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SEDIMENTOLOGICAL AND ICHNOLOGICAL SIGNATURES FROM A FLUVIAL-DOMINATED DELTA IN SUBSURFACE: LAJAS FORMATION, MIDDLE JURASSIC, NEUQUÉN BASIN, ARGENTINA

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ABSTRACT

Transitional marine systems are affected by the interaction of wave, tidal and fluvial processes, with different impacts on salinity, turbidity, energy and depositional rate. Benthic organisms are influenced by these processes, and so, the ichnological signatures of these deposits represent key elements for environmental analysis. The Lajas Formation (Middle Jurassic, Neuquén Basin Argentina) is characterized by deposits accumulated in shallow transitional marine environments, mainly deltaic systems. A detailed study of sedimentological and ichnological features of the Lajas Formation developed on subsurface core samples allows to reconstruct the depositional conditions and evolution of unit and determine that the prevalent processes on the reworking of the sediments is fluvial, with subordinated wave processes. Fourteen sedimentary facies were defined, grouped into five facies associations: interdistributary plain, distributary channels, fairweather and storm-generated waves bars, delta front mouth bars, and prodelta. The ichnological analysis allows to differentiate 21 trace fossils: representing 5 ichnofacies: *Skolithos* (*Mararonichnus* suite), *Skolithos* (or *Rosellia*), impoverished *Cruziana*, *Cruziana*, *Scoyenia* and *Zoophycos*. Two surfaces with *Glossifungites* suites were recognized, and they are interpreted in two different ways, one related to authigenic changes and the other as a surface of stratigraphic importance, related to the variation in sea level. Finally, the whole section studied constitutes a prograding fluvio-dominated deltaic system, representing a Highstand System Tract, with minor transgressive events.

INTRODUCTION

Transitional marine depositional environments characterize areas where sediment is transferred from the continent to the marine realm (Boyd *et al.*, 1992). Much of this sediment is carried by rivers and deposited in the form of deltas (Bhattacharya, 2006, 2010). The general morphology of deltas is the result of the interaction between fluvial, tidal and wave processes that rework the sediment provided by the river, the dominance of one over the others, and relative changes in sea level (Galloway, 1975; Boyd *et al.*, 1992; Olariu and Bhattacharya, 2006; Bhattacharya 2010; Ainsworth *et al.*, 2011).

However, the general predominance of one of the processes over the others does not imply the total absence of typical facies of secondary processes, in addition, the dominant process can change laterally and in time (Boyd *et al.,* 1992; Orton and Reading, 1993; Bhattacharya, 2006).

Organisms interact with the substrate in response to environmental factors. Ichnological studies provide detailed information on the environmental parameters involved during sediment deposition, and therefore serve as the basis for an analysis of the facies and the sedimentary environment (Seilacher, 1964a, 1967b; Frey and Seilacher, 1980; Bromley *et al.,* 1984; Frey and Pemberton, 1984, 1985, 1987; Bromley, 1990, 1996; Pemberton *et al.,* 1992b; Bromley and Asgaard, 1993a; Lockley *et al.,* 1994; Buatois and Mángano, 1995b, 2009; Genise *et al.,* 2000, 2010a; Ekdale *et al.,* 2007; Hunt and Lucas, 2007). Deltas represent very unstable and stressful environments for benthos (MacEachern *et al.,* 2005; Dasgupta *et al.,* 2016), since organisms are affected by a variety of factors like type of sediment, energy, turbidity, salinity, oxygen level, sedimentary rate and food availability. As a result, trace fossil associations are sensitive indicators of physico-chemical stresses, and could be very helpful to determinate the dominant processes in deltaic sedimentation (MacEachern *et al.,* 2005, Buatois and Mángano, 2011)

The Lajas Formation (Middle Jurassic, Neuquén Basin) records sediments mainly deposited in transitional marine environments, which have been interpreted primarily as deltaic systems. In the literature there have been different interpretations in outcrops regarding the processes that dominate these deltaic systems: fluvial, wave and tidal processes (Gulisano and Hinterwimer, 1986; Poiré and del Valle, 1992; Zavala, 1996a, 1996b; McIlroy *et al.,* 2005; McIlroy 2007; Rossi and Steel, 2015; Gugliotta *et al.,* 2015, 2016a, 2016b, 2016c; Canale *et al.,* 2015, 2016; 2020; Kurcinka *et al.,* 2018). In contrast, there are few studies carried on in subsurface (Veiga *et al.,* 2013), and most of them are located in the engulfment area, using seismic data (Gómez Omil *et al.,* 2002; Freguglia *et al.,* 2009; Brinkworth *et al.,* 2017; Vocaturro *et al.,* 2018.

The aims of this contribution are twofold: 1) to define the sedimentary paleoenvironments (including ichnology) where Lajas Formation was accumulated using data from the subsurface in the engulfment area of the basin; 2) to describe and interpret the stratigraphic evolution of the unit.

GEOLOGICAL SETTING

The Neuquén Basin is located in the west central of Argentina, and a small fraction in central Chile (Franzese *et al.,* 2006; Spalletti *et al.,* 2010). It covers an area of more than 200.000 km^2 (Yrigoyen, 1991). It is bounded by wide cratonic areas, the San Rafael System to the northeast and the North Patagonian Massif to the south, and by a magmatic arc on the active western margin of the Gondwanan-South American Plate (Spalletti *et al.,* 2010) (Fig. 1). The basin has a broadly triangular shape, and three main regions are commonly recognized: the Main Cordillera to the west and north, the Patagonian Cordillera to the west, and the embayment area to the east (Ramos *et al.,* 2011). The basin starts with a volcanic rift in the Triassic and evolved to a post-rift stage during the Jurassic, ending with a foreland stage that spans from the Late Cretaceous to the Cenozoic (Howell *et al.,* 2005, Spalletti *et al.,* 2005). The result is an almost continuous sedimentary record of *ca.* 7,000 m of marine and continental deposits, from the Late Triassic to the Paleocene (Arregui *et al.,* 2011a) (Fig.1).

The Cuyo Group (Dellapé *et al.,* 1978a), deposited during Sinemurian to middle Callovian, represents the first mayor marine flooding that covers the entire basin (Arregui *et al.,* 2011b). The Los Molles Formation (Wever, 1931) is the basal unit of the Cuyo Group, and its composed of gray and dark gray shales, which alternate with fine to coarse sandstone and conglomerates, as well as limestone and gray marl (Leanza *et al.*, 2001; Llambías and Leanza, 2005). Overlaying Los Molles Formation is the Lajas Formation (Weaver, 1931), which is mainly composed by sandstones and to a lesser extent by dark green shales with abundant plant debris and conglomerates (Zavala 1996a, b; McIlroy *et al.,* 1999). These deposits accumulate in marginal marine settings, mainly interpreted as deltaic systems (Spalletti, 1995; Zavala, 1996a, b; McIlroy *et al*., 2005). The 200-900 m thick Lajas Formation is regarded as Bajocian-Bathonian in age based in ammonoid zonations (Riccardi, 2008; Dietze *et al.,* 2012) (Fig 1). In the subsurface at the engulfment area, the Lajas Formation is covered by sandstones, conglomerates and fluvial red clays of the Punta Rosada Formation. (Digregory, 1972).

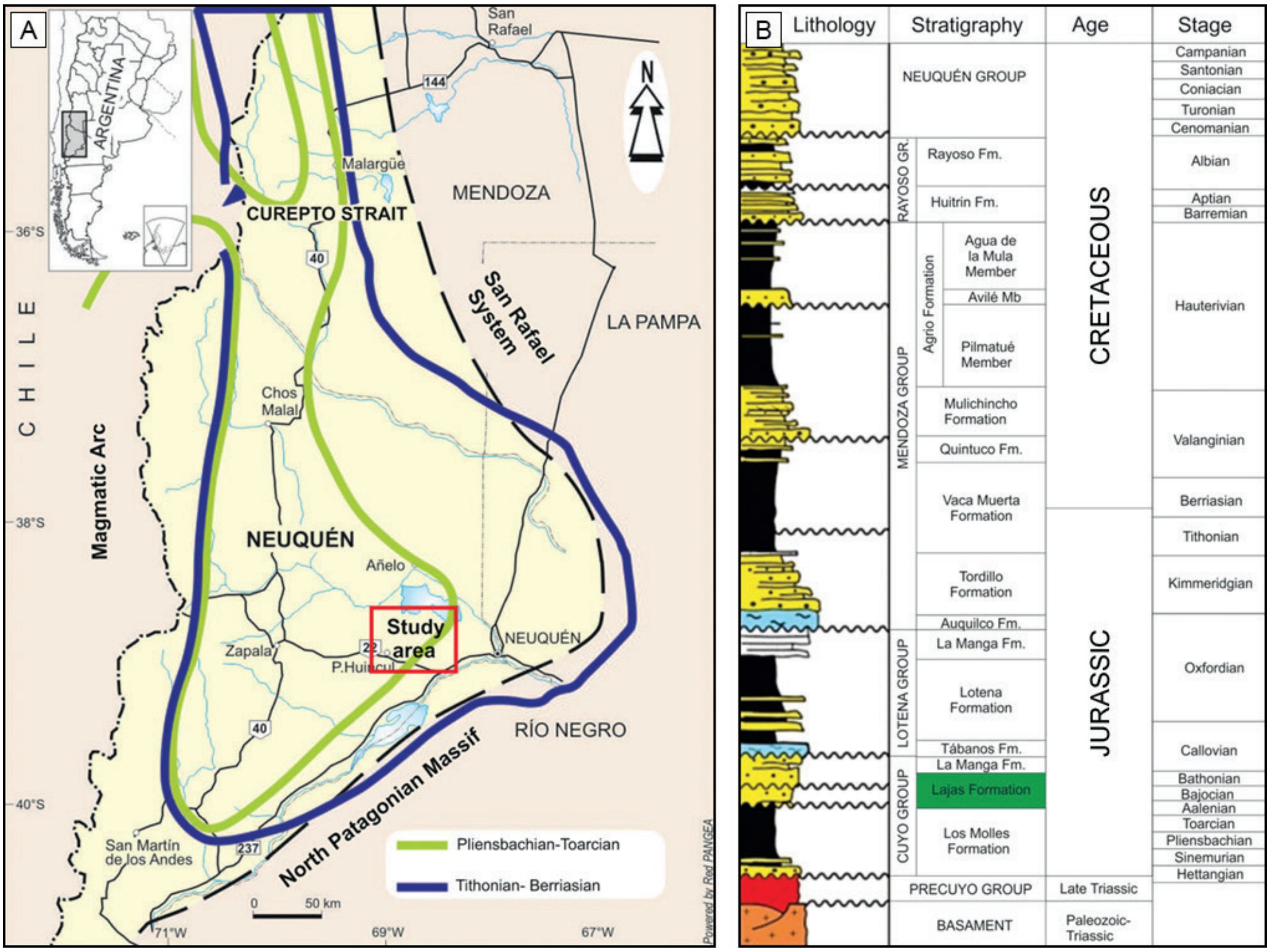

Figure 1. Study area and stratigraphic context. **a)** Neuquén Basin, with marine ingressions delimited. Study area in red. (Modified from Arregui *et al.*, 2011a). **b)** Stratigraphic column of the Neuquén Basin. Detail of the Cuyo group, showing the arrangement of second-order courtships (taken from Arregui *et al.*, 2011b).

The Lajas Formation in subsurface

In subsurface, the Lajas Formation constitute one of the traditional oil reservoirs along the Huincul Ridge, and it has a great potential as a tight-sand gas reservoir (Arregui *et al.*, 2011b, Giusiano, *et al.*, 2011). Most of the studies on subsurface of the Cuyo Group are focused on the southern sector of the basin, mainly in the engulfment area and the Huincul ridge and uses mainly seismic data (Gómez Omil *et al.*, 2002, Freguglia *et al.*, 2009, Brinkworth *et al.*, 2017; Vocaturro *et al.*, 2018) (Fig. 1). In these studies, different number of sedimentary sequences have been proposed: four (Gómez Omil *et al.*, 2002), nine (Freguglia *et al.*, 2009; Brinkworth *et al.*, 2017) and ten (Vocaturro *et al.*, 2018). The different number of sequences recognized in the previous works puts in evidence that the evolution of the progradation of clinoforms is directed in an East-West direction, which is influenced by changes in subsidence caused by tectonic activity related to the Huincul Ridge. In the Sierra Barrosa area, the informal division proposed by Freguglia *et al.* (2009) is followed in subsurface. In this model, nine depositional sequences are recognized, grouped in three stratigraphic intervals: Upper Cuyo Group (sequences 1, 2, 3), Middle Cuyo Group (Sequences 4, 5, 6), and Lower Cuyo Group (sequences 7, 8, 9). In the study area these divisions are practically ascribed to the Lajas Formation, and, therefore, the previously mentioned intervals are regarded as “Lower Lajas”, “Middle Lajas” and “Upper Lajas”. In this sector, the Lajas Formation has the greatest thickness, and the Los Molles (lower) and Punta Rosada (upper) Formations, are only thin strata in sequences 9 and 1 respectively (Fig. 2).

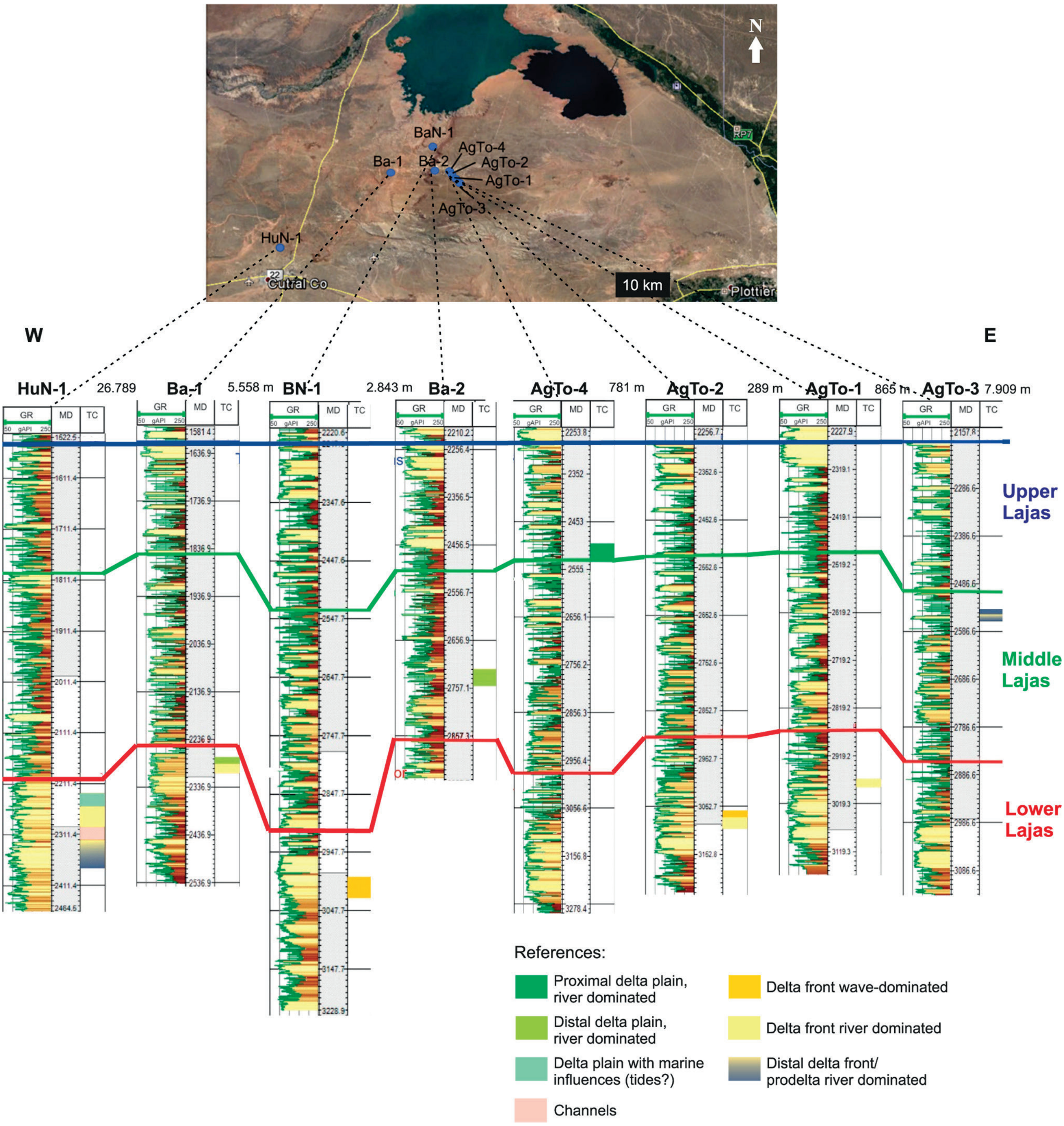

Figure 2. Location of the wells, and stratigraphic position of the core samples (colored sections), with the interpreted paleoenvironment.

MATERIALS AND METHODS

Eight core samples of the Lajas Formation were studied in the Huincul Ridge and the engulfment area. The wells are located in the Loma La Lata-Sierra Barrosa exploration block and the Dadin 1 block (Fig.2). In this area, the Lajas Formation is 800 m thick, and the total length of the studied core samples is 346 m. For confidentiality reasons, the names of the wells have been altered. The core samples studied are: for the "Lower Lajas" interval: Aguada Toledo 1 (AgTo-1), Barrosa 1 (Ba-1), Aguada Toledo 2 (AgTo-2), Barrosa Norte 1 (BaN-1) and Huincul Norte 1 (HuN-1); from "Middle Lajas": Barrosa 2 (Ba-2), Aguada Toledo 3 (AgTo-3) and Aguada Toledo 4 (AgTo-4); for the upper section Aguada Toledo 4

Core Sample	Lenght	Area	Stratigraphic interval
Aguada Toledo 4 (AgTo-4)	36,61 m	Aguada Toledo	Upper Lajas/Middle Lajas
Aguada Toledo 3 (AgTo-3)	23, 96 m	Aguada Toledo	Middle Lajas
Barrosa 2 (Ba-2)	34,73 m	Sierra Barrosa	Middle Lajas
Barrosa Norte 1 (BaN-1)	36,61 m	Barrosa Norte	Lower Lajas
Barrosa 1 (Ba-1)	36,55 m	Sierra Barrosa	Lower Lajas
Aguada Toledo 2 (AgTo-2)	36,87 m	Aguada Toledo	Lower Lajas
Huincul Norte 1 (HuN-1)	147 m	Huincul Norte	Lower Lajas
Aguada Toledo 1 (AgTo-1)	17,6 m	Aguada Toledo	Lower Lajas

Table 1. Core samples used in this work, with their geographical and stratigraphic location.

(AgTo-4) is considered “Upper Lajas” (Table1).

A facies description was made, using the methodology proposed by Miall (1978). In order to make an interpretation of the environmental evolution of each of the core samples, the described facies were grouped according to their spatial relationships and the interpretation of the processes that originated them, following the criteria of Collinson (1969) (Table 2). The methodology for ichnological analysis employed in this study follows conventional practices (Pemberton *et al.,* 1992, 2001; Gerard and Bromley, 2008; Knaust, 2017). Bioturbation intensity was recorded at intervals of 10 cm, using the bioturbation index (BI) of Taylor and Goldring (1993). The trace fossils were identified using ichnotaxobases (Bromley, 1990, 1996). The ichnodiversity is the number of ichnotaxa observed in 10 cm intervals. The sedimentological and ichnological analysis were performed on the 1/3 of the core slabbed, using a microscope Leica S8APO, with a Leica MC170camera.The images were processed using Leica LAS EZ software.

SEDIMENTOLOGY AND ICHNOLOGY

Facies Association 1: delta front mouth bars

Sedimentology and ichnology description. The FA1 consists mainly of up to 5-10 m thick amalgamated sandstone bodies with subordinate participation of conglomerate, heterolithic deposits and siltstones. The different lithologies displays vertically forming clear coarsening upward units (0,6-2 m thick). Sandstone beds show irregular erosive bases and are typically structureless (Sm), pervasively bioturbated (Smb) or show trough cross-bedding (Set and SGt). Conglomerates are structureless or show trough cross-bedding (Gm and Get). Silstone beds are typically structureless and the heterolithic deposits display wavy and lenticular bedding (Fm, Htw, Htl). Terrestrial plant remains and organic particles (phytodetritus) are abundant in this facies association. In general, the arrangement of this facies association is usually coarsening upwards strata stacking patterns, with fine sediments strata (Fm, Htw; Htl) at the bases of the successions, and sandy and conglomerate bodies upwards. This FA could be founded on top of FA5, and it could be interbedded with FA2 (Fig.3).

This FA is characterized by trace fossils of complex composition, of varied three-dimensional structures, with vertical and horizontal components. The diversity of trace fossils is highly variable, from low to high (1 to 6 ichnogenera), with also variable bioturbation index values (BI 1-6), being generally medium (3-4). It is dominated in order of abundance by *Ophiomorpha irregulaire*, *Gyrolithes* isp., *Haentzschelinia* isp., *Parahaentzchelinia* isp., *Lockeia* isp. and subordinate *Chondrites* isp., *Thalassinoides* isp. *Planolites* isp., *Rhizocorallium* isp. *Skolithos* isp., and *Arenicolites* isp. There are also cryptobioturbation in some levels.

Ophiomorpha irregulaire and *Gyrolithes* isp. are the dominant traces; “elite” traces, sensu Bromley

Facies	Lithology	Sedimentary Structures	Trace fossils	Interpretation
Fm	Siliciclastic Mudstones	Massive		Settlement deposits from a suspension and/or flocculation
Fmb	Siliciclastic mudstone	Massive	*Planolites*, *Teichichnus*, *Chondrites*, Mantle & Swirl, root traces, *Taenidium*	Massive by bioturbation
Fl	Siliciclastic Mudstones	Laminated	Rizoliths*, Taenidium*	Settlemen deposits from a suspension
Htw	Siliciclastic Mudstones/ Very fine sandstones	Wavy lamination	*Planolites, Teichichnus*	Deposits dominated by settling with episodes of alternating tractive events
Htf	Very fine to fine sandstones / Siliciclastic Mudstones	Flaser lamination	*Planolites, Teichichnus, Haenztchelinia, Ophiomorpha*	Deposits dominated by tractive events with pauses that allow settling
Sm	Medium to coarse sandstones	Massive		Rapid sand deposition by tractive flows without structure development
Smb	Coarse to fine sandstones	Massive	*Ophiomorpha, Gyrolithes, Parahaentzchelinia, Haenztchelinia, Thalassinoides, Chondrites*	Tractive deposits that present their sedimentary structures obliterated by bioturbation
Set	Medium to coarse sandstones	Trough cross-bedding	*Ophiomorpha, Gyrolithes, Haentzchelinia*	Deposit originated by migration of 3-D dunes in subaqueous environment
Shcs	Very fine to medium sandstones	HCS (Hummocky Cross Stratification)	*Macaronichnus*, *Ophiomorpha*	Deposits caused by a combination of unidirectional and oscillatory flows. associated with storms
Srw	Very fine to fine sandstones	Wave ripples	*Macaronichnus*	Deposits caused by oscillatory flows. Associated with waves
Sr	Fine to medium to silty sandstones	Climbing ripples		Deposits caused by unidirectional flows with suspended sediment load
SGt	Coarse sandstones/ conglomerates			Deposit originated by migration of 3-D dunes in subaqueous environment
Gm	Conglomerates	Massive		Rapid conglomerate deposition by tractive flows without structure development
Get	Conglomerates	Trough cross-bedding		Deposit originated by migration of 3-D dunes in subaqueous environment
Gmpi	Conglomerates	Massive		High energy deposit product of dense flows. Substrate erosion with removal of pelitic clasts

Table 2. Sedimentological facies, ichnological content and interpretation.

(1990, 1996). This concept not only implies that they are the most abundant traces and the most noticeable, but also due to their penetration capacity, they can obliterate other trace fossils and bioturbate deep levels below the water-sediment interface. As an example, *O. irregulaire* has been

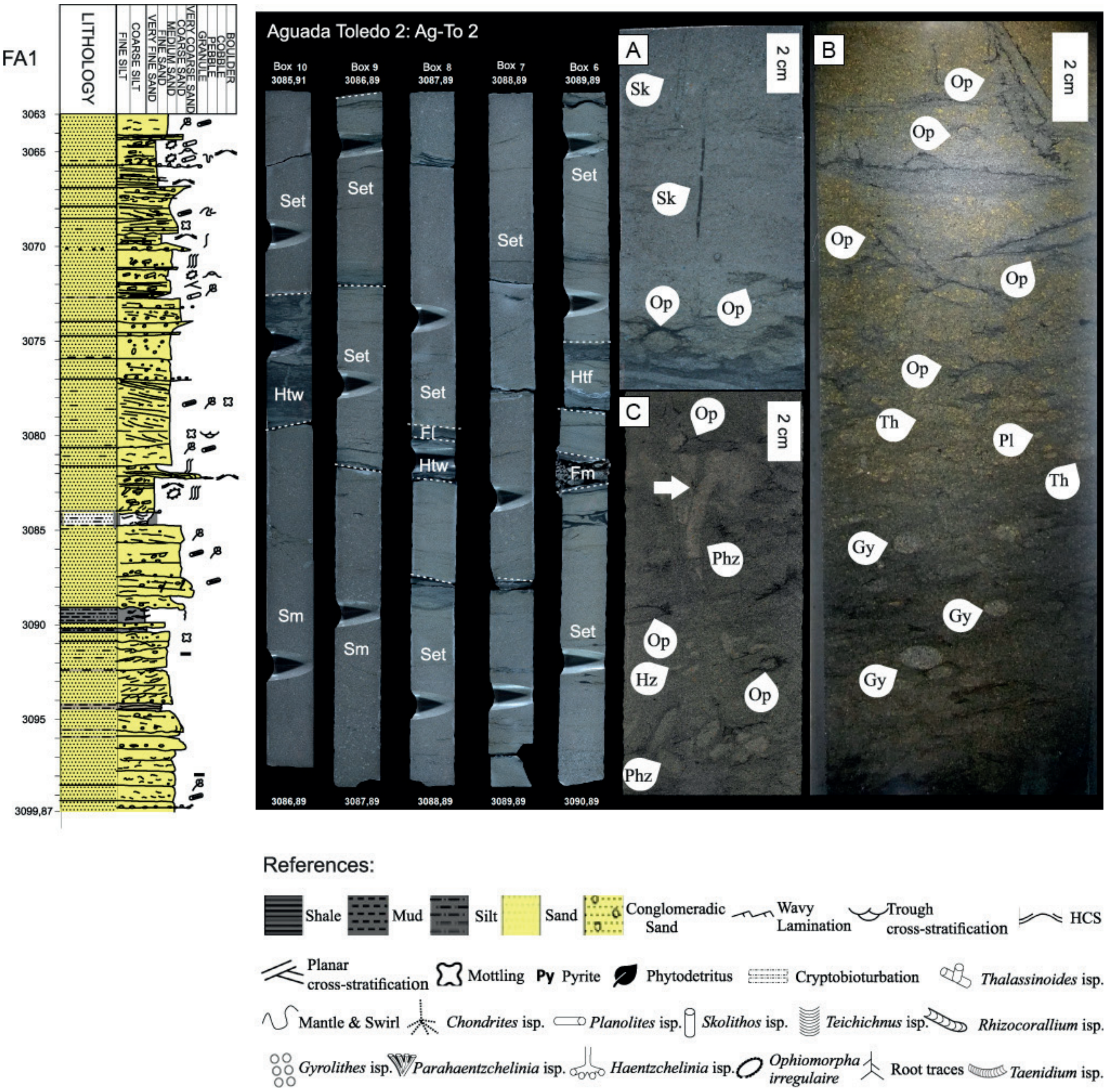

Figure 3. Facies Association 1 (FA1), delta front mouth bars. Trough cross-bedding sandstone (Set), massive sandstone (Sm), heterolithic wavy (Htw), heterolithic flaser (Htf), massive siliciclastic mudstones (Fm), laminated siliciclastic mudstones (Fl). **a, b)** *Skolithos*/*Rosselia* ichnofacies: Op: *Ophiomorpha irregulaire*, Gy: *Gyrolithes* isp., Hz: *Haentzchelinia* isp., Phz: *Parahaentzschelinia* isp., Th: *Thalassinoides* isp., Sk: *Skolithos* isp., **c)** White arrow pointing the siphon structure in *Parahaentzschelinia* isp.

found even at conglomerate bar bases. They are also one of the largest traces, both in size of the gallery and the general structure of the trace. Most of the members of this association of trace fossils are interpreted as detritivores, with a low representation of suspensivorous animals (Fig 3 a, b, c).

Sedimentology and ichnology interpretation. The coarsening upwards arrangement, the sedimentary structures that indicate unidirectional currents, as well as its relationship with FA2 (see below) suggest that FA1 was accumulated in a situation of mouth bars in a delta front depositional environment (Bhattacharya 2010; Schomacker *et al.,* 2010). These deposits are interpreted as a succession of sand bodies representing mouth bars interbedded with finer deposits (heterolithic) identified as bar foot areas or interbars. These bars were formed by fluvial tractive flows that decelerate when the distributary channels enter the sea, causing accumulations of sand at their mouths (Ainsworth *et al.,* 2016; Kurcika *et al.,* 2018; Van Yperen *et al.,* 2020). The different facies present refer to different depositional processes, being the Sm, Smb, Set, SGt, Gm, Gmpi facies deposited by fluvial-derived flows of variable density. Of the previous facies, the Gmpi, Gm, SGt facies present the greatest evidence of high-density fluxes since they have variable energy episodes in a single rock body. Facies Smb is interpreted as a product of fluvial deposition that is affected by marine processes (marine bioturbation). The heterolithic deposits, represented by the Htw, Hts facies mark episodes of lower energy, which alternate deposition by settling, with deposition by traction and / or traction settling of thicker sediments originating in minor fluvial avenues. These deposits are interpreted as interbar or distal fringe, since they are usually found between successions of bars, and do not necessarily show a deepening of the system, which would lead to interpret them as deposited in a prodelta environment (Ainsworth *et al.*, 2016; Van Yperen *et al.,* 2020).

The foreset of the bars present the coarsest grain sizes, and sedimentary structures that suggest a rapid deposition produced by the influences of rivers, while the bar foot is where the finest sediments accumulate, as they are the areas of lower energy (Enge *et al.,* 2010). Sand is deposited during high-energy events, and when the event loses energy, the finest material is deposited by settling from suspension (Gugliotta *et al.,* 2015, Kurcinka *et al.,* 2018). The scarce representation of wave- and tidal-generated structures suggest a deposition in a fluvial-dominated environment (Canale *et al.,* 2015, 2016).

The dominance of trace fossils assignable to detritivore strategies would lead to attribute them to *Cruziana's* ichnofacies, however, the fact that most of these structures are preferably vertical, and that overall energy of the system is high leads to think that it actually could be and expression of the recently prosposed for deltaic environments *Rosellia* ichnofacies (MacEachern and Bann 2020; Moyano-Paz *et al.,* 2022). This trace fossil association has its suspensivorous components limited by the amount of sediment in suspension, since only in a few places the presence of typical *Skolithos* ichnofacies components is observed. This may be due to the suppression of the suspensivorous component of the *Skolithos* ichnofacies product of the high amount of suspended sediment, a common situation in deltaic environments (MacEachern, *et al.,* 2005, 2007, MacEachern and Bann 2020, Buatois and Mángano, 2011, Moyano-Paz *et al.,* 2022).

Facies Association 2: Distributary channels

Sedimentology and ichnology description. the FA2 is composed mainly by interbedded conglomerates (Gm, Gmpi, Get) and sandstones (SGt, Sm, Set), with a highly variable thickness, ranging from 1 m up to 10 m. These coarse-grained bodies are disposed vertically forming fining upwards strata stacking units. The strata are dominated mainly by massive structures (Gm, Sm) sometimes with rip up mud clasts (Gmpi). Trough cross-bedding structures are less represented (Get, SGt, Set), and sometimes they become diffuse. The bases of these units are mainly erosive, but locally net and even transitional contacts have been observed. This FA2 usually erodes deposits from FA3 and also FA 1. The FA2 never show bioturbation of any kind (Fig.4).

Sedimentology and ichnology interpretation. The presence of erosive bases, the general fining upwards strata stacking pattern trend and variations in grain size within the same bed suggest deposition within channels under high-energy conditions, showing typical fluctuations of river discharges (Bhattacharya, 2006). The high energy and high deposition rates prevent the development of benthos, which is the reason why they are never bioturbated (MacEachern *et al.,* 2005). Commonly during periods of low river discharge, tides can move inland through these types of channels and favoring conditions for colonization by benthic organisms (e.g., Moyano-Paz et al., 2020). This doesn't happen in this case, so these channels were not affected by the action of tides. These deposits are interpreted as the infill of distributary channels in the deltaic plain, sometimes reaching the proximal delta front, eroding the mouth bar deposits.

Facies Association 3: Interdistributive plain

Sedimentology and ichnology description. These deposits show a great variety of facies, from fine-grained muddy facies (Fm, Fl, Fmb), heterolithic

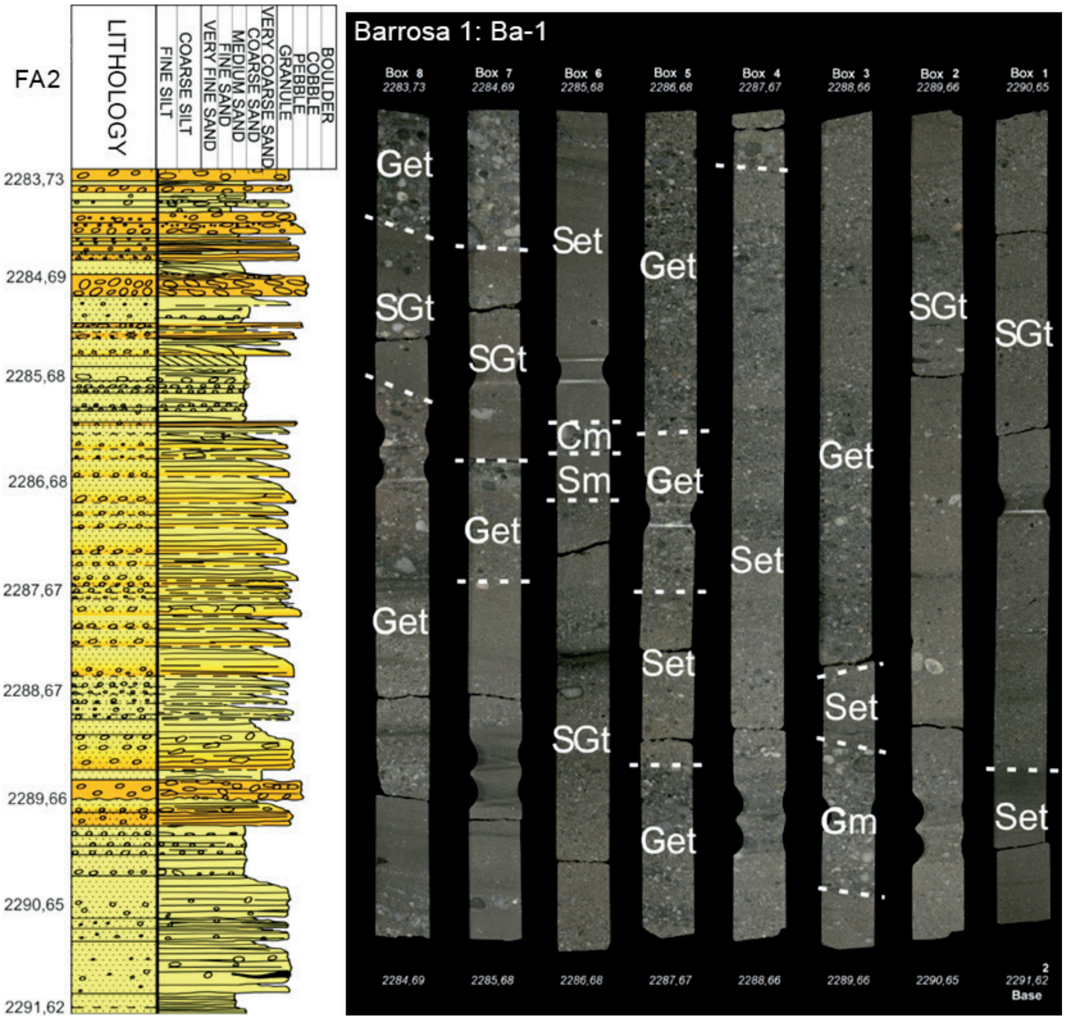

Figure 4. Facies Association 2 (FA2), distributary channels. Massive conglomerates (Gm), trough cross-bedding conglomerates (Get), trough cross-bedding sandstone to conglomerates (SGt), trough cross-bedding sandstone (Set), massive sandstone (Sm). References as in figure 3.

deposits (Htw and Hts), to sandstone facies (Sr and Sm). The muddy and heterolithic facies are the most abundant, with variable thickness, ranging from 10 cm to 3m, with transitional, net and erosional limits. Sandstone bodies are arranged displaying a fining upwars grain tendency, with net and erosional limits, with variable thickness ranging from 10 cm to 2 m. They also show in some levels evidence of pedogenic processes (pedogenetic mottling, soil peds, slickenside structures, pedogenic carbonate). It can present load deformation structures. This FA3 is usually eroded by the channel of the FA2 (Fig. 5).

Considering ichnology, in this FA two different trace fossils associations are present. The first one is characterized by a dominance of horizontal traces, relatively simple, shows low ichnodiversity (typically 1 to 3 ichnogenera), but in some levels it could reach 6 ichnogenera. Bioturbation index is also variable (BI 1-6), being generally low (BI 2-3), but in some localized sections it could reach BI 6. The dominant trace fossils are *Planolites* isp., *Teichichnus* isp., and mantle & swirl structures (Fig. 5 a). The second ichnoassociation presents root structures (rhizoliths), burrows with backfilling attributable to *Taenidium* isp., and very scarce *Planolites* isp. This trace fossil association has a very low ichnodiversity (from 1 to 3), and also generally presents low bioturbation intensity (BI 1-2), reaching only in some localized sectors a maximum of 4 (Fig. 5 B).

Sedimentology and ichnology interpretation. the fine-grained sediment facies are deposited in interdistributary plains between distributary channels, mainly by suspension settling processes

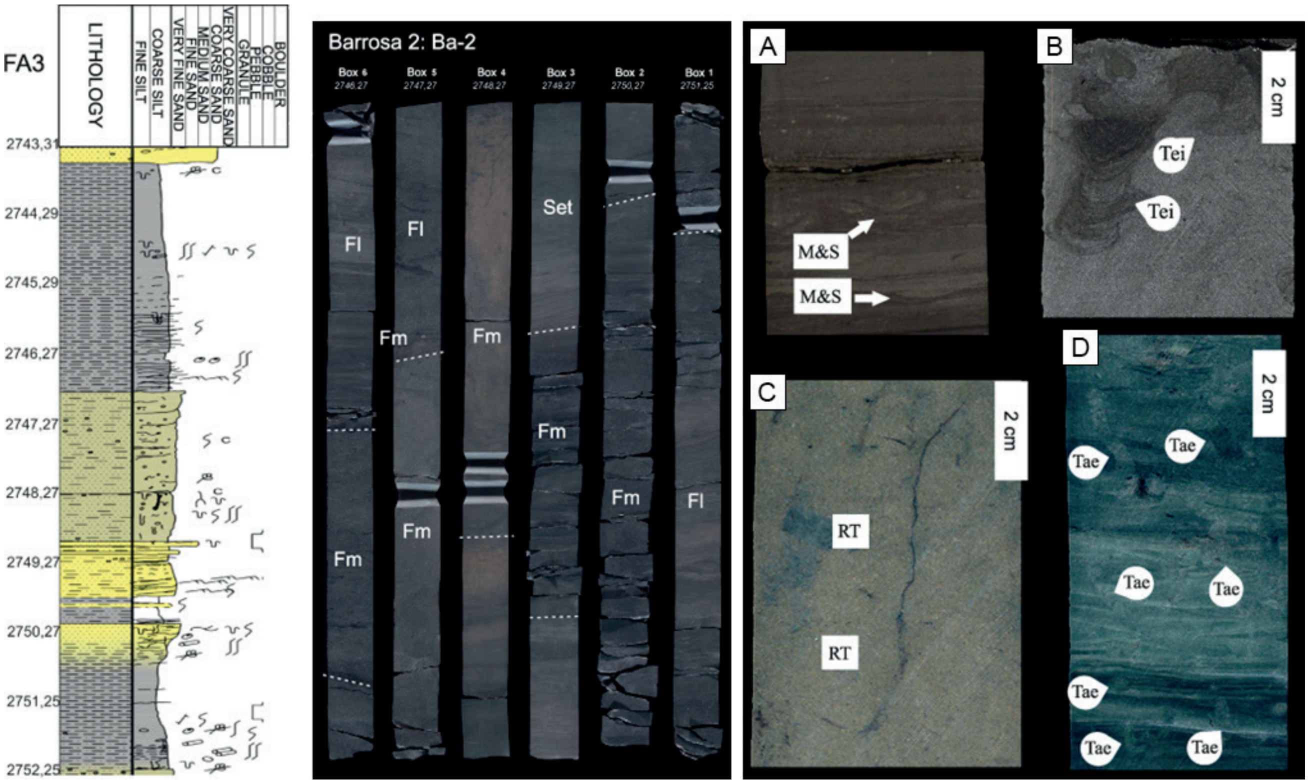

Figure 5. Facies Association 3 (FA3), interdistributive plain. Massive siliciclastic mudstones (Fm), laminated siliciclastic mudstones (Fl), trough cross-bedding sandstone (Set). **a, b)** Impoverished *Cruziana* ichnofacies: M&S: Mantle & swirl structures, Tei: *Teichichnus* isp. **c, d)** *Scoyenia* ichnofacies: RT: Root traces, Tae: *Taenidium* isp. References as in figure 3.

in low-energy environments. Interdistributary plains are characterized by brackish water conditions, influenced by fluvial and marine processes, but predominantly low-energy situations (Elliott 1974; Bhattacharya 2006; Gugliotta *et al.,* 2015). The facies Hts, Sm and Sr are interpreted as overflow lobe deposits (crevasse-splays) in the interdistribute plain. Sm, Fm facies are interpreted as plain deposits affected by pedogenetic processes (Buatois and Mángano, 2011).

The dominant ichnological components of the first ichnoassociation are horizontal structures, interpreted as feeding structures of. vermiform animals, mainly with a detritivore feeding strategy. The presence of mantle & swirl structures indicates a sediment with very little cohesion (soupground) (Lobza and Schieber 1999). Due to the aforementioned characteristics, this trace fossil association is assigned to the *Cruziana* ichnofacies, but due to the low ichnodiversity that exhibits, it is interpreted as an impoverished *Cruziana* ichnofacies (MacEachern, *et al.,* 2005, 2007; Buatois and Mángano, 2011). The second ichnoassociation, is dominated by root traces and *Taenidium* isp. Although *Taenidium* isp. is a trace fossil that occurs in a great variety of environments from marine to continental, in this case it is interpreted as a product of the activity of insect larvae in continental environments by the association with rizoliths. Therefore, this association of trace fossils is assigned to the *Scoyenia* ichnofacies, which is typical of continental environments, but impoverished, which is characteristic of transitional marine-continental environments. The poor and saltuary development of this association of trace fossils points to a stressed environment, due to large variations in energy, salinity and water level. In the studied sections, it is found in deposits interpreted as flood plain and / or overflow lobes (crevasse splays) developed in a delta plain with aerial exposure (MacEachern *et al.,* 2005, 2007; Buatois and Mángano, 2011) (Fig. 6. G, H).

Facies Association 4: Wave affected bars

Sedimentology and ichnology description. This facies association is composed mainly by amalgamated sand bodies (Sm, Smb, Shcsb, Srw SGt), with very little representation of heterolithic and muddy fine-grained facies (Htw, Fl). Sandstones with upward convex stratifications (*i.e.* hummocky cross-stratification; Hcs) and parallel lamination show net to erosive contacts at the bases and net limit at the top. The thicknesses vary from tens of centimeters to a maximum of 1 meter. The transition between different granulometries may show erosive contacts. Srw is composed by very fine to fine sandstones, with fine clayey sandstones with subordinate carbonaceous vegetal debris. They display small scale wave ripple lamination, and the thickness of this bodies never exceed 30 cm. This FA4 is similar to the FA1 previously described, in terms of the facies that comprise it. However, in this facies association, the proportion of sandstone vs fine-grained facies is higher than in FA1. In addition, there are two sandstone facies that are very abundant in this FA that does not appear in FA1, Shcsb and Srw, the contacts between the different sand bodies are usually sharp, and the presence of phytodetritus is less abundant than in the FA1 (Fig. 6).

In this FA4 the dominant trace fossil is *Macaronichnus* isp., sometimes conforming a monospecific association. Eventually *O. irregulaire* and *Gyrolithes* isp., and rarely *Planolites* isp., *Thalassinoides* isp. and *Teichichnus* isp. could be observed. The ichnodiversity is usually very low (1-3), and the bioturbation index could vary from BI 1-4. (Fig. 6a).

Sedimentology and ichnology interpretation. This FA4 is characterized by deposits accumulated in areas located in zones between the fair-weather waves level and storm waves level. Sands accumulated in bar and dune systems result from the action of unidirectional flows, while the presence of wave and hummocky ondulitic lamination-type structures are linked to development of combined unidirectional and oscillatory currents generated during storms (Duke, *et al.,* 1991). The lower concentrations of organic matter in FA4 suggests a deposition environment with less influence of a fluvial input, being more associated with a siliciclastic coastal geometry (shoreface), where wave action is the dominant process. This FA4 is interpreted as formed by tractive processes in high to very high energy environments, showing evidence of subsequent rework due to fair-weather and storm wave processes (Plint, 2010; Ainsworth *et al.,* 2016). Because wave lamination and storm wave structures (HCS) are preserved, it is interpreted that has been accumulated in beach environments in medium shoreface to offshore transition positions (Walker and Plint, 1992, Plint 2010). These sand bodies are interpreted as littoral bars, developed in a shoreface position, or strandplains related to mouth bars dominated by wave and storm action.

Macaronichnus isp. is produced by intrastratal deposit-feeding of opheliid polychaetes (Clifton and Thompson 1978; Seike 2008) feeding on sand grains. It is indicative of very high energy environmental conditions, and it has been proposed as an ichnosubfacies of the ichnofacies of *Skolithos* (Pemberton *et al.,* 2001), which would be characteristic of foreshore environments. However, in the studied cores, although it follows this trend, and represents high-energy conditions, in many sectors it is accompanied by storm-generated structures (HCS). In addition, there is no other element that indicates foreshore conditions. Other associations of *Macaronichnus* isp. have been described for different environments, some deeper than shoreface positions (Nara and Seike 2004; Seike 2007, Seike et al., 2011; Bromley et al. 2009; Quiroz et al. 2010, Rodríguez-Tovar and Aguirre 2014). The levels that contain *Macaronichnus* in FA4 are always storm levels, which indicates that the organism that produces this structure would have behaved as an opportunistic colonizer in these environments. The first traces formed in this environment are *Macaronichnus* isp., while the other traces present are colonizers of overlying sediments developed in fair-weather conditions that are not preserved as a result of the different storm events (Pemberton *et al.,* 2001; Seike, 2008, 2009). Due to all these evidences, this association is interpreted as developed in shoreface conditions, which can vary from middle to lower shoreface.

Facies Association 5: Prodelta

Sedimentology and ichnology description. This FA5 is dominated by fine-grained facies (Fm, Fl) and sandstone facies (Sm, Set, SGt). This FA includes massive fine-grained sediments with thickness from 40 cm to 2 m, with transitional bases. Heterolithic deposits with deformation structures as slumps or convolute beddings show variable thickness (from

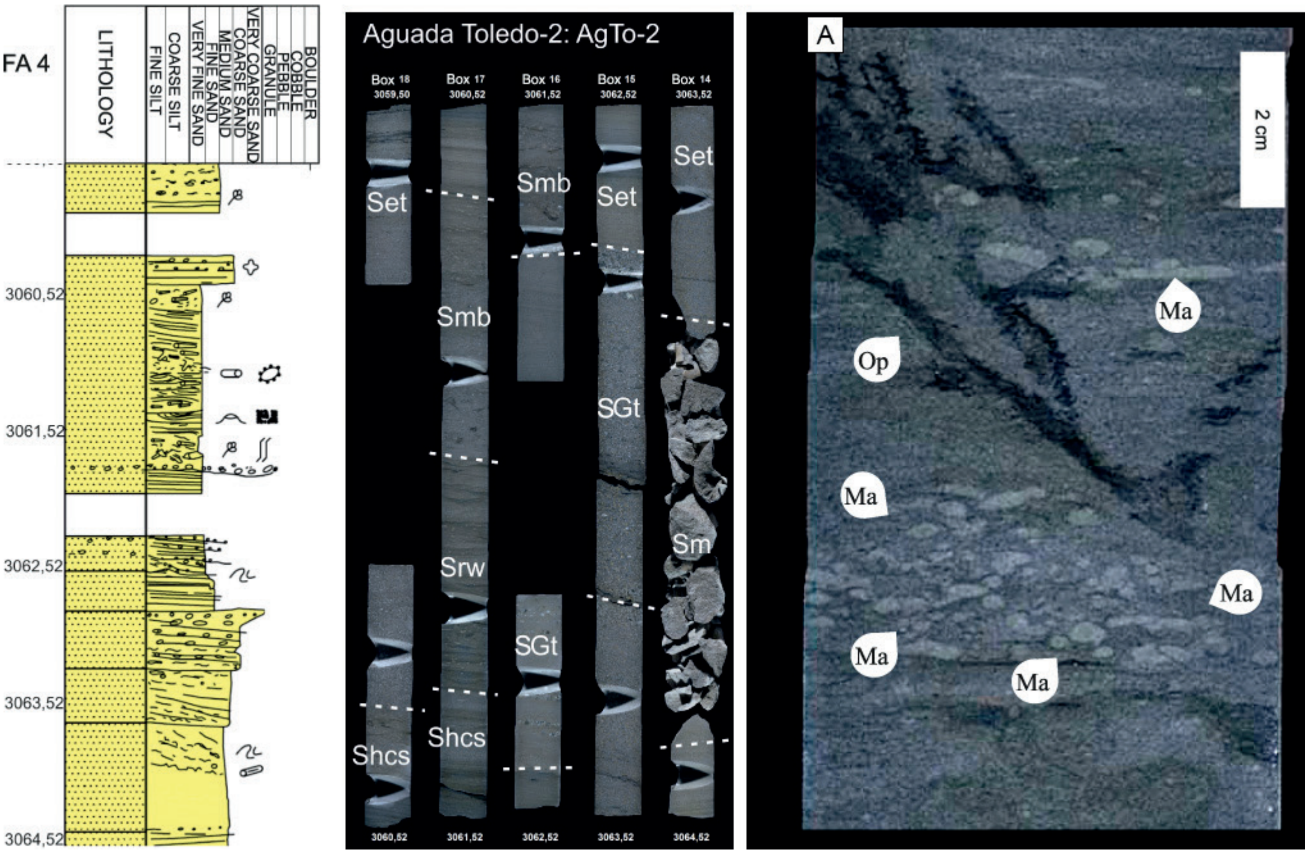

Figure 6. Facies Association 4 (FA4), wave affected bars. Wave affected bars: trough cross-bedding sandstone to conglomerates (SGt), trough cross-bedding sandstone (Set), massive sandstone (Sm), bioturbated massive sandstone (Smb), hummocky cross-stratification sandstone (Shcs). A) *Macaronichnus* suite Op: *Ophiomorpha irregulaire,* Ma, *Macaronichnus* isp. References as in figure 3.

30 cm to 2 m). Sandstones and conglomerates have erosive bases, dominated by massive structures and fining upward trends, with thickness from 1 to 5 m. The contacts between facies of dissimilar granulometries are usually erosional. The content of particulate organic matter is very abundant, as well as the development of syneresis cracks. This FA5 shows coarsening upwards strata stacking trends, as the fine sediments decrease (Fig.7).

The ichnological content is very scarce, but two trace fossil associations can be differentiated. One is represented by specimens of *Planolites* isp., *Teichichnus* isp, *Thallasinoides* isp., *Chondrites* isp. and cryptobioturbation, with low ichnodiversity (ranging from 1-4) and also low bioturbation intensity (BI 1-3) (Fig. 7a). The other ichnoassociation is even more scarce and it is represented by *Zoophycos* isp. and *Planolites* isp., the ichnodiversity is very low, being typically 1-2. Bioturbation intensity is also low (1-2) (Fig.7b).

Sedimentology and ichnology interpretation. This FA5 is interpreted as representative of low-energy environments, where settling processes dominated the sedimentary background, with sporadic high energy discharges, and also synsedimentary deformation due to rapid deposition is observed. In this environment, however, there are occasional arrivals of much more energetic hyperpycnal flows, which deposit the sandy facies tractively. Unburrowed to weakly burrowed mudstone intervals with abundant presences of phytodetritus are interpreted to represent rapid deposition of mud and the development of soupground substrates, due to bouyant plumes during post-storm river floods (Plint, 2014; MacEachern and Bann, 2020; Moyano-Paz *et al.*, 2022). These levels of fluid mud inhibit the development of infaunal communities as suggested by MacEachern *et al.* (2005). The recurrent presence of syneresis cracks indicates changes in salinity produced by the supply of fresh water from a nearby

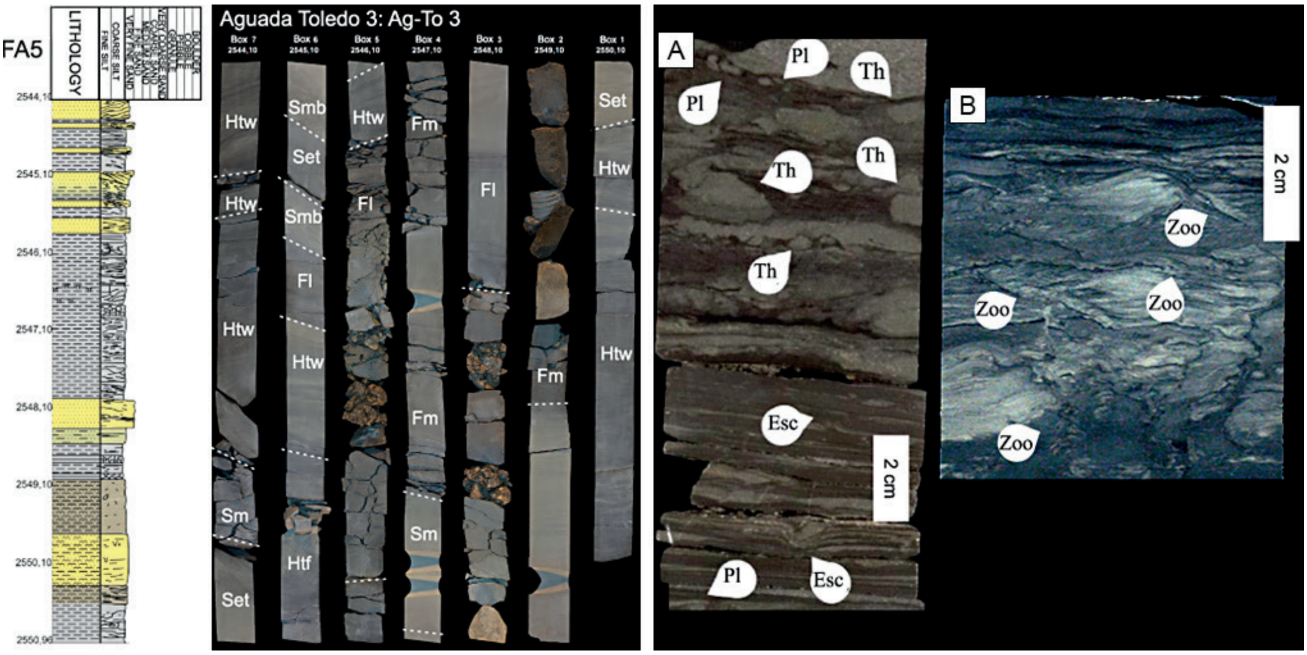

Figure 7. Facies Association 5 (FA5), prodelta. Trough cross-bedding sandstone (Set), massive sandstone (Sm), bioturbated massive sandstone (Smb), heterolithic wavy (Htw), heterolithic flaser (Htf), massive siliciclastic mudstones (Fm), laminated siliciclastic mudstones (Fl). **a)** *Cruziana* ichnofacies: *Thalassinoides* isp., Pl: *Planolites* isp., Esc: Escape burrows (Fugichnia). **b)** *Zoophycos* ichnofacies: Zoo: *Zoophycos* isp. References as in figure 3.

river system (e.g., MacEachern *et al.*, 2005). All these evidence of fluvial inflows in a distal position indicate that these sediments accumulated in a prodelta environment to which high-energy fluvial-derived flows still eventually arrive (Asquith, 1974; Bhattacharya, 2010).

The first trace fossil association, interpreted as *Cruziana* ichnofacies, is typical of low energy environments, and the scarcity of it is typical of the delta front-prodelta environment, due to the physico-chemical stress of this environment (MacEarchern *et al.,* 2005; Buatois and Mangano, 2011). *Zoophycos* isp. has been interpreted as a deposit-feeding behavior of a vermiform animal but also alternative interpretations, has been made (Löwemark 2012). *Zoophycos* isp., is a trace that usually develops at sea environments with marked dysoxia. Therefore, is the second trace fossil association is interpreted as belonging to the *Zoophycos* ichnofacies of low energy environment, with some oxygen restriction. These conditions can occur in deltaic environments in the prodelta positions, which are the most distal of the system (MacEachern, *et al.,* 2005; MacEachern and Bann, 2020; Bhattacharya *et al.*, 2020; Moyano-Paz *et al.*, 2022). An association of trace fossils with the presence of *Zoophycos* has been described for offshore-proximal and offshore distal to shelf environments in coronas cores of the Bardas Blancas Formation, which is homologous to the Lajas Formation north of Neuquén Basin (Veiga *et al.,* 2013).

Glossifungites surfaces

There are two levels that present quite particular bioturbation, and for that reason they are described separately. In the AG-TO2 core samples, at a depth of 3,080.71 m, a 30 cm thick level of massive bioturbated mudstones (Fmb) is observed, overlaying with erosive contact a coarse sandstone/conglomerate body with trough cross-bedding (SGt). The bioturbation is dominated by *Thallasinoides* isp., of approximated 1-2 cm in cross section, with sharp walls, infilled with medium massive sandstone (Fig. 8a). In AG-TO4 core sample, at 2,531 m depth, a level of 6 cm of alternating silt and very fine sand, with wavy lamination (Htw) shows *Rhizocorallium* isp., with sharp walls, infilled with fine sandstone. These burrows are arranged in the last centimeters of the stratum, which shows evidence of erosion at the top, and a sharp basal contact with an underlying sand body with trough cross-bedding (Set) (Fig. 8 B).

This two bioturbated levels are interpreted as belonging to the *Glossifungites* ichnofacies. This ichnofacies is characterized by the presence of trace fossils with varied morphologies, being common branched excavations and vertical, cylindrical, drop-shaped or U-shaped structures, with well-defined and clear limits (Seilacher, 1967; Frey and Seilacher, 1980; Frey and Pemberton, 1984, 1985; Pemberton *et al.,* 1992a, 1992c; MacEachern *et al.,* 1992; Uchman *et al.,* 2000; Carmona *et al.,* 2006). Generally, the filling of biogenic structures is passive, with a texture different from that of the host rock and similar to that of the overlying strata. The most common ichnotaxa in this ichnofacies correspond to the ichnogenera *Diplocraterion*, *Skolithos*, *Arenicolites*, *Gastrochaenolites*, *Thalassinoides*, *Spongeliomorpha*, and *Rhizocorallium* (Buatois and Mangano, 2011). The trace fossils that characterize this ichnofacies belong mostly to suspensivorous organisms, and the ichnodiversity is generally low, although the abundance of specimens of each ichnotaxon can be high.

DISCUSSION

Paleoenvironmental evolution of the Lajas Formation in subsurface in the Sierra Barrosa area

Considering that all the core samples are from a restricted area it is possible to reconstruct the environmental evolution of the depositional systems according to its depth and location. As discussed before, the Lajas Formation has been informally divided into Lower, Middle and Upper in the Sierra Barrosa area in subsurface, and that order is followed for the paleoenvironmental evolution (Fig. 2).

Lower Lajas. The five core samples assigned to Lower Lajas show mainly delta front environments (FA1), with deposits dominated by fluvial processes, and delta fronts with some evidence of wave action (FA4). Also, to a lesser extent, delta plain (FA2, FA3) and prodelta environments were identified (FA5). In the basal sector, there are located the core samples AgTo-2, BaN-1 and the lower part of HuN-1. The HuN-1 core sample begins with deposits interpreted as prodelta to distal delta front, while the AgTo-2 core sample begins with fluvial-dominated delta front environments, which passes upward into a delta front environment with wave influence, by the evidence of bioturbation and of wave and storm structures (Figs. 2, 8a). Then, the HuN-1 core shows distributary channel environments (FA2), while in BaN-1, the northernmost core sample, evidence of wave actions is observed (FA4), accompanied by a very well developed marine bioturbation that indicates normal salinities and high energy. This leads to interpret this core sample as a delta front with less fluvial influence and a dominance of wave processes. Therefore, the fluvial processes had a preponderance in the southern sector, while towards the north these processes were alternated with wave processes (Figs. 2, 8b).

In the upper stratigraphic interval of the Lower Lajas Formation, we see the final portion of the HuN-1 core sample, and in the northernmost sector of Sierra Barrosa area the Ba-1 and AgTo-1 core samples. The HuN-1 shows fluvial-dominated deltaic front with some evidence of waves (FA1, FA4) that pass to a delta plain environment (FA3) with evidence of marine bioturbation (possible tides?). However the dominance of fluvial processes is still evident, therefore the subenvironment is interpreted as a fluvial-dominated deltaic plain with tidal modulation, similar to those described by Gugliotta *et al.* (2015). Meanwhile, to the north, in the Sierra Barrosa sector, the Ba-1 core sample begins with a fluvio-dominated delta front (FA1) that passes into a fluvio-dominated deltaic plain (FA3), while the AgTo-1 core sample represents only river-dominated deltaic front environment (FA1). In summary, it is interpreted that the system evolves towards a situation where the fluvial contribution, although it continues in the south, becomes more important towards the Sierra Barrosa sector at north (Figs. 2, 8c).

Middle Lajas. The three core samples corresponding to the Middle Lajas (Ba-2, AgTo 2 and the base of AgTo-4) have less preponderance of coarse-grained intervals, and a larger representation of fine sediments. In none of these cores a delta front environment is interpreted. The Ba-2 core sample shows mainly distributary channels facies (FA2) and less interdistributary plain (FA3), with little influence of bioturbation, therefore it is interpreted as a distal fluvio-dominated deltaic plain environment. In the delta plains dominated by fluvial processes, the presence of the dendritic

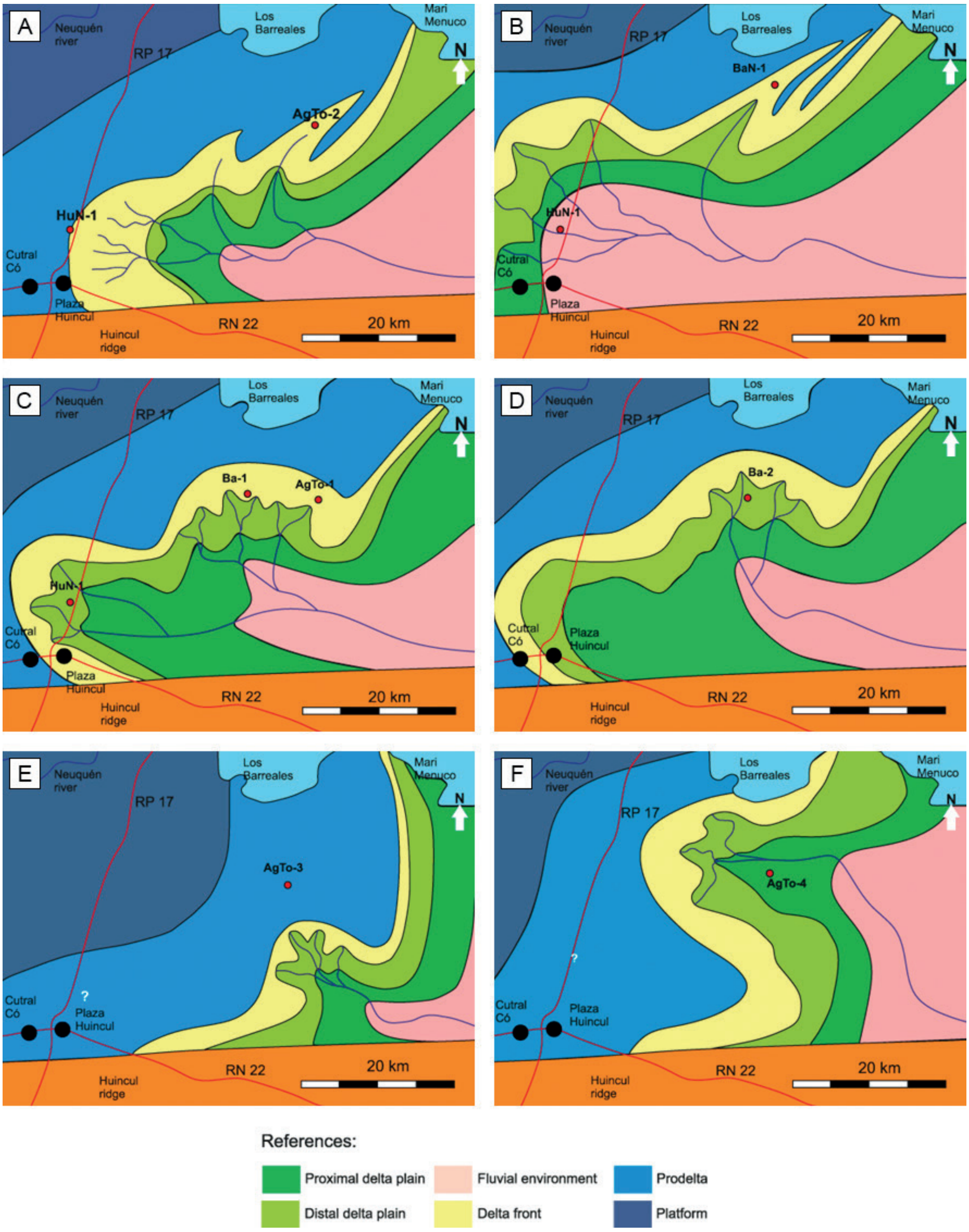

Figure 8. Diagram of the evolution of transitional marine systems in the Sierra Barrosa sector, Lajas Formation. **a, b, c)** Lower Lajas; **d, e)** Middle Lajas; **f)** Upper Lajas. **a)** Fluvial-dominated deltas develop in the Huincul Norte sector, while in the Sierra Barrosa area there is an alternation of fluvial and wave processes. **b)** River systems in the Huincul Norte sector, while in the Barrosa Norte sector deltas are developed with a dominance of wave processes. **c)** The fluvial influence is larger in Sierra Barrosa, while in Huincul Norte an alternation of fluvial and marine conditions (tides?) is observed. **d)** In Sierra Barrosa a progradation of fluvio-dominated deltaic systems is observed. **e)** New progradation of fluvio-dominated deltaic systems in Sierra Barrosa. **f)** A deepening of the system is observed in the Sierra Barrosa sector (transgression?).

network of channels becomes more important in the distal sector, therefore, the presence of abundant levels interpreted as channels could indicate this subenvironment (Olariu and Bhattacharya, 2006;

Canale *et al.,* 2015, 2016). Furthermore, the typical bioturbation of the delta plain with subaerial exposure, with evidence of root and insect, is poorly developed in this core sample, which is another evidence that the environment is a subaqueous distal plain (MacEachern *et al*., 2005; Buatois and Mángano, 2011) (Figs. 2, 8d).

The AgTo-3 core sample shows marked evidence of a deepening of the system, recording prodelta and distal delta-front deposits (FA5). This core is located between the Ba-2 (bottom) and AgTo-4 (top) core in a vertical position, therefore it would indicate a marine transgression, or a lobe avulsion. It is noteworthy to emphasize that prodelta environments has been interpreted in regional schemes from seismic studies from Wrinkworth *et al*. (2018) and Vocaturro (2018), that show a possible trasgresion of the system. The interpretation of the AgTo-3 core sample could corroborate this hypothesis (Figs. 2, 8).

The AgTo-4 core sample shows abundant evidence of delta plain environment with subaerial exposure (FA3) and does not show evidence of channels. Consequently, it is interpreted as developed in a proximal deltaic plain, mainly subaerial. In a fluvio-dominated deltaic plain, the distributary channels follow a dendritic development pattern, which makes it much easier to find a channel in a more distal sector, than upstream where the number of channels decreases markedly (Olariu and Bhattacharya, 2006; Canale *et al.,* 2015, 2016). In addition, bioturbation is very abundant, and is represented by a trace fossil assamblege corresponding to *Scoyenia* ichnofacies, typical of proximal deltaic plain environments (Buatois and Mángano, 2011). The absence of channels and the evidence of much lower water level allows us to interpret the AgTo-4 core sample as developed in a proximal delta interdistributary plain environment (Figs. 2, 8e). It is notable that the *Glossifungites* surface that separates both sections in AgTo-4, although it shows two successive clinoforms, they develop in a similar subenvironment (see Upper Lajas and discussion of *Glossifungites* surfaces).

Upper Lajas. The only core sample that has a representation of Upper Lajas is AgTo-4, which has the boundary between the so-called Middle Lajas and Upper Lajas. This limit, which was defined by the seismic used in the reservoir by YPF (Figs. 2, 8f), occurs in the lower section of the core sample and is represented in the core not only by a change of lithologies, but also by an omission surface characterized by an *Glossifungites* surface, with *Rhizocorallium* isp. After this limit, the core sample has a very similar aspect to its lower section, for that reason the environment is still interpreted as a proximal delta interdistributive plain environment. Being the only core sample representing Upper Lajas, we cannot claim that this environment is general throughout the entire section. However, it coincides with the environmental interpretations of the regional schemes from seismic studies carried out by Brinkworth et al. (2017) and Vocaturro et al. (2018) (Figs. 2, 7, 8).

Animal-substrate interactions

River-dominated deltas are the most stressful delta environments for marine biota (MacEachern *et al.,* 2005; Buatois *et al.,* 2011). In the core samples analyzed, the ichnofacies recognized are impoverished *Skolithos*, or the recently erected *Rossellia,* on the proximal delta front, *Cruziana* with *Skolithos* elements on the proximal delta front to the distal delta front, *Zoophycos* and *Cruziana* on prodelta environment and *Scoyenia* on the deltaic plain. The low diversity, low abundance, low bioturbation index in general and the simple tiering observed are interpreted as the result of short-time colonization windows that reflect suitable environmental conditions for the development of benthos only for very short periods. In facies that show more direct fluvial influence (FA1 of mouth bars, and mainly FA 3 of channels) trace fossils are almost absent. The environmental parameters that control benthos are salinity, turbidity, and hydrodynamic energy (MacEachern *et al.,* 2005; Buatois and Mángano, 2011; Dasgupta *et al.,* 2016). Therefore, it is interpreted that only when these parameters are not so stressful, it the colonization windows occur.

The distribution of trace fossils in a delta dominated by a river is conditioned by physical-chemical stress factors related to their discharges (MacEachern *et al*., 2005; Dasgupta *et al*., 2016; Canale *et al*., 2015, 2016; Gugliotta *et al*., 2015, 2016a; Arregui *et al*., 2019). These stress factors act differently in different sub-environments. In the proximal delta plain, the fluvial influence is mainly present into the distributary channels, and to a lesser extent, in the interdistributary plain. The main physical-chemical stress factors in this sector are related to the

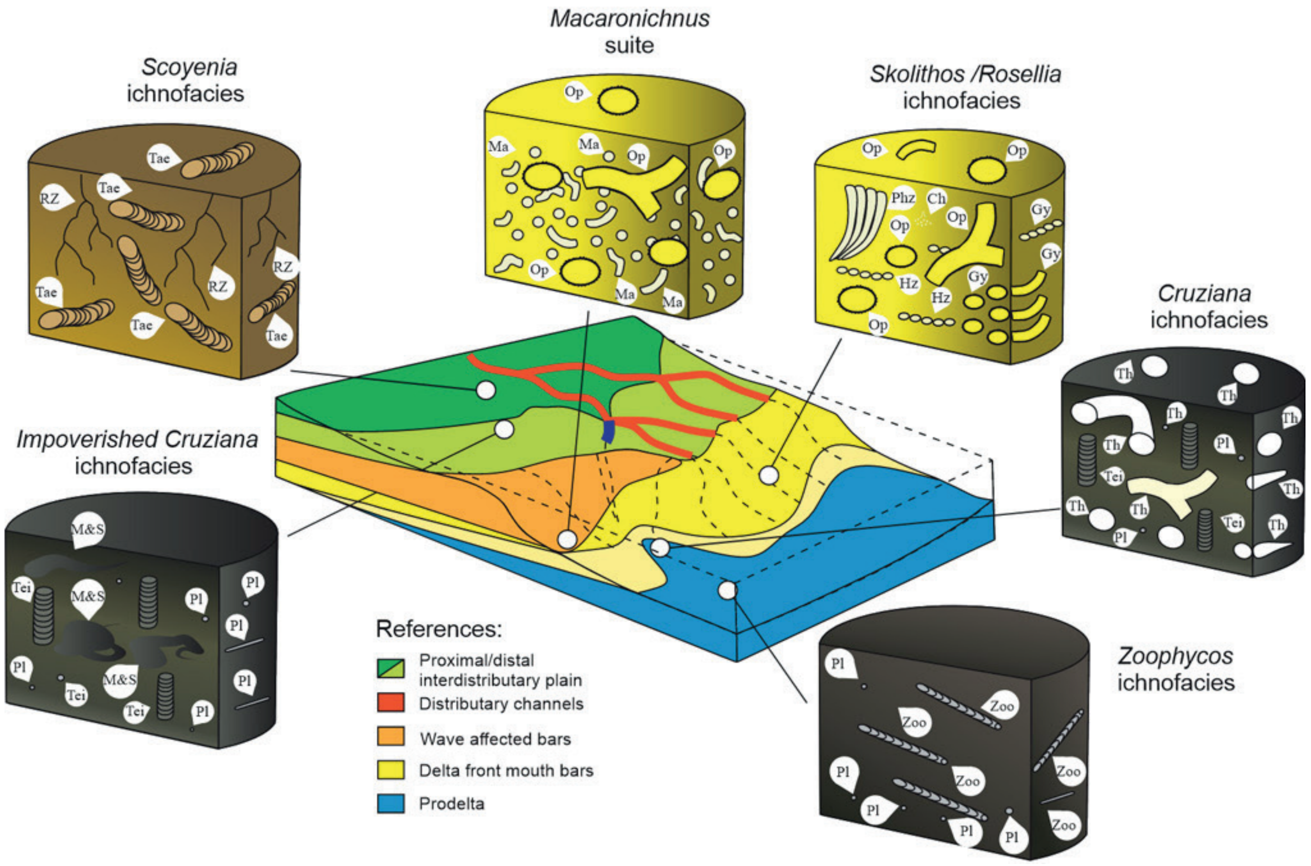

Figure 9. Schematic distribution of ichnofacies in a river dominated delta environment.

alternation of periods of aerial exposure with periods of flooding. In this area, the dominant trace fossils belong to the *Scoyenia* ichnofacies, but presenting less diversity than the typical continental *Scoyenia* ichnofacies due to the previously mentioned factors. In the distal delta plain, the aerial exposure is not as important, while the marine influence becomes more noticeable. Therefore, in this sector there is an alternation between periods of fluvial influence and periods of marine influence, which causes great variations in salinity. The dominant trace fossils of this subenviroment correspond to an empoverished *Cruziana* ichnofacies (Fig. 9).

The mouth bars described in the lower Lajas core samples in the Sierra Barrosa area are usually grouped in amalgamated sand bodies (Arregui *et al.*, 2019). They can be differentiated into non-bioturbated and bioturbated sand bodies. These two types of sand bodies are interpreted as two successive stages of development. High river discharge and rapid deposition, high energy and mobility of sediments, as well as significant freshwater discharge inhibit bioturbation during the main construction phase of the mouth bars. These bars are characterized by having sand-sized lithologies, and in some sectors they can even have gravels, with massive or through-cross bedding structures, with abundant remains of scattered phytodetrites or, more commonly, on top of the through-cross sets. During periods of reduced river discharge, the deposits are easily reworked by coastal processes (i.e., tides and waves), which facilitates the settlement of trace-makers, generating the bioturbated bars, which would constitute the next phase of development of the bar (Arregui *et al.*, 2019). The most common traces found in the mouth bars are those corresponding to the *Skolithos* ichnofacies, but without suspensivorous component, that could be the recently erected *Rossellia* ichnofacies. These bioturbated bars show grain sizes similar to the previous ones, but they usually exhibit a massive structure, which is the product of the activity of burrowing animals. The decrease of river discharge may be due to a channel avulsion, which is very common in deltaic environments (Olariu and Bhattacharya, 2006). Alternatively, it may be related to the episodic nature of river discharges resulting from seasonal floods (Plink-Bjorklund 2015; Gugliotta *et al.,* 2016b) (Fig. 9).

In the interbar or distal fringe of the mouth bars, and in distal delta front, the trace fossils found correspond to an impoverished *Cruziana* ichnofacies, that could be similar to the trace fossil association described for distal delta plain environments but showing more ichnodiversity (Coates and MacEachern, 2009). In prodelta, two trace fossils associations were described, the most abundant belonging to an impoverished *Cruziana*, and the least frequent to the *Zoophycos* ichnofacies (Coates and MacEachern, 2009; Buatois *et al*., 2011; MacEachern and Bann, 2022) (Fig. 9).

***Glossifungites* surfaces: autogenic vs allogeneic processes**

The recognition of surfaces assignable to the *Glossifungites* ichnofacies has been widely used in the context of sequence stratigraphy, basically because it indicates omission surfaces or unconformities (MacEachern *et al.,* 1992a; Pemberton *et al.,* 1984, 1995, 2004; Schwarz and Buatois, 2012; Dasgupta *et al.,* 2016). These surfaces coincide many times with surfaces of stratigraphic importance, for example, developed during the incision of fluvio-estuarine valleys (Lowstand unconformities), incision of underwater canyons (Lowstand unconformities), erosive displacement of the shoreline towards the continent during transgressions (transgressive erosion surfaces) and towards the sea during forced regressions (regressive surfaces of marine erosion) (MacEachern *et al.,* 1992, 2007; Pemberton *et al.,* 1992, 2004). All these processes that delimit areas of stratigraphic importance in the sequence stratrigraphic models imply sea level changes in response to allogenic controls. In contrast, the lateral migration of fluvial or tidal channels and the avulsion of lobes in deltaic contexts can generate erosive surfaces of discordance with trace fossils assignable to the *Glossifungites* ichnofacies, but they are inherent processes of the system (autogenic), therefore, not they are related to variations in sea level (Gingras *et al.,*1999; MacEachern *et al.,* 2007). Recently, Villegas-Martín *et al.* (2020) described two types of surfaces of *Glossifungites*, to which they assign different sequence stratigraphic meanings. *Glossifungites* surfaces developed in mudstone firmgrounds of estuarine deposits are interpreted as autogenic, while *Glossifungites* surfaces developed in stiffgrounds in shoreface deposits, with higher frequency of larger galleries is interpreted as allogeneic.

In the analyzed core samples, there are two records of surfaces assignable to *Glossifungites*, with two opposing interpretations. The *Glossifungites* surface observed in the AgTo-1 core sample is composed of galleries assigned to *Thalasinoides* isp., developed in mudstones, with a passive sandstone fill (Fig. 7). The inferred environment for the infra and overlying sections of this *Glossifungites* surface is a delta front environment. This surface is interpreted as a product of autogenic processes of the system (migration of lobes or deltaic channels). These types of erosive surfaces are very common in deltaic front settings, which is where the distributary channels arrive, and the avulsion processes occur (Olariu and Bhattacharya, 2006). *Glossifungites* surfaces with similar interpretations have been described for the Lajas Formation (Canale *et al.,* 2015).

On the other hand, the *Glossifungites* surface defined for the lower sector of the AgTo-4 core sample coincides exactly with the limit that divides two of the three divisions of the Lajas Formation in subsurface (Middle from Upper Lajas), according seismic and well data from the oil industry (Fig. 2). This suite is characterized by *Rhizocorallium* isp. which show passive sandstone fill (Fig 10a). These trace fossils are typical of marine environments (Knaust, 2013). The environment below and above the of this *Glossifungites* surface is proximal deltaic plain. In these environments, channel avulsion is less frequent than in a distal deltaic plain or delta front environments. Hence, this omission surface would imply an erosion due to a sea level fall and a subsequent rise that allows the colonization of the stiffground by the producers of *Rizocorallium* isp. Therefore, this erosive unconformity could represent an allogenic variation in sea level. This level could also be interpreted as a surface of stratigraphic importance, that is coincident with the limit between Middle and Upper Lajas according to seismic interpretations (Fig. 10b).

CONCLUSIONS

A detailed sedimentological and ichnological study on core samples allows to define the main

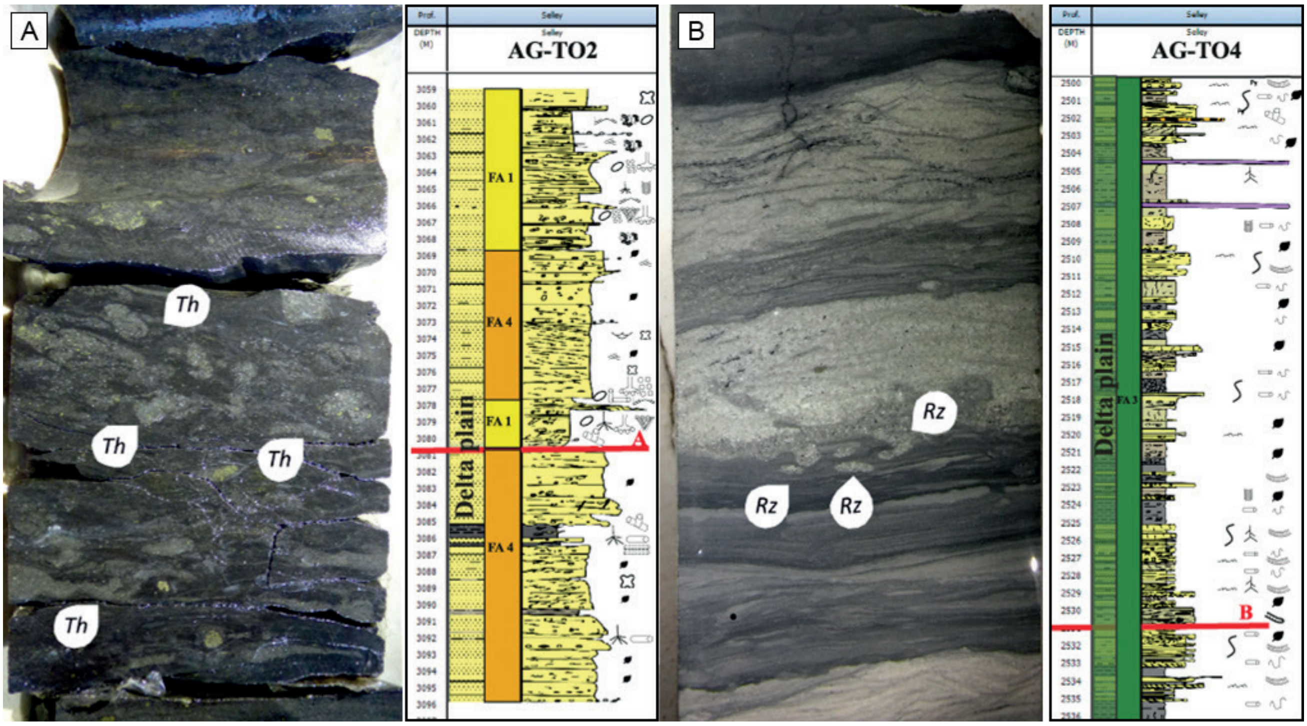

Figure 10. Glossifungites surfaces developed in different scenarios. **a)** *Glossifungites* related to lobe avulsion, in a delta front that alternates fluvial and wave conditions (Ag-To 2), **b)** *Glossifungites* related to sea level changes, in a delta plain environment (Ag-To 4). Th: *Thalassinoides* isp., Rz:*Rhizocorallium* isp. References as in figure 3.

processes that accumulated the deposits of theLajas Formation in the Sierra Barrosa area. The definition of the dominant process was posible by the recognition of the main physico-chemical stress factors that controlled the distribution of the bentos, inferred by their trace fossils.

The colonization phases of the delta front mouth bars affected by river were identified, with a first constructive phase related to fluvial input, and a second phase with a decrease in fluvial influence and colonization by benthos in a normal saline marine environment. The main limiting factors for colonization by marine biota during the stage dominated by fluvial inputs would be mainly salinity, high energy and water turbidity. Dominance of one or another stage of the bars implies the permanence of conditions of fluvial influence in non bioturated bars or of a marine environment in bioturbated bars.

An environmental evolution model is proposed in which, for Lower Lajas, in the most basal sector, it is interpreted that the fluvial processes had a preponderance in the southern sector, with development of a deltaic front dominated by fluvial processes, while to the north these processes alternated with wave processes, also developed in sub-environments of a deltaic front. Then, it is interpreted that the system evolves towards a situation where the fluvial contribution, although it continues in the south, becomes more important towards the Sierra Barrosa sector, with the recognition of river-dominated deltaic fronts.

For Middle and Upper Lajas it is interpreted as developed mainly in a fluvio-dominated deltaic plain environments, with abundance of channels with great mobility and cannibalization among themselves in the distal deltaic plain (Middle Lajas), and with less preponderance in proximal delta plain (Upper Lajas). However, prodelta evidence may be indicating a marine transgression in the Middle Lajas, which has implications in the sequential stratigraphic study of the region.

Two *Glossifungites* surfaces (AgTo-2 and AgTo-4) were recognized, representing unconformities formed during erosive events and subsequent colonization. In the first case, it would correspond to autogenic changes typical of deltaic systems, developed in delta front settings (migration of deltaic lobes and avulsion of channels). In the second case, it is interpreted as a surface of stratigraphic importance, developed in between two proximal delta plain settings of two successive deltaic clinoforms, related to the variation in sea level, and it marks the limit between the Middle Lajas and the Upper Lajas.

Therefore, the entire section studied in the Sierra Barrosa and Huincul area is interpreted as the result of the progradation of deltaic clinoforms that, although they show a preponderance of fluvial processes, in lateral settings, the influence of marine processes could be observed. This study shows that integrated sedimentology and ichnology analysis allows to achieve paleoenvironmental models of greater precision on deltaic successions, unraveling the complex interaction of fluvial, wave and tidal processes that affect these environments.

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REFERENCES

Asquith, D. O. (1974). Sedimentary models, cycles, and deltas, Upper Cretaceous, Wyoming. *AAPG Bulletin*, 58 (11), 2274-2283.

Ainsworth, R. B., Vakarelov, B. K., and Nanson, R. A. (2011). Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines: toward improved subsurface uncertainty reduction and management. *AAPG bulletin*, 95(2), 267-297.

Ainsworth, R. B., Vakarelov, B. K., MacEachern, J. A., Nanson, R. A., Lane, T. I., Rarity, F., and Dashtgard, S. E. (2016). Process-Driven Architectural Variability In Mouth-Bar Deposits: A Case Study From A Mixed-Process Mouth-Bar Complex, Drumheller, Alberta, Canada. *Journal of Sedimentary Research*, *86*(5), 512-541.

Arregui, C., Carbone, O., andLeanza, H.A. (2011a). Contexto tectosedimentario. In Leanza, H.A.; Arregui, C.; Carbone, O.; Danieli, J.C.; Vallés J.M.; (eds). *Relatorio Geología y Recursos Naturales de la Provincia de Neuquén: XVIII Congreso Geológico Argentino*, Neuquén, 2011- p 29-36.

Arregui, C., Carbone, O., andMartínez, R. (2011b). El Grupo Cuyo (Jurásico temprano-medio) en la cuenca neuquina. In Leanza, H.A.; Arregui, C.; Carbone, O.; Danieli, J.C.; and Vallés J.M.; (eds) *Relatorio Geología y Recursos Naturales de la Provincia de Neuquén: XVIII Congreso Geológico Argentino*, Neuquén, 77-89.

Arregui, M. G., Buatois, L. A., and Rodriguez, E. (2019). Shrimps and leaves: Phytodetrital pulses and bioturbation in deposits of a river-dominated delta (Middle Jurassic Lajas Formation, Neuquén Basin, Argentina). *Palaeogeography, palaeoclimatology, palaeoecology*, 516, 179-189.

Avanzini M., Masetti D., Mietto P., Piubelli D., Roghi G. y Romano R. (2006). Lower Jurassic (Hettangian-Sinemurian) Dinosaur track Megasites, Southern Alps, Northern Italy. *New Mexico Museum of Natural History and Science Bulletins*, 37. pp. 114-126.

Bhattacharya, J.P. (2010). Deltas. In: James, N.P. y Dalrymple, R.W. (Eds.). *Facies Models 4, Geological Association ofCanada*.

Bhattacharya, J.P., (2006), Deltas, in Posamentier, H., and Walker, R.G., eds., *Facies Models Revisited*: SEPM, Special Publication 84, p. 237–292

Bhattacharya, J. P., Howell, C. D., MacEachern, J. A., and Walsh, J. P. (2020). Bioturbation, sedimentation rates, and preservation of flood events in deltas. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 560, 110049.

Boyd, R., Dalrymple, R., and Zaitlin, B. A. (1992). Classification of clastic coastal depositional environments. *Sedimentary Geology*, 80(3-4), 139-150.

Brinkworth, W., Vocaturo, G., Loss, M. L., Giunta, D., Mortaloni, E., and Massaferro, J. L. (2017). Integración regional de subsuelo orientado a la exploración y desarrollo de Grupo Cuyo, Cuenca Neuquina. *Tucumán: Congreso Geológico Argentino.*

Bromley, R. G., and Pedersen, G. K. (2008). *Ophiomorphairregulaire*, Mesozoic trace fossil that is either well understood but rare in outcrop or poorly understood but common in core. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *270*(3-4), 295-298.

Bromley, R. G., Milan, J., Uchman, A., and Hansen, K. S. (2009). Rheotactic *Macaronichnus*, and human and cattle trackways in Holocene beachrock, Greece: reconstruction of paleoshoreline orientation. *Ichnos*, 16(1-2), 103-117.

Bromley, R.G. (1990). Trace Fossils. Biology and Taphonomy. Unwin Hyman.

Bromley, R.G. (1996). Trace fossils. Biology, Taphonomy and Applications. London: Chapman and Hall.

Bromley, R.G. andAsgaard, U. (1993a). Two bioerosion ichnofacies produced by early and late burial associated with sea-level change. *Geologische Rundschau*, 82, 276-280.

Buatois, L.A. and Mángano, M.G. (1995). The paleoenvironmental and paleoecological significance of the lacustrine *Mermia* ichnofacies: an archetypical subaqueous nonmarine trace fossil assemblage. *Ichnos*, 4, 151–161.

Buatois, L. A., and Mángano, M. G. (2011). Ichnology: Organism-substrate interactions in space and time. Cambridge University Press.

Buatois, L. A., Saccavino, L. L., and Zavala, C. (2011). Ichnologic signatures of hyperpycnal flow deposits in Cretaceous river-dominated deltas, Austral Basin, southern Argentina. *in* Slatt, R.M., and Zavala, C., eds., Sediment Transfer from Shelf to Deep Water: Revisiting the Delivery System: American Association of Petroleum Geologists, Studies in Geology, v. 61, p. 153–170.

Canale, N. y Ponce, J.J. (2012). Sedimentología de sistemas de lóbulos y canales hiperpícnicos en la Formación Lajas, área de Portada Covunco, Neuquén, Argentina. En XIII Reunión Argentina de Sedimentología Resúmenes, Argentina: Asociación Argentina de Sedimentología.

Canale, N., Ponce, J. J., Carmona, N. B., and Drittanti, D. I. (2016). Ichnology of Deltaic Mouth-Bar Systems of the Lajas Formation (Middle Jurassic) in the Sierra de la Vaca Muerta, Neuquén Basin, Argentina. *Ameghiniana*, 53(2), 170-183.

Canale, N., Ponce, J. J., Carmona, N. B., Drittanti, D. I., Olivera, D. E., Martínez, M. A., and Bournod, C. N. (2015). Sedimentología e Icnología de deltas fluvio-dominados afectados por descargas hiperpícnicas de la Formación Lajas (Jurásico Medio), Cuenca Neuquina, Argentina. *Andean geology*, 42(1), 114-138.

Canale, N., Ponce, J. J., Carmona, N. B., Parada, M. N., and Drittanti, D. I. (2020). Sedimentology and ichnology of a river-dominated delta, Lajas Formation (Middle Jurassic), Neuquén basin, Argentina. *Andean Geology*, *47*(1), 179-206.

Carmona, N. B., Ponce, J. J., Mángano, M. G., and Buatois, L. A. (2006). Variabilidad de la icnofacies de *Glossifungites* en el contacto entre las Formaciones Sarmiento (Eoceno medio-Mioceno temprano) y Chenque (Mioceno temprano) en el Golfo San Jorge, Chubut, Argentina. *Ameghiniana*, 43(2), 413-425.

Clifton, H. E., and Thompson, J. K. (1978). *Macaronichnussegregatis*; a feeding structure of shallow marine polychaetes. *JournalofSedimentaryResearch*, 48(4), 1293-1302.

Collinson, J. D. (1969). The sedimentology of the Grindslow shales and the Kinderscout grit; a deltaic complex in the Namurian of northern England. *Journal of Sedimentary Research*, *39*(1), 194-221.

Dasgupta, S., Buatois, L. A., and Mángano, M. G. (2016). Living on the edge: evaluating the impact of stress factors on animal–sediment interactions in subenvironments of a shelf-margin delta, the Mayaro Formation, Trinidad. *Journal of Sedimentary Research*, *86*(9), 1034-1066.

Dietze, V., Hillebrandt, A. V., Riccardi, A., and Schweigert, G. (2012). Ammonites and stratigraphy of a Lower Bajocian (Middle Jurassic) section in Sierra Chacaico (Neuquén Basin, Argentina). *Zitteliana*, 119-139.

Digregorio, J. H. (1972). Neuquén. In: Leanza, A.F. (Ed.): *Geología Regional Argentina*. Academia Nacional de Ciencias. República Argentina. pp. 439-506. Córdoba.

Duke, W. L., Arnott, R. W. C., and Cheel, R. J. (1991). Shelf sandstones and hummocky cross-stratification: new insights on a stormy debate. *Geology*,*19*(6), 625-628.

Ekdale, A.A., Bromley, R.G., and Loope, D.B. (2007). Ichnofacies of an Ancient Erg: A Climatically Influenced Trace Fossil Association in the Jurassic Navajo Sandstone, Southern Utah, USA. In *Trace Fossils: Concepts, Problems, Prospects*, ed. W. Miller III, Amsterdam: Elsevier, pp. 562–564.

Elliott, T. (1974). Interdistributary bay sequences and their genesis. *Sedimentology*,21(4), 611-622.

Enge, H. D., Howell, J. A., and Buckley, S. J. (2010). The geometry and internal architecture of stream mouth bars in the Panther Tongue and the Ferron Sandstone Members, Utah, USA. Journal of Sedimentary Research, 80(11), 1018-1031.

Franzese, J. R., Veiga, G. D., Schwarz, E., and Gómez-Pérez, I. (2006). Tectonostratigraphic evolution of a Mesozoic graben border system: the Chachil depocentre, southern Neuquén Basin, Argentina. *Journal of the Geological Society*, *163*(4), 707-721.

Freguglia, E., Agulleiro Insúa, L., Díaz, A. B., Navarro C., Barrionuevo, L., Pelaitai, H., Palazzetti, G., Villarroel, S., Boggetti, D. (2009). Estudio Estratigráfico Regional Fm. Lajas, Gr. Cuyo (Cuenca Neuquina – Provincia del Neuquén) *PyT Consultora S.R.L. Internal report. YPF.*

Frey, R. W., Howard, J. D., and Pryor, W. A. (1978). *Ophiomorpha*: its morphologic, taxonomic, and environmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *23*, 199-229.

Frey, R.W. and Pemberton, S.G. (1987). The *Psilonichnus* ichnocoenose, and its relationship to adjacent marine and nonmarine ichnocoenoses along the Georgia coast. *Bulletin of Canadian Petroleum Geology*, 35, 333– 357.

Frey, R.W. and Seilacher, A. (1980). Uniformity in marine invertebrate ichnology. *Lethaia*, 13, 183–207.

Frey, R.W. y Goldring, R. 1992. Marine event beds and recolonization surfaces as revealed by trace fossil analysis. Geological Magazine, 129. pp. 325–335.

Frey, R.W., Curran, H.A. and Pemberton, S.G. (1984a). Tracemaking activities of crabs and their environmental significance; the ichnogenus *Psilonichnus*. *Journal of Paleontology,* 58, 333–350.

Frey, R.W. y Pemberton, S.G. 1984. Trace fossils Facies Models. En: R.G. Walker (ed.), Facies Models. Geoscience Canada Reprints Series, pp. 189-207.

Frey, R.W. y Pemberton, S.G. 1985. Biogenic structures in outcrops and cores. I. Approaches to ichnology. Bulletin of Canadian Petroleum Geology 33: 72-115.

Frey, R.W., Pemberton, S.G. and Saunders, T.D.A. (1990). Ichnofacies and bathymetry: A passive relationship. *Journal of Paleontology*, 64, 155–158.

Galloway, W.E. (1975). Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In *Deltas, Models for Exploration,* ed. M.L. Broussard, Houston, TX: Houston Geological Society, pp. 87–89.

Genise, J.F., Mángano, M.G., Buatois, L.A., Laza, J. and Verde, M. (2000). Insect trace fossil associations in paleosols: The *Coprinisphaera* ichnofacies. *Palaios,* 15, 33–48.

Genise, J.F., Melchor R.N., Bellosi, E.S. and Verde. (2010). Invertebrate and Vertebrate Trace Fossils from Continental Carbonates. In *Carbonates in Continental Settings: Facies, Environments, and Processes*, ed. A.M. Alonso-Zarza

Gerard, J., and Bromley, R. (2008). Ichnofabrics in clastic sediments: applications to sedimentological core studies. Madrid. J. Gerard.

Gingras, M.K., Pemberton, S.G., Saunders, T.D.A. y Clifton, H.E. (1999). The ichnology of modern and Pleistocene brackish-water deposits at Willapa Bay, Washington; Variability in estuarine settings: *Palaios*, 14. pp. 352–374.

Giusiano, A., Mendiberri, H., and Carbone, O. (2011). Introducción a los Recursos Hidrocarburíferos. In Leanza, H.A., Arregui, C., Carbone, O., Danieli, J.C., and Vallés, J.M.(eds.), *Relatorio Geología y Recursos Naturales de la Provincia de Neuquén: XVIII Congreso Geológico Argentino*, Neuquén, 2011. p. 639–644.

Gómez Omil, R., Schmithalter, J., Cangini, A., Albariño L.M. y Corsi, A. (2002). El Grupo Cuyo en la Dorsal de Huincul, consideraciones estratigráficas, tectónicas y petroleras. Cuenca Neuquina. *V° Congreso de Exploración y Desarrollo de Hidrocarburos,* IAPG, Buenos Aires, Argentina, Actas. pp. 22.

Gugliotta, M., Flint, S. S., Hodgson, D. M., and Veiga, G. D. (2016a). Recognition criteria, characteristics and implications of the fluvial to marine transition zone in ancient deltaic deposits (Lajas Formation, Argentina). *Sedimentology*, 63(7), 1971-2001.

Gugliotta, M., Kurcinka, C. E., Dalrymple, R. W., Flint, S. S., and Hodgson, D. M. (2016b). Decoupling seasonal fluctuations in fluvial discharge from the tidal signature in ancient deltaic deposits: an example from the Neuquén Basin, Argentina. *Journal of the Geological Society*, 173(1), 94-107.

Gugliotta, M., Fairman Jr, J. G., Schultz, D. M., and Flint, S. S. (2016b). Sedimentological and paleoclimate modeling evidence for preservation of Jurassic annual cycles in sedimentation, western Gondwana. *Earth Interactions*, *20*(19), 1-21.

Gugliotta, M., Flint, S. S., Hodgson, D. M., and Veiga, G. D. (2015). Stratigraphic record of river-dominated crevasse subdeltas with tidal influence (Lajas Formation, Argentina). *Journal of Sedimentary Research*, *85*(3), 265-284.

Gulisano, C. A. and Hinterwimmer, G. (1986). Facies deltaicas del Jurásico medio en el oeste de Neuquén. *Boletín de Informaciones Petroleras*, 3a Época, III(8): 2-31.

Howell, J. A., Schwarz, E., Spalletti, L. A., and Veiga, G. D. (2005). The Neuquén basin: an overview. In Veiga, G.D., Spalletti, L.A.; Howell, J.A. and Schwartz, E. (Eds.). The Neuquén Basin,A case study in sequence stratigraphy and basin dynamics. Geological Society, Special Publications 252. London. pp. 83-108. *Geological Society, London, Special Publications*, *252*(1), 1-14.

Hunt, A. P., and Lucas, S. G. (2007). Tetrapod ichnofacies: a new paradigm. *Ichnos*, *14*(1-2), 59-68.

Knaust, D. (2013). The ichnogenus Rhizocorallium: classification, trace makers, palaeoenvironments and evolution. *Earth-Science Reviews*, 126, 1-47.

Knaust, D. (2017). Atlas of trace fossils in well core: appearance, taxonomy and interpretation. Springer.

Kurcinka, C., Dalrymple, R. W., and Gugliotta, M. (2018). Facies and architecture of river-dominated to tide-influenced mouth bars in the lower Lajas Formation (Jurassic), Argentina. *AAPG Bulletin*, 102(5), 885-912.

Lobza, V., & Schieber, J. (1999). Biogenic sedimentary structures produced by worms in soupy, soft muds; observations from the Chattanooga Shale (Upper Devonian) and experiments. *Journal of Sedimentary Research,* 69(5), 1041-1049.

Lockley, M.G., Hunt, A.P., and C. Meyer. (1994). Vertebrate tracks and the ichnofacies concept: implications for paleoecology and palichnostratigraphy. En: Donovan, S. (ed.), The paleobiology of trace fossils. John Wiley and Sons, Chichester: 241-268.

MacEachern, J. A., Bann, K. L., Bhattacharya, J. P., and Howell Jr, C. D. (2005). Ichnology of deltas: organism responses to the dynamic interplay of rivers, waves, storms, and tides.in Giosan, L., and Bhattacharya, J.P., eds., *River Delta: Concepts, Models, and Examples: SEPM, Special Publication* 83, p. 49–85.

MacEachern, J. A., Bechtel, D. J., and Pemberton, S. G. (1992b). Ichnology and sedimentology of transgressive deposits, transgressively-related deposits and transgressive systems tracts in the Viking Formation of Alberta..S.G. (Ed.), *Applications of Ichnology to Petroleum Exploration: A Core Workshop.* SEPM Core Workshop Notes 17, pp. 251–290.

MacEachern, J. A., Dashtgard, S. E., Knaust, D., Catuneanu, O., Bann, K. L., and Pemberton, S. G. (2012). Sequence stratigraphy. In *Developments in Sedimentology* (Vol. 64, pp. 157-194). Elsevier.

MacEachern, J. A., Raychaudhuri, I., and Pemberton, S. G. (1992a). Stratigraphic applications of the *Glossifungites* ichnofacies: delineating discontinuities in the rock record. S.G. (Ed.), *Applications of Ichnology to Petroleum Exploration: A Core Workshop*. SEPM Core Workshop Notes 17, pp. 251–290.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., Bann, K.L. and Dafoe, L.T. (2007c). Use of trace fossils in genetic stratigraphy. *In Trace Fossils: Concepts, Problems, Prospects,* ed. W. Miller III, Amsterdam: Elsevier, pp. 110–134.

MacEachern, J. A., and Bann, K. L. (2020). The *Phycosiphon* Ichnofacies and the *Rosselia* Ichnofacies: Two new ichnofacies for marine deltaic environments. Journal of Sedimentary Research, 90(8), 855-886.

MacEachern, J. A., and Bann, K. L. (2022). Departures from the Archetypal Deltaic Ichnofacies. Geological Society, London, Special Publications, 522(1), SP522-2022.

McIlroy, D. (2004). Some ichnological concepts, methodologies, applications and frontiers. In: McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geol. Soc. London, Spec. Publ., vol. 228, pp. 3–27.

McIlroy, D. (2008). Ichnological analysis: the common ground between ichnofacies workers and ichnofabric analysts. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 270, 332–338.

McIlroy, D., (2007). Ichnology of a macrotidal tide-dominated deltaic depositional system: Lajas Formation, Neuquén Province, Argentina. In: Bromley, R.G., Buatois, L.A., Mángano, M.G., Genise, J.F., and Melchor, R.N. (Eds), *Sediment–Organism Interactions: a Multifaceted Ichnology.* SEPM Special Publication, 88, pp. 193–210.

McIlroy, D., Flint, S., and Howell, J. A. (1999). Sequence stratigraphy and facies architecture of tidal succession, in an extensional basin; Neuquén Basin, Argentina. In *AAPG, Annual Meeting Expanded Abstracts* (Vol. 1999, pp. A91-A92).

McIlroy, D., Flint, S., Howell, J. A., and Timms, N. (2005). Sedimentology of the tide-dominated Jurassic Lajas Formation, Neuquén Basin, Argentina. In Veiga, G.D., Spalletti, L.A.; Howell, J.A. and Schwartz, E. (Eds.). The Neuquén Basin,A case study in sequence stratigraphy and basin dynamics. *Geological Society, London, Special Publications*, *252*(1), 83-107

Miall, A. D. (1978) Lithofacies types and vertical profile models in braided river deposits: a summary. En: *Fluvial Sedimentology*. Miall, A. D. (Ed.). *Canadian Society of Petroleum Geologists Bulletin*, *Memories5*, 579-604.

Moyano-Paz, D., Isla, M. F., MacEachern, J. A., Richiano, S., Gómez-Dacal, A. R., Varela, A. N., and Poiré, D. G. (2022). Evolution of an aggradational wave-dominated delta: Sediment balance and animal-substrate dynamics (Upper Cretaceous La Anita Formation, Southern Patagonia). *Sedimentary Geology,* 437, 106193.

Moyano-Paz, D., Richiano, S., Varela, A. N., Dacál, A. R. G., and Poire, D. G. (2020). Ichnological signatures from wave-and fluvial-dominated deltas: the La Anita formation, Upper Cretaceous, Austral-Magallanes Basin, Patagonia. Marine and Petroleum Geology, 114, 104168.

Mutti, E., Bernoulli, D., Ricci Lucchi, F. y Tinterri, R. (2009) Turbidites and turbidity currents from Alpine "flusch" to the exploration of continental margins. *Sedimentology* 56. 267-318.

Nara, M., and Seike, K. (2004). *Macaronichnus segregatis*-like traces found in the modern foreshore sediments of the Kujukuri-hama coast, Japan. *Journal-Geological Society of Japan,* 110(9), 545-551.

Olariu, C., and Bhattacharya, J. P. (2006). Terminal distributary channels and delta front architecture of river-dominated delta systems. *Journal of sedimentary research*, 76(2), 212-233.

Orton, G. J., and Reading, H. G. (1993). Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. *Sedimentology*, 40(3), 475-512.

Pemberton, S. G. (2001). Ichnology and sedimentology of shallow to marginal marine systems. *Geol. Assoc. Can., Short Course, 15,* 343.

Pemberton, S. G., and MacEachern, J. A. (1995). The sequence stratigraphic significance of trace fossils: examples from the Cretaceous foreland basin of Alberta, Canada. In: Van Wagoner, J.C., Bertram, G. (Eds.), Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America, AAPG Mem. 64, pp. 429–475.Pemberton, S.G., MacEachern, J.A., 1997.

Pemberton, S. G., Frey, R. W., Ranger, M. J., and MacEachern, J. (1992). The conceptual framework of ichnology. Pemberton SG (ed) (1992) *Applications of ichnology to petroleum exploration. A core workshop. SEPM Core Workshop*, vol 17,429 pp

Pemberton, S. G., MacEachern, J. A., and Brett, C. E. (1997). The ichnological signature of storm deposits: the use of trace fossils in event stratigraphy. Paleontological Events. Stratigraphic, ecological and evolutionary implications. Columbia University Press, New York, 73-109.

Pemberton, S.G. y Frey, R.W. (1984). Ichnology of storm–influenced shallow marine sequence: Cardium Formation (Upper Cretaceous) at Seebe, Alberta. En: Stott, D.F. y Glass, D.J (Eds.). *The Mesozoic of middle North America. Canadian Society of Petroleum Geologists Memoir*, 9. pp.281–304.

Pemberton, S.G., Kobluk, D.R., Yeo, R.K., Risk, M.J., (1980). The boring *Trypanites* at the Silurian-Devonian disconformity in southern Ontario. J. Paleontol. 54, 1258–1266.

Pemberton, S.G., MacEachern, J.A. and Saunders, T. (2004). Stratigraphic applications of substrate-specific ichnofacies: delineating discontinuities in the fossil record. In *The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis,* ed. D. McIlroy, Geological Society Special Publication, 228, 29–62.

Pemberton, S.G., MacEachern, J.A., (2005). Significance of ichnofossils in applied stratigraphy. In: Koutsoukos, E.A. (Ed.), Applied Stratigraphy. Springer, Dordrecht, pp. 281–302.

Plink-Björklund, P. (2015). M orphodynamics of rivers strongly affected by monsoon precipitation: review of depositional style and forcing factors. *Sedimentary Geology*, *323*, 110-147.

Plint, A.G. (2010). Chapter 8, Wave- and storm-dominated shoreline and shallow marine systems. En: Dalrymple, R.W. y James, N.P. (Eds.). *Facies Models, 4th Edition,* Geological Association of Canada. pp. 167-199.

Plint, A. G. (2014). Mud dispersal across a Cretaceous prodelta: storm-generated, wave-enhanced sediment gravity flows inferred from mudstone microtexture and microfacies. Sedimentology, 61(3), 609-647.

Poiré, D. G., and del Valle, A. (1992). Análisis sedimentológico de trazas fósiles de las Formaciones Los Molles y Lajas, Grupo Cuyo, Jurásico de Cuenca Neuquina, Argentina. *Cuarta Reunión Argentina de Sedimentología, Actas*, *1*, 25-32.

Quiroz, L.I., Buatois, L.A., Mángano, M.G., Jaramillo, C.A. and Santiago, N. (2010). Is the trace fossil *Macaronichnus* an indicator of temperate to cold waters? Exploring the paradox of its occurrence in tropical coasts. *Geology*, 38, 651–654.

Ramos, V.A., Folguera, A., Morabito, E. G. (2011). Las provincias geológicas del Neuquén. In Leanza, H.A., Arregui, C., Carbone, O., Danieli, J.C., and Vallés, J.M. (Eds). *Relatorio Geología y Recursos Naturales de la Provincia de Neuquén: XVIII Congreso Geológico Argentino*, Neuquén, 2011- p 317-326.

Riccardi, A. C. (2008). El Jurásico de la Argentina y sus amonites. *Revista de la Asociación Geológica Argentina*, *63*(4), 625-643.

Rodríguez-Tovar, F. J., and Aguirre, J. (2014). Is Macaronichnus an exclusively small, horizontal and unbranched structure? Macaronichnus segregatis degiberti isubsp. nov. Spanish Journal of Palaeontology, 29(2), 131-142.

Rossi, V. M., and Steel, R. J. (2016). The role of tidal, wave and river currents in the evolution of mixed-energy deltas: Example from the Lajas Formation (Argentina). *Sedimentology*, 63(4), 824-864.

Schomacker, E. R., Kjemperud, A. V., Nystuen, J. P., and Jahren, J. S. (2010). Recognition and significance of sharp-based mouth-bar deposits in the Eocene Green River Formation, Uinta Basin, Utah. *Sedimentology*, *57*(4), 1069-1087.

Seike, K. (2007). Palaeoenvironmental and palaeogeographical implications of modern *Macaronichnus segregatis*-like traces in foreshore sediments on the Pacific coast of central Japan. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 252(3-4), 497-502.

Seike, K. (2008). Burrowing behaviour inferred from feeding traces of the opheliid polychaete *Euzonus* sp. as response to beach morphodynamics. *Marine Biology*, 153(6), 1199-1206.

Seike, K., Yanagishima, S. I., Nara, M., and Sasaki, T. (2011). Large *Macaronichnus* in modern shoreface sediments: Identification of the producer, the mode of formation, and paleoenvironmental implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 311(3-4), 224-229.

Seilacher, A. 1967. Bathymetry of trace fossils. *Marine Geology* 5: 413-428.

Smith, J. J., Hasiotis, S. T., Kraus, M. J., and Woody, D. T. (2008). *Naktodemasisbowni*: new ichnogenus and ichnospecies for adhesive meniscate burrows (AMB), and paleoenvironmental implications, Paleogene Willwood Formation, Bighorn Basin, Wyoming. *Journal of Paleontology*, 82(2), 267-278.

Spalletti, L. A. (1995). Jurásico medio de la cuenca neuquina, República Argentina. *Rev. Soc. Geol. España*, 8, 3.

Spalletti, L., Veiga, G. and Schwarz, E. (2010). Facies and stratigraphic sequences of the Mesozoic Neuquèn Basin (Western Argentina): continental to deep marine settings. In: *Field Excursion Guidebook, 18th International Sedimentological Congress, Mendoza, Argentina,* FE C3 (Ed C.A. del Papa, R.), pp. 1-79, 2010, Mendoza, Argentina.

Taylor, A. M., and Goldring, R. (1993). Description and analysis of bioturbation and ichnofabric. *Journal of the Geological Society*, *150*(1), 141-148.

Uchman, A., Bubniak, I. y Bubniak, A. 2000. The *Glossifungites* ichnofacies in the area of its nomenclatural archetype, Aviv, Ukraine. *Ichnos* 7: 183-189

Van Yperen, A. E., Poyatos-Moré, M., Holbrook, J. M., and Midtkandal, I. (2020). Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA). The Depositional Record, 6(2), 431-458.

Veiga, G. D., Schwarz, E., Spalletti, L. A., and Massaferro, J. L. (2013). Anatomy and sequence architecture of the early post-rift in the Neuquén Basin (Argentina): a response to physiography and relative sea-level changes. *Journal of Sedimentary Research*, *83*(8), 746-765.

Vocaturo, G., Brinkworth, W., Loss, M. L., Mortaloni, E., Giunta, D., and Massaferro, J. L. (2018) PS Basin Scale Study of a Tight Gas Reservoir: Paleoenviromental Evolution of a Shallow Marine System in the Early-Middle Jurassic, Neuquén Basin, Argentina. *Search and Discovery Article #11123.AAPG 2018 Annual Convention and Exhibition, Salt Lake City, Utah,*

Walker, R.G. and Plint, A.G. (1992). Wave- and storm-dominated shallow marine systems. In *Facies Models, response to sea level change*, ed. R.G. Walker and N.P. James, St John's, NL: Geological Association of Canada, pp. 219–238.

Wang, Y., Zhu, D., y Wu, X. (2002). Chapter Thirteen Tidal flats and associated muddy coast of China. *Proceedings in Marine Science*, 4. pp. 319-345.

Weaver, C.E. (1931). Paleontology of the Jurassic and Cretaceous of West Central Argentina. University of Washington Memoir I. Washington. pp. 496.

Yrigoyen, M.R. (1991). Hydrocarbon resources of Argentina. In World Petroleum Congress, No. 13. *Petrotecnia, Special Issue*: 38-54. Buenos Aires.

Zavala, C. (1996a). High-resolution sequence stratigraphy in the Middle Jurassic Cuyo Group, South Neuquén Basin, Argentina. *GeoResearch Forum* (Vol. 1, No. 2, pp. 295-303).

Zavala, C. (1996b). Sequence stratigraphy in continental to marine transitions. An example from the Middle Jurassic Cuyo Group, south Neuquén Basin, Argentina. *GeoResearch Forum* (Vol. 1, No. 2, pp. 285-293).