly on preexisting local sources of skeletal materials. Moreover, fossil association can closely reflect the environmental conditions adjacent to the channels in spite of exhumation and transport, and good preservation seems to be more related to rapid burial than to the energy level of the environment of final accumulation.

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