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TSUNAMI VS STORM ORIGIN FOR SHELL BED DEPOSITS IN A LAGOON ENVIROMENT: AN EXAMPLE FROM THE UPPER CRETACEOUS OF SOUTHERN PATAGONIA, ARGENTINA

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Abstract: The criteria by which the deposits of tsunamis are distiguished from other deposits, including storm surges, have been controversial for more than 10 years. The Mata Amarilla Formation of the lower Upper Cretaceous of Southern Patagonia has excellent outcrops that in its lower section, sedimentary and taphonomic characteristics suggest a tsunami origin. This paper presents details of these aspects, as well as a model of temporal stages that led to their deposition within a lagoon. The sediments are composed of alternating white sandstones and mudstones, with interbedded bioclastic accumulations in the lower section. The depositional environment was characterised by a lagoon bounded by shallow marine bars. These fine-grained sediments are sporadically interrupted by tsunami events represented by coquinas, bioclastic sands and shell pavements with allochthonous and autochthonous mollusk associations from freshwater and marine habitats. Some areas of the lagoon became exposed, thus enabling the development of vegetation on the substrate and pedogenic processes. Subsequently, a forced regression occurred when a fluvial system invaded the lagoon area, representing the beginning of the deposition of the middle section of the Mata Amarilla Formation.

Resumen: Los criterios por los cuales los depósitos de los tsunamis son diferenciados de otros depósitos, incluidas las grandes tormentas, han sido motivo de controversia desde hace más de 10 años. La Formación Mata Amarilla del Cretácico Superior más bajo de la Patagonia Austral posee excelentes afloramientos en su sección inferior cuyas características sedimentológicas y tafonómicas permiten interpretarlos como originados por tsunamis. En este trabajo se presentan los detalles de sus características sedimentológicas y tafonómicas, así como un modelo de las etapas temporales de depositación en un ambiente albuférico. Los sedimentos están compuestos por la alternancia de arenicas blancas y fangolitas, con intercalaciones de acumulaciones bioclásticas en la parte inferior. El ambiente de sedimentación estuvo representado por una albufera de poca profundidad limitada por un sistema de barreras. Estos sedimentos de grano fino intercalan con depósitos asociados con el desarrollo de tsunamis, que incluyen coquinas, areniscas bioclásticas y pavimentos de valvas de moluscos con asociaciones de fauna tanto alóctonas (ambiente marino) como autóctonas (agua dulce). Algunas áreas de la albúfera quedaron expuestas, lo que permitió el desarrollo de vegetación sobre el sustrato y la generación de procesos

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pedogenéticos. Posteriormente, se produjo una regresión forzada cuando un sistema fluvial invadió la zona de la albufera, representando el inicio de la deposición de la sección media de la Formación Mata Amarilla.

Keywords: tsunami deposits, washover deposits, littoral deposits, taphonomy, Austral Basin, Mata Amarilla Formation
Palabras claves: Depósitos de tsunami, depósitos de sobrelavado, depósitos litorales, tafonomía, Cuenca Austral, Formación Mata Amarilla

INTRODUCTION

In recent years, the destruction caused by the tsunami in the Indian Ocean (December 2004), the Katrina hurricane in New Orleans (August 2005) and the Japanese tsunami (March 2011), was observed all around the world. These hazards attracted the interest of many scientists (Tappin, 2007; Lange and Moon, 2007; Kortekaas and Dawson, 2007; Dawson and Stewart, 2007; Nichol *et al*., 2007; Morton *et al*., 2007; Komatsubara *et al*., 2008 and Donato *et al*., 2008; 2009). These papers helped to understand many aspects of tsunami processes and of their sedimentary products, revealing features that would distinguish these deposits from large storm deposits. Despite all of this, it seems that there are more similarities than differences between these deposits (Bridge, 2008). The most significant characteristics of tsunami deposits are the thickness of the deposits (less than 60 cm), the absence of sedimentary structures, the number of layers (laminaset) and the presence of a return-flow or backwash flow (Witter *et al*., 2001; Tuttle *et al*., 2004; Morton *et al*., 2007; Lange and Moon, 2007; Kortekaas and Dawson, 2007; Dawson and Stewart, 2007; Nanayama *et al*., 2000; Komatsubara *et al*., 2008). A detailed taphonomic study might provide additional information on this approach, helping to distinguish between large storm and tsunami deposits (Donato *et al*., 2008). These authors suggested three tsunamigenic specific taphonomic traits characteristic of tsunami deposits, (1) thickness and lateral extension of the shell deposits; (2) presence of allochthonous articulated bivalves out of life position; and (3) extensive angular fragmentation of shells.

Both tsunamis and large storms cause great damage to towns, buildings, roads, etc., but tsunamis and storms do not appear to cause damage to coastal geomorphology (Kench *et al*., 2006; Kelletat *et al*., 2007; Nichol and Kench, 2008). Both tsunamis and storms occur regularly, although tsunamis are less frequent than coastal storms. Tsunamis occur about once per decade in the Pacific Ocean, where they are most common because of the active tectonic setting (Morton *et al*., 2007).

Because of their infrequency, tsunamis are poorly documented in historical records for many of the areas where they pose a threat. In these areas, interpreting the geologic record may be the only way to discover the history of past tsunamis and the likely hazard for future tsunamis. Both tsunamis and large storms, particularly hurricanes, are capable of flooding lagoon areas generating washover deposits (Schwartz, 1982; Lange and Moon, 2007 and Morton *et al*., 2007).

Following the criteria by Fürsich and Oschmann (1993) and Donato *et al*. (2008), this work combines sedimentological and taphonomical analyses on the lower section of the Mata Amarilla Formation in order to reconstruct different subenvironments and generate an accumulation model. The depositional environment for this succession was interpreted as a lagoon bounded by shallow marine bars (Varela, 2011).

Usually lagoons are areas with great potential for the preservation of tsunami deposits, because they are depressed with respect to adjacent areas (Lange and Moon, 2007; Morton *et al*., 2007; Komatsubara *et al*., 2008 and Donato *et al*., 2008; 2009). The aim of this paper is to distinguish tsunami deposits from large storm deposits, providing valuable insight into the understanding of tsunamis in ancient and modern lagoonal settings. Exceptional outcrops of Cretaceous lagoonal deposits of the Mata Amarilla Formation provide a rare opportunity for the study of sedimentological and taphonomical features of tsunami deposits. A series of events developed during a tsunami and deposits related to each of these events are here suggested for the study succession.

GEOLOGIC SETTING

One of the most representative units of the Upper Cretaceous in the Austral Basin is the succession called "Mata Amarilla Strata" (Feruglio, *in* Fossa Mancini *et al.*, 1938) or Mata Amarilla Formation (Bianchi, 1967; Leanza, 1972; Russo and Flores, 1972), that corresponds to Ameghino´s "Shehuenense" (Ameghino, 1906). The Austral Basin, also known as the Magallanes Basin, is located in the south-western end of the South American plate (Fig. 1). It comprises an area of approximately 230,000 km^2 covering the southern end of the Argentinean and Chilean territories. Its shape is elongated N-S; the eastern edge is parallel to the Chico River, extending towards the sea in the "Río Chico Dorsal" or "Dungeness Arch". The west edge is tectonic and it is formed by the Patagonian – Fueguian Andes, while the southern boundary is a transform fault that separates the South American plate from the Scotia plate (Fig. 1). The geological history of the Austral Basin is related to three main tectonic stages. The first one is the rift stage, the second one is the thermal subsidence stage or sag, and the third one corresponds to the foreland stage (Arbe, 1989, 2002; Biddle *et al.*, 1986).

The Mata Amarilla Formation was accumulated during the early Late Cretaceous (Fig. 2) and ranges from the Cenomanian to the Santonian (Poiré *et al.*, 2007; Varela, 2011) during the foreland stage, which can be related to the closure of the marginal Rocas Verdes Basin or Green Rock backarc basin (Biddle *et al.*, 1986).

The Mata Amarilla Formation is 350 m thick and includes gray and black mudstones, alternating with thin beds of whitish and grey-yellowish fine and medium-grained sandstones, deposited in littoral and continental environments (Russo and Flores, 1972; Russo *et al.*, 1980; Arbe, 1989, 2002; Poiré *et al.*, 2004; Varela y Poiré, 2008). The lower section of the Mata Amarilla Formation contains major levels of bioclastic accumulations (Goin *et al.*, 2002; Poiré *et al.*, 2004; Varela *et al.*, 2008).

The type section of the Mata Amarilla Formation is located at the southern margin of the Chalía (or Shuehuen) River, about 23 km to the east of the town of Tres Lagos, in the environs of the Estancia Mata Amarilla (known also as Estancia La Soriana). The Mata Amarilla Formation overlies the Piedra Clavada Formation with transitional contact, and underlies the La Anita Formation (Varela and Poiré, 2008).

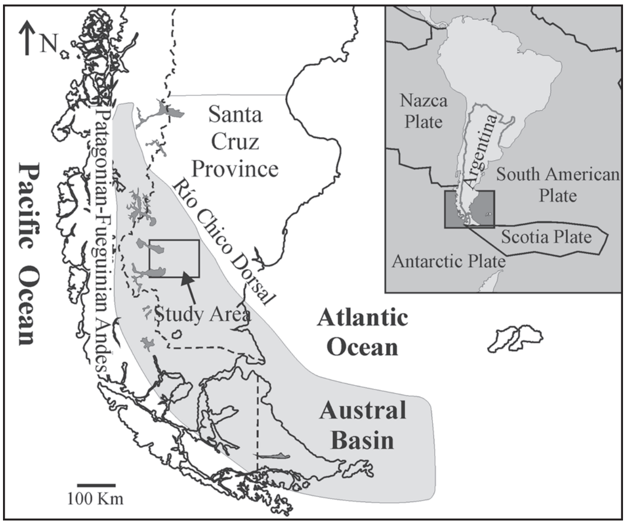

Figura 1. Geographical setting of the Austral Basin and location of the study area. The Austral Basin covers an area of approximately 230,000 km^2 at the southern end of the Argentine and Chilean territories. Its shape is elongated N-S and it widens toward the south.

The Mata Amarilla Formation contains the bivalves *Exogyra guaranitica* (Ihering), *Pterotrigonia aliformis* (Parkinson), *Corbula sehuena* Ihering, and the gastropod *Potamides (Pirenella) patagoniensis* Ihering (Ihering, 1907; Wilckens, 1907; Bonarelli and Nágera, 1921; Feruglio, 1936, 1938; Piatnitzky, 1938; Ferrer, 2002; Griffin and Varela, *in press*). Santonian ammonites have been reported at Cerro Índice (Blasco *et al.*, 1980), whose correct stratigraphic location is still unsolved. The stratigraphical criteria of Goin *et al.* (2002) are used in this paper (see stratigraphical discussion below). This area is rich in littoral and continental vertebrate fossils like crocodiles, turtles, amphibians and lungfish described by Goin *et al.* (2002) and Cione *et al.* (2007). The Mata Amarilla Formation also bears abundant remains of both theropod and sauropodomorph dinosaurs. Among the most characteristical ones are the iguanodont *Talenkauen santacrucensis* Novas, Cambiaso and Ambrosio 2004 and the titanosaurid sauropod *Puertasaurus reuili* Novas, Salgado, Calvo and Agnolin 2005 (Lacovara *et al.*, 2004; Novas *et al.*, 2004a, 2004b, 2005, 2008). Plesiosaur vertebrate have recently been found in the lower section of Mata Amarilla Formation in Estancia La Blanca, located to the south of the study area (O´Gorman and Varela, 2010).

The Mata Amarilla Formation also contains

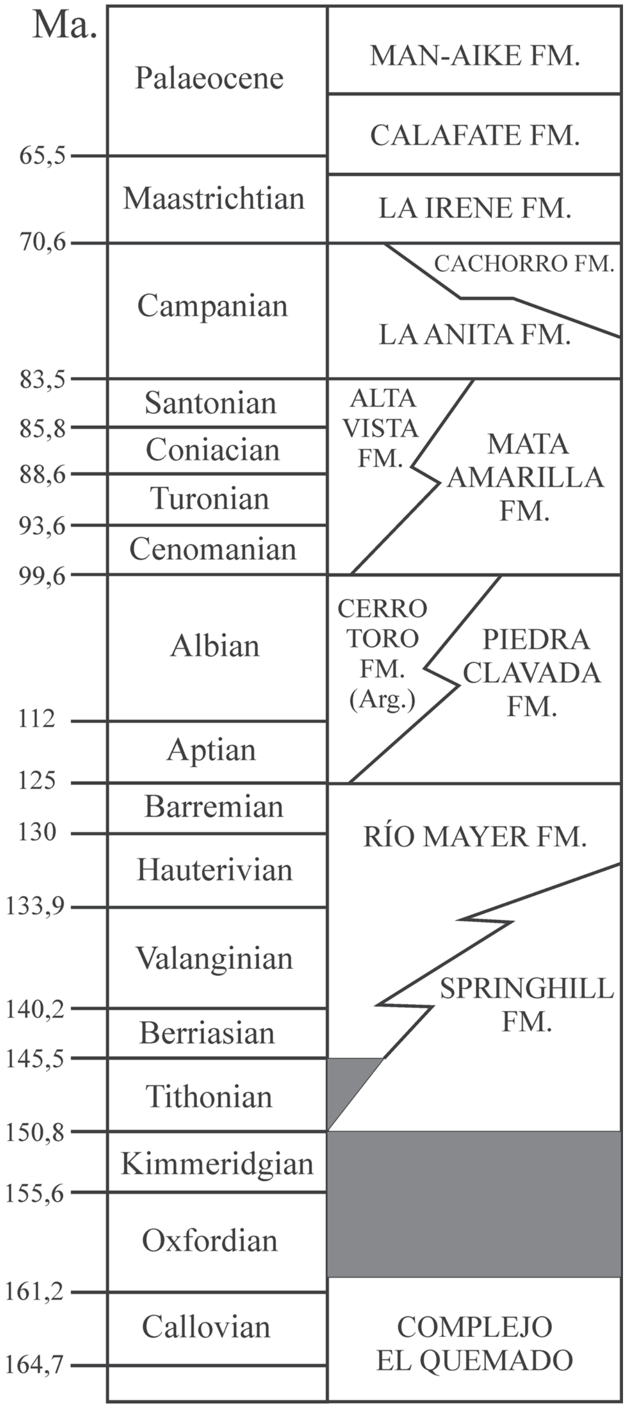

Figura 2. General stratigraphic column of the austral Basin modified from Poiré *et al.* (2006) and Varela (2011).

carbonaceous levels with an abundant flora of *Laucophyllum* sp. and *Araliaephyllum* sp. (Arrondo, 1983), as well as algae, *Botryococcus* sp., *Palambages* sp. and *Chizosporis reticulata*. Iglesias *et al.* (2007) have described an abundant and very diverse angiosperm taphoflora. A petrified forest with trees in life position called "*Bosque petrificado María Elena*" (María Elena Petrified Forest) has been also reported (Poiré *et al*., 2004; Zamuner *et al*., 2004, 2006).

Recently, Varela (2009; 2011) divided the Mata Amarilla Formation into three sections:

1. The lower section in the western area shows distal fluvial facies (mudstones with subordinate fine and medium-grained sandstones), while, at the eastern side, the deposits form a coarsening upward succession of littoral deposits (mudstones, flaser and wavy heterolithic and herringbone sandstones) and bayhead delta facies (sandstones).

2. The middle section is mainly fluvial and shows, from west to east, a clear transition from conglomerate braided systems to sandy meandering and, at the farther estern end, anastomosing systems.

3. The upper section shows fine grained distal fluvial deposits to the western area and littoral facies to the east.

The lower and upper sections represent higher accommodation / sediment supply conditions, whereas the medium section corresponds to a lower accommodation/sediment supply stage (Varela, 2009, 2011). From a sequence stratigraphic point of view, the lower section of the Mata Amarilla Formation denotes a marine transgression; the middle section, a forced regression; and the upper section, a further transgression. This relative sea-level variation might respond to a tectonic control over a pure eustatic fluctuation (Varela, 2009, 2011).

The study area is located in the southwest of the Santa Cruz province, Patagonia, Argentina, 60 km to the east of Lake Viedma, near the town of Tres Lagos and between Estancia Mata Amarilla and Estancia María Elena (Fig. 3). This work focuses on the lower section of the Mata Amarilla Formation, near the type locality of Estancia Mata Amarilla, located on the northern part of the basin (Varela *et al*., 2008).

MATERIALS AND METHODS

The lower section of the Mata Amarilla Formation was analyzed in two sedimentologic sections, A and B (Fig. 3), at a 1:50 scale. Primary sedimentary structures were described and sedimentary facies were analyzed in detail. The facies codes of Friend *et al*. (1979), Miall (1996) and Veiga *et al*. (2008) were used (Table 1). Geometrical data and scales of the rock bodies were obtained in order to determine the lithosome architectures (Friend *et al*., 1979; Miall, 1996, Veiga *et al*., 2008). This analysis, together with a taphonomical study, enabled the distinction of

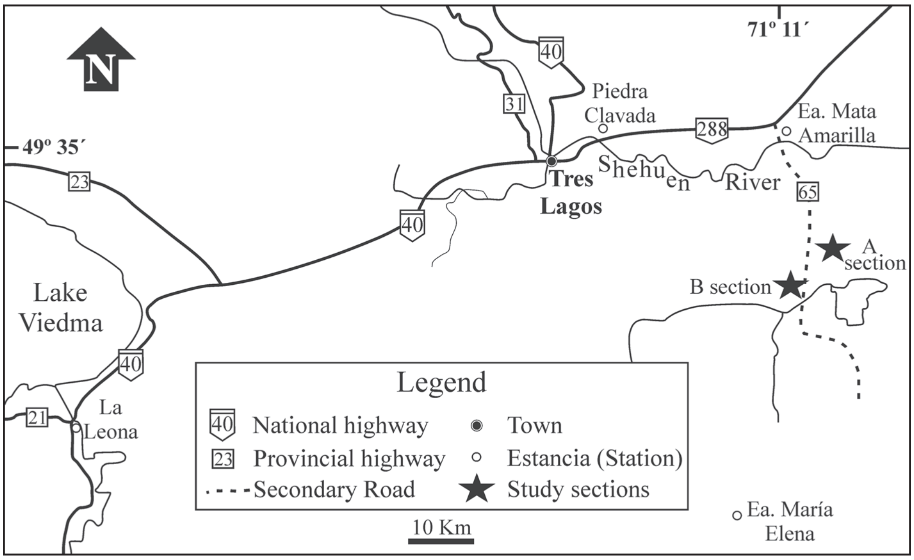

Figura 3. Map of the study area with the location of the localities: A and B.

12 sedimentary units (Table 2). Vertical and lateral facies variations, as well as the spatial arrangement of different sedimentary units, were described. The detailed description and interpretation of the sedimentary units were crucial in the definition of the conceptual model of accumulation.

A bed-by-bed field description of the taphonomical features of the different malacological associations was carried out. Thirteen beds were described for section A (Table 3) and nine for section B (Table 4) (Fig. 4). The following taphonomical parameters were considered: disarticulation, abrasion, dissolution, fragmentation, bioerosion, encrustation, sorting, packing, orientation and polarity (see Kidwell *et al.*, 1986; Fürsich and Oschmann, 1993). These parameters were separately described in the field and hierarchically arranged for the different taxonomic groups present in each bed, following the criteria of Mendahl (2001) and Kidwell and Holland (2002). The following categories were used: absent, rare, common, abundant and very abundant for abrasion, dissolution, fragmentation, bioerosion, and encrustation parameters. Articulated, partially articulated and disarticulated were used for disarticulation. Poor, moderate and good sorted were used for sorting, and loose, disperse and dense packed for packing (Tables 3, 4). Taphofacies were subsequently defined on the basis of taphonomic and sedimentologic data. A conceptual accumulation model was elaborated for each of the taphofacies in the different interpreted sedimentary subenvironments. The results were compared and contrasted with recent examples of deposits from tsunamis and large storms in the literature.

RESULTS

From the sedimentological description, 29 sedimentary facies were identified (Table 1, Fig. 4, 6, 7). These facies were grouped into 12 sedimentary units of littoral and continental origin (Table 2, Fig. 5, 7, 8). Table 2 shows the recognized sedimentary units and their facies associations as well as the external geometries, dimensions and bounding surfaces. The fossil content was also considered in this distinction.

The taphonomic features for the 9 levels of bioaccumulations found in section B were described and analyzed (Fig. 4, Table 3), as well as for the 13 levels found in section A (Fig. 4, Table 4). Tables 3 and 4 exhibit the different degrees of intensity for each taphonomic feature showed and the taxonomic diversity for each of the bioclastic levels. Bioerosion and encrustation are absent in all the bioclastic levels, therefore, they were not included in the tables.

Correlation of the two sections is tentative because of the rapid lateral change of the facies associations, contiditioned by the ancient coastline.

Sedimentary Units

Within the littoral units, bars and fine-grained background deposits were distinguished; these units are characteristic of the lower section of the

Facies code	Texture	Sedimentary structure	Thickness
SGt	very coarse-grained sandstones to conglomerate	trough cross-stratification	10 to 30 cm
St	medium to fine-grained sandstones	trough cross-stratification	40 to 60 cm
Sti	medium to fine-grained sandstones	trough cross-stratification with mud intraclasts	40 to 60 cm
Stbi	bioclastic fine to medium-grained sandstones with pelitic matrix	trough cross-stratification with mud intraclasts	80 to 100 cm
Sp	coarse to medium-grained sandstones	planar cross-stratification	20 to 50 cm
Spi	coarse to medium-grained sandstones	planar cross-stratification with mud intraclasts	20 to 50 cm
Spd	coarse to medium-grained sandstones	planar cross-stratification with deformational structures	20 to 50 cm
Sm	fine to medium-grained sandstones	massive	< 1 m
Smi	coarse to medium-grained sandstones	massive structure with mud intraclasts	< 1 m
Smb	bioclastic medium-grained sandstones	massive structure	1 to 2 m
Smbi	bioclastic medium-grained sandstones	massive structure with mud intraclasts	2 to 2 m
Sh	fine to medium-grained sandstones	horizontal bedding with parting lineation	< 30 cm
Sx	medium to fine-grained sandstones	herringbone cross-stratification	30 cm
Sl	very fine to medium-grained sandstones	lamination	30 to 50 cm
Sr	fine to medium-grained sandstones	ripples (current and wave ripples)	< 30 cm
HCS	fine to medium-grained sandstones	hummocky cross-stratification	50 to 100 cm
Hf	heterolithic very fine grained-sandstones to mudstones	flaser bedding	cm to m thick
Hl	heterolithic very fine grained-sandstones to mudstones	lenticular bedding	cm to m thick
Hw	heterolithic mudstone to very fine grined-sandstones	wavy bedding	cm to m thick
Hd	heterolithic very fine grained-sandstones to mudstones	heterolithic with deformation	cm to m thick
Hi	heterolithic very fine grained-sandstones to mudstones	heterolithic with mud intraclasts	cm to m thick
Lr	siltstones	ripple lamination	cm to m thick
Lm	siltstones	massive	cm to m thick
Fm	mudstones	massive	cm to m thick
Fl	mudstones	lamination	cm to m thick
Fb	bioclastic mudstones	lamination	< 5 cm
C	coquina (bioclastic supported upper medium sandstones)	massive	20 to 60 cm
T	tuff	massive	< 60
P	mudstones	pedogenetic (i.e. rizolith, cutans, slickensides, mottles)	cm to m thick

Table 1. Sedimentary facies of the Mata Amarilla Formation.

Mata Amarilla Formation. Continental units were subdivided into channel and non-channel units according to the external geometry and bounding surfaces. Continental units are characteristic of the middle section of the Mata Amarilla Formation (sections A and B) and appear interbedded with littoral units in the lower section of the Mata Amarilla Formation in the northern locality (section A).

Littoral Units

Sand bars: This unit is composed of grey to greenish-grey fine to medium-grained sandstones. They usually show hummocky cross-stratification, which suggest storm deposition. Geometry is tabular. They are 0.5 to 0.8 m thick and 50 m wide. Bioclasts are uncommon. This sedimentary unit is not very common in the study area. These hummocky cross-stratified sandstones are assigned to shoreface deposits.

Bioclastic bars: This unit is characterized by white to grey sandstones. Average grain size varies from medium to coarse-grained sand (Fig. 7a, 7b). Thickness ranges from 1 to 4 m. Generally massive, they occasionally show trough cross-stratification to planar cross-stratification. The external geometry is tabular to lenticular (lateral dimention are > 150 m); bases are horizontal and tops are undulating to horizontal (Fig. 7a). Locally the base is erosive, few mud intraclasts and great concentrations of disarticulated shells (oysters) are observed. Bioclasts are generally dominated by trigonids, mostly articulated and in life position, and by partially disarticulated oysters. The general trend is fining-upward. When the base is slightly erosive, in the

Group	Sedimentary Units	Sedimentary Facies	Geometry	Dimensions	Bounding surfaces	Interpretation
Littoral Units						
Bars	Sand Bars	Sx – Sl – Sp – St Sm – HCS	Tabular	0,5-0,8 m thick; up to 50 m wide	Base: sharp and horizontal Top: horizontal	Shoreface bars
	Bioclastic Bars	Smb – Smbi HCS – Stbi	Tabular to lenticular	1-4 m thick; up to 150 m wide	Base: horizontal to erosional Top: ondulate to horizontal	Barrier system
	Bioclastic Lobes	C - Smb	Lenticular	0,2-0,6 m thick; more than 250 m wide	Base: sharp and horizontal Top: sarp, convex up	Tsunami deposits (washover and basal lag)
Fine-grained	Mudstones with shell pavements	Fl – Fb	Tabular	0,1 m to tens of meters thick	Base and Top: sharp and horizontal	Tsunami pavements
	Heterolitic beds with marine fossils	Hf – Hl – Hw – Fl Sr – Hd – Lr – Sl –Hi	Tabular	Centimetres to tens of meters thick	Base and Top: horizontal, sharp to transitional	Lagoon deposits
Continental Units						
Channel Units	Complex ribbons	St – Sti– SGt – Sp Spi – Spd – Sh	Lenticular to tabular	2-6 m thick; less than 25 m wide	Base: concave up and erosional Top: sharp and horizontal	Distributary channel complexes with little lateral accretion
	Large-scale simple ribbons	Sp – Spi – St – Sm	Lenticular	1-2 m thick; 8-15 m wide	Base: concave up and erosional Top: sharp and horizontal	Small distributaries
Non-Channel Units	Small-scale bars	Lm – Fm – Fm/Lm Sm/Lm – Sm – Sr Sp – Fl – Sh – Lm	Tabular	0,2-5 m thick	Base: sharp horizontal to transitional Top: sharp horizontal to transitional	Levee and crevasse splays
	Large-scale bars	Sp – Sh	Tabular Wedge shaped	5-8 m thick	Base: sharp and horizontal. Top: horizontal to lenticular	Lagoon mouth bars
	Lobes	Sm – Smi – Sp	Lenticular	0,1-1,2 m thick; 5-15 m wide	Base: sharp and horizontal. Top: convex up	Crevasse splays
	Fine-grained beds	Fm – Lm – Fl Hl – T – P	Tabular	Centimetres to tens of metres thick	Base and Top: sharp to horizontal and transitional	Floodplain, paleosols and lacustrine deposits
	Heterolitic beds with continental fossils	Hf – Hl – Hw – Fl Sr – Sl – Lr	Tabular to lenticular	Centimetres to tens of metres thick	Base: sharp and horizontal Top: horizontal sharp to transitional	Lacustrine

Table 2. Sedimentary units identified in the lower section of the Mata Amarilla Formation.

middle part of fining-upward cycles, this unit presents very good sorting and mollusks are found in life position (Table 4). Bioclastic bar unit is located towards the bottom and the middle parts of the lower section of the Mata Amarilla Formation; usually covering the mudstones with shell pavements units (Fig. 5). Commonly, bioclastic bar units are grouped in pairs and locally tend to leave fine-grained deposits between them, suggesting that they might represent bar migration (Fig. 7b). These units were interpreted as a part of a barrier system based on sedimentological and paleontological features, such as trough cross-stratification (3D sandwaves) to planar cross-stratification (2D sandwaves), well sorting, and the presence of trigonids in life position.

Bioclastic lobes: represented by red coquinas, with sandy matrix and bioclastic sandstones. The matrix is moderate to well sorted, medium-grained sandstone and sometimes normally graded. This unit is massive and lacks sedimentary structures. These deposits are characterized by lenticular geometry with slightly erosive to horizontal basal surfaces and sharp and convex-up tops (Fig. 7c). Shell abundance increases toward the top, especially the larger articulated shells. Bioclasts are generally articulated and are

Bed	Articulation	Abrasion	Dissolution	Fragmen-tation	Sorting	Packed	Orienta-tion	Polarity	Fauna	Interpretation
CME 1	articulated	absent	very abundant	absent	good	disperse	in situ		trigonids	Barrier system
CME 2	partial	absent	very abundant	absent	good	disperse	concordant	concave-up	trigonids, other marine bivalves, corbulids	Distal washover pavements
CME 4	disarticulated	common	rare	abundant	poor	dense	oblique		oysters, other marine bivalves, gastropods	Basal lags (backwash)
CME 5	partial	absent	very abundant	common	poor	dense	concordant	concave-up	corbulids, other marine bivalves, conchostracans, gastropods	Distal washover pavements
CME 7	articulated to partial	absent	very abundant	rare	poor	dense	concordant	concave-up	corbulids, conchostracans, gastropods	Mass mortality pavements
CME 15	disarticulated	absent	very abundant	abundant	moderate	disperse	oblique		trigonids	Barrier system
CME 16	disarticulated	absent	very abundant	abundant	moderate	disperse	oblique		trigonids	Barrier system
CME 17	articulated	absent	very abundant	absent	good	dense	oblique		trigonids, oysters, other marine bivalves, gastropods	Washover (wave run-up)
CME 18	articulated to partial	absent	very abundant	absent	good	loose	concordant	concave-up	corbulids, gastropods	Mass mortality pavements

Table 3. Taphonomic attributes of shell beds at section A. The following descriptive parameters were considered: disarticulation, abrasion, dissolution, fragmentation, sorting, packing, orientation and polarity. Bioerosion and encrustation are absent in all the shell beds.

represented mostly by trigonids, oysters and other marine bivalves and, to a lesser extent, gastropods (Fig. 8b). These mollusks are not preserved in life position. These lens-shaped bodies range between 0.2 to 0.6 m, not exceeding 0.4 m in thickness (Fig. 4, 5), and their lateral extension is thinning landward over the course of kilometers. They are characterized by a relatively simple internal structure and there is no apparent bioturbation. Occasionally, such deposits are reworked, the geometry is channelized and the basal surface is conspicuously erosional. In those cases, the deposits are generally less than 0.3 m thick and their lateral extension attain several tens of meters. Bioclasts are mostly disarticulated, usually broken and almost without siliciclastic matrix (Tables 3, 4). Bioclastic lobes invariably overlie bioclastic bar units (Fig. 5); vertically, they in turn pass abruptly into mudstones with shell pavements unit. In landward direction, bioclastic lobes decrease in thickness, are laterally replaced by mudstones with shell pavements unit.

The bioclastic lobe unit was interpreted as washover deposits by Schwartz (1982). The top of some bioclastic lobes is reworked, the deposits have a channelized geometry and the bioclast are totally broken, it was interpreted as a basal lag produced by backwash reworked and sedimentation, following Brenner and Davies (1973).

Mudstones with shell pavements: This unit is characterized by laminated or massive dark green and black mudstones, with occasional root cast. The diagnostic signature is the presence of shell pavements (Fig. 7a). The geometry of the unit is tabular at outcrop scale with sharp and horizontal base and top. Thickness ranges from 0.1 m to tens of meters, whereas pavements are less than 5 cm. There are two types of pavements. The first type is formed by mostly concave-up mixed autochthonous and allochthonous mollusk fauna association deposited by subaquatic decantation processes (Allen, 1984), where decantation corresponds to passive settling of shells from suspension (Fig. 8e, Tables 3, 4). The allochthonous mollusk fauna has marine affinity

Bed	Articulation	Abrasion	Dissolution	Fragmen-tation	Sorting	Packed	Orienta-tion	Polarity	Fauna	Interpretation
MaFer 1	disarticulated to articulated	rare	very abundant to rare	rare	moderate	disperse	oblique		oysters, trigonids, other marine bivalves	Barrier system
MaFer 2	disarticulated to articulated	rare	very abundant to rare	rare	moderate	disperse	oblique		oysters, trigonids, other marine bivalves	Barrier system
MaFer 3	desarticulated to partial	absent	common	common	moderate	disperse	concordant	probably concave-up	marine bivalves, conchostracans, gastropods	Distal washover pavements
MaFer 17	desarticulated	rare	very abundant to rare	rare	moderate	dense	oblique		oysters, trigonids, other marine bivalves, gastropods	Washover (wave run-up)
MaFer 18	disarticulated to partial	absent	very abundant	absent	good	dense	concordant	concave-up	marine bivalves, corbulids, conchostracans	Distal washover pavements
MaFer 21	disarticulated	absent	very abundant	rare	moderate	loose	concordant	concave-up	corbulids, gastropods, conchostracans	Mass mortality pavements
MaFer 28	desarticulated	absent	common	abundant	good	loose	oblique		marine bivalves	Barrier system
MaFer 29	articulated to disarticulated	absent	common	common	moderate	loose	oblique		trigonids, other marine bivalves	Washover (wave run-up)
MaFer 30	articulated	absent	very abundant	absent	good	disperse	oblique		marine bivalves	Washover (wave run-up)
MaFer 37	disarticulated	absent	abundant	absent	good	dense	concordant	concave-up	conchostracans	Mass mortality pavements
MaFer 42	disarticulated to partial	absent	rare	common	moderate	dense	concordant	probably concave-up	conchostracans, corbulids	Distal washover pavements
MaFer 44	desarticulated	absent	rare to absent	very abundant	good	dense	oblique		oysters, gastropods	Basal lags (backwash)
MaFer 50	disarticulated	absent	very abundant	very abundant	moderate	dense	concordant	concave-up	conchostracans	Mass mortality pavements

Table 4. Taphonomic attributes of shell beds at section B. The following descriptive parameters were considered: disarticulation, abrasion, dissolution, fragmentation, sorting, packing, orientation and polarity. Bioerosion and encrustation are absent in all the shell beds.

and is composed of trigonids, oysters and other marine bivalves (Fig. 8d), sometimes containing partially articulated organisms such as butterfly-shaped trigonids. The autochthonous mollusk fauna shows a freshwater character and is composed mostly of conchostracans, gastropods and corbulids. The second type of pavement is formed exclusively by conchostracans and is usually accompanied by a smaller proportion of gastropods and corbulids (Fig. 8f, Tables 3, 4).

The units of mudstones with shell pavements generally overlie and can also laterally replace bioclastic lobe unit (washover deposits). These mudstones with shell pavementse units often grade upward into the heterolithic beds with marine fossils unit and are also interbedded by fine-grained beds unit (Fig. 5). Units consisting of mudstones with mixed mollusk fauna association (allochthonous and autochthonous) were interpreted as the distal end of the washover deposits. On the other hand, these units were interpreted as episodes of mass mortality when consisting only of conchostracans and freshwater mollusk fauna.

Heterolithic beds with marine fossils: characterized by interbedded dark grey mudstones and white fine-grained sandstones (Fig. 7d). Dominant sedimentary structures include parallel laminations, ripple marks, wavy and flaser laminations, which show alternating periods of traction and decantation (Boyd *et al*.,

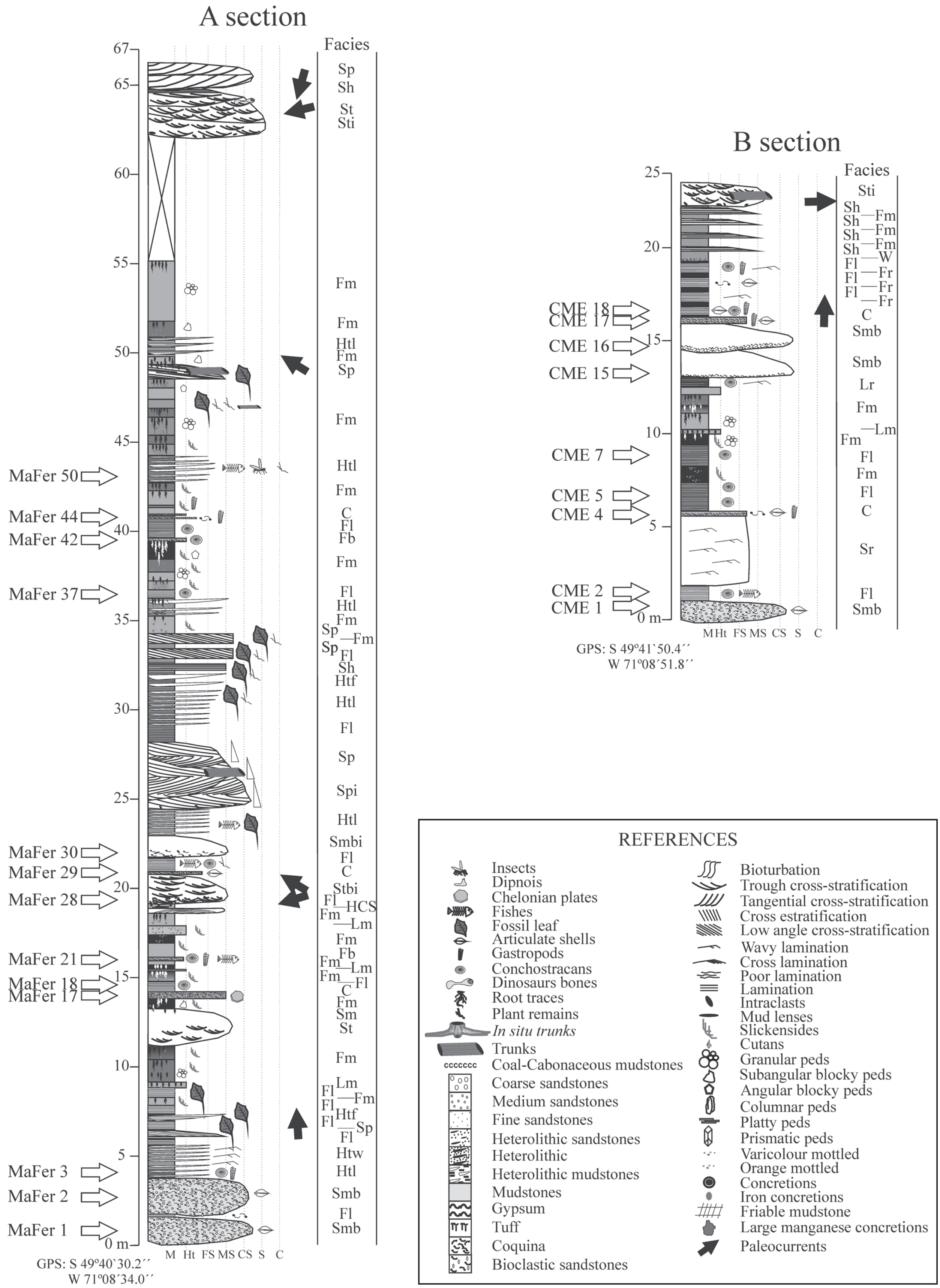

Figure 4. Sedimentological section showing vertical and lateral distribution of sedimentary facies in the Mata Amarilla Formation. Facies code see Table 1 and 2. Note that the bioclastic levels show in the logs are analysed in Table 3 and 4. No horizontal scale.

2006). The geometry is tabular and the thickness ranges from centimeters to tens of meters. The bases and tops are horizontal and sharp to transitional. Locally, these heterolithic intervals show an upward increase in the proportion of sand. This arrangement is typically shallowing upward. They are overlaying bioclastic bar units and usually are interbedded with muddy units (mudstones with shell pavements and fine-grained beds) (Fig. 5). These units were interpreted as lagoon deposits formed in fair weather conditions.

Continental Units

Complex ribbons: This unit is composed by whitish medium to coarse-grained sandstones with planar cross-stratification and trough cross-stratification, commonly with intraclasts. These sandstone units are characterized by lenticular to tabular geometry, ranging from 2 to 6 m in thickness and 25 m in width as average dimensions (Fig. 7a) (ribbons sensu Friend *et al*., 1979; width/depth ratios between 4 and 10). Bases are concave-up and erosional, tops are sharp and horizontal. They present a complex internal organization, defined by the vertical (and less frequently, lateral) amalgamation of individual channel units. A thinning upward succession can be recognized. These complexes might have been filled with solitary channels with some minor degree of lateral migration, or by relatively straight channels with lateral bars and meandering thalweg. In each case, the mobility of the channels was always restricted to the basal main scouring surface of the ribbon (Veiga *et al*., 2008). This unit is characteristic of the middle section of the Mata Amarilla Formation, but it also appears toward the top of the lower section in the section A, just below the large-scale bar unit (Fig. 5). These sandy units probably formed a tributary channel complex.

Large-scale simple ribbons: These channel units are characterized by a single lenticular body whose dimension ranges from 1 to 2 m thick and 8 to 15 m wide (low width/depth ratio), composed of whitish medium-grained sandstones. Bases are concave-up and erosional and tops are sharp and horizontal. These units show cross-stratification with abundant mud intraclasts at their bases. This unit is present at the section A in the lower Mata Amarilla Formation and is interbedded with mudstones units (Fig. 5). The fact that these deposits are represented by isolated ribbons within floodplain (fine-grained beds unit) deposits suggests a meandering simple-channel pattern which flowed across muddy coastal plains

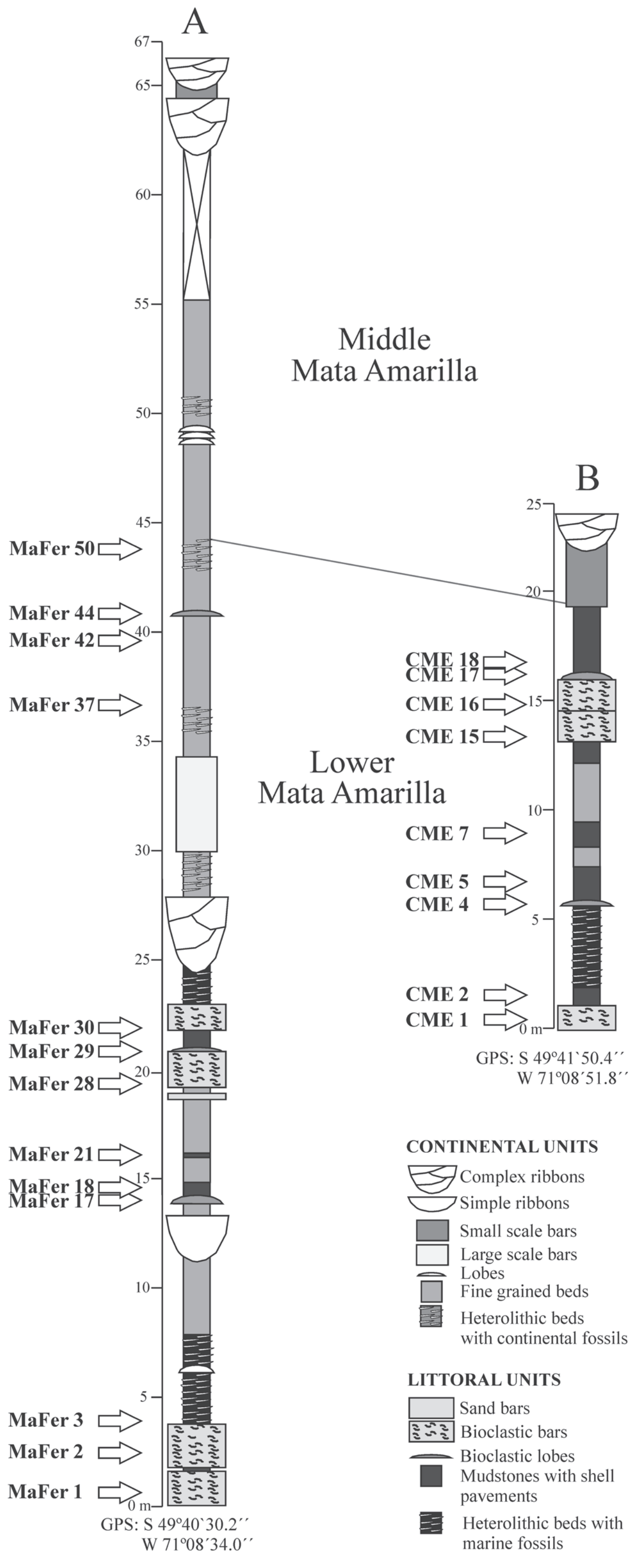

Figure 5. Vertical and lateral distribution of the sedimentary unit. Sedimentary units as in Table 2.

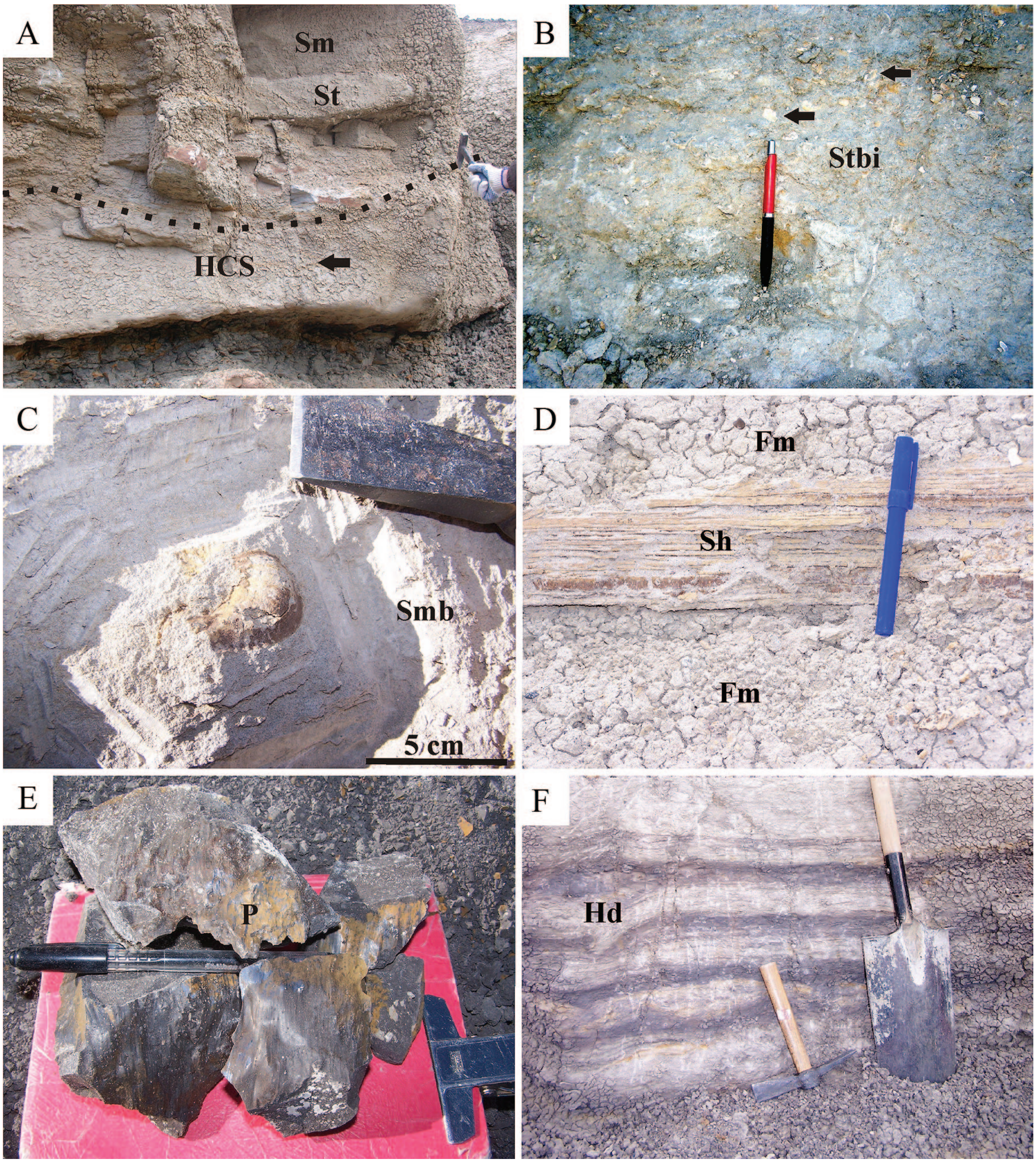

Figure 6. a) Sandstone with hummocky cross-stratification (HCS), which passes upward to trough cross-stratification (St) and massive sandstone (Sm) in a sands bars unit, hand for scale; b) Bioclastic sandstone with trough cross-stratification (Stbi), black arrows point to bioclastic fragments, pen (14 cm) for scale; c) Bioclastic masive sandstones (Smb) with a trigonid in life position, bar scale (5 cm); d) Sandstones with horizontal bedding (Sh) intercalated with masive mudstones (Fm), pen (15 cm) for scale; e) Mudstones with paleosols development (P) showing slickenside structure, pen (14 cm) for scale; f) Heterolithic bedding with load structures (Hd), hammer (30 cm) for scale.

(fine-grained bed units). Therefore, these units can represent small distributary channels.

Small-scale bars: This unit is characterized by interbedded mudstones (grey and greenish) and very fine-grained sandstones (white). These small-scale bars are predominantly laminar and massive; occasionally ripple marks are present. They also show occasional roots, motts and slickensides. The geometry at outcrop scale is typically tabular; it presents an increase in the proportion of sandstones to the top and a thickening upward succession. Their thickness ranges from 0.5 to 5 m. Bases and tops are horizontal and sharp to transitional. They occur only

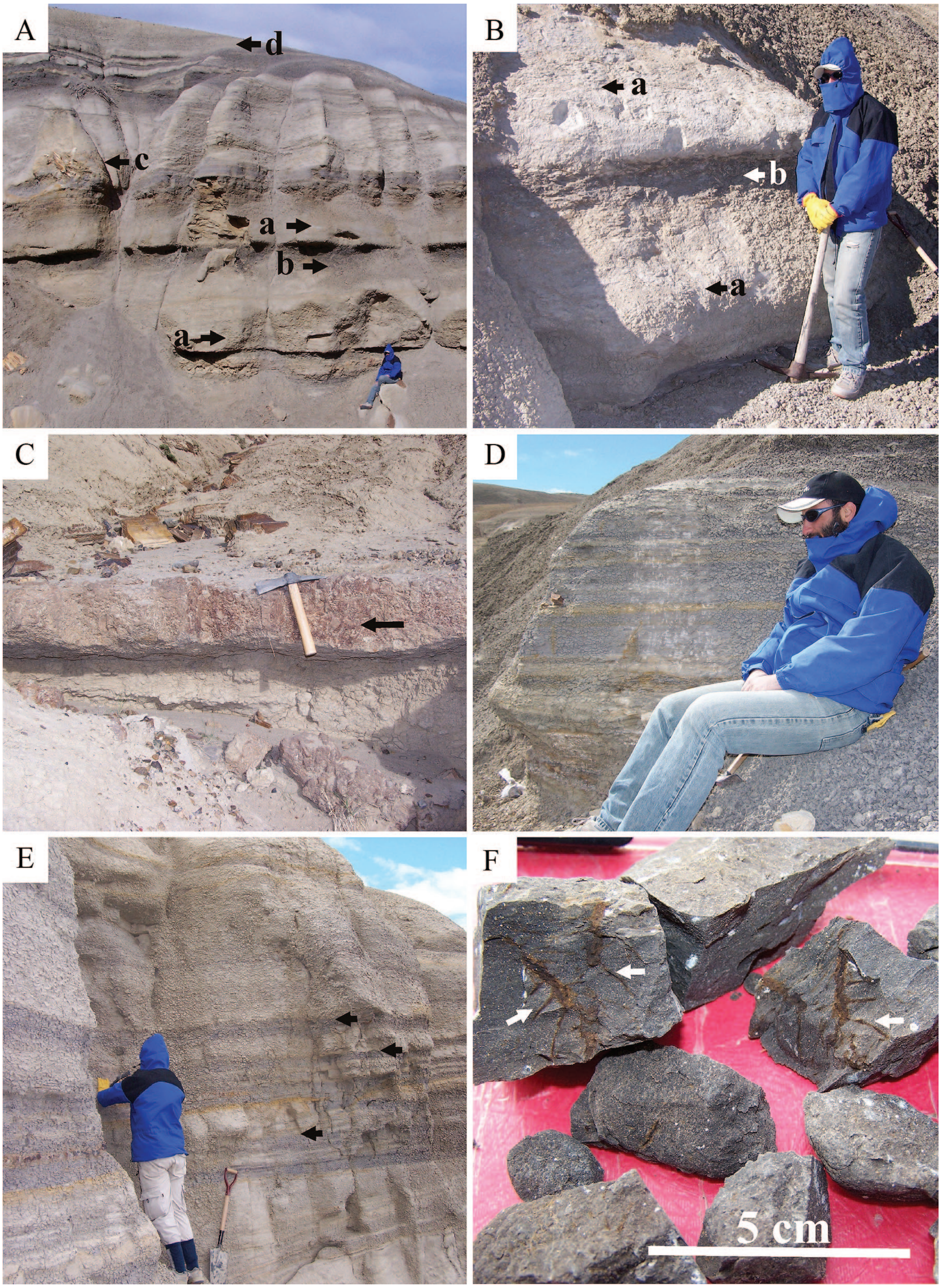

Figure 7. a) A general view of section A. Bioclastic bar (a), mudstones with shell pavements (b), complex ribbons (c), and large-scale bar (d) units; person (1.75m) for scale; b) Base of section A showing bioclastic bars unit (a) and (b) mudstones with shell pavements unit; person (1.75 m) for scale; c) Bioclastic lobes unit was interpreted as a washover deposit; hammer (30 cm) for scale; d) Heterolithic beds with marine fossils unit was interpreted as a lagoon deposit in fair weather conditions; person (1.75 m) for scale; e) Large-scale bars unit, showing the leaf levels studied by Iglesias *et al.* (2007), the black arrows show the sharp and horizontal bases of sand bodies in the thickening-up strata. Succession interpreted as small mouth bar deposits in a bayhead delta; person (1.75 m) for scale; f) Fine-grained beds unit showing paleosol development, white arrows show root traces.

in the middle section of the Mata Amarilla Formation in the two studied sections (Fig. 5). These small-scale bars are associated laterally and vertically with complex channel units, and were interpreted as levee and crevasse splay deposits following criteria of Bridge (2003). The vertical and lateral relationship to fluvial channels suggests that these deposits might represent accumulation in a proximal floodplain environment and sandstones layers were probably the result of overbank flows associated with flood events.

Large-scale bars: These sandy units are composed of white upper fine to lower medium-grained sandstones with planar and low-angle cross-stratification. Geometry is wedge-shaped to tabular, ranging from 5 to 8 m in thickness. Bases are sharp and horizontal and tops are horizontal to undulatory (Fig. 7e). They present a thickening-up arrangement bearing the taphoflora described by Iglesias *et al*. (2007). These units are present at the top of the lower Mata Amarilla Formation in section A. They are overlying complex ribbon units and are covered by fine-grained beds units (Fig. 5); accordingly, they were interpreted as river mouth bars within the lagoon (bayhead delta).

Lobes: These deposits are characterized by a lenticular geometry with a flat and sharp basal surface and convex-up top. These mounds-shaped units are 0.1 to 1.2 m thick and 5 to 15 m wide. They are formed by whitish fine to medium-grained sandstones, predominantly massive, but sometimes with low-angle cross-stratification. Usually, they present isolated rip-up clast. These lobe-shaped units are interpreted as small-scale splay deposits developed in floodplain environments due to overbank flooding events. These units are characterized by simple internal structure and geometry. This implies that these deposits represent a single flood event as opposed to more complex deposits (crevasse splay deposits) which represent multiple flood events (Miall, 1996).

Fine-grained beds: These fine-grained units are composed of grey-greenish and greenish mudstones generally presenting pedogenetic structures like rhizoliths, mottles, nodules and slickensides. The geometry is tabular, ranging from centimeters to tens of meters in thickness. Bases and tops are sharp and horizontal. The paleosols developed in this unit have a high content of expansive clay type clustered within the smectites. These types of soils (vertisols) are characteristic of tropical climates, under conditions of impeded drainage, which are very common in coastal plains. In this sense, it is inferred that the climate at the moment of deposition of the studied successions of the Mata Amarilla Formation was seasonal owing to the abundance of slickensides product of successive periods of expansion-contraction of the smectite clays (Retallack, 2001). These tabular units are present in the middle part of the lower section of the Mata Amarilla Formation and are also present in the middle section (Fig. 5). At the beginning of the middle section of the Mata Amarilla Formation, a thick paleosol associated with the "in situ" María Elena Petrified Forest was recognized. This unit was interpreted as floodplains with paleosols developed under bad or impeded drainage conditions.

Heterolithic beds with continental fossils: this heterolithic unit is characterized by interbedded grey greenish mudstones and whitish fine-grained sandstones. Frequent sedimentary structures are parallel lamination, ripple marks, wavy and flaser lamination, which record alternating periods of traction and decantation process. Geometry is tabular, ranging from centimeters to tens of meters in thickness. Base and top are horizontal and sharp to transitional. These heterolithic intervals show locally an upward-increase in the proportion of sand, implying shallowing upward trend. They are interbedded with muddy floodplains (fine-grained beds unit) (Fig. 5). Plant fragments, fish scales, vertebrate and Coleoptera remains are abundant. This unit was interpreted as a lacustrine deposit.

Taphofacies

Barrier System: this taphofacies is included in the bioclastic bar unit described above. In section A, shells are articulated to completely disarticulated, do not have features of abrasion, the sorting is moderate, are organized in a dispersed to loosely packing, oriented oblique to the bedding plane and their matrix is a dirty fine to medium-grained sandstone (Fig. 6b). The bioclasts are composed of oysters, trigonids and other marine bivalves. In locality B, the bioclasts are dispersely packed and composed almost exclusively

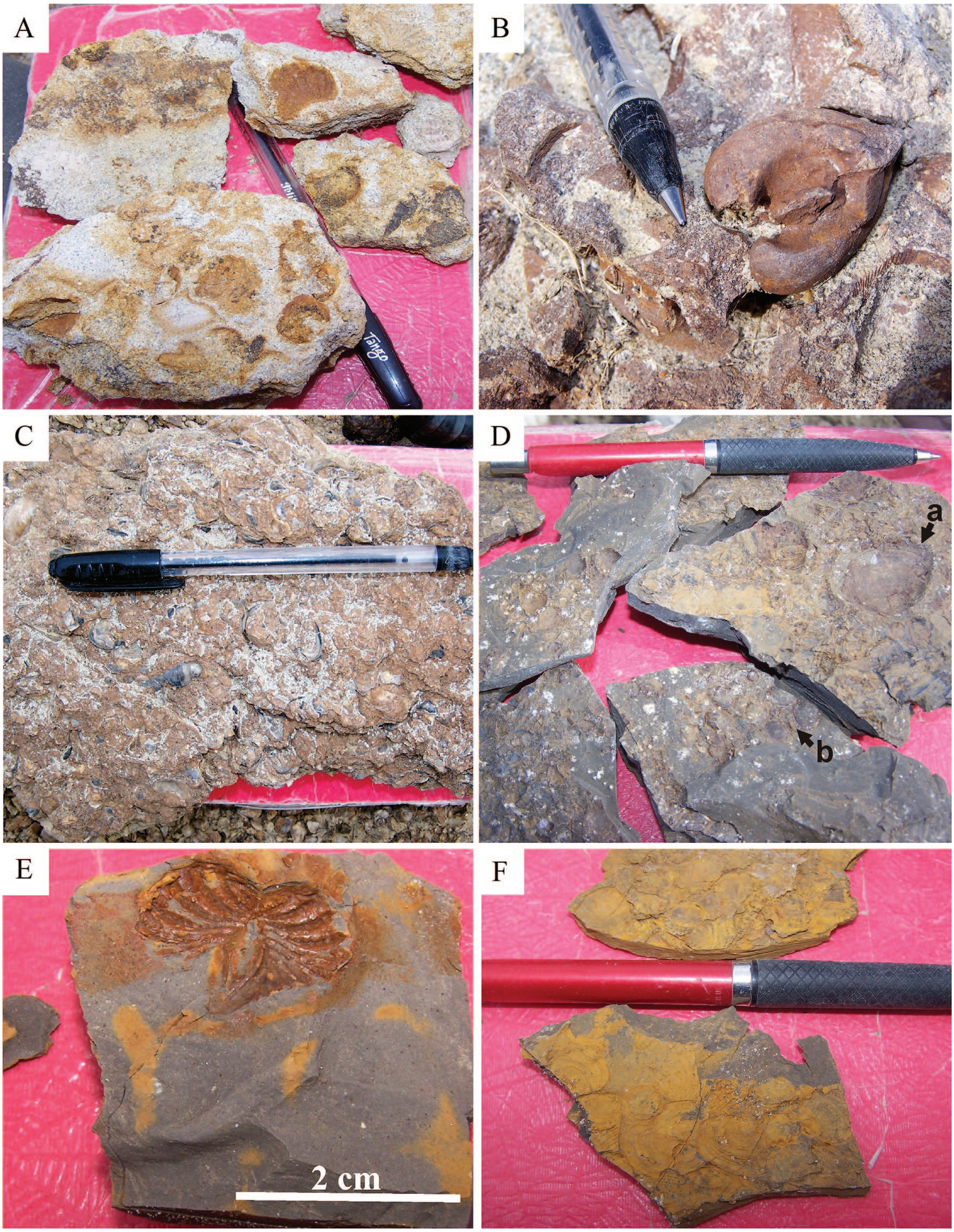

Figure 8. a) Articulated *in situ* trigonid molds; shells completely dissolved and oxidized; medium-grained sandstone forms the matrix of the bioclastic bars unit; pen (14 cm) for scale; b) Zoom view showing articulated bivalves in the bioclastic lobes unit; pen (14 cm) for scale; c) Reworked bioclasts, represented by densely packed fragments of trigonids, gastropods and oysters, it was interpreted as basal lags in the bioclastic lobes unit; pen (14 cm) for scale; d) Pavements of concave-up bivalves (a) and conchostracans (b), forming in the mudstones with shell pavements unit; pen (14 cm) for scale; e) Concave-up partially articulated (butterfly) trigonid shells, mudstones with shell pavements unit; f) Pavements of conchostracans whit a minor proportion of gastropods; pen (14 cm) for scale.

of trigonids mainly articulated and in life position; and the matrix is medium-grained sandstone (Fig. 6c). However, disarticulated shells with abundant fragmentation are also present in these deposits. In both localities, shells dissolution is abundant.

Washover (wave run-up): this taphofacies is included in the bioclastic lobe unit. Shells are mostly articulated, without trace of bioerosion or encrustation, organized in a dense packing, distributed oblique to the bedding plane though there is a smaller proportion of shell fragments broken at right angles, and are supported by a siliciclastic upper medium-grained sandy mattrix. The bioclasts are composed of a mixture of both autochthonous and allochthonous faunas, dominating the latter. The most common organisms are: trigonids, oysters, other marine bivalves and gastropods.

Basal lags (backwash): This taphofacies is also included in the bioclastic lobe unit. It has the particularity to be associated with small channeled bodies with basal erosive surfaces. These bodies are less than 30 cm thick and tens of meters of lateral extension filled by coquinas without a siliciclastic matrix. The shells are always disarticulated, well sorted, organized in a dense packing, distributed oblique to the bedding plane, the fragmentation is abundant and abrasion is common. The bioclasts are composed of oysters, other marine bivalves and gastropods.

Distal washover pavements: This type of taphofacies is characterized by disarticulated to partially articulated bioclasts (butterfly trigonids, Fig. 8e). The shells are organized in a dense packing, distributed parallel to the bedding plane and all are concave upward, the sorting is moderate because the shells are small to big, fragmentation is rare, and do not have features of abrasion. They are into the mudstones with shell pavements unit. The bioclasts are composed of both allochthonous and autochthonous faunas such as corbulids, conchostracans, gastropods, trigonids and other marine bivalves.

Mass mortality pavements: This taphofacies is similar to the taphofacies of distal washover pavements. It has the peculiarity that the shells are disarticulated, organized in a dense packing, distributed concordant to the bedding plane and concave-up, the sorting is good to moderate, and do not have features of abrasion, fragmentation, bioerosion or encrsutation (Fig. 8f). The bioclasts are composed exclusively of conchostracans, gastropods and corbulids.

DISCUSSION

Drawing on the collected data and the interpretation of the sedimentary units, this study yielded a depositional model consisting of a series of sedimentary events developed under the influence of large waves (Fig. 9). At a first stage, a barrier system and, behind it, a restricted lagoonal system in fair weather conditions is present (Fig. 9a). During large wave events, bioclasts are removed by shoreface erosion and are deposited as washover deposits (Schwartz, 1982) behind the barrier system (Fig. 9b, c). These bioclasts, towards the centre of the lagoon are deposited by subaquatic decantation (Fig. 9d); this in turn generated pavements characterized single shell layer with shells parallel to the stratification plane and mostly oriented concave-up, suggesting settling of shells from suspension (see also Allen, 1984; Kidwell *et al*., 1986; Fursich and Oschmann, 1986, 1993; Kidwell and Bosence, 1991; Kidwell and Holland, 1991; Simões and Kowalewski, 1998). These washover deposits are characterized by a mixed autochthonous and allochthonous mollusk association. The allochthonous fauna has marine affinity and is composed of trigonids, oysters and other marine bivalves; the autochthonous fauna shows a freshwater character and is composed of conchostracans, gastropods and corbulids. During the backwash stage (Fig. 9e), all the water that came into the lagoon had to return to the sea (backwash flows or return flow). During this time, the washover deposits are reworked and became resedimented as basal lags (see also Fig. 10, 8c), characterized by their channelized form and by high proportions of disarticulated and broken bioclasts.

The depositional environment for the lower section of the Mata Amarilla Formation along the northern shore of the Late Cretaceous Sea was represented by a lagoon bounded by a barrier system (Fig. 10). This lagoon may have been affected by large wave events that interrupted the normal background deposition of mudstones and laminated heterolithic sediments, and led to the deposition of coquinas and bioclastic sands at the proximal zones of the barrier system forming washover deposits and basal lags. Preservation of articulated shells without evidence of bioerosion and/or inlays could be proof of sudden burial, leaving bioclasts isolated from the water-sediment interface and outside the taphonomically active zone.

The large wave events in the deepest area of the lagoon generated distal washover pavements within the laminated mudstones facies and represent the distal lateral continuation of the washover deposits (Fig. 8d, 9d, 10). The pavements may also contain marine and freshwater organisms, locally semi-articulated (butterfly shaped trigonids), showing no bioerosion or encrustations; this type of preservation also evidence rapid sediment deposition (Fig. 8e). Interbedded paleosols and the presence of freshwater malacofauna suggest that the pavements were deposited in shallow water close to emerged land areas.

The variations in salinity and pH/Eh conditions into the lagoon generated other type of pavement composed by conchostracans, gastropods and corbulids (i.e. organisms living within the coastal lagoon); these pavements were unrelated to the large wave events but represent episodes of mass mortality. Conchostracans are highly sensitive to changes in pH/ Eh conditions. An example of seasonal mass mortality caused by anoxic conditions during the summer in an Early Cretaceous lake in China was illustrated by Fürsich *et al*. (2007).

Decreasing pH condition might have been generated by an input of freshwater and river sediments flowing into the lagoon (section A; Fig. 4, 5, 7e). Large scale-bars in the bayhead delta contain a taphoflora dominated by angiosperms (Iglesias *et al*., 2007); the imput of organic matter and its eventual degradation would contribute to decreasing pH conditions and to the decrease in oxygen content in the environment.

Nichol *et al*. (2007) recognized fluctuations in the salinity and water level of Okarito Lagoon, New Zealand, and they were able to account for periodic opening and closing of the tidal inlet entrance. Goff *et al*. (2004) propose tsunamis as one posible mechanism for barrier breaching.

There has been no boring or encrustation evidence in the well-preserved molds or in specimens with preserved shells in spite of bioerosion and encrustation are common features in lagoon environments (Hauser *et al*., 2008). Therefore, their

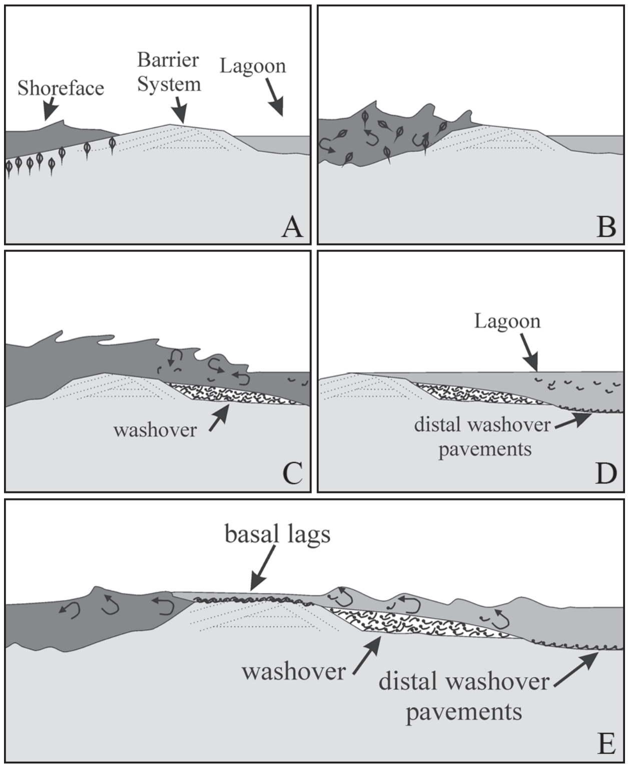

Figure 9. Series of sedimentary events during a large wave event: a) Barrier system and behind a lagoon in fair weather conditions; b) During wave run-up, bioclasts are removed by shoreface erosion; c) The shells are transported and deposited as a washover deposit behind the barrier system; d) The washover flow moves towards the centre of the lagoon and forms decantation as pavements; e) During backwash stage, the waters retreat to the sea and the backwash flow reworks the washover deposits which are resedimented as basal lags. These reworked deposits are characterized by their channel form and because all the bioclasts are disarticulated and mostly broken.

absence constitutes a further evidence of sudden sediment deposition. In addition, the high degree of articulation of shells and simple internal stratigraphy of shell beds also indicate rapidly buriedt shell beds. According to Kidwell (1991), shell beds with simple internal stratigraphy and no bioturbation represent an ecologically brief episode of shell concentration, i.e. "event concentration". Although these deposits represent an episode of rapid sediment burial during one catastrophic event, sea-floor sediments frequently contain older dead shells that died long time before burial, and the final deposit thus captures some mixture of old shells (time averaging). Probably the older dead shells correspond to the lower proportion of disarticulated and broken shells in the Mata Amarilla deposits.

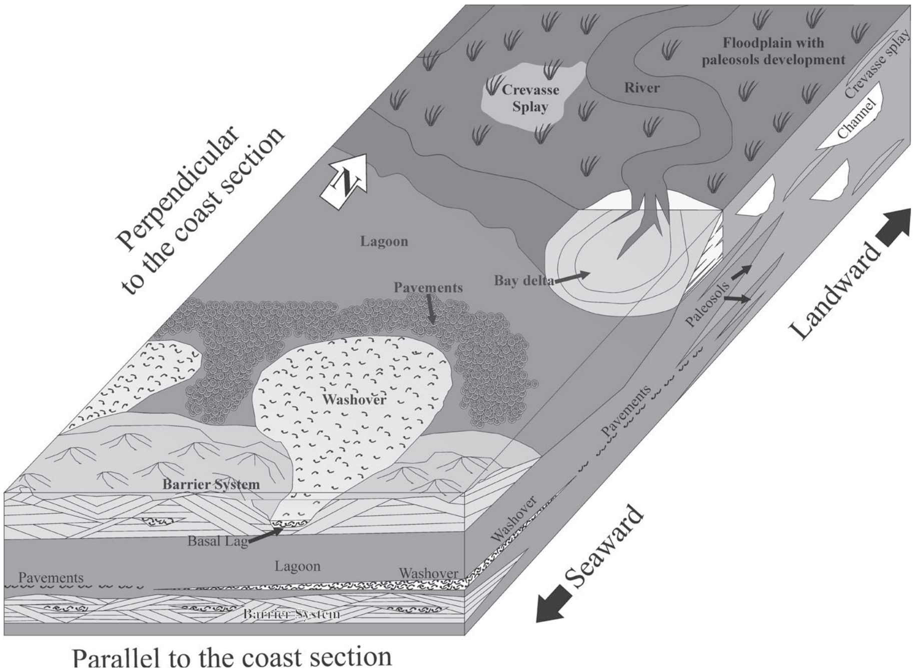

Figure 10. Palaeoenvironmental model for the lower section of the Mata Amarilla Formation showing the vertical and lateral distribution of the sedimentary units and their geometry parallel and perpendicular to the coast. The spatial distribution of the different taphofacies is also shown. Note the interdigitation between the lagoon and the barrier system seaward, and the lagoon and fluvial system landward.

Sea-level rises during the episode of large waves temporarily flooding the emerged land areas. Once the effect of the large wave was over, some areas would be exposed due to fluctuations in the lagoon water level. This probably paved the way for vegetation growth and the development of pedogenetic processes landwards. This would explain why paleosols interfinger with lagoon facies (Fig. 10).

Paleocurrents of washover deposits run to the north, which would explain the presence of more distal river deposits and bay deltas in section A, located 2.5 km further north than section B (Fig. 10).

The waves generating the Mata Amarilla deposits might have been induced either by climate (storms and hurricanes) or by tectonics (tsunamis). Both major storms (hurricanes) and tsunamis are capable of breaking the barrier system and generate washover deposits, such as storm washover studied by Schwartz (1982) in North Carolina, USA, and the tsunami washover studied by Lange and Moon (2007) in New Zealand. Storm washover deposits are much more complex than those generated by tsunamis, are generally thicker, have abundant sedimentary structures and laminaset, because the storms are more prolonged over several hours and recurrent in time than tsunamis. Tsunami deposits, on the other hand, are thinner (less than 60 cm), simpler and show few sedimentary structures. The return flow or backflow deposit are characteristic of tsunami deposits (Nanayama *et al.*, 2000; Witter *et al.*, 2001; Tuttle *et al.*, 2004; Morton *et al.*, 2007; Komatsubara *et al.*, 2008; Donato *et al.*, 2008).

Varela *et al.* (2006) and Varela (2011) described vertisoils and gleysoils developed in bad drainage conditions, where slickensides and motts are the distinctive pedofeatures. Another climatic evidence is the taphoflora study by Iglesias *et al.* (2007) in which they compared the Mata Amarilla one with other known middle-lower Upper Cretaceous taphofloras from the Southern Hemisphere. They found, a slightly greater morphological diversity in angiosperm leaves which provides the first evidence of an angiosperm-dominated macroflora in south-west Gondwana. The different states of biological degradation in the foliar assemblage indicate that leaf fall was constant and that plants were not deciduous. The presence of fungal activity suggests high temperatures and high relative humidity (Iglesias *et al.*, 2007). Other evidence of these climatic conditions are: crocodiles, turtles, amphibians and

Deposit features	1998 tsunami Papua New Guinea	2001 tsunami Peru	1961 Hurricane Carla Gulf of Mexico	2003 Hurricane Isabel western Atlantic Ocean	Lower Mata Amarilla Formation deposits
Grain size range	mud to boulders, mostly medium sand	mud to bulders, mostly fine to medium sand	sand and pebbles (shell)	Sand	upper medium sand
Internal mud layer	Mud cap at surface	Mud cap at top of layers or at surface where mud is in sediment souce	No mud	No mud	No mud
Sorting	Moderate to well sorted	Moderate to well-sorted within sand layers	Poorly sorted (proximal) to well sorted (distal), depends on cross-shore position within deposit	Well sorted	Moderate to well sorted
Event deposit thickness	0,5 to 26 cm, average 8 cm (60 sites)	0,5 to 26 cm, average 7 cm (60 sites)	26 to 126 cm, average 56 cm (6 sites)	19 to 97 cm, average 43 cm, (13 sites)	20 to 60 cm in proximal washover, less than 0,2 cm in distal washover
Sedimentary structures	None	Usually not present, ripple crossbeds found in return flow deposits near beach	Mostly planar laminae	Mostly planar laminae with some foresets	None
Number of layers / laminasets	1 to 2	1 to 3 typical, up to 8	More than 15	7 to more than 20	None to 1
Rip-up clast	Some	Found in muddy environments, usually at base of sand beds and on surface of deposit	None observed	None observed	None observed
Basal contact	Abrupt contact above organic-rich soil, occasionally erosional	Erosional base	Erosional base or abrupt shelly sand contact with underlying organic-rich soil	Abrupt sand contact with underlying organic-rich soil	Erosional base
Shell lamina	Few shells on surface	Rare within deposits	Common (source dependent)	Rare (source dependent)	Abundant shells on all the deposit, specially on the top
Cross-shore geometry	Tabular, sometimes landward thinning	Landward thinning, local thickening or thinning related to local topography	Narrow thick deposits (terraces) and moderately broad thin deposits (fans)	Narrow thick deposits (terraces)	Lenticular, landward thinning

Table 5. Characteristics of modern tsunami and coastal storm deposits taken from Morton *et al.* (2007) compared with those features of the lower section of the Mata Amarilla Formation deposits.

lungfish described by Goin *et al*. (2002) and Cione *et al*. (2007). This, together with the funnel outline of the basin during the Cretaceous, may have favored the hypothesis of hurricane and tropical storm related origin for the Mata Amarilla deposits (Varela, 2011).

On the other hand, the geodynamic framework of the basin and its strong tectonic activity, some sedimentological characteristics of the sedimentary deposits, and certain taphonomical features of the deposits favor the hypothesis of a tsunami related origin.

During the foreland stage, tectonic activity (earthquakes) associated with the closure of the Rocas Verdes Basin or Green Rocks Basin (Biddle *et al*., 1986) could have generated tsunamis. Moreover, to the south of the study area, in the basin depocentre, contemporaneous thrusting with the deposition of the deep-marine transition between Zapata and Punta Barrosa formations was dated in ~100 Ma (Fosdick *et al*., 2011). These thrusts could have been the triggering mechanisms of the Mata Amarilla tsunamis.

Modern examples of tsunamis and coastal storm deposits studied by Morton *et al*. (2007), like those from New Guinea and Peru are more similar to the Mata Amarilla deposits than those from the hurricanes in the Gulf of Mexico and the Western Atlantic Ocean (Table 5).

Some authors argued that most significant characteristics of tsunamis are the thickness of the deposits (less than 60 cm), the absence of sedimentary structures, the number of layers (laminaset) (less than 2 laminaset), and the presence of backflow (Nanayama *et al*., 2000; Witter *et al*., 2001; Tuttle *et al*., 2004; Morton *et al*., 2007; Tappin, 2007; Lange and Moon, 2007; Kortekaas and Dawson, 2007; Dawson and Stewart, 2007; Nichol *et al*., 2007; Komatsubara *et al*., 2008 and Donato *et al*., 2008; 2009).

Due to the many similarities and few differences in the sedimentary deposits of tsunamis and large storms (Table 5), it is necessary to resort to taphonomy for a more accurate interpretation. Organisms constitute a diagnostic tool, because they are highly sensitive to changes in environmental conditions and, moreover, they become particles to be transported either dead or alive by sedimentary agents.

Taking into consideration the three tsunamigenic specific taphonomic traits suggested by Donato *et al*. (2008), namely, (1) thickness and lateral extension of the shell deposits, (2) presence of allochthonous articulated bivalves out of life position, and (3) extensive angular fragmentation of shells, we suggest that shell beds of the lower section of the Mata Amarilla Formation were deposited by tsunamis.

Additional evidence implying tsunami waves are: 1) pavements formed by concave–up allochthonous and autochthonous bivalves, and 2) the presence of semiarticulated “butterfly shaped” trigonids in muddy lagoonal sediments with a superimposed paleosol development (trigonids were found in life position in the barrier system). These pavements represent the distal part of a wave run-up process that penetrates so far into landward environments.

The combination of taphonomic and detailed sedimentologic studies has proved to be a valuable tool to understand the sedimentary processes and the sequence of sedimentary events involved in the accumulation of the lower section of the Mata Amarilla Formation as well as in the generation of a conceptual accumulation model.

CONCLUSION

1. The palaeoenvironment from the lower section of the Mata Amarilla Formation in the study area corresponds to a lagoon limited by a barrier system.
2. The barrier system is characterized by medium-grained sandstone with articulated trigonids preserved in life position, and by disarticulated oysters.
3. During tsunami events, the large waves generated washover deposits and carried allochthonous mollusk fauna from the shoreface inside the lagoon.
4. Proximal washover deposits are composed of red coquinas and bioclastic sandstones with allochthonous, marine articulated mollusk fauna.
5. Distal washover deposits are composed of dark green and black mudstones with concave-up oriented shells forming pavements. The mollusk fauna association shows mixed marine and freshwater components.
6. Variations in water salinity in the lagoon generated mass-mortality pavements composed only by conchostracans and freshwater fauna; not related to the tsunami events.
7. By considering the three tsunamigenic specific taphonomic traits, namely, (1) thickness and lateral extension of the shell deposits, (2) presence of allochthonous articulated bivalves out of life position, and (3) extensive angular fragmentation of shells, it is suggested that those shell beds were deposited by tsunamis. We also suggest adding to this tsunamigenic trend two extra traits: 4) pavements formed by allochthonous and autochthonous concave -up oriented bivalves, and 5) the presence of semiarticulated “butterfly shaped” trigonids in mud sediments interfingered with paleosols.

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