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Simón Gaitán, José I. Cuitiño, Damián Moyano-Paz, J. Marcelo Krause, Ana M. Parras, Diego Pol

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A brackish, muddy, wave-dominated embayment depositional model for the La Colonia Formation (Maastrichtian–Danian) in the Cañadón Asfalto Basin, Argentina

Gaitán, S. [1*], Cuitiño, J. I. [2,8], Moyano-Paz, D. [1,3,8], Krause, M. J. [4,5,8], Parras, A. M. [6,8] and Pol, D. [7,8]

1 – Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata, Argentina.

2 – Instituto Patagónico de Geología y Paleontología, Centro Científico y Tecnológico CONICET-CENPAT, Puerto Madryn, Argentina.

3 – Centro de Investigaciones Geológicas, Universidad Nacional de La Plata-CONICET, La Plata, Argentina.

4 – Museo Paleontológico Egidio Feruglio, Trelew, Argentina.

5 – Universidad Nacional de Río Negro, General Roca, Argentina.

6 – Instituto de Ciencias de la Tierra y Ambientales de La Pampa, CONICET-UNLPam, Santa Rosa, Argentina.

7 – Museo Argentino de Ciencias Naturales, Buenos Aires, Argentina.

8 – Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina.

**Corresponding author*: gaitansimon03@gmail.com

ABSTRACT

The La Colonia Formation (LCF) is a Maastrichtian to Danian mud-dominated succession cropping out in northern Patagonia and considered part of the post-rift stage of the Cañadón Asfalto Basin. The unit is world-famous for its wealth of terrestrial (mostly) and marine fossils. Prior depositional interpretations were inconsistent, proposing diverse marginal marine systems,

while dedicated sedimentological studies remained absent. In this work, we provide a detailed sedimentological and ichnological analysis of the LCF at the Sierra de La Colonia/Arroyo Mirasol Chico area, northern Chubut. Using marker beds as stratigraphic references, we logged sections at two localities and obtained a composite section (227 meters-thick) for the whole unit. Nine sedimentary facies were determined, whose depositional processes indicate accumulation by wave action of different energy and bathymetric conditions, together with mud accumulation from suspension fallout or possible sediment gravity flows. The persistent shallow-water conditions, pervasive wave processes, marine-affinity trace fossil assemblages, absence of valley incision, and fine-grained sediment dominance collectively support a wave-dominated shallow-marine embayment with distal fluvial supply as the depositional model for the LCF. Based on vertical trends, the unit was divided into 6 Facies Associations that, from base to top, record accumulation in the lower shoreface, offshore transition to offshore, sublittoral embayment, littoral embayment, wave- influenced central embayment, and fluvial-influenced central embayment. The LCF is related to several synchronous shallow-marine units from northern Patagonia, which are interpreted to be the result of a Maastrichtian Atlantic transgression that flooded a pre-existent irregular topography.

Keywords: Facies analysis, marine transgression, wave-dominated, river-influenced, Patagonia

INTRODUCTION

Restricted marine settings comprise a broad range of depositional environments characterized by variable interactions between marine and terrestrial processes. The restriction generally reflects reduced influence of open-marine processes on coastal areas, particularly wave energy, as well as departures from normal marine salinities. As a result, these settings encompass a variety of environments, including coastal lagoons, delta-related

bays (*e.g.,* interdistributary bays), estuaries, and shallow embayments (Boyd *et al.,* 1992; Ainsworth *et al.,* 2011).

Successions of fine-grained (clay, silt, and very fine-grained sand) sediments at the hundreds of meters-scale were traditionally conceived as a result of accumulation after suspension fall-out from sediment plumes in usually deep, quiet-water settings (Pettijohn, 1975; Nichols, 1999). Recently, some investigations pointed out that other processes, rather than suspension, may act during the deposition of these kinds of successions (Parsons *et al.,* 2001; Plint, 2014; Levell and Plint, 2026). The recognition of clay aggregates (floccules or intraformational clasts) behaving as coarser-grained sediments prone to being transported as bedload revolutionized the way sedimentologists understand fine-grained accumulation (*e.g.,* Schieber and Southard, 2009; Plint, 2014). In this context, some mud-dominated successions were reinterpreted as wave-dominated deposits within the shoreface-to-shelf system, prompting new conceptual frameworks for understanding how these sedimentary systems operate. Based on detailed sedimentological and ichnological field observations and considering these recent approaches, in this work, we analyze and contextualize a poorly understood, 227 meters-thick, fine-grained sedimentary succession of Maastrichtian–Danian age from the Cañadón Asfalto Basin (CAB) in northern Chubut province, northern Patagonia. This succession, assigned to the La Colonia Formation (LCF), has been interpreted as a result of deposition in a variety of dissimilar coastal to terrestrial depositional environments (Pascual *et al.,* 2000; Cúneo *et al.,* 2014; Gasparini *et al.,* 2015; Clyde *et al.,* 2021). In addition, this unit contains a vast fossil assemblage, recording a mixture of marine, freshwater, and terrestrial fossils that makes paleoenvironmental interpretations even more elusive. Based on our new data set, we aim to discuss a depositional model that explains this complex, thick marginal marine mud-dominated succession.

GEOLOGIC CONTEXT

The LCF (Pesce, 1979) is part of a Maastrichtian to Danian fine-grained marine, transitional to terrestrial sedimentary succession distributed in the surroundings of the Somuncurá Plateau in northern Patagonia (Fig. 1; Page *et al.,* 1999). The Somuncurá is an elevated plateau, composed of widespread Cenozoic flat basalt beds. Below these basalts, a mostly Mesozoic sedimentary succession is known, considered part of the infill of the CAB.

The CAB developed during a regional Jurassic extensional tectonic episode, initially as a series of synrift depocenters in central Chubut province (Fig. 1) that evolved to a wider sag basin, culminating with an episode of Late Cretaceous compressional tectonic inversion (Ranalli *et al.,* 2011; Figari *et al.,* 2015; Allard *et al.,* 2022; Bilmes *et al.,* 2026). During the Campanian–Danian interval, the CAB records deposition in fluvial, shallow-marine, and transitional depositional paleoenvironments. In northwestern Chubut, the Paso del Sapo and Lefipán formations are composed of a thick deltaic, estuarine, and shallow-marine deposits that accumulated in the Atlantic-related Paso del Sapo embayment (Scasso *et al.,* 2012; Vellekoop *et al.,* 2017; Guler *et al.,* 2019). East of this embayment, age-equivalent LCF deposits are exposed. Although the area of exposure is beyond the traditional boundaries of the CAB (Fig. 1b), the similarities and genetic links with the Lefipán Formation allow us to consider it as part of the sedimentary evolution of this basin.

Several shallow marine/estuarine deposits from Río Negro and Neuquén provinces were correlated to the Lefipán and La Colonia Formations, such as the Coli Toro, Alamitos, Allen, Jagüel, Arroyo Barbudo formations (among others), conforming a large shallow-marine embayment whose paleogeographic details, sediment sources, and marine gateways are still dubious (Page *et al.,* 1999; Malumián and Náñez, 2011; Scasso *et al.,* 2012; Guler *et al.,* 2019; Clyde *et al.,* 2021; González Estebenet *et al.,* 2026).

La Colonia Formation (LCF)

Because detailed sedimentologic analyses of the LCF are scarce (*e.g.,* Navarro, 2012; in the Telsen area), the depositional setting for this unit has been inferred generally within paleontological and regional geological mapping contributions. Paleoenvironmental interpretations vary from shallow-marine, brackish-marine, coastal-lagoon, and to lacustrine settings (Ardolino and Delpino, 1987; Page *et al.,* 1999; Cúneo *et al.,* 2014). In a study on fossil mammals, Pascual *et al.* (2000) defined three facies associations: 1) a lower fluvial association (today included in the underlying continental Puntudo Chico Formation); 2) a middle association accumulated in estuary, tidal flat, or coastal plain environments; and 3) an upper association accumulated in an upper tidal flat. The most detailed sedimentological study for the LCF at the study area corresponds to Gasparini *et al.* (2015), where the unit is divided into six facies, representing accumulation in muddy floodplains, marshes, and ponds cut by meandering channels, probably at the mixed-energy central zone of an estuary. Recently, Ardolino *et al.* (2021) interpreted an estuarine-like transitional to coastal environment, partly protected and influenced by tidal currents and fluvial floods. In the Telsen area, some 80 km northeast of the study area (Fig. 1b), Navarro (2012) logged a 15 meters-thick exposure of the LCF, describing and photographing facies which were interpreted as accumulated initially in a shoreface setting that grades upward to an offshore transition, and finally to a tidal flat.

Over recent decades, the LCF has yielded a variety of fossils, including vertebrates such as mammals, birds, ophidians, turtles, dinosaurs, plesiosaurs, and anurans (Pascual *et al.,* 2000; Rougier *et al.,* 2009; Gasparini *et al.,* 2015; Sterli *et al.,* 2021; O'Gorman *et al.,* 2023, 2026; Pol *et al.,* 2024, among others). Plant remains are well preserved, including terrestrial and aquatic plants (Gandolfo and Cúneo, 2005; Cúneo *et al.,* 2014) together with a diverse palynomorph assemblage (De Benedetti *et al.,* 2023). Few marine fossils are described, including plesiosaurs (O'Gorman *et al.,* 2023, 2026), dinoflagellates, and foraminifera (Guler *et al.,* 2014; Borel *et al.,* 2016;

Carignano *et al.,* 2023), together with several lobster specimens of uncertain affinity (Andrada, personal communication).

The age of the LCF is constrained to the Maastrichtian–early Danian interval (Fig. 1c) based on two lines of evidence: a detrital zircon U-Pb age of ~71.7 Ma obtained from a tuffaceous siltstone layer at the top of the underlying fluvial Puntudo Chico Formation, and paleomagnetic data from the LCF at Cerro Bayo or Cerro Buitre Norte (Clyde *et al.,* 2021).

METHODOLOGY

We investigate the LCF in the Arroyo Mirasol Chico area just southeast of Sierra de La Colonia in northern Chubut (Fig. 1a, b, d), where the unit is best exposed. Since several deformational structures are present and stratigraphic correlation between outcrops is sometimes difficult in the field, we identified and followed marker horizons characterized by distinctive colour changes visible in Google Earth™ satellite imagery (Fig. 1d). Four marker beds (labeled M1 to M4 from base to top) were satisfactorily established across the study area and used to determine the best location for sedimentological logging and to establish the stratigraphic position of additional field observations at more distant localities. Because most of the unit consists of highly weathered badlands (Fig. 1e, f), we systematically excavated the weathered surface to observe the fresh rock every 1.5 m of vertical section measured with a Jacob staff. Where conspicuous sedimentological changes, particularly in colour, were observed at the surface, the spacing between excavation points was reduced to document the nature of these changes in greater detail. We photographed, and characterized the fresh rocks, recording grain size, sedimentary structures, lamina thickness, trace fossils, bioturbation index (BI), and macrofossil content. Bed contacts and stratigraphic surfaces were recorded whenever identifiable. Laminae were defined following the genetic criteria of Biddle *et al.* (2025): their boundaries reflect internal variations within a single depositional process, whereas beds/strata represent larger-scale units. Thickness was not used as a defining criterion. Two stratigraphically

correlated and complementary sections were logged for the LCF at Chiva Muerta and Cerro Bosta Norte (Fig. 1d), comprising the whole exposed thickness of the unit, while several other observations within the study area complemented the survey.

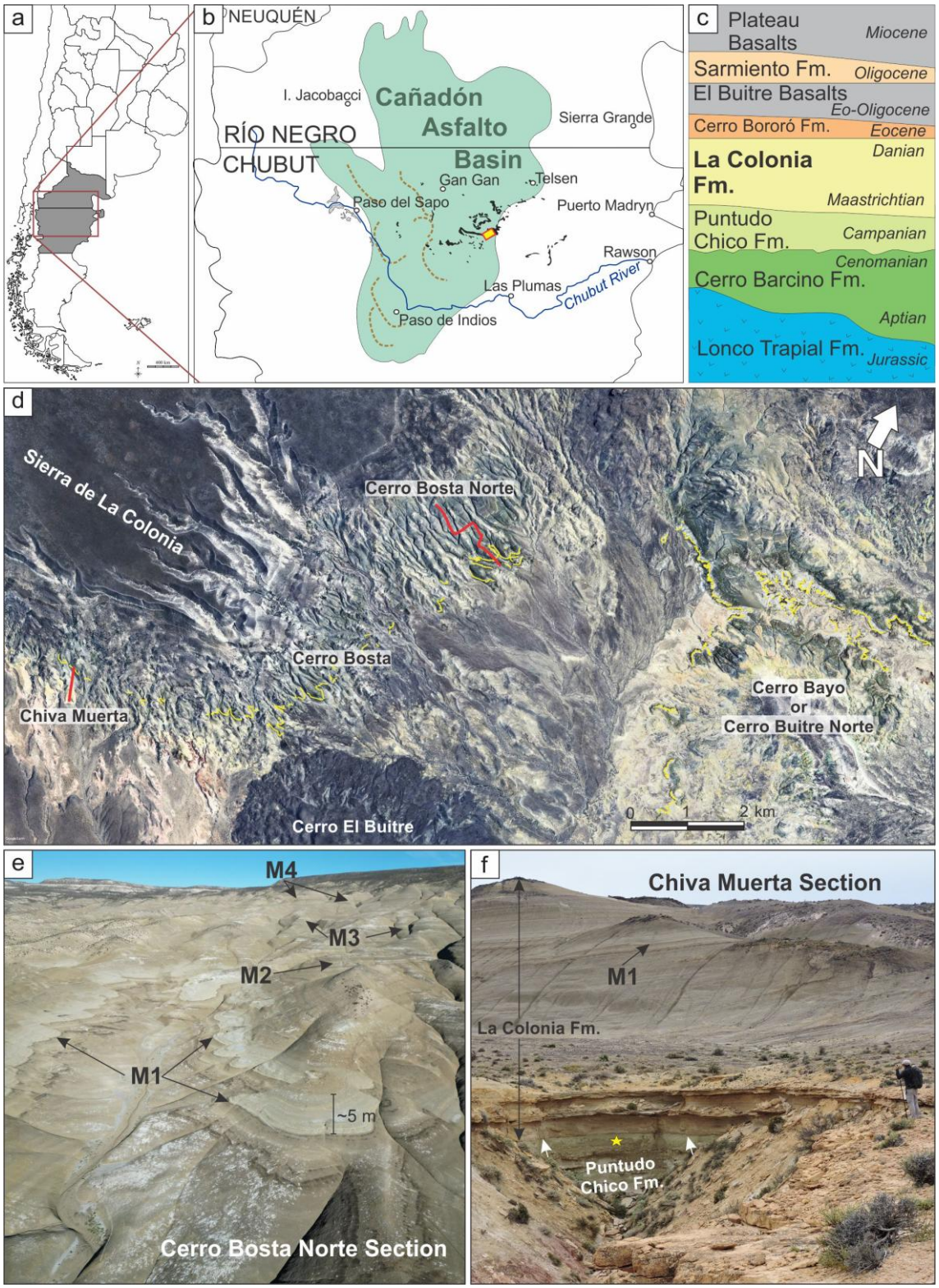


Figure 1. Maps and general stratigraphic data for the study area and the La Colonia Formation. **a)** Map of Argentina showing the location of the map in b). **b)** Extent of the Cañadón Asfalto Basin *sensu lato* (after Figari *et al.,* 2015). The outcrops of the La Colonia Formation are mapped in black, whereas the outcrops of the Lefipán Formation are mapped in light grey. After geological charts of Ardolino and Franchi (1996), Anselmi *et al.* (2004), Sacomani *et al.* (2007), Ardolino *et al.* (2021), and Lizuaín *et al.* (2022). The yellow rectangle corresponds to the area shown in D. **c)** Schematic stratigraphic column of the study area, based on ages and mapped units from Clyde *et al.* (2021). **d)** Satellite image (Google Earth TM) of the study area showing exposures of the badlands of the La Colonia Formation and main geographic elements. The marker bed M1 is highlighted in yellow. The path of each logged section is marked in red. **e)** Aerial view of the exposure at Cerro Bosta Norte with indication of the position of the four marker beds. M1, the most continuous marker, is defined at the sharp base of a light sandy horizon and is clearly visible in the foreground. **f)** Exposure at Chiva Muerta Hill, where the base of the La Colonia Formation (white arrows) and the prominent yellowish sandy lower beds are well exposed. The yellow star indicates the position of the dated horizon from Clyde *et al.* (2021). Up in the section, the M1 marker allows correlation with the Cerro Bosta Norte Section.

STRATIGRAPHIC FRAMEWORK

Marker horizons and sections

The marker horizons form the basis for field stratigraphic positioning. M1 is the lowest marker and is defined by a white, sandy bed 2–3 meters-thick (Fig. 1d). Immediately below is a black layer a few tens of centimetres-thick. M1 is the least deformed of the four markers. Its elevation increases from 300 m a.s.l. in the eastern sector to 420 m a.s.l. in the westernmost sector, where it lies approximately 60 m above the base of the LCF. M2 marks a sharp colour change, from brownish beds containing green and white bands below to greenish beds above. The latter contain two thin, closely spaced white beds. This marker is clearly identifiable in the eastern sector but becomes more diffuse westward. Its elevation ranges from 340 m a.s.l. in the east to 400 m a.s.l. in the west. M3 marks the base of a whitish bed overlain by brownish beds, which contrast with the underlying greenish beds. Its elevation ranges from 375 m a.s.l. in the eastern sector to 450 m a.s.l. in the western sector. Finally, the upper M4 is the most discontinuous marker, owing to the

extensive deformation affecting this part of the LCF. It is commonly duplicated by sliding. It corresponds to a dark brown band bounded by well-stratified light grey, black, and greenish beds. Overall, the elevation of the marker horizons defines a gentle eastward tilt of the LCF strata.

Both sections were integrated using marker horizons, resulting in a 227 meters-thick section for the LCF. The unit sharply overlies the Puntudo Chico Formation (Fig. 1f) and is usually capped by modern detritus, slumps, or by greenish to reddish sandstones that in Cerro Bayo (Fig. 1d) were mapped as the Cerro Bororó Formation (Clyde *et al.,* 2021). The boundary between the LCF and these overlying sandstones is covered.

SEDIMENTARY FACIES OF THE LA COLONIA FORMATION

Nine sedimentary facies were determined in the LCF based on field observations. A code for each facies is used, with the capital letter indicating dominant grain size, followed by additional letters indicating sedimentary structures or other diagnostic features. The facies are described below in order of decreasing abundance, and their main depositional processes are interpreted.

Heterolithics (Hf and Hs)

Heterolithic facies, *i.e.,* beds composed of alternating muddy and sandy laminae at the mm to a few cm scales, are the most abundant facies of the LCF, accounting for 41.3 % of the succession. Heterolithics are divided into two groups according to the sand-to-mud ratio: muddy heterolithics (Hf; 31.7% of the LCF), where mudstones volumetrically compose 50% or more of the succession, and sandy heterolithics (Hs; 9.6% of the LCF), where sandstones dominate. Heterolithic deposits form tabular beds from 0.3 to 9 meters-thick. Bed contacts are either sharp or transitional to other fine-grained facies (Fig. 2a). The muddy laminae are commonly massive or show rare parallel lamination (Fig. 2b, c) or normal grading from silt to clay. Sandy layers are light-colored and composed of coarse silt to very fine-grained sand,

which are massive or exhibit parallel lamination or low-angle cross-lamination (Fig. 2d). Occasionally, symmetrical or nearly symmetrical rippled bedforms are preserved. Laminae thickness varies from a few mm to less than 5 cm, and lenticular geometries are common, in some cases showing ripple formsets or deformed lenses. Occasionally, millimetres-thick, laterally continuous sandy laminae intercalated within thicker muddy laminae form distinctive “pinstripe” lamination patterns (Fig. 2c). Carbonaceous debris are usually observed as dispersed particles within massive beds or forming high concentrated discrete laminations (Fig. 2a), whereas some layers show well-preserved leaves. Soft-sediment deformation structures (flame structures, convolute bedding, small clastic dykes) and synaeresis cracks are common. Heterolithic deposits display low to moderate bioturbation intensity (BI 0–4, typically 0–2).

Heterolithic facies are interpreted as the combination of several alternate subaqueous depositional processes. On one side, muddy laminae are interpreted as the result of suspension fallout from a turbid water column. Alternatively, some structureless, graded, or faintly laminated muddy layers can be formed after gravity-induced muddy flows (Schieber and Southard, 2009; Macquaker *et al.,* 2010; Plint, 2014). Ine contrast, coarse silt-to-sand laminae are interpreted to have formed through tractional deposition. The abundance of low-angle lamination and symmetrical ripple bedforms suggest that wave-induced oscillatiory motion was an important mechanism sediment reworking at the seabed, although combined flow processes were also likely involved. The frequency recurrence of these depositional processes a dynamic depositional environment characterized by repeated wave-reworking events. As each event waned, coarser sediment settled first, forming very low-amplitude combined-flow ripples, which were subsequently draped by progressively finer silt and clay. The dominance of sandier (Hs) or muddier counterparts (Hf) is determined by the relative frequency with which each process operates on the depositional surface. Soft-sediment deformation structures are interpreted as the consequence of the high proportion of pore-water within the unconsolidated substrate, which makes them prone to deformation under slight stresses. Synaeresis cracks are interpreted as a

product of fluctuations in pore-water salinity in surface sediments, whereas the presence of carbonaceous debris is attributed to the input of plant remains from the continent. Well-preserved leaves suggest that plant remains were supplied from nearby areas.

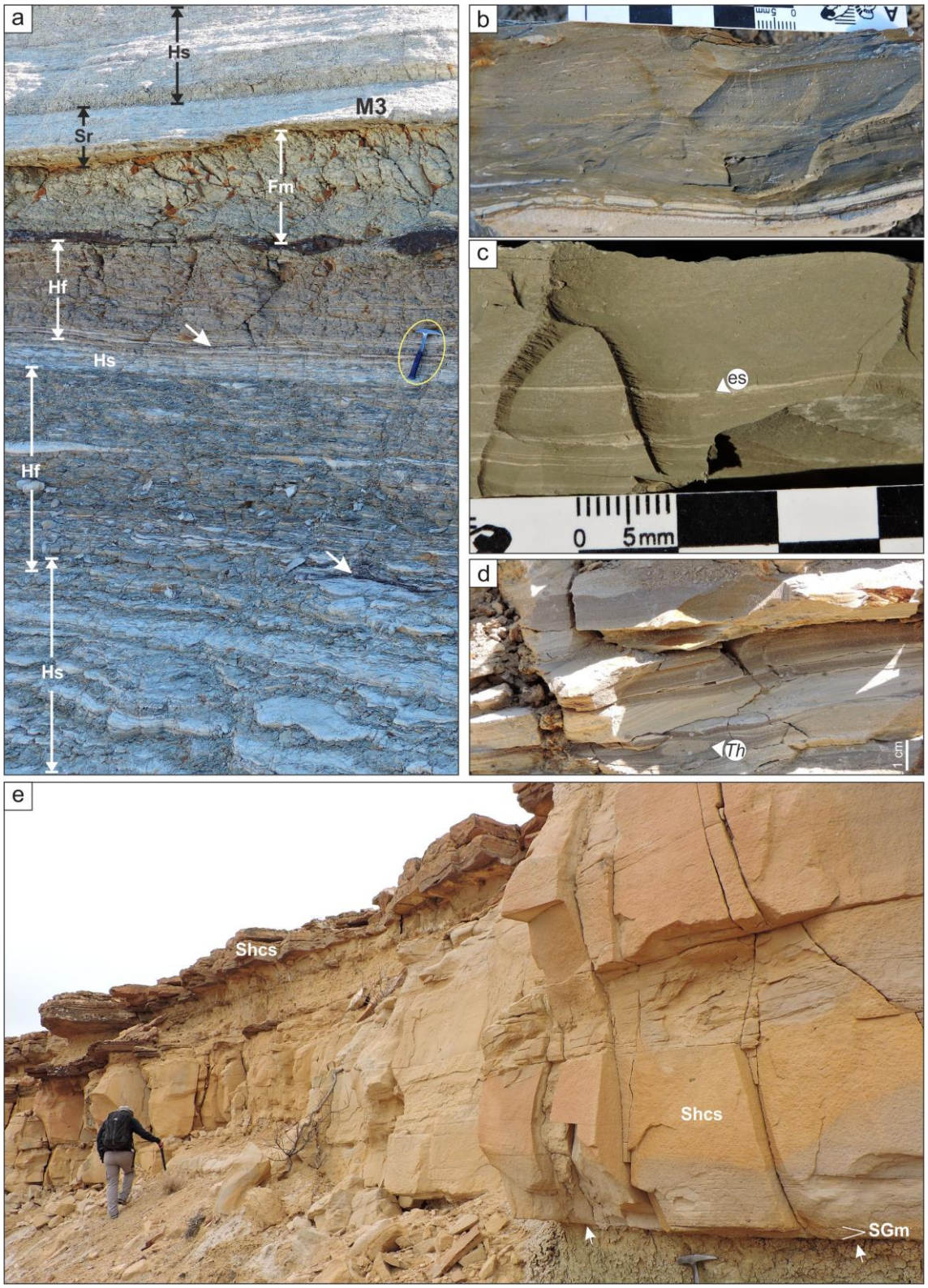


Figure 2. Field photographs of dominant sedimentary facies from the La Colonia Formation. **a)** One of the few natural outcrops showing several of the most common facies, including intercalations of sandy (Hs) and muddy heterolithics (Hf), massive, clay-dominated fines (Fm), and ripple-laminated very fine-grained sandstones (Sr). White arrows point to dark laminae rich in carbonaceous debris. Note the sharp and irregular base of the ripple-laminated horizon that constitutes the M3 marker bed. **b)** Muddy heterolithic facies (Hf) with few sandy laminas and some soft-sediment deformation. **c)** Muddy heterolithic facies (Hf) with sandy laminas usually less than 1 millimetres-thick and scarce escape trace fossils (es). **d)** Sandy heterolithic facies (Hs). Note ripple cross lamination and parallel lamination in the sandy layers. *Th*: *Thalassinoides*. **e)** Protrusive beds at the base of the La Colonia Formation are mostly composed of very fine-grained sandstones with low-angle or hummocky cross-stratification (Shcs). White arrows point to the basal surface of the unit, on which a 10 centimetres-thick gravel-to-granule bed (SGm) is observed.

Bioturbated Siltstones (Fsb)

This facies constitutes 27.4% of the LCF and is composed predominantly of highly bioturbated siltstones, with subordinate muddy sandstones or very fine-grained sandstones. It forms homogeneous, non-stratified successions of tabular bodies that reach up to 35 meters-thick. Primary sedimentary structures have been largely obliterated by pervasive bioturbation (BI 1–5; typically, 4–5), although diffuse parallel lamination has been locally observed.

The dominance of silt and the high degree of bioturbation observed in facies Fsb are interpreted as resulting from accumulation in a low-energy marine setting. Bioturbation obliterated primary sedimentary structures, but the mixtures of clay, silt, and very fine-grained sand suggest that events of different energy reworked the seafloor.

Massive Mudstones (Fm)

Facies Fm is common, making up 26.3% of the LCF. It forms tabular beds 0.2 to 7.4 meters-thick, composed of massive, homogeneous olive- to dark-green claystone or mixed claystone-siltstone deposits (Figs. 2a and 3e). On some occasions, when grain size variations are present, soft-sediment deformation structures are visible. Carbonaceous debris and synaeresis cracks

are also observed in minor proportions. Reddish to orange small rhizoliths are observed in some beds (Fig. 3e). Fm exhibits low BI values (0–1).

The interpretation of thick, structureless claystone or mudstone deposits is striking because no sedimentary structures are present. This facies is interpreted as rapid mud deposition via suspension fallout or bottom-current processes (*i.e.,* fluid mud flows), where elevated sedimentation rates promote soft-sediment deformation and account for the prominent massive aspect of this facies (Traykovski *et al.,* 2000; Plint, 2014). The rhizolith-bearing beds are interpreted as modified by pedogenetic processes during episodes of subaerial exposure.

Ripple Laminated Sandstones (Sr)

Facies Sr represents 1.7 % of the LCF and is composed of well-sorted, coarse siltstone to very fine-grained sandstone (Figs. 2a and 3c). It forms tabular or lenticular beds of a few centimetres-thick, reaching a maximum of 0.7 m. Internally, the beds show low-angle ripple lamination, sometimes preserving symmetrical ripple bedforms with rounded crests. Typical heights are 1.5 cm and wavelengths of 8 cm. Sr is largely unburrowed or shows rare, isolated facies-crossing ichnotaxa (BI 0–2).

Facies Sr is interpreted to record the migration of ripples generated by oscillatory or combined flows under conditions of water depth above the wave base level.

Hummocky Cross-Stratified Sandstones (Shcs)

Facies Shcs accounts for 1.6 % of the LCF and is restricted to its lower part. It is composed of tabular to wedge-shaped sets of low-angle, swaley, or hummocky cross-laminated fine- to very fine-grained sandstone (Figs. 2e and 3b). The wavelength of structures ranges from several meters to a minimum of about 0.3 meters. Shcs shows patches with vertical trace fossils mostly at the top of the beds (BI 0–2).

The hummocky, swaley, and low-angle cross-lamination sets are commonly formed during high-energy bottom reworking by storm waves in shallow-marine environments (Dumas and Arnott, 2006). The vertical stacking of sets with storm-wave structures usually forms above fair-weather wave base level.

Massive Muddy Sandstones (SFm)

Facies SFm represents 0.6 % of the LCF. It is composed of structureless, poorly sorted fine to very fine-grained sandstone that from 0.2 to 0.3 meters-thick tabular beds (Fig. 3a). Upper and lower bed contacts are sharp. It shows low BI intensity values (0–2).

The lack of visible sedimentary structures and the reduced bioturbation suggest facies SFm accumulated by short-lived sediment gravity flows.

Massive Granule-Rich Sandstones (SGm)

This facies, accounting for 0.6% of the LCF, represents the coarsest-grained terrigenous deposits of the unit, exclusive to its lower interval. It is composed of massive or faintly laminated fine-grained conglomerates (maximum grain size of 2 cm), forming lenticular bodies up to 0.3 meters-thick. SGm also includes a few-centimetres-thick lenses or wedges of structureless, quartz-rich, well-sorted, granule-rich sandstones, which locally show large symmetrical ripple forms. It appears at the base of, or intercalated with, Shcs facies (Figs. 2e and 3b).

Thin lenses or wedges of clast-supported, rounded pebbles and granule-rich sandstones are interpreted as the result of short-lived, high-energy depositional events. The fact that facies SGm is only found near the base of the unit suggests it formed after a combination of high-energy events, with the presence of residual particles left by erosion or omission. The association of SGm with wave-generated facies (*e.g.,* Shcs) suggests it resulted from high-energy reworking of the substrate by storm waves.

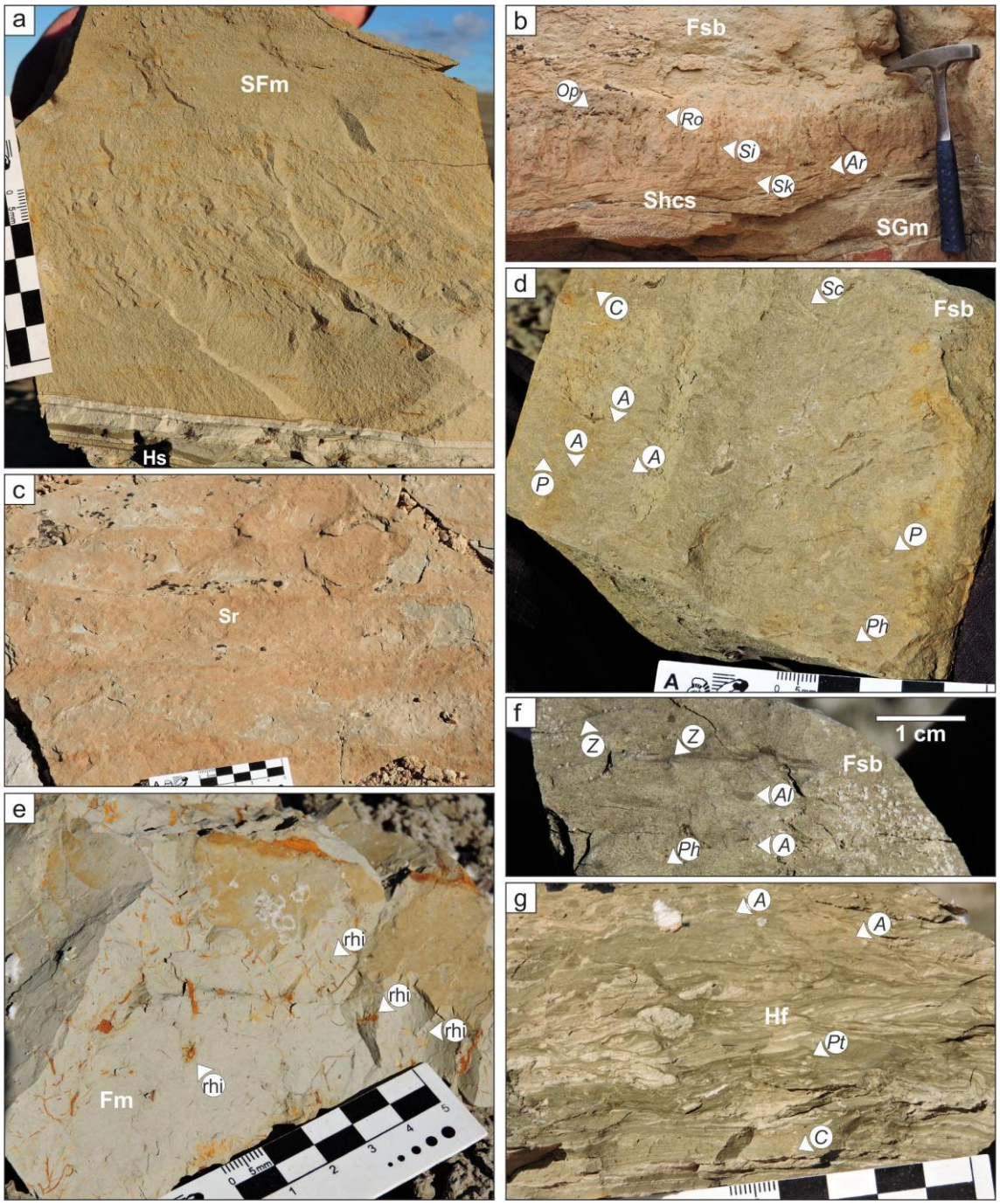


Figure 3. Field photographs of sedimentary facies of the LCF. **a)** Bed of massive muddy sandstones (SFm) sharply covering sandy heterolithics (Hs); **b)** Interbedding of granule-rich sandstones wedges (SGm) within sets of Shcs low-angle beds. Note the top-down bioturbation pattern in Shcs, which grades upward to fully bioturbated fine-grained deposits (Fsb); **c)** Plan view of a symmetrical rippled surface; **d)** Highly bioturbated muddy sandstones (Fsb); **e)** Massive claystone deposits (Fm) with oxidized root structures; **f)** Bioturbated muddy sandstones (Fsb) with horizontal trace fossils. **g)** Highly deformed muddy heterolithics (Hf). Abbreviations: *A* = *Asterosoma*; *Al* = *Alcyonidiopsis*; *Ar* = *Arenicolites*; *C* = *Chondrites*; *N* =

Nereites; *O = Ophiomorpha*; *P = Planolites*; *Ph = Phycosiphon; R = Rosselia*; *Sc = Scolicia*; *Si = Siphonichnus; Sk = Skolithos*; *Z = Zoophycos*; rhi = rhizoliths.

Intraformational Fine Conglomerates (Gi)

This facies is considerably reduced in volume (0.5 % of the LCF). It forms tabular or lenticular beds which are usually a few-centimetres-thick, composed of rounded, pebble-sized clasts of greenish mudstones lithologically similar to the underlying beds. Locally, lenses containing abundant accumulations of rounded bone fragments, dominated by freshwater fish remains (Cardozo *et al.,* 2025), are also present. Facies Gi always lies on top of sharp, sometimes irregular surfaces, covering facies such as Fm or Hf, and in some cases, these surfaces coincide with the bases of marker horizons.

The accumulation of reworked intraformational pebble clasts suggests erosion of the substrate and resedimentation of the eroded materials. The concentration of reworked bones on top of erosion surfaces reinforces this interpretation.

FACIES ASSOCIATIONS AND THEIR VERTICAL ARRANGEMENTS

The observation of the distribution of facies along the integrated column, together with the position of specific horizons such as the marker beds, allowed us to divide the LCF into six facies associations (FA; Fig. 4), each characterized by a specific set of sedimentological attributes and trace fossils that represent particular environmental conditions for sediment accumulation. From base to top, these FAs are described and interpreted below.

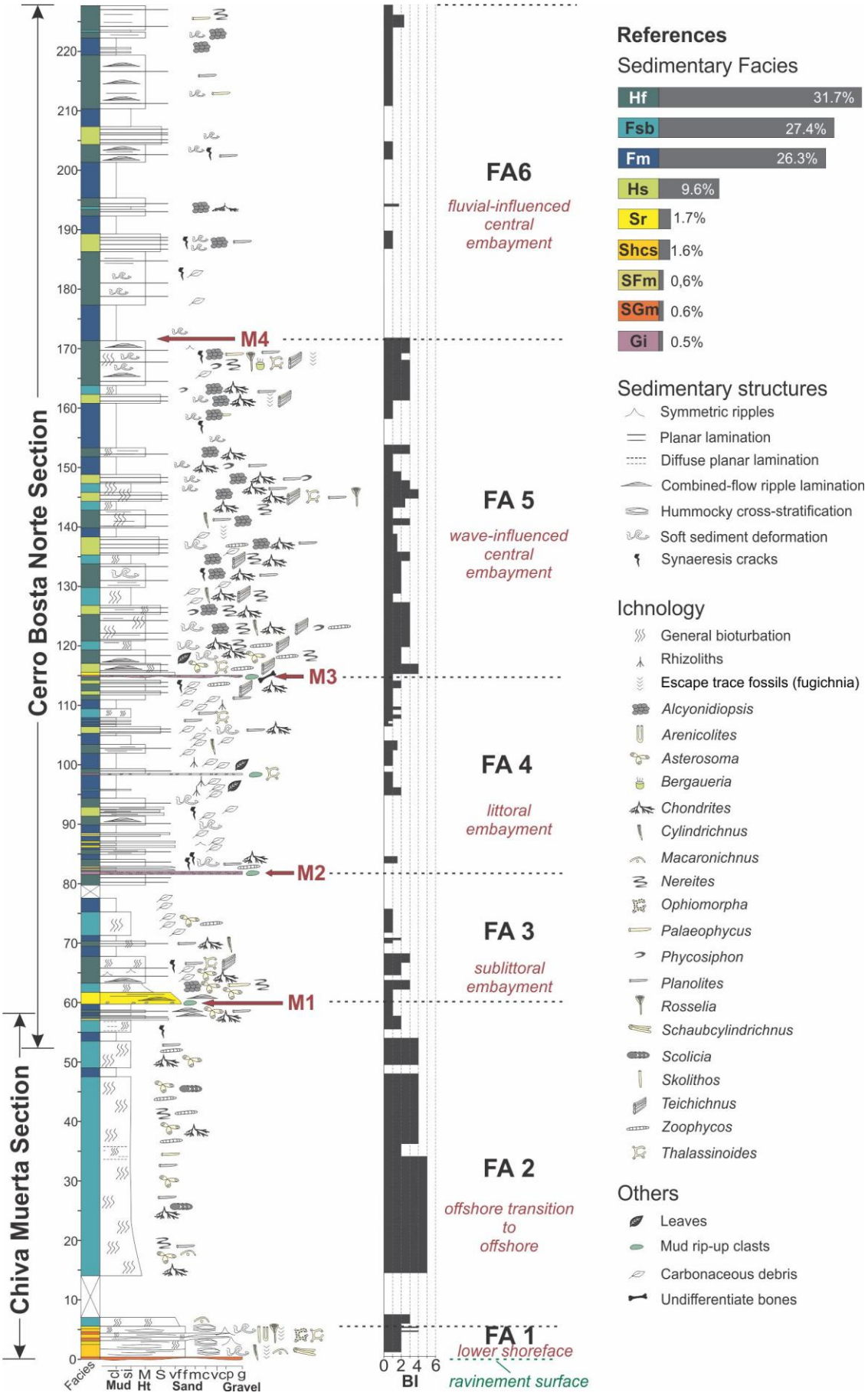

Cerro Bosta Norte Section
Chiva Muerta Section
M4
M3
M2
M1
FA6
fluvial-influenced central embayment
FA 5
wave-influenced central embayment
FA 4
littoral embayment
FA 3
sublittoral embayment
FA 2
offshore transition to offshore
FA 1
lower shoreface
ravinement surface
Facies
Mud
Ht
Sand
Gravel
BI
References
Sedimentary Facies
Hf 31.7%
Fsb 27.4%
Fm 26.3%
Hs 9.6%
Sr 1.7%
Shcs 1.6%
SFm 0,6%
SGm 0.6%
Gi 0.5%
Sedimentary structures
Symmetric ripples
Planar lamination
Diffuse planar lamination
Combined-flow ripple lamination
Hummocky cross-stratification
Soft sediment deformation
Synaeresis cracks
Ichnology
General bioturbation
Rhizoliths
Escape trace fossils (fugichnia)
Alcyonidiopsis
Arenicolites
Asterosoma
Bergaueria
Chondrites
Cylindrichnus
Macaronichnus
Nereites
Ophiomorpha
Palaeophycus
Phycosiphon
Planolites
Rosselia
Schaubcylindrichnus
Scolicia
Skolithos
Teichichnus
Zoophycos
Thalassinoides
Others
Leaves
Mud rip-up clasts
Carbonaceous debris
Undifferentiate bones

Figure 4. Integrated sedimentary log of the La Colonia Formation at Chiva Muerta and Cerro Bosta Norte sections (see Fig. 1d for location). BI: Bioturbation Index. Sedimentary facies are indicated with color references, and their proportion is estimated against total thickness. The position of marker horizons is indicated as M1 to M4.

Facies Association 1. Lower shoreface deposits

FA 1 is defined as a set of relatively coarse-grained sediments registered within the lowermost 6 m of the LCF at the Chiva Muerta Section (Fig. 4). It forms a prominent, yellowish tabular bed, laterally extended for tens of km across the study area, lying on top of a sharp and flat, locally irregular surface above the fluvial Puntudo Chico Formation (Figs. 1f, 2e). The most common facies is Shcs, although some thin beds of Sr and SGm are intercalated, forming cross-bedded sets a few decimetres-thick. Several erosional surfaces separate beds of the Shcs facies, sometimes showing granule layers (SGm) covering surfaces. This facies association shows low bioturbation intensity (BI 0–4, typically, 0–2). Bioturbation structures occur toward the top of the beds, and the trace-fossil assemblage includes *Arenicolites*, *Cylindrichnus*, *Macaronichnus*, *Ophiomorpha*, *Rosselia*, *Schaubcylindrichnus*, *Siphonichnus*, *Skolithos*, *Thalassinoides,* and escape trace fossils.

FA 1 is interpreted as accumulated by high-energy storm-wave action in a sharp-based, shoreface depositional setting. The amalgamation of storm-event deposits suggests recurrent storm activity. Fair-weather deposits are volumetrically subordinate and represented by wave-ripple-laminated sets. The trace-fossil assemblage of this facies association reflects top-down, post-event colonization of the substrate (MacEachern *et al.*, 2012, 2026). Combined sedimentological and ichnological features are consistent with deposition in the proximal part of the lower shoreface, between the fair-weather wave base level and the surf diasteme (Clifton, 2006).

Facies Association 2. Offshore transition to offshore deposits

FA 2 transitionally overlies FA 1 forming a fining upward succession that continues as a relatively homogeneous 54 meters-thick succession dominated by facies Fsb. Upward, subordinate occurrences of facies Fm, Hf, and Sfm

intercalate (Fig. 4), with occasional synaeresis cracks and combined flow ripple bedforms. The upper boundary is marked by the clearly visible basal surface of a ripple-laminated very fine-grained sandstone bed designated as marker M1 (Fig. 4). FA 2 is largely dominated by high bioturbation intensity (BI 0–5; typically, 4–5). The trace-fossil suite is characterized by *Asterosoma*, *Chondrites*, *Nereites*, *Palaeophycus*, *Planolites*, *Scolicia,* and *Zoophycos*. The upper 10 m of this facies association show facies variability and reduced bioturbation intensity (BI 0–2), which allows recognizing layering and sedimentary structures such as combined-flow cross-lamination.

The high degree of bioturbation observed in this facies association suggests intense substrate reworking by benthic communities under prolonged favourable and stable environmental conditions. In contrast, the uppermost beds of this facies association exhibit reduced bioturbation intensities, synaeresis cracks, and the occurrence of heterolithic deposits, suggesting the influence of environmental stress and increased sedimentation rates (MacEachern *et al.,* 2026). The dominance of fine-grained deposits indicates deposition in an offshore to-offshore-transition setting, where suspension fallout prevailed below the fair-weather wave base level during fair-weather conditions, whereas the interbedded sandstone laminae record episodic storm-induced sedimentation (Clifton, 2006).

Facies Association 3. Sublittoral embayment

FA 3 is 22 meters-thick, and its base is marked by a flat, sharp lower boundary of the ripple-laminated coarse siltstone to very fine-grained sandstone (Marker M1), whereas its top is marked by another sharp flat surface defined as marker M2 (Fig. 4). FA 3 consists of very fine sandstone (Sr), muddy sandstone (SFm), mudstone dominated-heterolithic (Hf), and massive mudstone (Fm) deposits, forming a general fining-upward trend. Combined-flow ripple cross-lamination and preserved symmetric ripples are common in sandy and heterolithic deposits, whereas mudstones and muddy sandstones are mostly massive. Synaeresis cracks are common. This facies association is characterized by low bioturbation intensity (BI 0–2; typically, 0–

1) and abundant carbonaceous debris. The trace-fossil suite is composed of *Alcyonidiopsis*, *Asterosoma*, *Chondrites, Cylindrichnus*, *Nereites*, *Palaeophycus*, *Planolites, Teichichnus*, *Thalassinoides,* and *Zoophycos*.

This facies association represents clear environmental differences compared with the underlying FAs 1 and 2. Combined-flow ripples suggest wave action on the seafloor. The recurrent presence of carbonaceous debris and the high abundance of mudstone deposits suggest a significant sediment supply from fluvial sources and/or proximity to the coastline (Plint, 2014). Additionally, the abundance of fine-grained deposits and the dominance of horizontal trace fossils suggest deposition under overall low-energy and well-oxygenated conditions. The marked reduction in BI values, together with the presence of synaeresis cracks, may indicate intermittent fluctuations in salinity. Overall, these features can be associated with accumulation in a shallow-marine, restricted embayment influenced by river discharges (Buckley *et al.,* 2016).

Facies Association 4. Littoral embayment

FA 4 is 33 meters-thick and is mostly composed of clay-rich facies such as Hf and Fm. The base and top are defined by two thin intraformational beds (facies Gi), corresponding to markers M2 and M3, respectively. Thin lenses containing thousands of reworked vertebrate remains were observed at the base of M3, the majority of which are of terrestrial origin and a lesser proportion of marine origin (Harper *et al.,* 2019; Sterli *et al.,* 2021; Cardozo *et al.,* 2025). Mudstone deposits exhibit recurrent root marks, a diagnostic feature of this facies association. Deposits of FA 4 show low bioturbation intensity (BI 0–2; typically, 0–1) and low ichnodiversity, including *Chondrites*, *Cylindrichnus, Planolites*, *Thalassinoides*, *Teichichnus,* and *Zoophycos*. Carbonaceous debris and soft-sediment deformation structures are abundant, whereas well-preserved leaves, including a horizon bearing aquatic plants (Cúneo *et al.,* 2014), combined-flow and oscillation ripples, and synaeresis cracks are common elements of this FA.

The fine-grained nature of this FA suggests a low-energy depositional setting, while the presence of root structures and well-preserved leaves suggests episodes of plant colonization, probably in water-saturated continental settings. Although well-developed paleosols are missing, the presence of roots implies a very shallow subaqueous to occasionally subaerial depositional setting. The paucity of bioturbation, synaeresis cracks, and dominance of clay deposits, suggests stressful conditions for benthic fauna such as salinity fluctuations, turbid waters, and episodic subaerial exposure. In addition, the abundant carbonaceous debris and plant remains further point to fluvial input from adjacent, emergent vegetated areas. Since tidal indicators are not observed and deltaic mouth bar deposits are absent, we suggest deposition in a protected, river-influenced, mud-dominated embayment margin (Levell and Plint, 2026).

Facies Association 5. Wave-influenced central embayment

FA 5 is 57 meters-thick and is composed entirely of fine-grained deposits, dominated by facies Hf, Fm, and Fsb, with minor Hs. It is limited by marker M3 at the base and marker M4 at the top. Bioturbation intensity is low to moderate (BI 0–4; typically, 2–3). The trace-fossil assemblage includes *Alcyonidiopsis*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Cylindrichnus*, *Nereites*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Rosselia*, *Thalassinoides*, *Teichichnus,* *Zoophycos*, and escape trace fossils. Sparse ellipsoidal benthic fecal pellets are abundant within mudstone and heterolithic facies. Soft-sediment deformation structures and synaeresis cracks are common. Combined-flow and/or wave-ripple cross laminated coarse-grained siltstone to very fine-grained sandstone layers are frequent. Carbonaceous debris are occasionally present.

Even though high-frequency grain size changes occur, the overall homogeneous vertical succession throughout tens of meters suggests accumulation in an aggradational, subaqueous low-energy depositional setting. Water depth remained above wave base level, indicated by the presence of wave-generated (both combined- and oscillatory-flow) ripples or cross lamination. The abundant deformational structures are probably a

consequence of the development of soft to soupy, clay-rich substrates. Frequent carbonaceous remains suggest proximity to a fluvial source, whereas synaeresis cracks and low bioturbation intensity suggest the occurrence of salinity fluctuations. Altogether, the evidence suggests nearly constant stressful conditions for benthic fauna, like brackish, turbid waters derived from fluvial sources, probably occurring in a shallow and protected, low-energy central embayment.

Facies Association 6. Fluvial-influenced central embayment

FA 6 comprises the uppermost 56 m of the LCF and is bounded at its base by marker M4, the only one that does not represent an erosion surface but instead consists of a dark, clay-rich bed. This FA is dominated by clay-rich deposits with subordinate intercalated laminae of coarse siltstone to very fine-grained sandstone, represented by facies Hf, Fm, and Hs, in decreasing order of abundance. These deposits are characterized by pervasive soft-sediment deformation structures, including flame structures, small-scale clastic dykes, and convolute lamination and synaeresis cracks. Some sand-rich heterolithic deposits show combined-flow ripple cross-lamination. Carbonaceous debris are common, but not abundant. Bioturbation intensity is consistently low (BI 0–2, mainly 0–1). Ichnodiversity is also low, including *Alcyonidiopsis*, *Chondrites*, *Nereites*, *Palaeophycus,* and *Planolites*.

This facies association is the finest-grained of the LCF, suggesting sedimentation under low-energy settings. The presence of beds with combined-flow ripple cross-lamination indicates that at least parts of them accumulated in water depths above the wave base. Synaeresis cracks and overall reduction in bioturbation intensities suggest brackish-water conditions, and the abundant soft-sediment deformation structures suggest high pore-water content in clay-rich deposits, probably developing soupgrounds, which might additionally act against the morphological preservation of trace fossils. The high proportion of mud can be explained by the abundant supply of mud from a fluvial source towards the central part of the embayment (Levell and Plint, 2026).

DISCUSSION

La Colonia Formation: a wave-dominated, river-influenced muddy shallow-marine embayment

The occurrence of thick, shallow-marine mudstone successions, as observed in modern systems, is determined not only by the energy regime of the shelf (*i.e.*, fluvial, wave, and tidal currents) but also by the sediment supply rate and the availability of accommodation space due to the pre-existing physiography (Levell and Plint, 2026). Depending on the capacity of the receiving water body to disperse fluvial muddy sediments, sedimentary bodies can be related to subaqueous deltaic clinoforms, estuarine accumulation-dominated systems, or marine dispersal-dominated systems (Walsh and Nittrouer, 2009). The latter are common when the sea level is high, shelves are wider, and coasts are at a highstand or transgressive stage. In this context, the LCF embayment is envisaged as a marine dispersal-dominated system subjected to strong, distal fluvial sediment supply.

The LCF depositional system is characterized by: 1) a thick, mudstone-dominated succession, with only a few beds occasionally exceeding the very fine-grained sandstone; 2) abundant carbonaceous debris, some leaf-bearing beds, syneresis cracks, overall low and fluctuating bioturbation intensity (BI), and low ichnodiversity, with trace fossil assemblages suggesting brackish-water stress in a marine realm; 3) the widespread occurrence of wave-generated sedimentary structures throughout the unit; (4) the relative scarcity of sedimentary structures indicative of unidirectional currents; (5) beds bearing root marks, indicating episodes of continentalization, without evidence of intervening coarse-grained shoreline deposits; and (6) laterally extensive, predominantly tabular beds with little evidence of erosional scouring or incision at the outcrop scale. Collectively, these features suggest deposition under conditions of high accommodation space and sustained fine-grained sediment supply from fluvial sources, but with limited impact of fluvial and tidal currents on sediment accumulation. The recurrent

occurrence of wave-generated structures indicates that wave action exerted a persistent control on sediment accumulation, whereas the absence of major erosional surfaces, valley-scale incision and overall tabular bed geometry, argues against fluvial valley infilling.

The observed sedimentological, ichnological, and stacking pattern features suggest that the LCF corresponds to a single depositional system, defined as a shallow, open- to marginal-marine, wave-dominated system under variable fluvial influence. As proposed by Guler *et al.* (2014) and Clyde *et al.* (2021), the unit accumulated within a complex transgressive paleogeography.

The lower part of the unit (FAs 1 and 2) shows sedimentological attributes linked to wave dynamics in shallow-marine settings. Particularly, FA 1 is dominated by high-energy, storm-wave-generated structures (*i.e.,* HCS and oscillation or combined-flow ripples) and well-sorted, fine-grained sandstones, typical of wave-agitated lower shoreface depositional settings (Clifton, 2006). The trace-fossil suites indicate brief colonization windows during inter-event periods by vertical elements attributable to the *Skolithos* Ichnofacies (MacEachern *et al.,* 2007; Buatois and Mángano, 2011). The overlying FA 2 reflects deposition under prolonged low-energy conditions in offshore-to-offshore transition settings and shows a highly bioturbated ichnofabric with abundant specialized fully marine ichnogenera which are characteristic of the distal expression of the *Cruziana* Ichnofacies (MacEachern *et al.,* 2007, 2012, 2026). Altogether, both FA 1 and FA 2 indicate deposition under fully marine conditions with a clear retrogradational stacking pattern formed during a period of marine transgression and limited at the base by a wave ravinement surface (Catuneanu, 2022). The lower surface of FA 3, marked as the M1, is recognized as a major depositional turnover in the system, since it marks a sharp grain-size change from mud-dominated, upward to sand-dominated accumulation (Figs. 4, 5a, b), after a widespread erosional episode.

Transitionally upward, FAs 3 to 6 are fairly mud-dominated (Fig. 4). These associations could be interpreted as a continuation of the transgressive

process, reaching deeper depositional settings and lower energy levels. However, the presence of beds with abundant continental vertebrates (Harper *et al.,* 2019; Sterli *et al.,* 2021; Cardozo *et al.,* 2025) and leaf-bearing horizons (Cúneo *et al.,* 2014), together with abundant carbonaceous debris and ubiquitous wave-generated (oscillatory and combined-flows) structures, it is suggested that water depths had never reached fully offshore conditions. Events of wave-generated (storms?) combined-flows are interpreted to have accumulated coarse-grained silt to very fine-grained sand subsequently draped by mud, forming heterolithic deposits along and across a low-gradient ramp (Buckley *et al.,* 2016). Structureless clay-rich layers probably represent the settling or gelling of fluid mud (Bhattacharya and MacEachern, 2009) or deposition by wave-enhanced gravity flows (Macquaker *et al.,* 2010; Moyano-Paz *et al.,* 2026). Evidence for very shallow depositional conditions are further supported by the presence of beds with very shallow-water to subaerial features (*i.e.,* rhizoliths) and by freshwater shallow bodies with aquatic plants (Cúneo *et al.,* 2014) from FA 4. The terrestrial affinity of vertebrate remains at the base of marker M3 also suggests reworking of fluvially derived carcasses eroded from FA 4. Remarkably, sandy shoreface deposits are absent at FA 4, suggesting that wave energy was not enough to build a sandy facies belt and thus favoring the development of muddy shorelines (Clifton, 2006; Buckley *et al.,* 2016; Levell and Plint, 2026). Tidal flats or interdistributary bays are typically coastal marine environments that produce successions comparable to FA 4. Nevertheless, no evidence of tidal or fluvial currents was recognized, suggesting the development of a littoral, low-energy wave-dominated, river-influenced embayment. This setting probably reflects episodic pulses of fluvial sediment supply that exceeded the capacity of waves to winnow and redistribute fine-grained sediment offshore. This mechanism is particularly likely in restricted marine settings, where wind fetch and thereby wave energy are reduced (Clifton, 2006; Buckley *et al.,* 2016; Levell and Plint, 2026). Sharply overlying the marker M3 (Fig. 4), the LCF begins recording sedimentation within a deeper central embayment; however, wave action is frequently observed, suggesting the persistence of shallow-water conditions. In this context, FA 5 shows higher BI values and greater trace-fossil diversity,

whereas FA 6 records sedimentation in similar settings but with a stronger distal fluvial influence, as indicated by the recurrent and pervasive soft-sediment deformation structures and the markedly lower BI values (Figs. 4, 5b, 5c). Compared to the underlying counterparts, FAs 3–6 exhibit a marked reduction in bioturbation intensity and heterogeneous bioturbation patterns (Fig. 4). They contain recurrent unburrowed beds interspersed with sparsely bioturbated deposits. This pattern suggests increasingly stressful environmental conditions, such as elevated sedimentation rates, increased water turbidity, substrate instability, subaerial exposure, and fluctuations in bottom-water physicochemical conditions, which limited benthic colonization (MacEachern *et al.,* 2005; Gingras *et al.,* 2011; Buatois *et al.,* 2012; Moyano-Paz *et al.,* 2020; Celis *et al.,* 2024). In particular, the recurrent occurrence of synaeresis cracks suggests repeated episodes of salinity fluctuations, which likely contributed to departures from typical fully marine trace-fossil assemblages representing expressions of the *Teichichnus* Ichnofacies (Gingras *et al.,* 1999, 2012, 2025; MacEachern *et al.,* 2026).

Hundreds of meters-thick muddy to heterolithic successions with salinity fluctuations are commonly reported for prodelta and distal delta-front depositional settings (Bhattacharya, 2006; Bhattacharya and MacEachern, 2009), forming coarsening-upward successions culminating with mouth-bar or distributary channel deposits. We found no record of such stacking patterns in the LCF. Alternatively, either wave- or tide-dominated estuaries are common traps for fine-grained deposits, particularly in the central estuarine basins or on large tidal flats, respectively (Dalrymple *et al.,* 1992). Estuarine mud-rich successions are architecturally complex, typically no thicker than a few tens of meters, and tightly linked to coastal sand bodies such as spits, tidal deltas, beach ridges, or tidal channel bars (Dalrymple *et al.,* 1992; Dalrymple and Choi, 2007). None of these features were recognized in the LCF. The few sand bodies described within FAs 3–6 (*e.g.,* just above M1 and M3) are sharp-based, tabular beds a few meters-thick, ranging from symmetric to nearly symmetric rippled coarse-grained siltstone to very fine-grained sand to sandy heterolithic deposits, dominated by combined-flow ripple cross-lamination. Some beds show intraformational lag conglomerates with reworked vertebrate remains at

their bases, interpreted as formed after periods of wave winnowing of previous deposits.

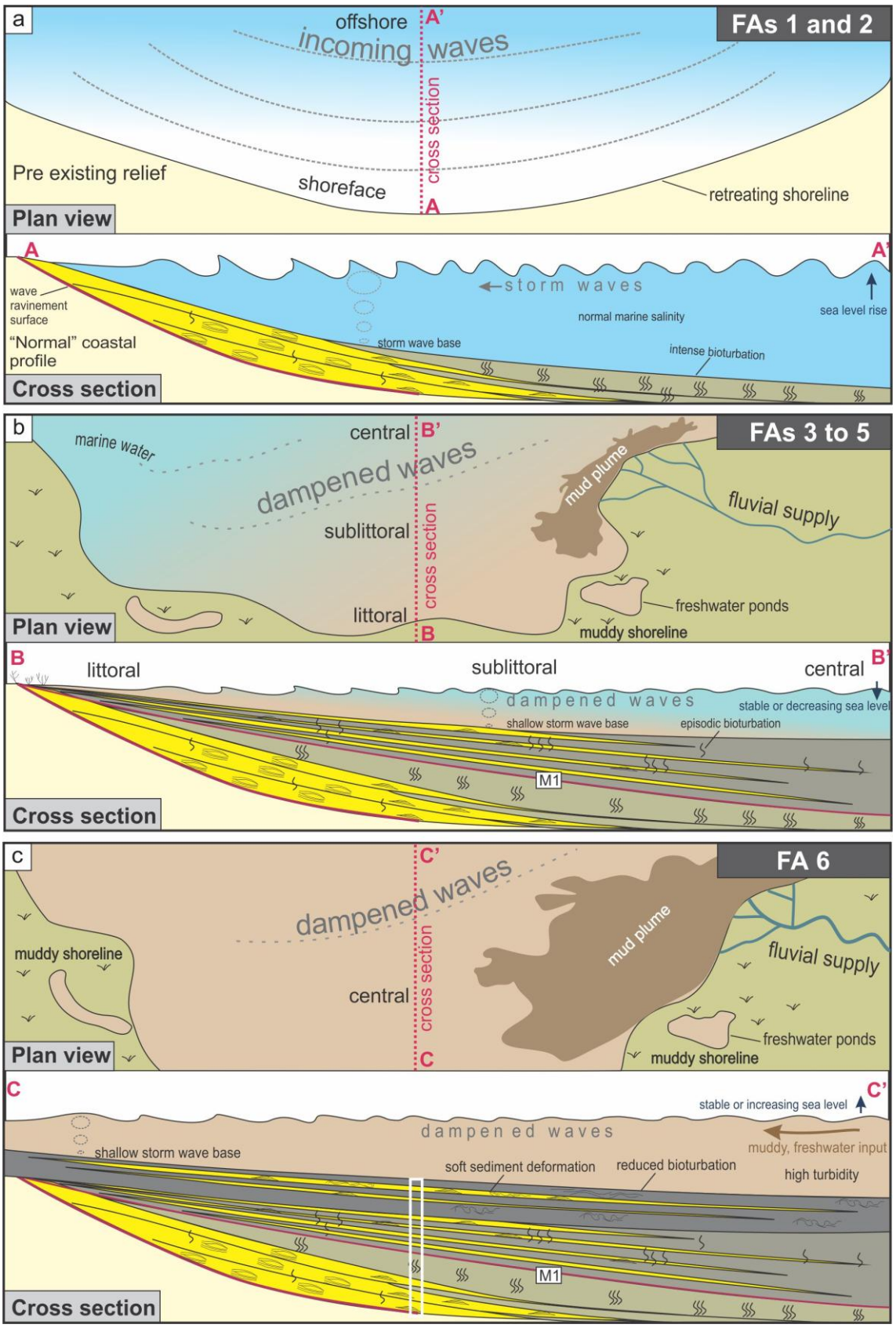


Figure 5. Conceptual model of the LCF embayment depositional system. The plan view schemes do not represent paleogeographic reconstructions. **a)** Shoreface to offshore wave-dominated embayment, with mostly normal marine salinity; **b)** FAs 3, 4 and 5 record littoral, sublittoral, and central subdivisions of a shallow, brackish embayment with variable, distal fluvial supply; and **c)** Brackish central embayment system under stronger fluvial influence. The white rectangle indicates the hypothetical position of the surveyed column (not at scale).

The evidence presented above led us to interpret that the LCF accumulated in a shallow-marine to transitional depositional system (Fig. 5). Particularly for the FAs 3 to 6, a fine-grained, wave-dominated, river-influenced embayment system is interpreted (Fig. 5). In contrast to open shallow-marine depositional models, shallow embayments are partly sheltered from the influence of marine hydrodynamic processes and consequently have restricted exchange with open-ocean water masses, limiting the mixing with the receiving fluvial input. For the embayment system, the ramp morphology and the high concentration of suspended river-derived mud would have dissipated wave energy in the nearshore region (Figs. 5b, c), allowing the accumulation of muddy sediments in these areas. As a result, the embayment would have acted as an efficient sink for fine-grained sediment and experienced intermittent to persistent brackish-water conditions (Buckley *et al.,* 2016).

Maastrichtian paleogeography and paleoclimate in the Cañadón Asfalto Basin (CAB)

During the Maastrichtian, the CAB behaved as a post-rift basin, with evidence of Andean tectonic inversion in the west (Allard *et al.,* 2022; Bilmes *et al.,* 2026). Sedimentation during this interval exceeded the Jurassic half-graben depocenters (Figari *et al.,* 2015; Allard *et al.,* 2022). The LCF was reported as one of several units (Coli Toro, Los Alamitos, Allen, Jagüel, Arroyo Barbudo formations, among others) representing the Maastrichtian–Danian extensive shallow epeiric sea that developed in northern Patagonia (Page *et al.,* 1999). This occurred after a regional-scale Atlantic marine transgression (Guler *et al.,* 2019; Clyde *et al.,* 2021) that flooded parts of the CAB and extended northwards towards the Neuquén and Colorado basins. Marine

transgressions over irregular pre-existing topographies may produce complex, irregular shallow-marine bodies (*e.g.,* Buckley *et al.,* 2016), as seems to be the case for northern Patagonia during the Maastrichtian. Particularly relevant are the abundant Jurassic volcanic rocks (Marifil and Lonco Trapial formations) in the area that acted as positive relief during a long-time interval, either in the Cretaceous or most of the Cenozoic (Guler *et al.,* 2019). Even though this complex paleogeographic scenario is still poorly understood, it is the probable cause of the restricted connection with open ocean processes recorded in the LCF. Approximately 200 km west of the study area, coeval deltaic to inner shelf deposits of the Lefipán Formation (370 meters-thick) accumulated in the shallow-marine Paso del Sapo Embayment (Scasso *et al.,* 2012), which supposedly was connected with the LCF area (Guler *et al.,* 2019; Clyde *et al.,* 2021). Each accumulation zone may likely constitute isolated depocenters or sub-basins, whose marine interconnections remain unsolved. The similarity in facies between LCF exposures in the study area and those in the Telsen area, approximately 80 km to the northeast (Navarro, 2012), suggests the development of a laterally extensive depositional system, consistent with a large shallow-marine embayment.

Fossil pollen and macrophyte records from the LCF indicate a humid and warm climate during the Maastrichtian at the study area (Cúneo *et al.,* 2014; De Benedetti *et al.,* 2023). This likely promoted high weathering rates, high watershed runoff, and an associated increase in fine-grained sediment delivery to the LCF embayment. The orientation and extent of the drainage basin of the supplying fluvial system remain unknown. The underlying Campanian Puntudo Chico Formation represents a fluvial system that was drowned during the Maastrichtian transgression and likely retreated towards the basin headlands. However, no fluvial systems coeval with the LCF have been reported to date. Thermochronological and tectonostratigraphic analyses suggest that at the time of LCF deposition, some compressional Andean structures were reactivated in the broken foreland area in western Chubut (Echaurren *et al.,* 2016; Bilmes *et al.,* 2026), possibly controlling drainage patterns and creating new topographic relief that may have shaped semi-

enclosed shallow-marine bodies. This marine restriction possibly had acted as a trap for fine-grained sediments and as a protection from oceanic waves.

Additional regional paleogeographic studies for the LCF, including lateral thickness and grain-size variations, shoreline orientations, and establishing regional bioturbation patterns, among others, are needed to better understand the nature of this shallow-marine embayment. In particular, the possible presence of a previously unrecognized muddy deltaic lobe remains an important hypothesis to be tested by future work.

CONCLUSIONS

Systematic sedimentological and ichnological observations through a 227 meters-thick mud-dominated succession of the La Colonia Formation at the Arroyo Mirasol Chico/Sierra de La Colonia area (northern Chubut) allow determining nine sedimentary facies. They indicate depositional processes including wave action of variable energy and bathymetric conditions, together with mud accumulation by suspension fallout or minor gravity flows. Because wave processes are ubiquitous, trace fossils show marine affinity, valley incision is not recorded, and fine-grained sediments dominate, we propose a shallow-marine embayment under wave and fluvial influence as the depositional model for the LCF.

Based on the vertical variation of these facies, the unit was divided into six facies associations that, from base to top, record a progressive shift from the lower shoreface though offshore transition to offshore, to sublittoral embayment, littoral embayment, and wave- and fluvial-influenced central embayment.

This embayment system is interpreted as a consequence of the Maastrichtian Atlantic transgression over an irregular topographic relief, forming complex, semi-enclosed shallow-marine bodies. Similar interpretations of other coeval units in northern Patagonia suggest that these

embayments should be connected. Additional studies are needed to complement the paleogeographic context for the LCF.

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