SPANISH JOURNAL OF PALAEONTOLOGY

# Ichnology and sedimentology of estuarine deposits, Mata Amarilla Formation, Austral Basin, Argentina

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Richiano, S., Varela, A.N., Cereceda, A. & Poiré, D.G. 2014. Ichnology and sedimentology of estuarine deposits, Mata Amarilla Formation, Austral Basin, Argentina [Icnología y sedimentología de depósitos estuarinos en la Formación Mata Amarilla, cuenca Austral, Argentina]. *Spanish Journal of Palaeontology*, 29 (2), 117-130.

*Manuscript received* 17 April 2013
*Manuscript accepted* 29 January 2014

 ISSN 2255-0550

**ABSTRACT**

The Mata Amarilla Formation (Upper Cretaceous) is part of the infilling of the Austral Basin (Patagonia, Argentina). This unit is mainly composed of grey to black mudstones interbedded with fine- to coarse-grained sandstones, deposited in littoral and continental environments. Three informal sections have been defined; the littoral deposits of the lower and upper sections constitute the object of this study. The intervals contain *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Ophiomorpha*, *Palaeophycus*, *Skolithos*, *Thalassinoides*, *Teredolites* and fugichnia. The sedimentological and ichnological analyses allowed the distinction of three facies associations (FA) developed in an estuarine palaeoenvironment. The more proximal FA1 is the bay-head delta, comprising delta-front bars of coarse-grained sandstone, containing *Arenicolites*, *Skolithos* and allochthonous petrified wood with *Teredolites.* This trace fossils association indicates high-energy conditions. The FA2, interpreted as estuarine bars, is composed of fine- to medium-grained sandstone containing herringbone cross-stratification and mud drapes with *Cylindrichnus*, *Ophiomorpha*, *Skolithos*, *Thalassinoides* and fugichnia. This reflects a setting with a high sedimentation

**RESUMEN**

La Formación Mata Amarilla (Cretácico Superior), parte del relleno de la Cuenca Austral (Patagonia, Argentina), se compone principalmente de pelitas grises a negras con intercalaciones de areniscas finas a gruesas depositadas en ambientes litorales y continentales. Se definieron tres secciones informales; las secciones inferior y superior (depósitos litorales) constituyen el foco de este estudio. Los intervalos contienen *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Ophiomorpha*, *Palaeophycus*, *Skolithos*, *Thalassinoides*, *Teredolites* y fugichnia. El análisis sedimentológico-icnológico permitió distinguir tres asociaciones de facies (AF) desarrolladas en un paleoambiente de estuario. La AF1 es la más proximal, es el delta de cabecera de estuario, comprende barras arenosas de grano grueso, que contienen *Arenicolites*, *Skolithos* y madera petrificada alóctona con *Teredolites*. Esta icnoasociación indica condiciones de alta energía. La AF2, interpretada como barras estuarinas, se compone de areniscas finas a medianas con estratificación *herringbone* y pausas pelíticas, *Cylindrichnus*, *Ophiomorpha*, *Skolithos*, *Thalassinoides* y fugichnia. Esto refleja altas tasas de sedimentación, energía moderada, sustratos inestables, y

http://doi.org/10.7203/sjp.29.2.17680

rates, moderate energy, unstable substrates, and normal salinity. Finally, the FA3 (fine-grained estuarine deposits) are characterized by heterolithic rocks with synaeresis cracks and *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Palaeophycus*, *Thalassinoides* and *Skolithos*. These ichnogenera are generally characterized by small sizes, consistent with a salinity stressed palaeoenvironment. The distribution, size and abundance of the trace fossils were controlled by several environmental factors, e.g. energy, sedimentation rate and salinity contents. The palaeoenvironmental factors variability is directly related to the fresh water and sediment input from rivers flood, which took place during the wet seasons of a warm, temperate climate.

**Keywords:** Ichnology, palaeoenvironmental controls, littoral facies, Upper Cretaceous, southern Patagonia.

salinidad normal. Finalmente, la AF3 (depósitos estuarinos de grano fino) se caracterizan por rocas heterolíticas con grietas de sinéresis y *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Palaeophycus*, *Thalassinoides* y *Skolithos*. Estos icnogéneros generalmente se caracterizan por un pequeño tamaño, en consonancia con paleoambiente estresado. La distribución, tamaño y abundancia de las trazas fósiles fueron controlados por varios factores ambientales, entre ellos energía, tasa de sedimentación y salinidad. La variabilidad de los factores paleoambientales estuvo controlada por la entrada el agua dulce y sedimentos al estuario producidas por avenidas fluviales durante las estaciones húmedas de un clima estacional templado-cálido.

**Palabras clave:** Icnología, controles paleoambientales, facies litorales, Cretácico Superior, Patagonia Sur.

## 1. INTRODUCTION

The Mata Amarilla Formation (Feruglio, in Fossa Mancini *et al*., 1938) is part of the Austral Foreland Basin (Varela *et al*., 2012a, 2013). It is located in the west-southwest of the Santa Cruz province, Argentina (Fig. 1), and is regarded to be early Upper Cretaceous. Deposition took place during a greenhouse period in a warm temperate climate (Varela *et al*., 2012b). The fossil contents of the littoral intervals in the Mata Amarilla Formation are quite abundant. Littoral bivalves and gastropods (Griffin & Varela, 2012 and other references there), and ammonites (*cf*. Riccardi, 2002 and other references there) comprise the dominant invertebrate elements, with vertebrate fossils represented by *Plesiosaurus* remains (O´Gorman & Varela, 2010), and turtle remains, fish bones and shark teeth (Goin *et al*., 2002; Cione *et al*., 2007). Moreover, in these littoral deposits, plant fossils (*cf*. Iglesias *et al*., 2007 and other references there) as well as dinoflagellate remains (Marensi *et al*., 2003) have also been recorded. In these sedimentary rocks, record of trace fossils had not been published, and is documented here.

The main goal of this paper is to analyze the ichnology of the littoral intervals of the Mata Amarilla Formation and interpret the trace fossil associations in order to provide more information on the intervening sedimentary processes, so as to generate a more accurate palaeoenvironmental reconstruction. This analysis is essential to cover a gap in the studies regarding the relations between the burrowing organisms and the sedimentary environments of the early Upper Cretaceous in the Austral Basin. Previous studies were largely focused on the Lower Cretaceous materials (e.g., Poiré *et al*., 2001, 2002; Poiré & Franzese, 2008; Richiano *et al*., 2013). Additionally, the ichnological analyses of littoral sequences are of great interest in the understanding of the influences of environmental factors in the generation and preservation of fossil traces.

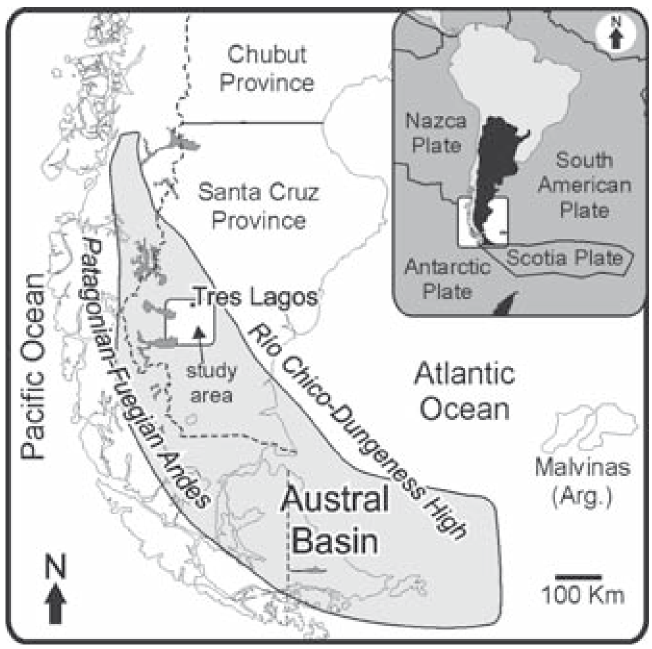



**Figure 1.** General view of the Austral Basin location.

## 2. GEOLOGICAL FRAMEWORK

The Cenomanian-Santonian Mata Amarilla Formation marks the beginning of the foreland stage of the Austral Basin (Varela, 2011; Varela *et al*., 2012a; Fig. 2). It is composed of grey and black mudstones, alternating with whitish to yellowish grey sandstones, interpreted to have been deposited in littoral and continental environments (Arbe, 1989; Varela & Poiré, 2008; Varela, 2011; Varela *et al*., 2011). The formation overlies the passive margin deltaic deposits of the Piedra Clavada Formation, and is overlain by the La Anita Formation across an erosional contact (Fig. 2).


**Figure 2.** General stratigraphic column of the Austral Basin, modified from Poiré *et al*. (2006) and Varela *et al*. (2013).

The Mata Amarilla Formation is divided into three informal sections: lower, middle and upper (Fig. 2; Varela, 2011; Varela *et al*., 2012a, b). The lower section shows, on its western margin, distal fluvial facies (mudstones with subordinate fine- and medium-grained sandstones), whereas to the east, a coarsening-upward succession of littoral deposits alternate with palaeosols (Varela, 2011; Varela *et al*., 2011, 2012a). Varela *et al*. (2012a) obtained an accurate U-Pb age from the middle section of the Mata Amarilla Formation by using laser ablation in zircons from a tuff, which yielded an age of 96.23 ± 0.71 Ma (Middle Cenomanian).

The middle section is mostly fluvial, and shows a decrease in grain sizes from west to east, accompanied by a variation in the fluvial systems from gravelly braided in the west, to high-sinuosity and low-sinuosity meandering with aggradation in the east (Varela, 2011; Varela *et al*., 2012b). This section is characterized by the presence of *in situ* fossil tree trunks (Zamuner *et al*., 2008) and dinosaur remains (see Novas *et al*., 2008 and references therein) in the equivalent Pari Aike Formation (*nomen vanum*; *cf*. Varela, 2011; Varela *et al*., 2012a). Finally, the upper section also shows distal fluvial deposits in the west and littoral deposits to the east (Varela, 2011; Varela *et al*., 2012b).

## 3. STUDY AREA AND ANALYZED DEPOSITS

The study area is located to the south-west of the Santa Cruz province, Austral Patagonia, Argentina (Figs 1, 3), in the surroundings of the Tres Lagos locality (Fig. 3). Two detailed sedimentological profiles derived from the littoral outcrops of the studied unit were completed in the eastern part of the study area (LB: Estancia La Blanca; LR: Estancia La Regina; Figs 3, 4). Moreover, a bed-scale identification of the trace fossils was also carried out (Fig. 4).

The three sections of the Mata Amarilla Formation are identified in the two studied localities (LB and LR; Fig. 4). The lower and upper sections shows dark colorations as a result of the large proportion of fine-grained sediments, and the middle section shows a whitish coloration due to the preponderance of sandy sediments.

## 4. FACIES ASSOCIATIONS AND ICHNOLOGY

In the littoral deposits of the Mata Amarilla Formation, Varela (2011) performed detailed sedimentological studies,

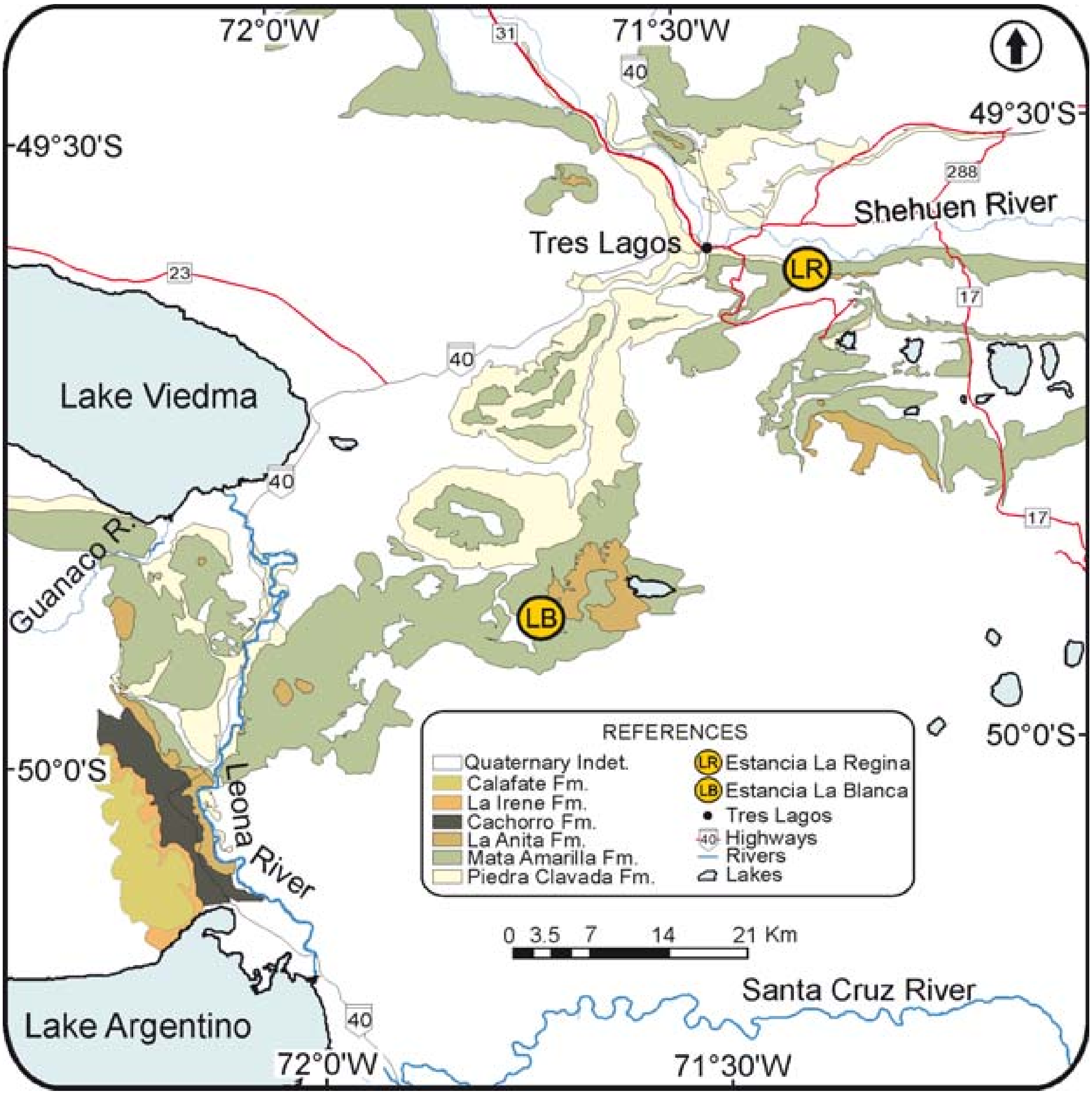



**Figure 3.** Geological map of the studied area showing the Cretaceous units.

which allowed the identification of three main facies associations (FA) interpreted to record three discrete depositional environments: 1) the bay-head delta; 2) the estuarine bars; and 3) the fine-grained estuarine bay deposits that locally contain intercalated palaeosols. Such FAs comprise the main focus of this paper, and their principal sedimentological and ichnological characteristics are described below.

## 4.1. The bay-head delta

The bay-head delta FA is located in Estancia La Blanca (LB), in the lower section of the Mata Amarilla Formation (see Figs 3, 4).

### *4.1.1. Sedimentology*

This FA is composed of bodies of yellowish white, coarse-grained sandstones that grade into granule conglomerates (Fig. 5a). The predominant primary sedimentary structures are planar tabular and trough-cross bedding stratification, grouped in sets 50 cm wide and with lateral extents > 200 m. The external geometry is tabular to lenticular, and with thickness between 5 and 10 m (Fig. 5a). The FA has abundant mud intraclasts and it locally shows transported (allochthonous) *Teredolites*-bored tree trunks (Fig. 5b).

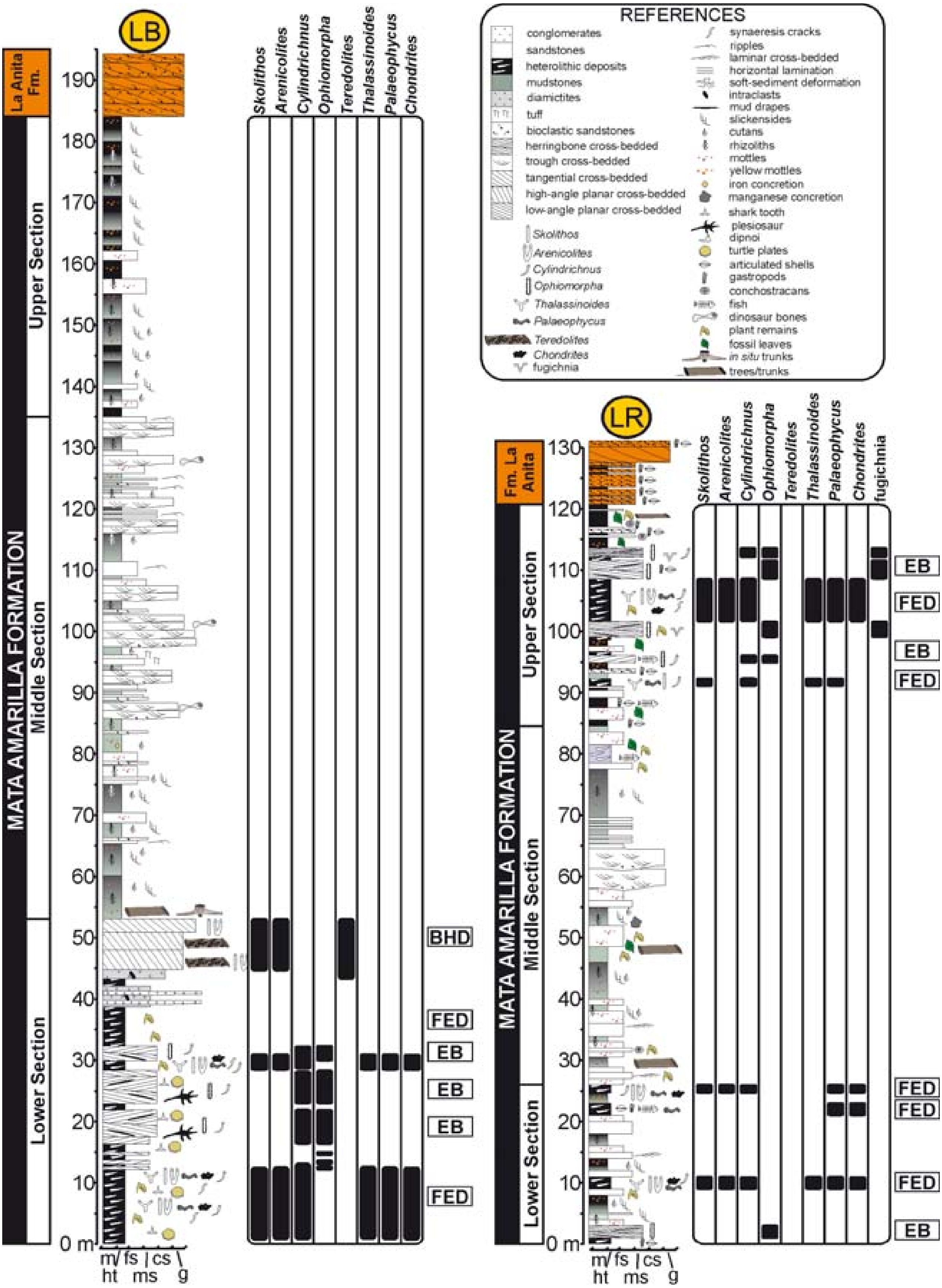



**Figure 4.** Sedimentological sections of the Mata Amarilla Formation at Estancia La Blanca (LB) and Estancia La Regina (LR). m: mudstone; ht: heterolithic; fs: fine-grained sandstone; ms: medium-grained sandstone; cs: coarse-grained sandstone; g: granule conglomerate. BHD: bay-head delta deposits; EB: estuarine bar deposits; FED: fine-grained estuarine bay deposits.

### 4.1.2. Ichnology

In this FA, two *in situ* ichnogenera were recognized: *Skolithos* and *Arenicolites* (Figs 5c-5d). *Teredolites* borings occur in transported wood fragments and tree trunks (Fig. 5b). The *in situ* ichnogenera have been preserved in the lowest bars of this succession and, in general, have diameters of about 0.3 to 0.5 cm. They are homogeneously distributed over the whole upper surface of the sandy strata (Bioturbation Index; BI= 2; Figs 5c-5d). *Teredolites* borings have been preserved in petrified wood remains. They display a clavate to tear-drop shape with sub-circular section reaching a maximum diameter of 1 cm (Fig. 5b). This ichnogenus correspond to bivalve borings into wooden substrates while the trunks must have been submerged in seawater (Bromley *et al*., 1984; Aguirre Urreta, 1987; Savrda, 1991; Beynon & Pemberton, 1992; Gingras *et al*., 2004).

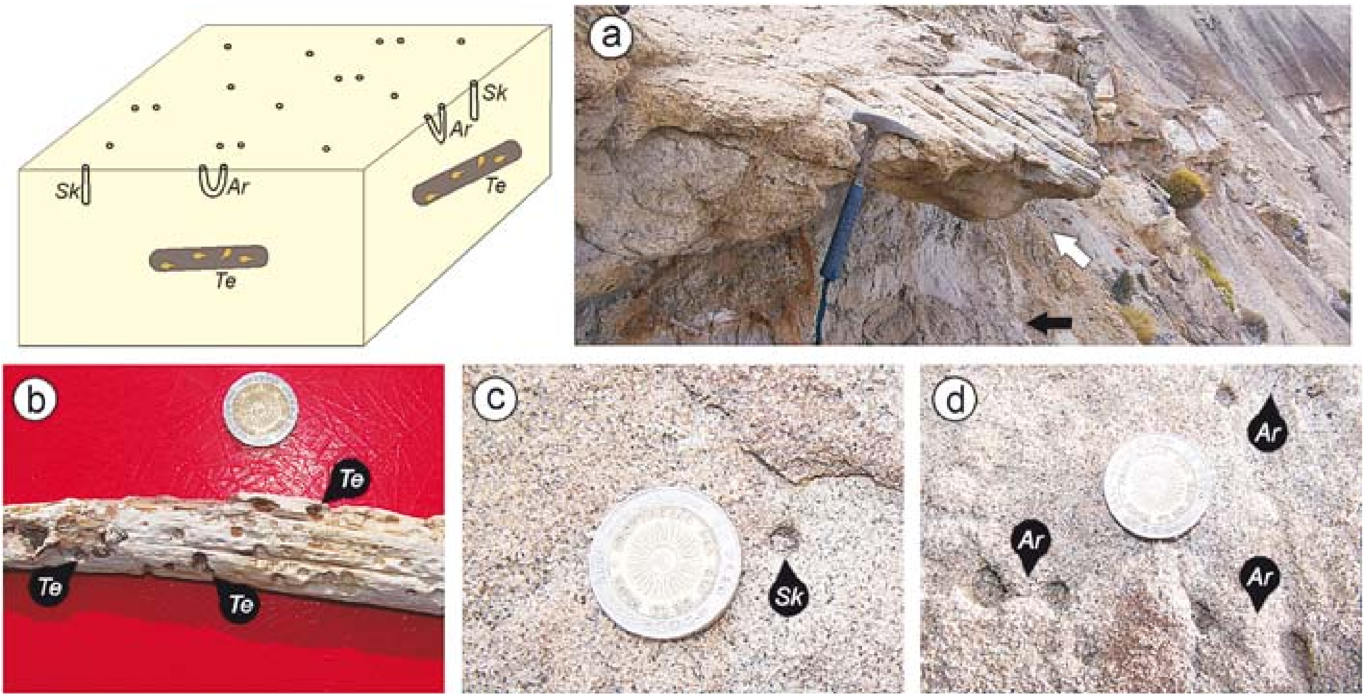



**Figure 5.** Sedimentological and ichnological features of the bay-head delta facies association (schematic block diagram). **a)** Delta-front deposits (white arrows), prodelta deposits (black arrows); hammer length: 33 cm. **b)** Petrified wood with *Teredolites* (*Te*). **c)** *Skolithos* (*Sk*). **d)** *Arenicolites* (*Ar*). (Coin diameter: 2.2 cm). See legend of Fig. 4 for symbols and abbreviations.

### 4.1.3. Interpretation

This unit is part of a coarsening-upward succession, interpreted as a progradational arrangement caused by the migration of the delta-front bars in a small delta developed in the bay-head area of an estuary (i.e., *bay-head delta*; Varela, 2011). The *in situ* bioturbation corresponds to high energy conditions, where the filtering- and deposits-feeding organisms colonized the substrate, and generated dwelling structures (*Skolithos*-*Arenicolites*). Due to the fact that tree trunks represent allochthonous material and do not define an *in situ* substrate, they do not produce a *Teredolites* Ichnofacies.

## 4.2. The estuarine bars

FA interpreted as estuarine bars are characteristic of the lower section of the Mata Amarilla Formation in the localities of Estancia La Blanca (LB) and Estancia La Regina (LR), as well as in the upper section at Estancia La Regina (LR) (Figs 3, 4).

### 4.2.1. Sedimentology

These estuarine bar deposits are composed of grayish to greenish grey sandstones with yellowish stains, whose grain size varies between fine- and medium-grained sand (Fig. 6a). They are characterized by herringbone cross-stratification and mudstone drapes (Fig. 6b) internally grouped in sets 20-to-30 cm thick. The geometry of the FA is tabular at the outcrop scale, is between 3 and 6 m thick, and is greater than 50 m long in its lateral extent (Fig. 6a). These sandy bars have an abundant fossil content, including plesiosaurian remains (O'Gorman & Varela, 2010), shark teeth, and fish, as well as abundant plant debris.

### *4.2.2. Ichnology*

In this FA, specimens of *Cylindrichnus*, *Ophiomorpha nodosa*, *Skolithos*, *Thalassinoides* and fugichnia (Figs 6c-6g) were found. *Skolithos* and *Cylindrichnus* specimens appear as short, 1-to-3 cm long vertical tubes (Fig. 6c). *Ophiomorpha nodosa* examples are characterized by tubes 1 to 2 cm in diameter, covered by rounded pellets, which form gallery systems containing "Y" junctions (Figs 6d-6e). The *Thalassinoides* specimens generally appear dispersed in the sandy strata. They have an approximate diameter of 2 cm and show darker colors than the enclosing rock (Figs 6e-6f). Fugichnia show downward deflected laminae reflecting the upward movement of infaunal through a sedimentary unit, and are typically 2-3 cm in length (Fig. 6g). In general terms, the beds presents BI= 2.

### *4.2.3. Interpretation*

This FA has typical characteristics of tide-influenced environments, and is interpreted as sub-tidal bars in estuarine bay environments (Varela, 2011). The ichnology suggests conditions of loose, shifting substrate, with possible abrupt changes in energy and episodic sedimentation.

## 4.3. The fine-grained estuarine bay deposits

The fine-grained heterolithic estuarine bay deposits are located in the lower section of the Mata Amarilla Formation, in both of the studied localities (Fig. 4), and are interbedded with the deposits of the estuarine bars (Fig. 6a). These deposits are also located in the upper section in the locality of Estancia La Regina (LR).

### *4.3.1. Sedimentology*

These fine-grained heterolithic deposits are characterized by interbedded black-to-dark-grey mudstones and white, fine-grained sandstones (Fig. 7a). The sedimentary structures present are: cross and parallel lamination and the full range of heterolithic bedsets (i.e., flaser, wavy to lenticular bedding; Figs 7a-7b). These bedsets show alternating processes of traction sediment transport and suspension sediment settling (Reineck & Wunderlich, 1968; Collinson & Thompson, 1989). Numerous units also show synaeresis cracks (Fig. 7c). Their external geometries are tabular and their thicknesses vary from centimeters to dozens of meters. The bases and the tops of the beds are from sharp to gradational. The general arrangement tends to be thickening-upwards with an increase in the sand proportion in the heterolithic intervals towards the top (prograding arrangements, Fig. 7a), although locally there are retrograding or transgressive arrangements. Locally, in this unit there is a mixture between normal marine and brackish-water fauna (Griffin & Varela, 2012).

### *4.3.2. Ichnology*

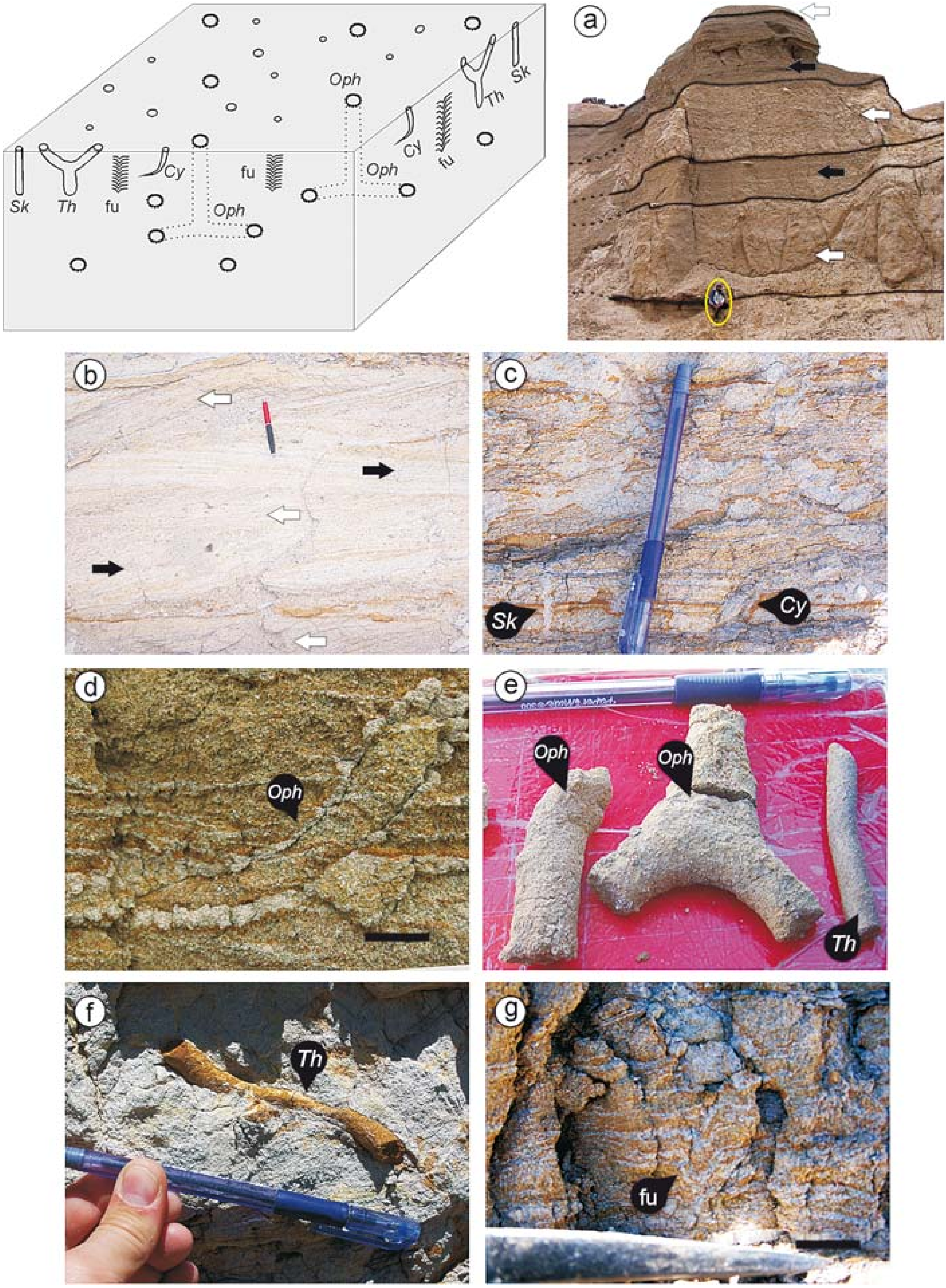
The FA shows *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Palaeophycus*, *Skolithos* and *Thalassinoides* (Figs 7d-7f). In general, there is a predominance of simple trace fossils, both horizontal and vertical structures, locally with diameters of less than 1 cm and short development (less than 3 cm long). The intensity of bioturbation is moderate (BI= 2-3), based on the widespread preservation of primary stratification and trace fossil morphology. In some horizons, however, a more intense bioturbation generates a partial homogenization of the strata (BI= 5; Fig. 7g).

### *4.3.3. Interpretation*

This FA is interpreted as deposited in a brackish-water environment. In the studied area, tidal features are noticeable through the widespread heterolithic bedsets. The succession is regularly interbedded herringbone cross-stratified sandstones, interpreted as estuarine tidal bars, consistent with deposition in an estuarine environment (Varela, 2011). Bioturbation has the characteristics of impoverished trace fossil suites, reflected by their simple designs, generally small sizes, and paucity in the succession (Beynon *et al*., 1988; Pemberton & Wightman, 1992). Such suites are common to salinity stressed, brackish water environments such as estuarines (e.g., MacEachern & Pemberton, 1992; Gingras *et al*., 1999; Buatois *et al*., 2002, 2005; MacEachern & Gingras, 2007).

# 5. DEPOSITIONAL PALAEOENVIRONMENTS

During the early Upper Cretaceous, the Austral Basin possessed a large embayment in the study area into which fluvial systems flowed, forming deltaic, estuarine and lagoon palaeoenvironments (Varela *et al*., 2011, 2013). From the sedimentological studies performed on the lower and upper sections of the Mata Amarilla Formation, an estuarine palaeoenvironment was proposed. These estuarine deposits are composed of three main FAs: bay-head delta, estuarine bars, and fine-grained estuarine bay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deposits. The locality of LB is approximately located in a central position in an estuarine embayment (Fig. 8). In the lower section, the FAs have a clearly progradational arrangement, from fine-grained estuarine bay deposits into the bay-head delta deposits (Fig. 4). By contrast, the LR locality does not show a well-defined vertical arrangement in any of the sections; however, the intercalated palaeosols suggests a marginal position within the estuary (see Varela *et al*., 2012b; Figs 4, 8).

From the ichnological point of view, the delta-front bars are characterized by the presence of *Arenicolites*, *Skolithos* and *Teredolites* in allochthonous wood fragments (Figs 5, 8). The estuarine bar deposits possess *Cylindrichnus*, *Ophiomorpha nodosa*, *Skolithos*, *Thalassinoides* and fugichnia (Figs 6, 8), whereas the fine-grained heterolithic estuarine bay deposits show *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Palaeophycus*, *Skolithos* and *Thalassinoides* (Figs 7, 8). The ichno-associations reflect benthonic palaeocommunities, which are conditioned by the palaeoenvironmental parameters to which they were exposed (Gibert & Martinell, 1993). The estuarine areas are recognized as regions where the palaeoenvironmental parameters (salinity, oxygenation, and sedimentation rate, among others) tend to be temporally stable. For this reason, ichnological analyses in littoral environments (especially in deposits of deltas and estuaries) have been the object of numerous studies on the physico-chemical controls in fossil traces (Remane & Schlieper, 1971; Grassle & Grassle, 1974; Pemberton *et al*., 1982; Savrda & Bottjer, 1987; Beynon *et al*., 1988; Droser & Bottjer, 1988; Pemberton & Wightman, 1992; Gibert & Martinell, 1993; Bann *et al*., 2004; Buatois *et al*., 2005; MacEachern *et al*., 2005; MacEachern & Gingras, 2007; MacEachern & Bann, 2008; Gingras *et al*., 2011, among others). In this sense, the deposits in the Mata Amarilla Formation also show an arrangement partially controlled by palaeoenvironmental factors. In more inner estuarine regions (i.e., the bay-head delta), trace fossils show high-energy conditions. *Skolithos* and *Arenicolites* occur in a wide range of depositional environments (e.g., continental to marine environments; MacEachern *et al*., 2007), while *Teredolites* are assigned to littoral marine environments (MacEachern *et al*., 2007). The burial and preservation of the petrified tree trunks supports settings with periods of high sedimentation rates. Moreover, during river flood, the conditions of high energy favoured the development of the *Skolithos*-*Arenicolites* association. These alternations in river discharge may have been a function of climatic conditions related to a seasonal tropical climate, previously suggested by Varela *et al.* (2012b), based on sedimentological evidence.

With respect to the estuarine bars, the ichnoassociation supports high sedimentation rate, moderate energy, unstable substrates and normal salinity. The presence of fugichnia is related to episodic sedimentation and/or erosion, reflecting the movement of the organisms attempting to avoid burial or transport. The no cohesive sandy substrates favoured the predominance of *Ophiomorpha nodosa*, an ichnospecies accompanied, to a lesser extent, by simple *Skolithos* and *Thalassinoides*.

Finally, the fine-grained heterolithic estuarine bay deposits show the highest ichnodiversity (six ichnogenera) of the succession. Most commonly, however, the suites are characterized by small-sized traces, suggesting a stressed palaeoenvironment, prone to salinity fluctuations. This is supported by the presence of synaeresis cracks, which are likewise regarded to be produced by fluctuations in salinity (Burst, 1965; Plummer & Gostin, 1981). The general energy of the palaeoenvironment is low; the deposition of muds predominates over the brief tractive events recorded. Sedimentation rates appear to have alternated between high and low controlled by seasonality marked by the climate (Varela *et al*., 2012b).

## 6. CONCLUSIONS

In the Mata Amarilla Formation, eight ichnogenera and fugichnia traces were identified, distributed spatially into different subenvironments of a palaeo-estuary. In the bay-head delta facies association, *Arenicolites*, *Skolithos* and *Teredolites* were identified. In the estuarine bar deposits, the *Cylindrichnus*, *Ophiomorpha nodosa*, *Skolithos*, *Thalassinoides* and fugichnia are present. In the fine-grained, heterolithic estuarine bay deposits, *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Palaeophycus*, *Skolithos* and *Thalassinoides* appear. The distribution, size and abundance of these trace fossils were controlled by different palaeoenvironmental factors, including the energy of the environment, sedimentation rates and fluctuations

**Figure 6.** Sedimentological and ichnological features of the estuarine bar facies association (schematic block diagram). **a)** Estuarine bar (white arrows) interbedded with fine-grained estuarine bay deposits (black arrows) at Estancia La Blanca locality (person for scale). **b)** Detail of estuarine bar deposits with herringbone cross-stratification and mudstone drapes. White and black arrows indicate tidal directions. **c)** *Skolithos* (*Sk*) and *Cylindrichnus* (*Cy*). **d)** *Ophiomorpha nodosa* (*Oph*). **e)** Typical "Y"-shaped junctions of *Ophiomorpha* (*Oph*) and a small tube of *Thalassinoides* (*Th*). **f)** Longitudinal section of *Thalassinoides* (*Th*). **g)** Fugichnia (fu). Scale bar: 1cm; pencil for scale: 14 cm. See legend of Fig. 4 for symbols and abbreviations.


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**Figure 7.** Sedimentological and ichnological features of the fine-grained heterolithic estuarine bay deposits facies association (schematic block diagram). **a)** Fine-grained estuarine bay deposits in a prograding arrangements; lenticular (Htl), wavy (Htw) and flaser (Htf) heterolithic sedimentary rocks (person for scale). **b)** Close-up of the wavy lamination. **c)** Syneresis cracks (Sy). **d)** *Thalassinoides* (*Th*) (scale bar: 1 cm). **e)** *Cylindrichnus* (*Cy*), *Palaeophycus* (*Pa*), *Arenicolites* (*Ar*) and *Skolithos* (*Sk*). **f)** *Chondrites* (*Ch*) (scale bar: 2 cm). **g)** Deposits with high bioturbation grade. Pencil for scale: 14 cm; coin diameter: 2.2 cm. See legend of Fig. 4 for symbols and abbreviations.

in salinity. Such variability in palaeoenvironmental factors was directly related to the fresh-water and sediment input supplied by fluvial processes, probably attributed to developed wet seasons in a seasonal, tropical climate.

## ACKNOWLEDGEMENTS

The authors deeply thanks to the editors J.A Gámez Vintaned, A.A. Ekdale, J. Martinell and R. Domènech for inviting us to participate in this special volume. Very special thanks are due to J.A. MacEachern and an anonymous referee for their comments and corrections on the first version of this manuscript. This research was financially supported by grants by the CONICET (PIP 6237/05 and PIP 1016/10) and the National University of La Plata (Project N/511). The authors would specially like to thank J. Cuitiño, A. Barrueco, G. Pedersen, A. Zamuner, A. Iglesias and P. García for their collaboration during fieldwork.

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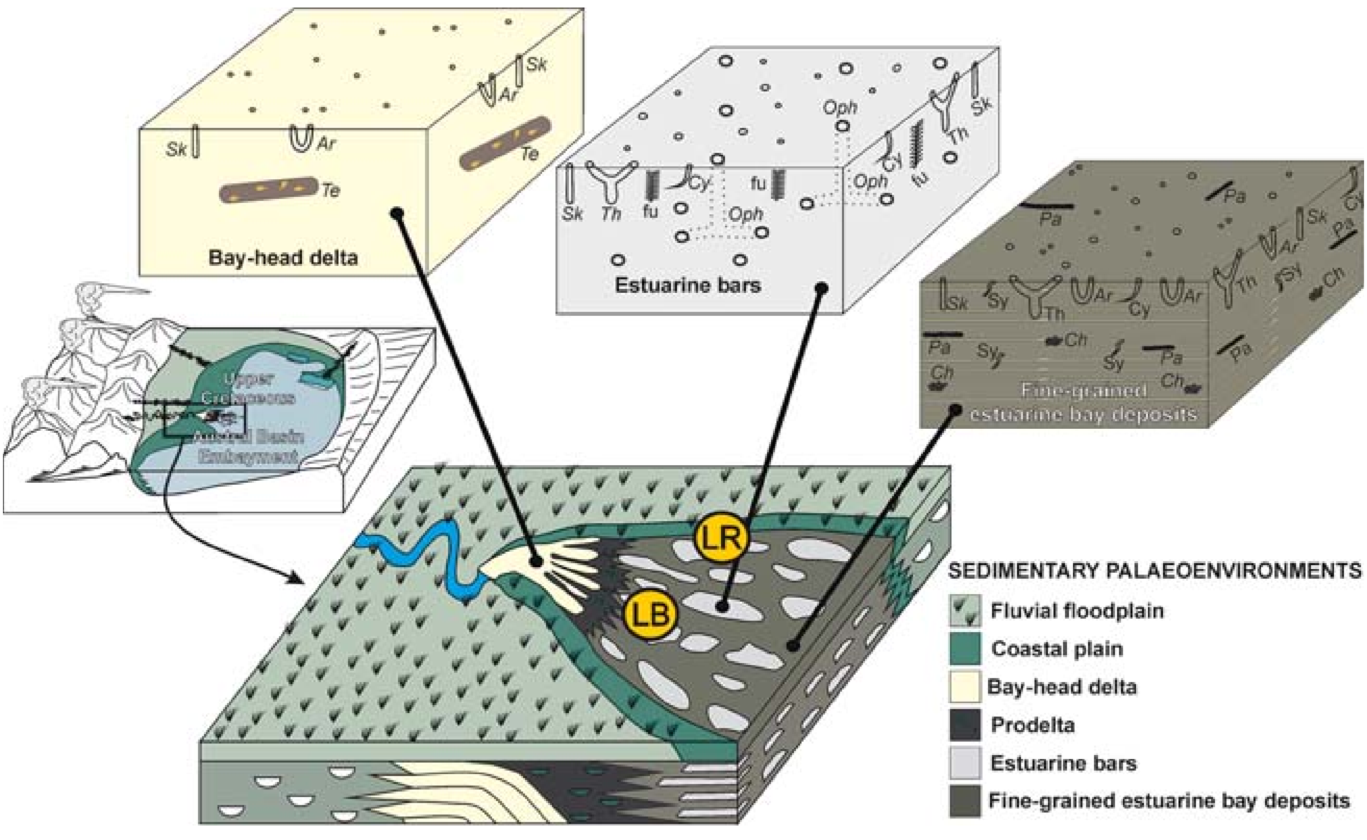


**Figure 8.** Block diagram of the estuarine palaeoenvironment from the lower and upper sections of the Mata Amarilla Formation showing the relationships between the ichnology and the three facies associations recognized. Regional palaeogeographic reconstruction modified from Varela *et al*. (2013). See legend of Fig. 4 for symbols and abbreviations.

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