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Los Santos Formation in the Platanalito section: A fluvial and transgressive river-mouth estuary deposit of the Eastern Cordillera of Colombia

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Abstract

This study provides a new perspective in relation to the Los Santos Formation in the Mesas area, Eastern Cordillera of Colombia. The deposition at the base of the Los Santos Formation, referred to as Segment A, forms a coarsening-upward succession consisting of smaller entities of fining-upward type. This suggests a fluvial bay-head delta below the overlying Segment B, which is characterized by predominantly muddy succession. This lutitic domain of Segment B shows intercalated thin-bedded, very-fine-grained sandstones with double mud drapes, occasional plant remains, and the local appearance of *Kinneyia*. It has been interpreted as the deposit in the central part of an estuary. The presence of a tabular body of quartz sandstones, several meters thick (Segment C), observable at a distance in the landscape of the Mesas area, which develops a remarkable ravinement surface or some gullying features over the underlying lithologies at the bottomset. Segment C is mainly constituted by compound dune fields, where reactivation surfaces are oriented in the same direction as the internal stratification. These sedimentological features allow us to deduce its genesis from sediments coming from a source area located westward or southwestward, deposited obliquely or almost perpendicular to the fluvial deposit in Segment A. Segment C is interpreted as a transgressive sandy deposit at the mouth of the consolidating estuary. Subsequent minor tectonic activity reintroduces subaerial and muddy fluvial facies followed by scattered intertidal bars and channels in the fine-grained deposits of the coastal plain (Segment D). This reflects base-level fluctuations prior to the emergence of fossil-contained, tidal-influenced facies in the Cumbre Formation.

Keywords: *Kinneyia*; Transgression; Facies association; Compound dune; Base level.

La Formación Los Santos en la sección de Platanalito: un depósito fluvial y un depósito transgresivo en la desembocadura de un estuario, Cordillera Oriental de Colombia

Resumen

Se documenta una nueva mirada con relación a lo que la Formación Los Santos representa en el área de Mesas, Cordillera Oriental de Colombia. El depósito de la base de la Formación Los Santos, denominada aquí como Segmento A, forma una sucesión granocreciente compuesta por entidades más pequeñas del tipo granodecreciente que sugieren al tope un depósito similar a un delta en la

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cabecera de la bahía debajo del Segmento B suprayacente, el cual es una sucesión eminentemente lodosa. Este dominio lutítico muestra intercalaciones de capas delgadas de areniscas de grano muy fino con presencia de tapices dobles de lodo, restos vegetales ocasionales y la aparición local de *Kinneyia.* Se interpreta como el depósito en la parte central de un estuario. Es muy destacable la presencia de un cuerpo tabular de areniscas cuarzosas de varios metros de espesor (Segmento C), actualmente observable a lo lejos en el paisaje de la zona de Mesas, que desarrolla a la base una superficie de abarrancamiento o algunos rasgos de cárcavas de las litologías subyacentes. El Segmento C está constituido principalmente por asociaciones de dunas compuestas, donde las superficies de reactivación están orientadas en la misma dirección que la estratificación interna. Estas son las características sedimentológicas que permiten deducir su génesis a partir de sedimentos provenientes de un área fuente ubicada al oeste o suroeste y depositados en disposición oblicua o casi perpendicular al depósito fluvial del Segmento A. El Segmento C se interpreta como un depósito arenoso transgresivo en la desembocadura del estuario en consolidación. Un episodio menor de actividad tectónica reintroduce facies sub-aéreas y fluviales lodosas, seguidas de barras y canales intermareales esparcidas en depósitos más finos de llanura costera (Segmento D). Esto refleja las fluctuaciones del nivel base antes de la aparición de facies con contenido fósil e influenciado por mareas en la Formación Cumbre.

Palabras clave: *Kinneyia*; Transgresión; Asociación de facies; Dunas compuestas; Nivel de base.

Introduction

Sedimentary rocks from Jurassic to early Cretaceous in the region west of Bucaramanga have been studied extensively, yet several unresolved questions persist despite the efforts of numerous researchers. An important part of this problem involves understanding the sedimentological evolution in an area characterized by documented extensional tectonics.

According to the evaluations by Jiménez et al. (2021) and Laverde-Montaño (2023b), it appears that Los Santos Formation records the transition from the late Jurassic to the early Cretaceous. The new concepts about the sedimentological behavior of this rock package defined by Cediel (1968), re-studied by Laverde-Montaño (1985) in the El Roto type section, have enabled its correlations with other locations in the region.

Based on the stratigraphic column measured in the road to the Platanalito mine (Figure 1A, Figure 1B, and Figure 1C), located near Zapatoca town, the main objectives of this paper are: 1) describe the facies and stratal architecture of the Los Santos Formation, including facies analysis and three-dimensional architecture of the stratigraphy; and 2) provide a general facies description and paleoenvironmental analysis of the constituent units.

Methodology

The recognition and delimitation of facies variability patterns, along with the shapes of the sediment bodies defining them, provide an appropriate framework for understanding facies associations, the processes responsible for them, and their controls on the architectural development of deposits. To describe the Los Santos Formation, we used the following parameters:

1. Polygonal mapping along the road to the Platanalito mine, using a topographer, compass, and measuring tape. This data has been complemented with information obtained using Jacob's staff (Figure 1B).
2. Recognition and determination of the geomorphic units (*i.e*., sand-dominated or mud-dominated) into which the formation can be subdivided. This initial subdivision approach is termed segments, which can further be subdivided into intervals or facies associations.
3. Analysis of geometry aspects, internal stratification of bedforms, texture, and biogenic parameters following the methods of Campbell (1967), Merrill (1973), Allen (1980), Ashley (1990), Taylor and Goldring (1993), Miller and Smail (1997), and Desjardins *et al.* (2010a, 2010b, 2012).
4. Facies and facies associations result from a detailed analysis of each of the segments or intervals defined.

Brief stratigraphic and structural background

This paper provides a brief introduction to the most relevant stratigraphic and structural aspects of the area where the Platanalito section is located, as Laverde-Montaño (2023a, 2023b) provided a slightly more detailed account of the regional geological framework. Table 1 shows some of the most significant denominations and estimated ages for the Los Santos Formation. As observed, there have been significant discrepancies in both the name of the unit and its dating.

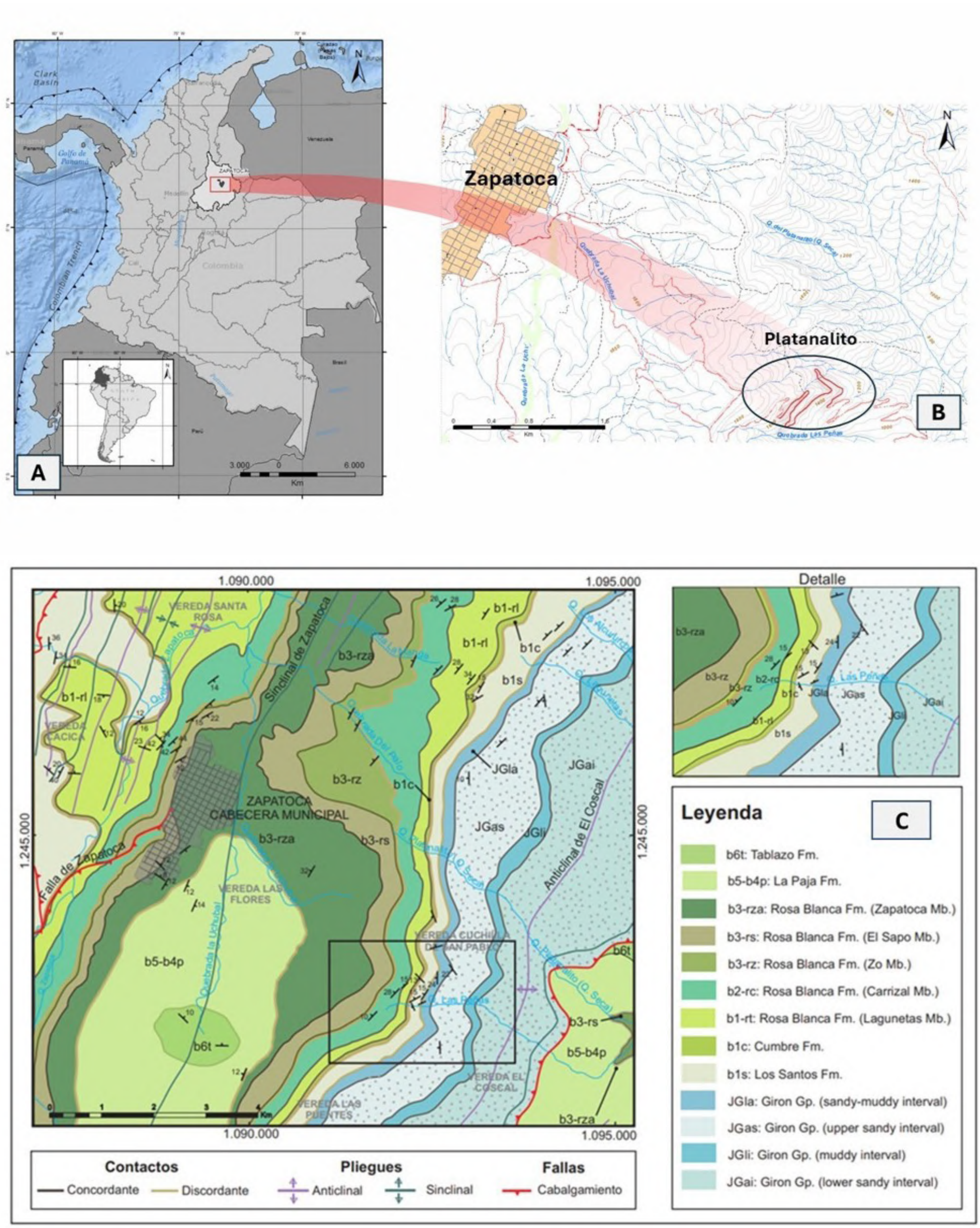

Figure 1. A. Location of the study area in northeastern Colombia. **B.** Route layout on to Platanalito mine near the town of Zapatoca (highlighted in red), where the stratigraphic section was measured. **C.** Geological map extracted from the study conducted by Moreno-Sánchez (2019) in the Sogamoso River canyon in the Villanueva-Los Santos-Zapatoca-Betulia areas. The black box indicates the area where the stratigraphic survey was conducted. Similarly, the map enclosed in the box is presented on the right side of the graph.

Table 1. Different denominations and postulated ages for the lithostratigraphic units of the Mesas and Cuestas region.

Authors/ Age	**Morales (1958)**	**Julivert (1958a, 1958b)**	**Cediel (1968)**	**Etayo-Serna (1989)**	**Horton *et al.* (2015)**	**Moreno-Sánchez (2019)**	**Etayo-Serna and Guzmán (2019)**	**Jiménez *et al.* (2021)**	**Laverde-Montaño (2023b)**
Early Cretaceous	Rosablanca Formation	Rosablanca Formation	Rosablanca Formation	Rosablanca Formation Cumbre Formation	Rosablanca Formation	Rosablanca Formation Cumbre Formation	Rosa Blanca Formation Cumbre Formation	Rosablanca Formation Cumbre Formation	Rosa Blanca Formation Cumbre Formation
	Tambor Formation	Tambor Formation	Los Santos Formation	Los Santos Formation	Los Santos Formation	Los Santos Formation	Los Santos Formation	Los Santos Formation	Los Santos Formation
Late Jurassic	Giron Formation	Giron Formation	Giron Formation	Angostura del Rio Lebrija Formation	Angostura del Rio Lebrija Formation	Giron Group		Angostura del Rio Lebrija Formation	Rio Lebrija Formation
Middle Jurassic									
Early Jurassic					Jordan Formation				
Triassic			Jordan Formation		Bocas Formation				
Paleozoic		Igneous and metamorphic basement	Bocas Formation						

Hettner (1891), defined "Estratos or Piso de Giron" as a succession of sandstones, red mudstones and limestones outcropping between Zapatoca and Giron. Other researchers attempted to understand the lithologies below the fossiliferous Cretaceous units, including Notestein in Schuchert (1935), Oppenheim (1940), Dickey (1941), Trumpy (1943), among others.

Morales (1958) confused a small outcrop located in the Bocas-Conchal area of reddish conglomerates, which was named Tambor by Hedberg (1931) with a lithostratigraphic unit underlying the fossiliferous Cretaceous succession consisting of intercalations of sandstones and shales of wide distribution in the Mesas and Cuestas region.

Julivert (1958a, 1958b, 1959, 1961, 1963) and Julivert and Tellez (1963) conducted pioneering work that laid the basis for the initial understanding of structural and stratigraphic aspects of the region, such as:

- The main geological features of the Mesas and Cuestas region include a package of Cretaceous strata overlying Triassic-Jurassic rocks, which rest upon an igneous-metamorphic basement. A common structural characteristic of the Mesas and Cuestas Region (Ruitoque, Los Santos, and Barichara) is the general westward dip observed in both the Cretaceous successions and the underlying Triassic-Jurassic rockbodies.
- Pre-Cretaceous erosion resulted in the beveled of the Jurassic units, which are tilted to the west. This important geologic feature is responsible for the absence or reduced thicknesses of the Jurassic rock bodies to the east.
- In addition to Langenheim (1959), Julivert *et al.* (1964) defined that the base of the Cretaceous is comprised of a siliciclastic unit (initially named the Tambor Formation) characterized by three segments. These segments include, a lower section consisting of sandstone and some reddish conglomerates, similar in appearance to the underlying Jurassic unit; a middle part composed of reddish shale with thin beds of intercalated sandstones, and an upper part consisting of distinctive white sandstones, that cover the entire surface of the Mesas region.
- Cediel (1968) reviewed and changed the Tambor Formation denomination, naming the new as the Los Santos Formation (Figure 2). Additionally, he established the Giron Group as comprising the Jurassic Giron Formation at the base and the Berriasian-aged Los Santos Formation at the top. The Los Santos Formation was interpreted as a marine deposit of proto-quartzites with occasional intercalations of red shale beds, transitioning to dark shales at the top.

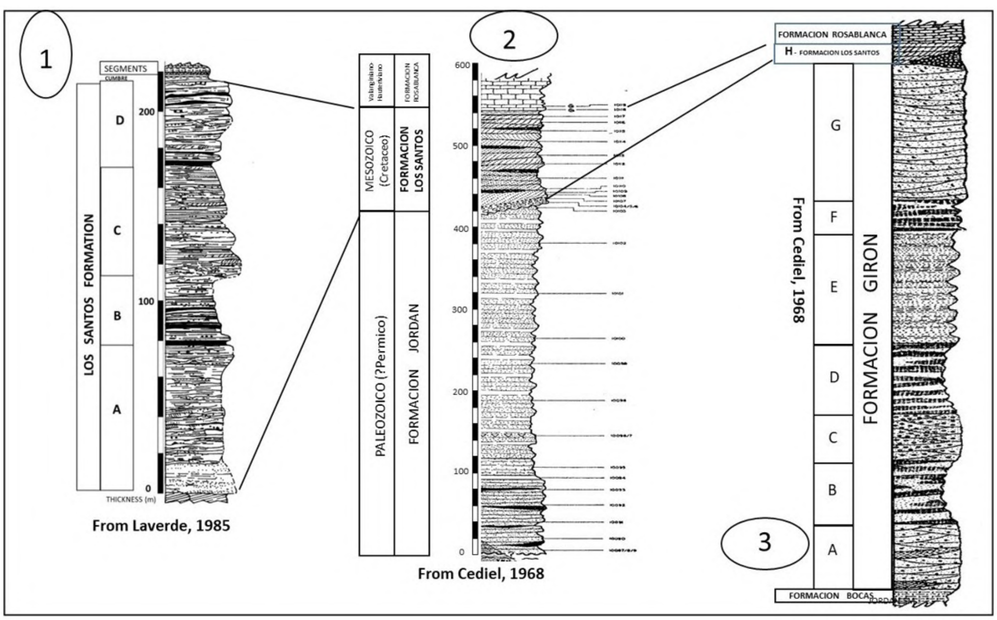

Figure 2. Correlation between the columnar sections surveyed by Cediel (1968) and Laverde-Montaño (1985). Number 1 corresponds to the survey of the Los Santos Formation in the type locality (Laverde-Montaño, 1985), the same location as that referred to by Cediel (1968) and identified with the number 2. On the right is the representation of the Giron Group formed at the base by the Giron Formation and the top by the Los Santos Formation according to Cediel (1968). Modified from Laverde-Montaño (2023a).

Laverde-Montaño (2023a) conducted a more detailed study of the Los Santos Formation (Figure 2) at the type section locality of the El Roto, defining:

Segment A: A fining upward succession consisting of clast-supported to matrix-supported sandy conglomerates interposed with conglomeratic sandstones, medium-coarse-grained sublithic sandstones, and local thin-bedded mudstones.

Segment B: Thick-bedded mudstones to fine-grained muddy sandstones, with locally occurring pebbly sandstone lenses.

Segment C: A thick to very thick-bedded package of planar cross-bedded sandstones, developing remarkable reactivation surfaces. Medium to fine-grained quartz-rich sandstones, with occasional intercalations of thin-bedded to thick-laminae of muddy sandstones and clayey siltstones.

Segment D: An intercalated package of thick-bedded mudstone and thin-bedded, to very fine-grained muddy sandstones. Abundant pipe-shaped ichnofossils noteworthy within these lithologies. Toward the upper part of the segment, there is a noticeable increase in trace fossils, such as burrows and tracks.

Clavijo-Torres (1985) and Laverde-Montaño and Clavijo-Torres (1985) subdivided this unit into three segments: A (lower) consisting of: conglomeratic sandstones, sandstones, and minor shales; B (medium) consisting of: sandy mudstones to mudstones; and C (upper) consisting of: intercalated quartzose sandstones and mudstones. A fluvial deposit was the interpretation.

Renzoni (1985a) used the name Tambor Formation to refer to the sequence of the Pujamanes creek instead of the new name of Los Santos Formation, agreed upon by the members of the Cretaceous Project. Etayo-Serna (1989) proposed a new nomenclature defining the Angostura del rio Lebrija Formation as the lower unit of the Giron Group, while the Los Santos Formation, constitutes the upper unit of the group.

Clavijo-Torres and Camacho (1993), based on the Code of Stratigraphic Nomenclature rules, adjusted the name of Angostura del Río Lebrija proposed by Etayo-Serna in 1989. They conceptualized that this unit should be called the Rio Lebrija Formation, a term used in this study. Moreno-Sánchez (2019) assigned the name of Giron Group to four lithostratigraphic intervals named from base to top as "Intervalo arenitico inferior", "Intervalo lodolitico inferior", "Intervalo arenitico superior", and "Intervalo lodolitico-arenitico". Consequently, the Los Santos Formation denomination has been excluded as an integral part of the Giron Group.

In recent times there has been a refinement of structural geology concepts, which has led to a better understanding of the various mechanisms that controlled sedimentation prior to Cretaceous deposition (Figure 3). Extensional tectonism created several half-graben systems that were filled with thick sequences of volcanoclastic and clastic deposits, predominantly of continental affinity (Velandia-Patiño, 2017; Jiménez et *al.*, 2021; Osorio-Afanador and Velandia, 2021); For example, the Jurassic Yariguíes Basin, situated close to the location of the Platanalito section. The Yariguíes Basin was formed as one of the multiple depressions generated during lithospheric stretching and extension, bounded by former normal faults (Velandia-Patiño, 2017).

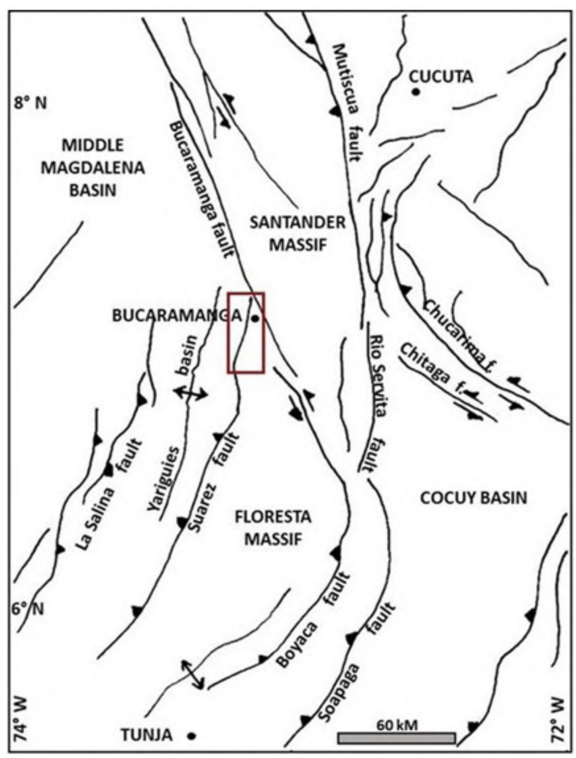

Figure 3. Map taken from the regional study prepared by Forero-Ortega *et al.* (2020), identifying the main regional structural features. The region where the Platanalito section was measured is enclosed in the red rectangle.

Tesón *et al*. (2013), Jiménez *et al*. (2016, 2021), Osorio-Afanador and Velandia (2021) among others, argued that synrift successions were segmented by transverse structures and regional longitudinal faults of the rift-shoulder, such as the Suarez Fault. This fault, is a pre-existing early Mesozoic normal fault, a tectonically inverted structure that controlled the exhumation of the Los Yariguíes Basin (anticlinorium).

Stratigraphic Column at the Platanalito area

Uppermost Rio Lebrija Formation

Near the road to the Platanalito mine, where the Rio Lebrija Formation is in contact with the Los Santos Formation, it forms an escarpment allowing observation of both its texture and geometry (Figure 4, Figure 5). The uppermost part of the Rio Lebrija Formation is thick to very thick-bedded, with lenticular to wedge-shaped bedsets, erosive-based, featuring common reactivation surfaces. It consists of massive, fining-upward, and coarsening-upward successions, medium to very coarse-grained, pale greenish-yellow (10Y 8/2) conglomeratic sandstones to sandy conglomerates, with local development of lenses and stringers of diverse pebble-size clasts along internal erosion surfaces.

At the uppermost part of the unit, the conglomeratic facies exhibit a disordered fabric, very poor selection, and proportions of the sand to gravel fractions vary randomly both vertically and laterally. Clasts are mostly subangular to subrounded, consisting of milky-quartz and quartzite, with minor chert, and intraformational siltstone pebbles. Generally, the conglomerate portion shows poor sorting to weak imbrication of clasts. In other nearby locations, the Rio Lebrija Formation comprises superimposed sets of lenticular-shaped coarse-grained sandstones that may contain pebble-lag horizons developed between sets and on foresets. Locally, sandy and conglomeratic successions are intercalated with grayish red purple (5RP 4/2) to grayish red (5R 4/2) fine to medium-grained muddy sandstones to sandy mudstones.

Los Santos Formation

The succession overlying the massive, mostly amalgamated conglomerates and conglomeratic sandstones that constitute the Rio Lebrija Formation in the Platanalito area is a very distinctive and geomorphological unit subdivided into four segments in this study, named from base to top as (Figure 4):

- Segment A consists of intercalated grayish red mudstones and very pale orange, medium to very thick-bedded, fair-sorted, sublithic sandstones, developing a coarsening-upward trend from minor fining-upward entities.
- Segment B is composed of a dominantly grayish red mudstone domain with minor intercalations of light brown very fine-grained sandstones.
- Segment C is a remarkable package of quartzose grayish pink to yellowish gray, medium-very thick-bedded fine to medium-grained sandstones that stand out throughout the area.
- Segment D, the bottomset is a dominant mudstone Interval (D1) presenting minor sandstone interbeds, whereas the remaining Interval (D2) consists of intercalated grayish red mudstones and yellowish gray sandstones, some of them with abundant bioturbation.
- At the uppermost part, there is a thin package of bioturbated siltstones, muddy sandstones, and dolomitized sandstones with the presence of small bivalves, micro-gastropods, known in the literature as the Cumbre Formation (*i.e.*, Etayo-Serna, 2019). A more detailed lithologic description, facies analysis, and depositional environment interpretation is presented below:

Segment A: Segment A rests on the Rio Lebrija Formation with little difference in bedding attitude data. However, the conglomeratic bodies that make up the top of the Rio Lebrija unit generally have a greater dip angle than those that make up the base of the Los Santos Formation, thus configuring an apparent overlapping contact geometry. In addition, the textural characteristics, geometry, and thickness of each of its constituents define a marked contrast between both lithological domains, suggesting a paraconformable contact.

On the other hand, a general coarsening-upward trend of Segment A is observed, resulting in a greater concentration of sandy levels in the middle to upper part of the segment. The lower part is dominated by thinner-bedded sandbodies intercalated with significant mudstone bodies, while in the upper middle part, the percentage of mudstones has decreased in concordance with an increase in the sandy fraction (Figure 4, Figure 6, Figure 7). Based on the facies associations, we have differentiated the following intervals:

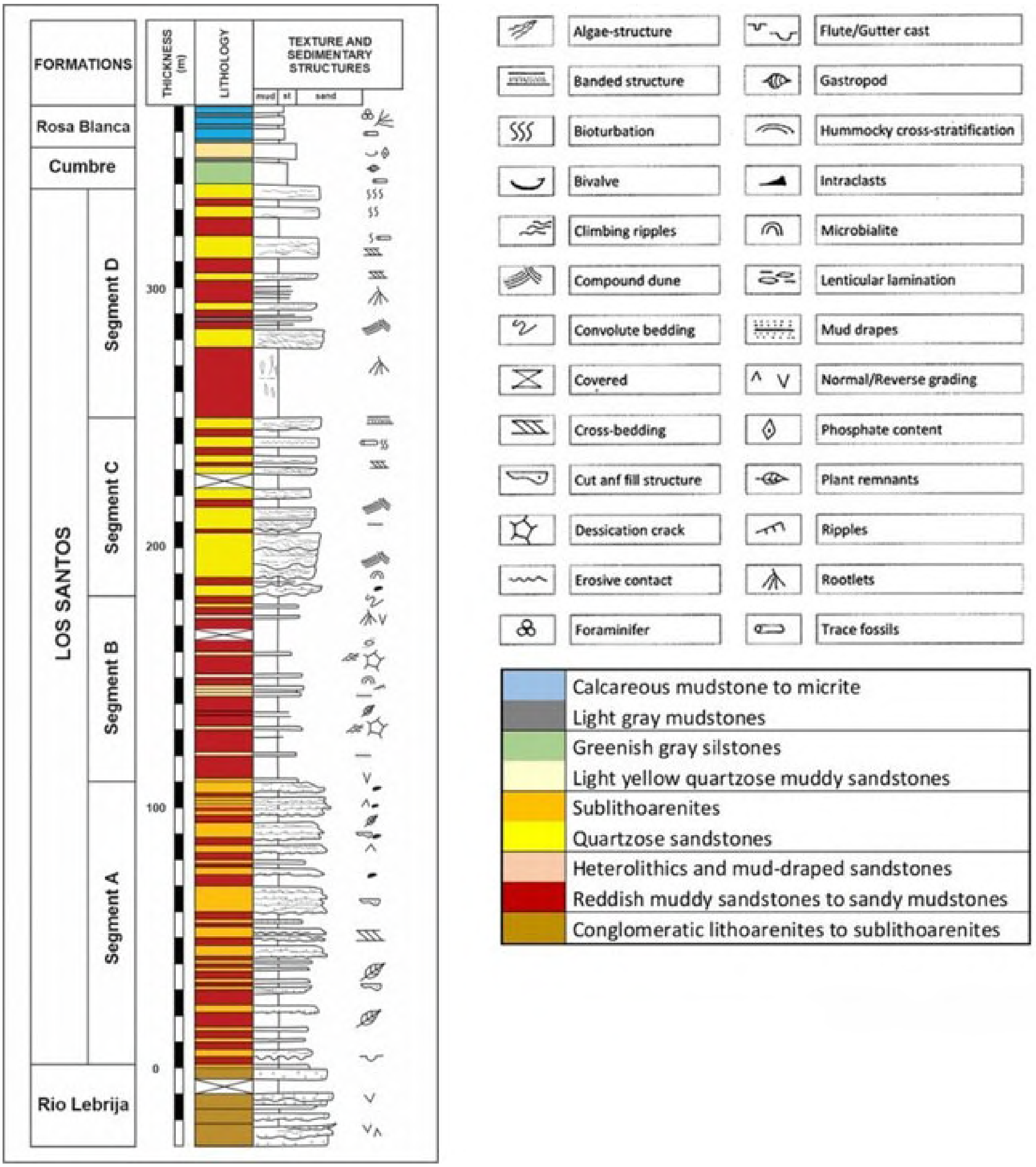

Figure 4. Generalized stratigraphic column of the Los Santos Formation in the Platanalito area.

Figure 5. General features of the uppermost Rio Lebrija Formation at the Platanalito area. **A.** Very thick-bedded and massive conglomeratic sandstone, 73°14´11´´W, 6°47´34´´N. **B**. Bottomset showing fining-upward trend. At the topset abundant gravel-sized constituents. 73°14´09´´W, 6°47´40´´N.

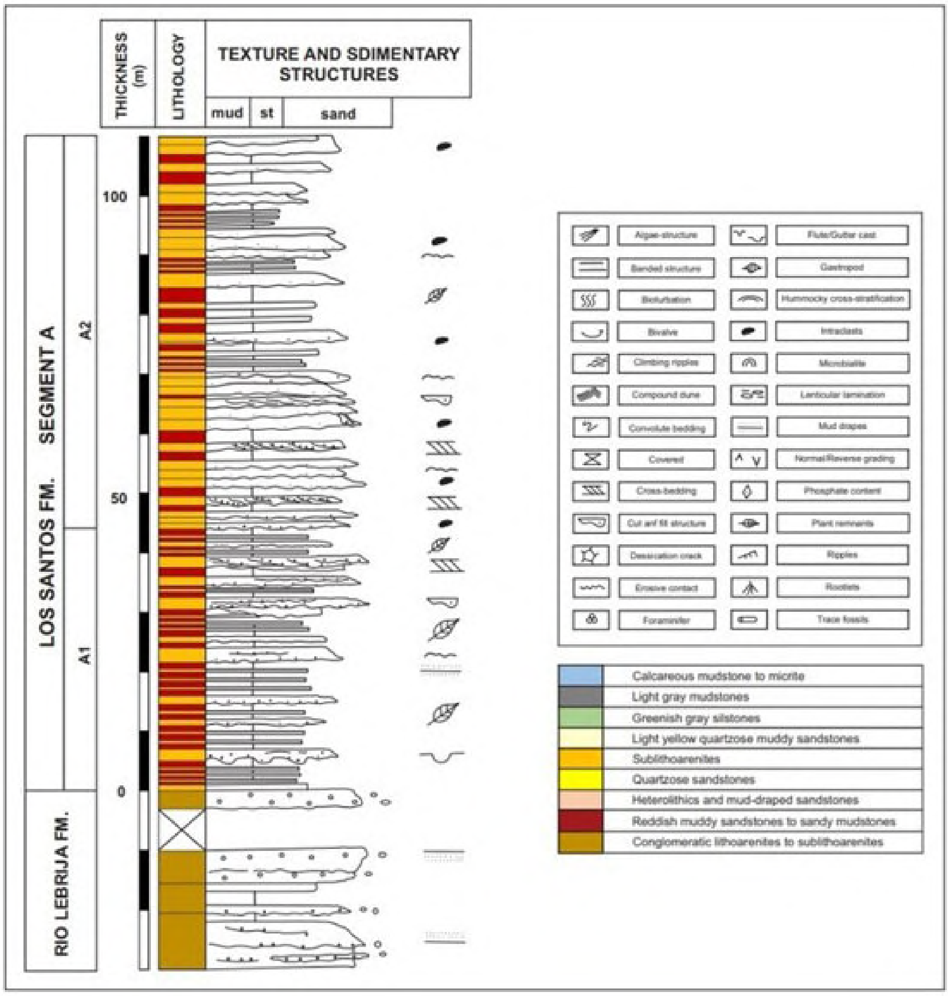

Figure 6. Stratigraphic column of Segment A.

Interval A1, approximately from 0 to 43 meters thick. It is composed of predominantly massive grayish red (10R 4/2) sandy mudstones to moderate reddish brown (10R 4/6) fine to very-fine-grained muddy sandstones. These are intercalated with medium to thick-bedded, planar, and small-scale planar cross-stratified, medium-to-fine- grained, very pale orange (10YR 8/2) sublithic fining-upward sandstones in sub-horizontal sets. There is local development of bipolar cross-stratified sandstones, small-scale heterolithic inclined stratification, and low-angle cross-stratified sandstones. The sandbodies exhibit reactivation surfaces, and some are eroded at the top. Locally, the topsets are fine-grained rippled sandstones, mud draped, and plane-parallel-laminated. Leaves, wood, and other plant fragments, vertical or irregular greenish gray horizons are observed in the finer sediments.

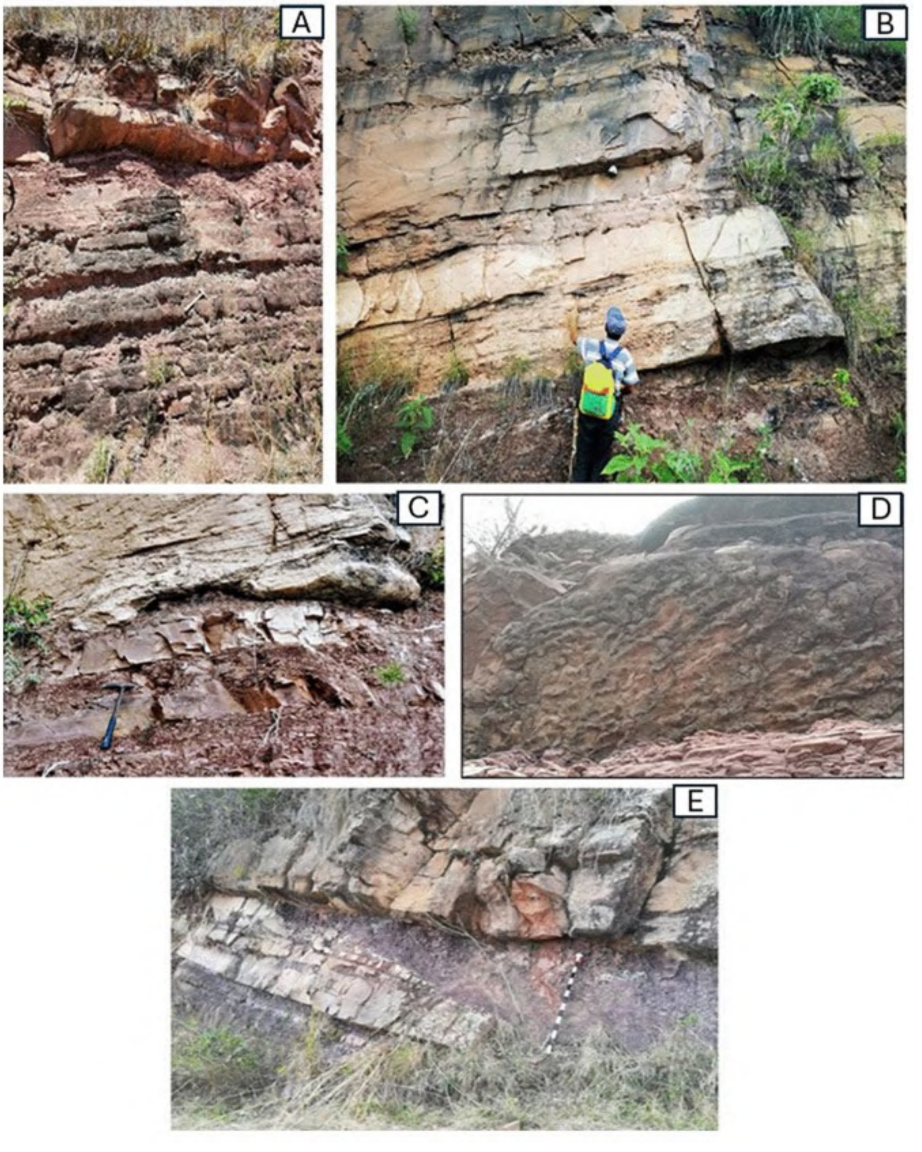

Figure 7. Main facies association within Segment A. Photographs **A, B, C,** and **D** show intercalated thick-to-very-thick-bedded mudstones-muddy sandstones and medium to thick-bedded sandstones at the lower part of Interval A1. Gutter and flute casts are widespread (see photos C and D respectively). A fining-upward succession from fine-medium-grained sandstone to siliceous siltstone and claystone is shown in B, whereas intercalated tabular thin-medium-bedded fine-grained sandstones and mudstones observable in D and E suggest overbank deposits. In the lower half of **E**, an irregular and erosive surface is cutting the medium-bedded and tabular-like geometry of sandbodies that represents a crevasse splay complex. This erosive feature and later infilling by reddish-gray mudstones are indicative of channel abandonment in Interval A1. The scale is given by stick divisions accounting for 10 cm each. The hammer is 30 cm long. Locations range from 73°14´14´´W, 6°47´42´´N to 73°14´22´´W.

Interval A2, developed approximately from 43 to 110 meters thick. It consists of medium to very thick-bedded, lenticular to wedge-shaped bedsets of fine to medium to coarse-grained, very pale orange (10YR 8/2) sandstones. These sandstone bodies typically feature multiple internal erosion surfaces and consist of laterally and vertically amalgamated, erosional-based, large-scale inclined strata, locally planar and trough-cross-stratified. Thin to medium-bedded, tabular geometry of fine-grained sandstones is notable in most of the muddy intercalation intervals. These facies exhibit normal and reverse grain-size grading, but in general, each specific bedset is fining-upward. All the sandy successions are intercalated with grayish red purple (5RP 4/2) to moderate red (5R 5/4), grayish red (5R 4/2) very fine-grained muddy sandstones to sandy mudstones showing plant fragments and scattered vertical or irregular, greenish-rooted gray horizons.

Interpretation: Interval A1 is interpreted to represent deposition within a mature fluvial system, likely in a meandering domain, indicated by the bedding shape, muddy-sandy ratio, the geometry of some of the intercalations, and the presence of cut-and-fill structures generating abandoned channels or "ox-bow lake deposits" (Figure 7E). Some small periods of tidally influenced deposits are suggested by the presence of rhythmic mudstone drapes, plane parallel-laminated to rippled-laminated sandstones, and local bidirectional cross-stratified sandstones. The thin laminae of mudstone drapes suggest deposition during slack-water periods. Rippled-laminated sandstones could represent channel abandonment or inter-channel areas (Miall, 1996). According to Dalrymple and Choi (2007), areas with no tidal influence during times of high river discharge may experience appreciable tidal influence during times of low river flow.

The texture and geometry of the of the sandy bedforms, plant fragments, and associated rooted horizons of Interval A2, suggests deposition in fluvial channels. Following research by Plink-Bjorklund (2005) in Spitsbergen Norway, the multiple erosion surfaces indicate repeated episodes of channel incision and infill. Medium-scale cross-stratified sandstones and the fining-upward units are interpreted as migrating bars. Locally, the low abundance of lateral accretion units, amalgamation of the channel fills, and the minor presence of overbank deposits suggest that the channels had relatively less sinuosity than the fluvial system represented in Interval A1, where the overbank deposits geoforms dominate.

In conclusion, Segment A presents a sum of individual fining-upward successions with a lateral accretion pattern, typical characteristics of point bar deposits in a meandering river (Miall, 1996). The tabular to lenticular shape of interbedded planar cross-stratified sandstones and mudstone beds indicates crevasse splay deposits, while mudstone facies are interpreted as floodplain deposits. The predominance of reddish brown soils suggests seasonal dry and wet climatic conditions. Stacked (multi-storey) channels, as we observe in Interval A2, it suggests deposition in response to a relative fall in base level. These sands have the largest lateral continuity compared to the meandering (single-storey) channel sands (in Interval A1). The coarsening-upward trend of Segment A and the remarkable increase in sand content of the uppermost part of Segment A suggest fluvial bay-head delta deposition.

***Segment B*:** Interval B1, approximately 22 meters thick from the base of Segment B, constitutes the lower facies association of Segment B. It is composed of grayish red (10R 4/2) very fine-grained muddy sandstones to sandy mudstones, medium to thick-bedded, with a mostly massive appearance. There are locally discontinuous undulated to even-parallel internal laminations, intercalated to greenish gray (5GY 6/1) thin-bedded slightly calcareous siltstones, and beds of coarsening-upward very fine to fine-grained, well-rounded, slightly muddy sandstones. Scattered vegetal remnants are present (see Figure 4, Figure 8, and Figure 9).

Interval B2, with a measured thickness of 33 meters, overlies Interval B1. It consists of grayish red (10R 4/2) tabular geometry, thin to medium-bedded, very fine-grained muddy sandstones to sandy mudstones. In sectors, it is interposed by thin beds of slightly calcareous siltstones of greenish gray color (5GY 6/1), and locally intercalated by pale yellowish orange (10YR 8/6) thin to medium-bedded fine-grained quartz-arenites. These quartz-arenites present double mud drapes and slightly inclined, low-angle laminations forming a heterolithic cross-bedding. Additionally, other lithologies exhibit flat-parallel, wavy, lenticular-wavy, and climbing ripple lamination. Pipe-shaped ichnofossils parallel to the stratification are present on some bed surfaces.

In the upper part of this facies association, there is a sedimentary structure that, at the top of the bed, resembles the arrangement of a train of ripples.

However, upon closer observation, these same sedimentary structures are present in each split lamination sheet, forming a stacking of structures with the same shape and arrangement of apparent ripples. These structures are found on a flat to slightly wavy arrangement surface, consisting of irregular and sinuously curved ridges, partially forked. The ridges are separated by depressions measuring up to 2 mm. The structure, in general, does not present a preferential orientation. These sedimentary structures seem to correspond to the development of *Kinneyia*.

Interval B3 is developed at the uppermost part of Segment B, with a thickness of about 18 meters. The lower part exhibits thin to medium-bedded, tabular geometry, plane-parallel to slightly wavy internal stratification, predominantly siltstones to very fine greyish red sandstones (10R 4/2), with a conchoidal fracture. In this domain, there are interpositions of thin beds of slightly calcareous siltstones, greenish gray colored (5GY 6/1), with the presence of root ghosts, while woody fragments and desiccation cracks are visible in the rest of the succession. From the middle part to the top of this facies association, there are thick to very thick beds, tabular geometry, pale reddish brown (10R 5/4) very fine-grained muddy sandstones that alternate with thin to medium bodies of greenish gray (5GY 6/1) slightly calcareous siltstones. Locally, root remnants are present.

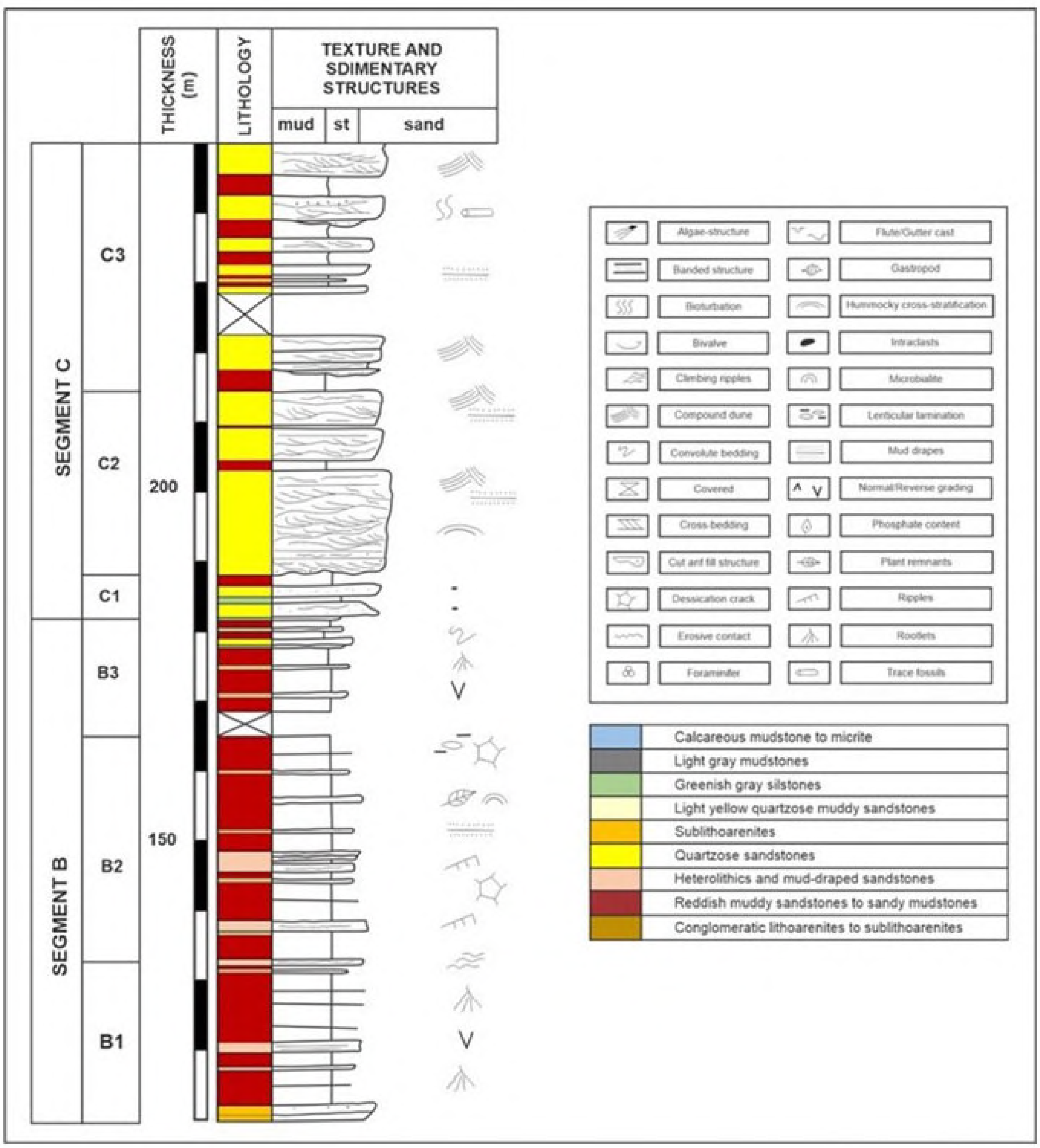

Figure 8. Stratigraphic column of the Segments B and C.

Interpretation: Sandy mudstones and muddy sandstones with plant remains may characterize deposits in floodplain areas. The root traces indicate that soil formation processes were taking place during the deposit of these sediments (Intervals B1 and B3). Crudely coarsening-upward and thickening-upward trends, in addition to the presence or bottomsets ripples, wavy lenticular stratification, and topsets climbing ripple-lamination, seem to suggest deposits from prograding and waning stage processes (Intervals B2 and B3). The greenish gray color of siltstones at the top of successions of reddish mudstones suggests deposition in a subaqueous environment.

The great predominance of tabular geometry and distinctive horizontal stratification in Interval B2, are indicative of a very flat paleotopography, possibly in a coastal plain or in a quiet lagoon zone due to the sediments deposited there. The intercalations of fine-grained quartz sandstone with the presence of double mud drapes suggest deposits with some tidal influence and record littoral sands deposition.

Kinneyia is the commonly used term to describe a class of trace fossil that is strongly associated with microbial mats. The appearance of *Kinneyia* (or wrinkle structures) in the fossil record has recently led to several possible mechanisms being proposed to explain its formation (Porada *et al*., 2008).

Recent research has shown that *Kinneyia*-type wrinkled sedimentary structures most likely form beneath cohesive microbial mats in the peritidal and intratidal zones. A genetic model to form such *Kinneyia* structures considers specific hydraulic conditions, such as those that occur in certain floods or storm events in siliciclastic tidal flats. The lithological record of the *Kinneyia* structures in Segment B reaffirms the presence of a tidal influx in this area.

Due to parallel-laminated and massive packages of mudstones with minor heterolithic sand/mud rhytmites participation, often wavy bedded, and the local presence of very thin-bedded siltstones to very fine-grained sandstone intercalations, these lithofacies suggest mud flat and mixed flat deposition, following Desjardins *et al*. (2012). Based on the previous considerations, we propose that Segment B constitutes the lithological record of an area where materials contributed by river currents from the continent (Segment A), located towards the ancestral Santander Massif to the east, converge with those from a coastal area located to the west or southwest in a relatively flat terrain. According to this, we suggest that Segment B corresponds to a central estuary or estuary basin (Allen and Posamentier, 1994; Dalrymple and Choi, 2007), among others.

Segment C: Interval C1: Thin to thick-bedded, lenticular to wedge-shaped, sigmoidal reactivation surfaces form compound cross-stratified, fine to medium-grained pinky gray (5YR 8/1) sandstones that laterally vary to light brownish gray (5YR 6/1) muddy sandstones. The sandstones are interbedded with thin-thick beds of grayish red (10R 4/2) mudstones and greenish gray (5GY 6/1) siltstones. The succession exhibits a general coarsening-upward trend. Low-angle planar cross-bedding and locally micro-hummocky cross-stratification are delineated by organic to mud drapes. In the lower part of this facies association, there is a sandbody more than 30 cm thick, with a significant percentage of oriented intraclasts. These rip-up clasts consist of grayish green mudstones with oxidized organic matter, they are elongated and are arranged laminarly in a continuous to discontinuous manner. Slumping structures are present at the top of this facies association (Figure 8, Figure 10).

Interval C2: The lower part is characterized by thin to very thick-bedded, intercalated tabular-dominated to lenticular and wedge-shaped geometry, fine to medium-grained, well-sorted, quartzose grayish pink (5R 8/2) to pale red (10R 6/2) sandstones (Figure 8, Figure 11). The individual sandstone beds are 20-50 cm thick, and when stacked, they form tabular to slightly undulating sets up to 180 cm thick, developing a general coarsening and thickening upward trend. Sigmoidal reactivation surfaces, planar cross-stratified, mud-draped low-angle, and hummocky cross-stratified beds are observable. Cross-laminae dips in the same direction as the reactivation surfaces. This succession is predominantly non-bioturbated. In this large packet of compound dune sandstones, there are locally thick laminae to very thin-bedded intercalations of lenticular and wavy-bedded grayish red (10R 4/2) siltstones and claystones.

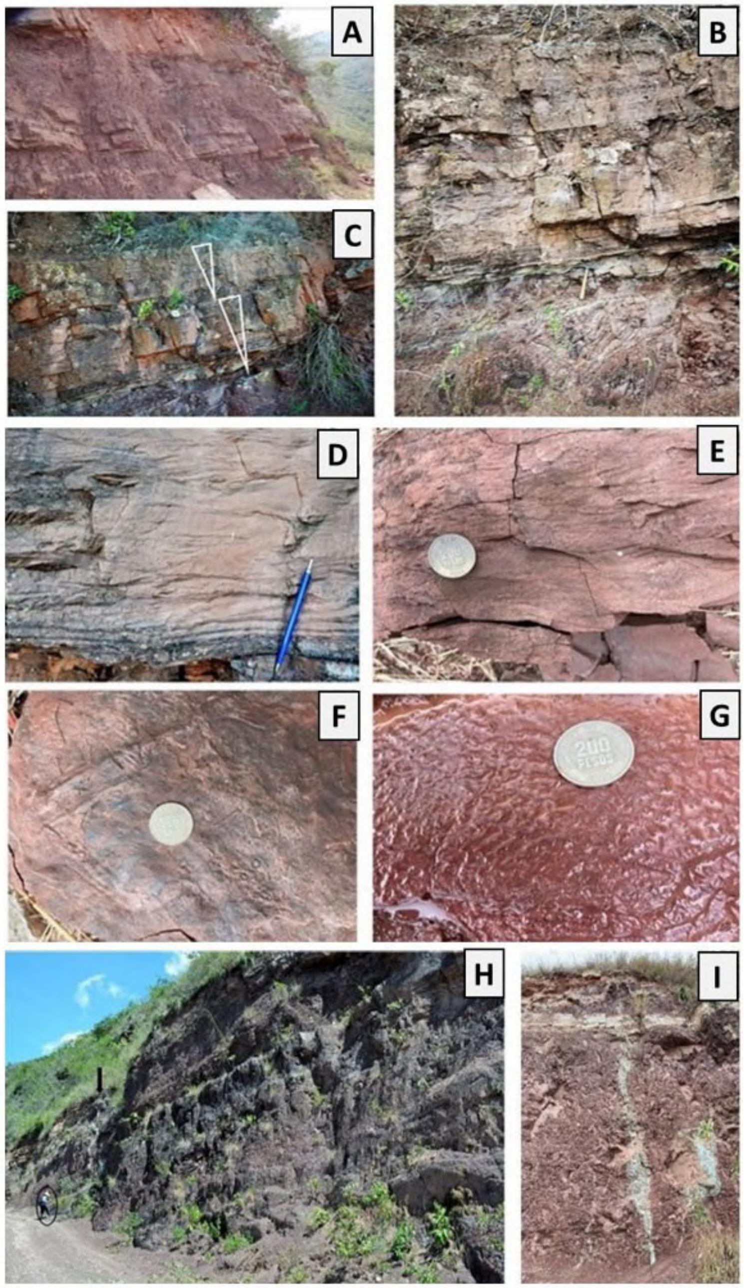

Figure 9. Distinctive features of Segment B. **A.** Medium-bedded, fine-grained sandstones encased in dominant grayish red mudstones of the Interval B1. **B.** Tabular-dominated geometry of the intercalated very fine-grained sandstones and mudstones of the Interval B2. **C.** At the bottom, interpositions of grayish red (10R 4/2) mudstones and greenish gray (5GY 6/1) siltstones, overlain by two bedsets, form a package of thin to very thick-bedded, coarsening-upward, and thickening-upward (see arrows) muddy sandstones to very fine-fine-grained sandstones defining a tabular geometry. Sandbodies' internal stratification shows planar-parallel to slightly undulating laminations defined by organic to mud drapes. The hammer is 30 cm long. **D.** Very thick-bedded, fine-grained sandstone at the bottom exhibits repeated double mud drapes, and the rest of the bed displays ripple cross-lamination. The mud drapes may record semi-diurnal tidal events (Dalrymple, 2010). **E.** Lenticular mud-draped lamination delineates a climbing-ripple lamination. **F.** Elongated trace fossils are observed on bedding planes. **G.** The structure found on a flat to slightly wavy arrangement surface consists of irregular and sinuously curved ridges, and partially forked, suggesting the presence of *Kinneyia*. Photographs from B to G were taken at Interval B2. **H.** and **I.** are distinctive photographs of Interval B3, featuring very thick-bedded, tabular geometry, a general massive aspect, pale reddish brown (10R 5/4) mudstones varying to very fine-grained sandstones, and slightly calcareous greenish gray (5GY 6/1) siltstones. The scale is indicated by a person within an oval to the left of the photograph. The location spans from 73°14´17´´W, 6°47´41´´N at the interval B1 to 73°14´22´´W, 6°47´39´´N at the interval B3.

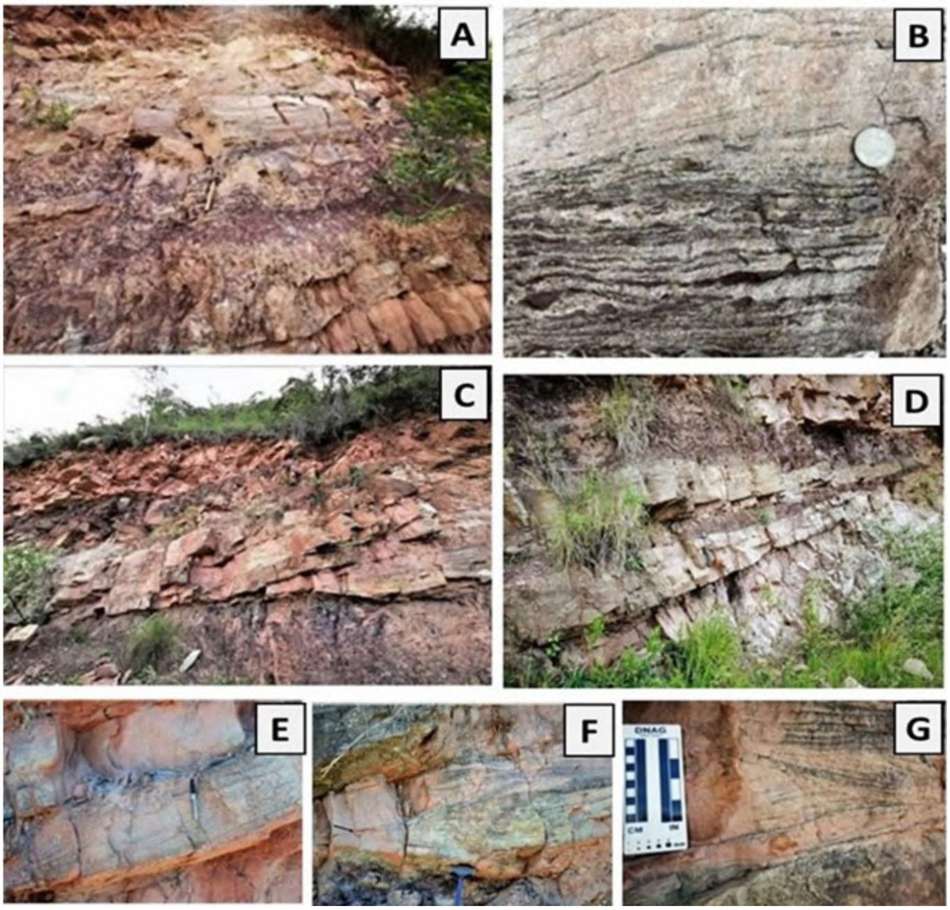

Figure 10. Distinctive features of the Interval C1. **A.** Intercalated very thick-bedded mudstones exhibiting soft deformation and medium-bedded sandstones, some with oriented rip-up clasts. **B.** Close-up of the sandstones described in A. Medium-bedded quartzose fine-medium-grained sandstone with a significant percentage of oriented rip-up clasts. These are arranged laminarly, composed at the bottomset by a mixture of organic matter with some oxidized minerals and at the topset by discontinuous grayish green mudstone intraclasts. **C.** Lenticular to wedge-shaped fine-medium-grained sandstones are interposed in a muddy succession. **D.** Medium to thick-bedded, lenticular to wedge-shaped, sigmoidal geometry, fine to medium-grained sandstones that laterally vary or are intercalated with muddy sandstones. **E.** Medium-bedded, low-angle planar cross-stratified, fine-grained sandstone. The cross-strata are delineated by organic matter drapes which become tangential at the bottom. **F.** Thick-bedded, lenticular geometry, micro-hummocky mud-draped at the top and low-angle cross-stratified to the bottom, fine-grained quartzose sandstone showing a sigmoidal-shaped surface separating different cross-stratified beds. **G.** Thin laminae of black organic drapes intercalated with very fine-grained quartzose sandstones delineate bidirectional cross-stratified dunes. The hammer is 30 cm long. The pen is 14 cm long. The coin is 25 mm diameter. Locations at 73°14´25´´W, 6°47´37´´N.

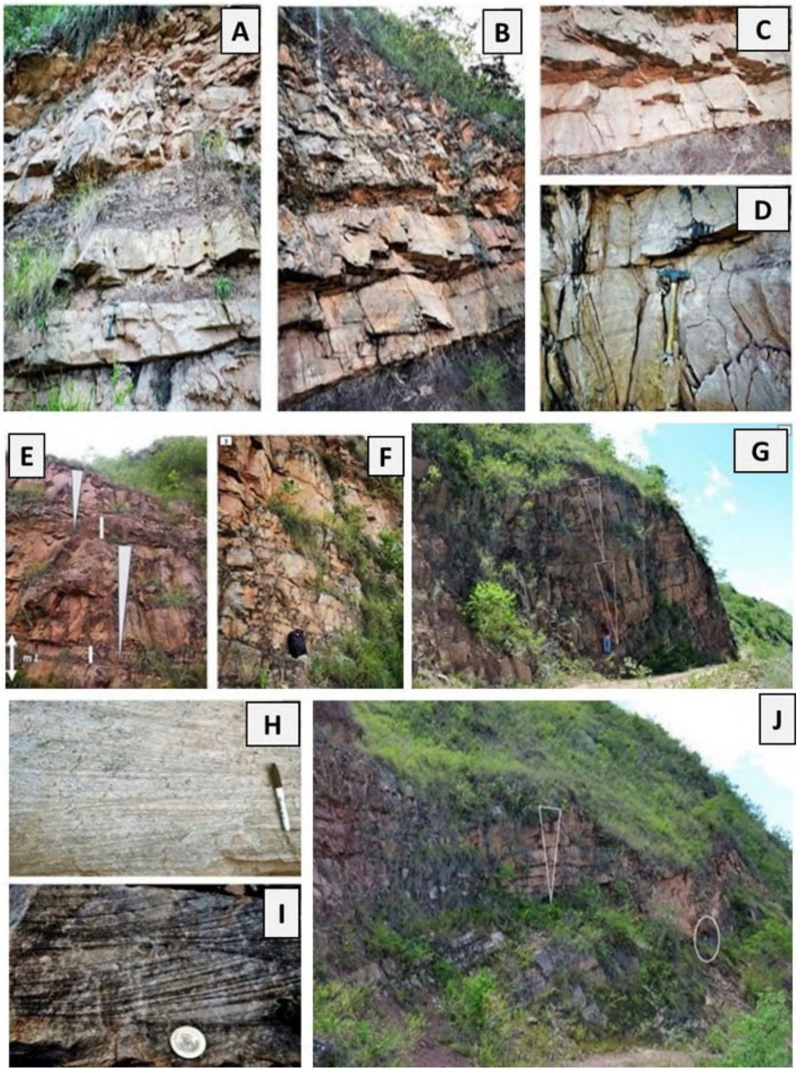

Figure 11. General features of Interval C2. **A.** Apparent amalgamated thick-bedded sandstones of Interval C2 are resting upon some intercalated grayish red mudstones and medium-bedded, sigmoidal-shaped sandstones of Interval C1. **B.** Contact between the reddish gray mudstones of Interval C1 and the base of the thick package of sandstones of Interval C2. **C.** The bottom of Interval C2 is characterized by sigmoidal and wedge-shaped geometry of the sandstones, resting in sharp contact with the grayish red mudstones of Interval C1. **D.** Planar and tangentially based cross-bedded fine-grained sandstones are presented at Interval C2 bottomset. **E.** Progradational succession package is composed of at least two bedsets of coarsening-upward and thickening-upward compound dune beds (the white arrow points to the boundary between packages). The lower part of each bedset (white line) is composed of medium to thick-bedded, low-angle cross-stratified, medium to fine-grained sandstones, whereas the upper part of each package consists of very thick-bedded, massive-appearance, medium-grained-sandstones, both representing a tabular to slightly sigmoidal geometry. **F.** Roughly tabular to slightly undulated geometry of thick-very thick-bedded quartz arenites are found at the lower part of Interval C2. The field bag is 40 cm in height. **G.** Progradational succession package composed of at least two bedsets of coarsening-upward and thickening-upward compound dune beds (the white arrow points to the boundary between packages). The lower part of each bedset is composed of medium to thick-bedded, low-angle cross-stratified, medium to fine-grained sandstones, whereas the upper part of each package consists of very thick-bedded, massive-appearance medium-grained sandstones, both representing a tabular to slightly sigmoidal geometry. **H.** Mud-draped low-angle planar cross-stratified and micro-hummocky cross-stratified at the bottomset, showing different reactivation surfaces and an oscillated flow direction nearly to the left at the lower part and then turning to the right at the upper part of the photograph. The pen is 14 cm long. **I.** In a sigmoidal-shaped, erosive-based, quartzose fine-grained sandstone, there are cross-bedded cosets mostly 10 cm thick, presenting concave foreset laminae, trough, or spoon-shaped delineated by very thin-laminae of dark gray organic matter drapes. The coin is 27 mm in diameter. **J.** At the upper part, medium to very thick-bedded, lenticular to wedge-shaped, coarsening-upward, and thickening-upward compound dune package of fine-medium to locally coarse-grained sandstones are merging in a progradational way the thick bedded, continuously bedforms of predominant medium-grained sandstones with tabular geometry. The white arrow points to the boundary between the upper compound dune sigmoidal package and the lower tabular-dominated package. A person inside the circle provides a scale. Location from 73°14´27´´W, 6°47´35´´N to 73°14´26´´W, 6°47´35´´N.

Interval C2 in the upper part consists of medium to very thick-beddded lenticular to wedge-shaped coarsening upward and thickening-upward compound dune package that progradationally overlies thick-very thick bedded bedforms with tabular-dominated geometry (individual beds are 15-60 cm thick and stacked, sets up to 170 cm thick). Internal stratification shows sigmoidal reactivation surfaces and low-angle cross-stratified, where lamination dips in the same direction as first-order reactivation surfaces. The sandbodies are grayish pink (5R 6/2), fine-grained, well-sorted, quartzose, sparsely bioturbated, with occasional muddy intraclasts at the topsets. Intercalated at the bottom and in the middle part are medium to thick-bedded grayish red (10R 4/2) siltstones and sandy mudstones.

Interval C3: It is composed of an alternation of mudstones and sandstones. Reddish gray (10YR 4/2) very thick, muddy siltstones and thin to very thick, lenticular to wedge-shaped pale yellowish brown (10YR 6/2) fine to medium-grained sandstones, locally thinning-upward, fining-upward compound dune, planar-laminated to low-angle cross-stratified internal stratification predominate over undulating laminae (Figure 8, Figure 12).

At the topset, intercalated thin to thick-bedded, heterolithic, pale yellowish brown (10YR 6/2) mudstone and yellowish gray (5Y 7/2) to light greenish gray (5G 8/1) very fine to fine-grained sandstone, parallel-laminated to symmetrical-rippled foresets and mud draped, forming thick laminae to thin-bedded tabular geometry, some of them wedge-shaped. The contacts between layers are predominantly sharp and slightly undulating.

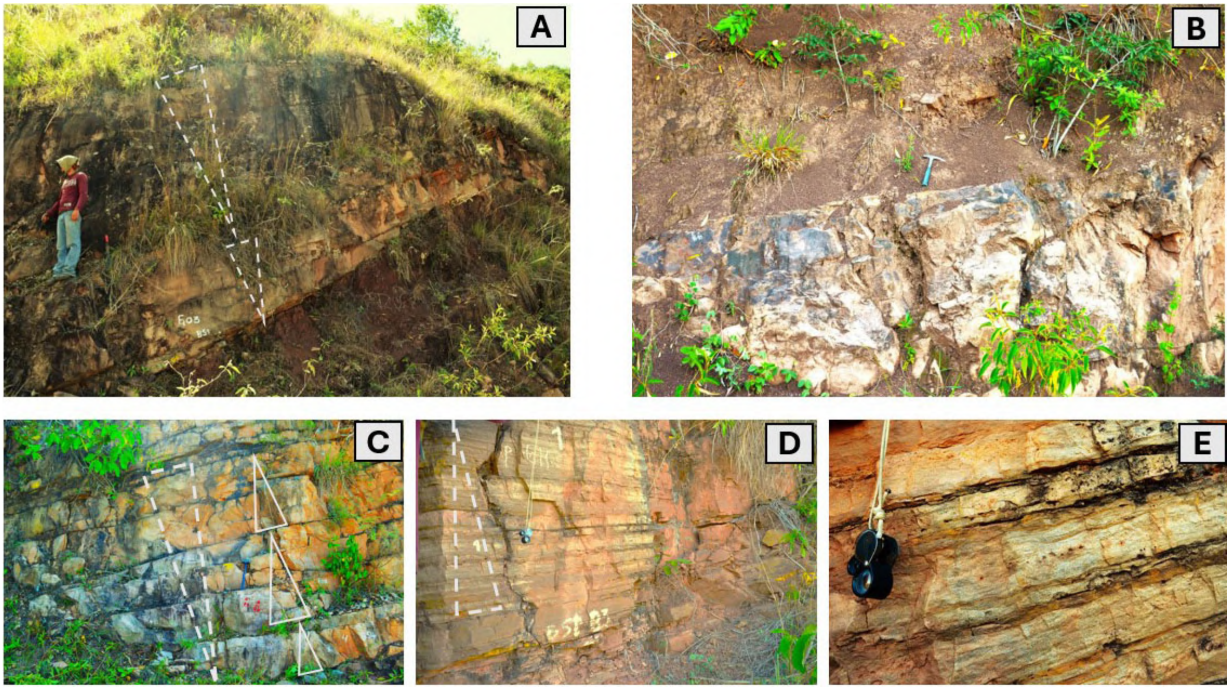

Figure 12. Interval C3. **A.** Thin to thick-bedded, lenticular, and wedge-shaped geometry: two packages of roughly coarsening-upward and thickening-upward compound dune, fine to medium-grained sandstones embedded in reddish gray mudstones. **B.** Outcrop aspect of the intercalated very thick packages of sandstones and medium to thick-bedded mudstones of Interval C3. **C.** Progradational succession package composed of three sets of fining-upward and roughly coarsening-upward compound dune beds. They have lenticular and wedge-shaped geometry, sigmoidal surfaces delineated by slightly undulating surfaces, some of them erosive-based, medium-thick-bedded, medium-grained sandstone. **D.** Thin to medium-bedded light greenish gray (5G 8/1) intercalated very fine to fine-grained sandstones and thick laminae to thin-bedded pale yellowish brown (10YR 6/2) symmetrical-shaped rippled mud drapes. The dashed blue arrow shows a fining-upward trend succession. **E.** Widespread, horizontal-arranged small, rounded holes of trace fossils. Contacts are predominantly sharp and undulating. Tabular geometry. Location at 73°14´23´´W, 6°47´33´´N.

Interpretation: Segment C represents an amalgamated and progradational compound dune package complex (Desjardins *et al*., 2011), or large compound tidal dunes (Olariu *et al*., 2012). Most of the cross strata is formed by simple superimposed dunes, dip in the same direction as the inclined master bedding planes within the compound dune, forming a forward-accretion architecture.

The significant percentage of elongated rip-up clasts in a sandbody of Interval C1 suggests an initial episode of a ravinement process. Remaining lithologies of this facies association are interpreted to have formed in areas of moderate to low current and wave energy, possibly very shallow subtidal areas. A position above storm wave-base is inferred based on the presence of micro-hummocky cross-stratified sandstone in this facies association.

The sharp contact between Interval C1 and Interval C2 records the early progradational phase of a shallow-subtidal compound dune field. The base of Interval C2, with the presence of large bedforms, is interpreted as evidence of increased sediment supply due to the migration of larger bedforms that mark the consolidation of the first transgressive ravinement surface (tRS1) of the estuarine deposits. The base of Interval C2 constitutes a major erosional surface, incising into the older inner surface of estuarine mudstone-dominated Segment B. This net, incisive, erosive-appearing surface at the base of Interval C2 results from tidal scouring at the mouth of the estuary and is known as the tidal ravinement surface (Allen, 1991). Interval C2 records the migration of medium to large compound dunes under strong unidirectional currents within a compound dune field in a probable shallow subtidal setting. The absence of significant mudstone beds intercalated into the sandstone packages in this facies association reflects high-energy conditions typical of shallow subtidal settings (*i.e.*, Desjardins *et al*., 2011).

Interval C3 is interpreted to represent the transition of compound dunes to intertidal sand flats, and the intercalated intertidal muds. The topset of Interval C3 is suggested to be deposited as a part of a lowermost tidal-flat complex, comprising several fining-upward progradational cycles.

The sediments of Segment C were probably provided by wave erosion of older nearshore marine and dune deposits from the adjacent coasts located toward the west or southwest as accumulated estuary-mouth shallow subtidal compound dune fields and intertidal sand flats (*sensu* Desjardins *et al*., 2011, 2012). In other terms, a marine sand body such as that represented by Segment C in this study accumulates in the area of high energy at the mouth of the estuary. It consists of a core of transgressive subtidal shoals and/or washover deposits on which is built an "estuary mouth sand plug" (*sensu* Boyd *et al*., 2006) or a barrier cut by one or more tidal inlets (Roy *et al*., 1980). Segment C, in general, suggests a dominant landward progradation of flood tidal deposits (*i.e*., Dalrymple, 2010).

Segment D: Segment D overlies Segment C and has been subdivided into Intervals D1 and D2. The reason for this subdivision lies in that at the base of Segment D, there is a predominantly muddy interval whose thickness is considerable (about 25 meters), and its continuity has been verified in the other stratigraphic sections of the Mesas region. On the other hand, Interval D2 is a very thick package made up of an intercalation of sandstones and mudstones that have features that will be described later.

Interval D1: It consists of a very thick package of massive grayish red (10R 4/2) sandy mudstones varying to muddy sandstones and grayish red to moderate red (10R 4/2 - 5R 4/6) siltstones to mudstones with varied light olive gray (5Y 5/2) forms, with the vertical arrangements capped by a horizontal whitest and faintly banded disposition. In other localities, lenticular and fairly wavy bedding is observable. Some local thin-bedded interpositions of fine-grained sandstones are present (Figure 13, Figure 14, Figure 15A).

Interval D2: This interval consists, at the lowermost portion, of a progradational succession package about 8 meters thick, composed of medium-thick-bedded bedsets of crudely fining-upward compound dune beds. They have lenticular geometry, sigmoidal-shaped surfaces that are delineated by sharp and undulating contacts, some of them erosive-based. Low-angle planar cross-stratification is dominant, local trough cross-stratified. Grayish orange pink (5YR 7/2) to very pale orange (10YR 8/2) fine-grained sandstones, well-sorted, with local mud drapes and interbeds of thick laminae to thin-bedded greenish gray mudstones (5GY 6/1). Deformation structures are visible at the topset. No bioturbation is observable (Figure 13, Figure 14, Figure 15, Figure 16). Overlying are 10 meters of intercalated, massive, thick-very thick-bedded, brownish red (5YR 4/1) mudstones and tabular-shaped, planar-laminated medium to thick-bedded pale yellowish brown (10YR 6/2) fine-grained sandstones. Muscovite and plant remnants are present on bedding surfaces.

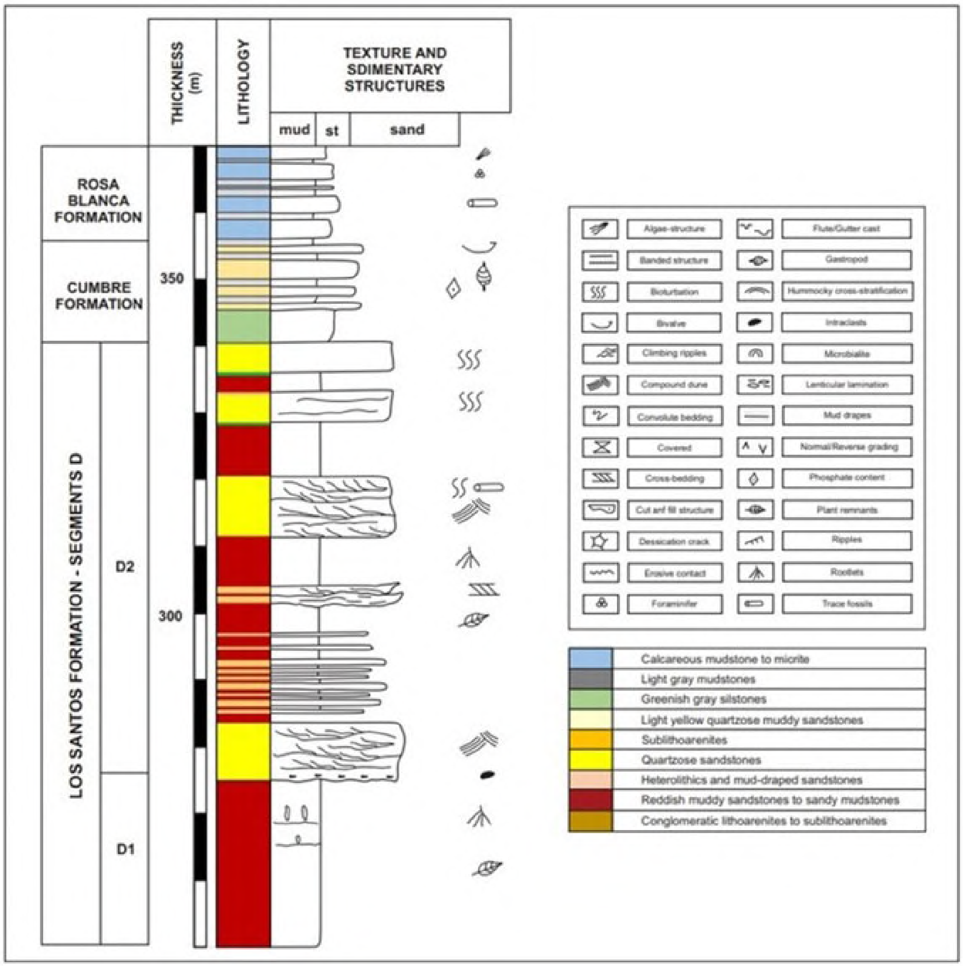

Figure 13. Stratigraphic column of Segment D - Intervals D1 and D2.

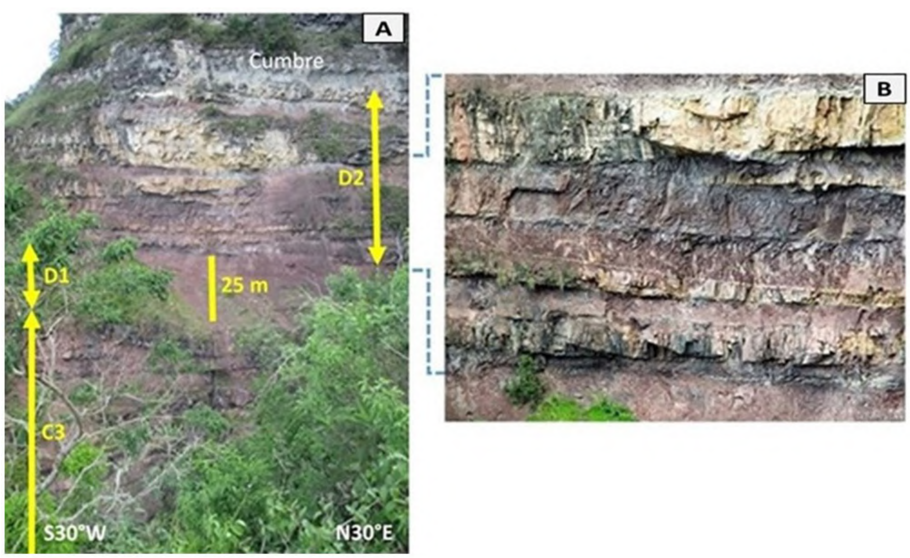

Figure 14. A. Interesting panoramic view of the upper part of the Los Santos Formation taken westward of the Platanalito pathway showing the main subdivisions from the upper part of Intervals C3, through D1 and D2. **B.** Distinctive close-up of the dominant tabular geometry of the rock bodies and an apparent channeled geoform with accretional signatures of a sandbody (73°14´33´´W, 6°47´29´´N).

Resting upon the previous facies, a very thick package of grayish red (10R 4/2), sandy siltstones to clayey siltstones rests upon the previous facies, with abundant vertical-shaped grayish green disruptions related to root remnant traces, showing lenticular and discontinuous thin-medium-bedded pale yellowish brown (10YR 6/2) fine-grained sandstone interbeds. Interposed in this very thick, muddy package is a small compound dune, 3 meters thick, lenticular and wedge-shaped, thin-thick bedded, fine-medium-grained sandstone, with thin-bedded muddy intercalations showing erosive-based contacts, and channeled geometry (Figure 15B).

On the wall located toward the west (Figure 14), this succession is represented by a wide lateral extension (sheet-like), tabular geometry, erosive-based and sharp flat top, which is locally superimposed by canaliform and erosive bodies. Both tabular-sheet-like bedforms and canaliform bodies show lateral accretion surfaces.

Another compound dune development, similar to those at the bottom of Interval D2, is found in its upper part. The toeset of this compound dune is well-represented on the wall situated toward the west (Figure 13, Figure 14, Figure 17), and is tectonically deformed on the way to the Platanalito mine (Figure 18A). In the outcrop, it consists of a progradational succession package, approximately 10 meters thick, composed of a medium-very thick-bedded compound dune. They have lenticular to wedge-shaped geometry, and apparent sigmoidal reactivation surfaces. Low-angle planar cross-stratification is observable. Texturally, it consists of very pale orange (10YR 8/2) fine to medium-grained sandstones, well-sorted, mud-draped, with local interbeds of thick laminae to thin-bedded greenish gray mudstones (5GY 6/1). Some beds show abundant, non-recognized trace fossils (Figure 18B), and some others depict a "Chinese writing" and are interpreted as *Scoyenia* ichnofacies (Figure 18C).

Overlying are grayish red (10R 4/2) very fine-grained massive muddy sandstones to sandy mudstones with abundant and irregular-shaped spots of greenish gray mudstones indicating plant remnants. This succession is interposed by two bedsets of sandstones. The lower sandbody, approximately 5 meters thick, is affected by tectonism in the outcrop, but it has better exposure on the wall situated toward the west. Following the main textural features in the outcrop is a yellowish gray (5Y 7/2), fine-medium-grained sandstone, well sorted. The sandstone is burrowed (BI=3-4 scale from Taylor and Goldring, 1993) at the topset.

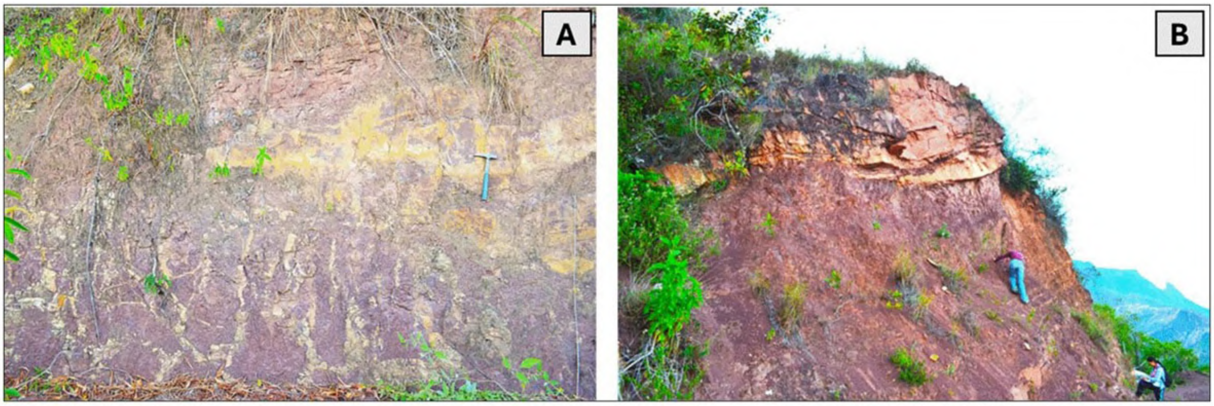

Figure 15. A. Segment D, Interval D1 is characterized by reddish red color (10R 4/2) mudstones that have abundant vertical structures of light olive gray color (5Y 5/2) root-shaped, manifesting a well-drained vertical soil-profile. **B.** The mudstone-dominated succession that overlies the basal compound dune of Interval D2 has lenticular and discontinuous thin-medium-bedded sandy interbeds. At the top, a lenticular and wedge-shaped thin-thick bedded, fine-medium-grained sandstone package with thin, muddy intercalations showing erosive-based contacts and well-defined channeled geometry.

Figure 16. Bottomset of Interval D2: **A.** Very thick package of compound dunes, fine to medium-grained sandstones, well-sorted, composed by medium to very thick-bedded sigmoidal and wedge-shaped bedsets, some erosive-based with the development of reactivation surfaces capping thick-laminae to thin-bedded greenish gray mudstones. **B.** Detail of sandbodies described in Figure 16A, medium to thick-bedded, sigmoidal-shaped surfaces defining a wedge-shaped to lenticular geometry, low-angle planar cross-stratification. Fine to medium-grained sandstones, well-sorted, local mud drapes, thin laminae to thin-bedded greenish gray (5GY 6/1) mudstones interbeds. No bioturbation is observable. **C.** Additional observation of sandbodies mentioned in Figure 16A. Thick-bedded, erosive-based, sigmoidal-shaping surfaces, planar cross-stratification (tangentially-based). Fine-grained quartzose sandstone, well-sorted, thick-laminae of greenish gray mudstone is underlying the undulating sharp contact of the sandbody. Pen´s length is 14 cm (73°14´25´´W, 6°47´40´´ N).

The upper sandbody, 6 meters thick, is made up of thick to very thick-bedded, tabular geometry, pale greenish yellow (10Y 8/2) to yellowish gray (5Y 7/2) fine-medium-grained sandstone. The sandstone body is almost completely bioturbated (BI=5-6), with the presence of disseminated siderite, glauconite, and phosphate (Dalrymple, 2010). This sandbody has been recognized by many geologists as the top of the Los Santos Formation and is overlain in transitional contact by medium gray (N3) siltstones, mostly fossiliferous, belonging to the so-called Cumbre Formation (Figure 18E).

Interpretation: The predominant red mudstone package of Interval D1, with irregular, greenish, vertical oriented muddy sediments, suggests pedogenesis and indicates a soil profile developing on a gradually aggrading coastal to estuarine floodplain. The bluish or greenish grey color of the silty fraction at the top of the reddish mudstones suggests deposition in a subaqueous setting. Lenticular and roughly wavy bedding in the Interval D1 imply alternating current flow and slack-water conditions (Reineck and Singh, 1980).

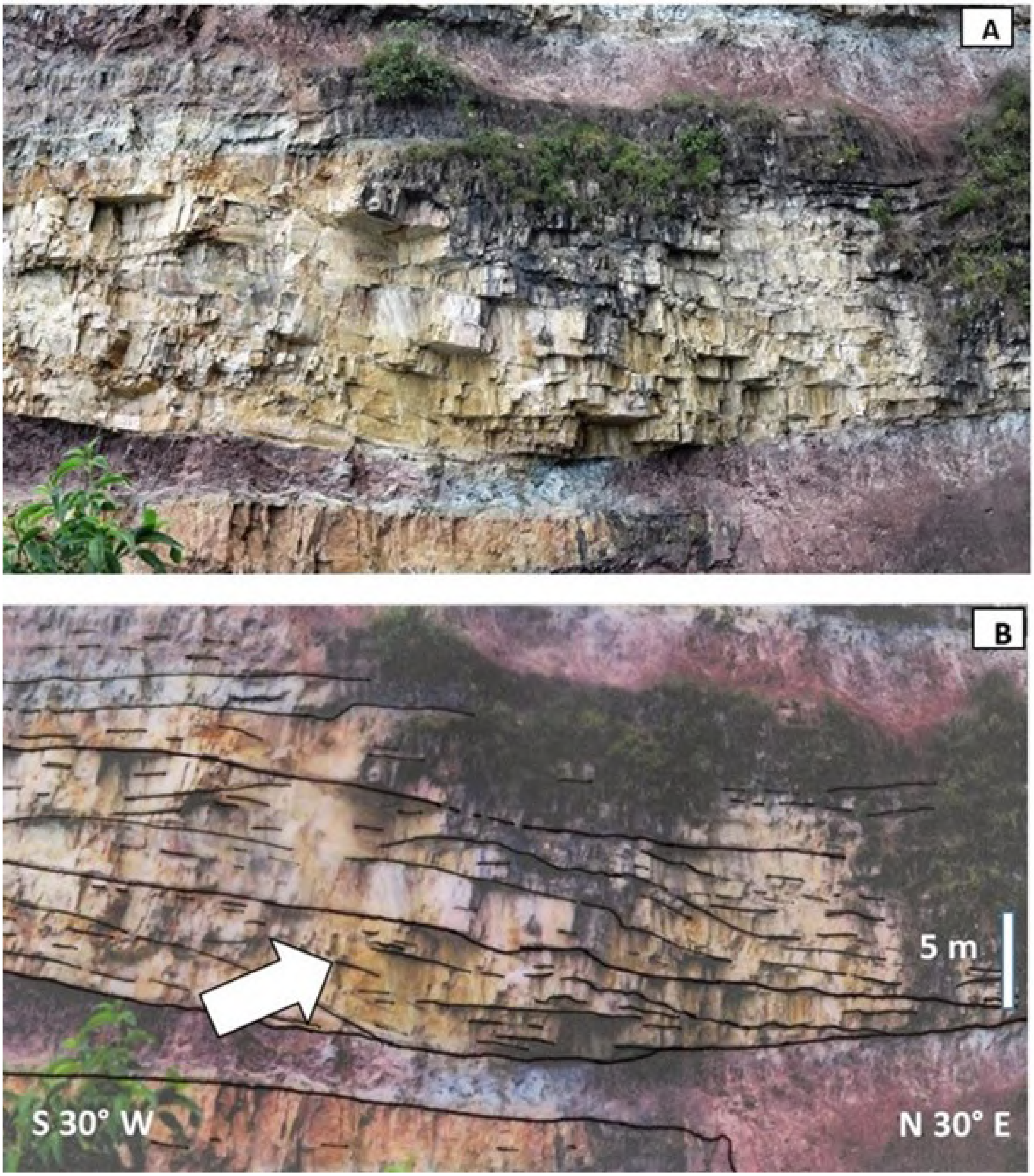

Figure 17. A. Panoramic view of a wall located westward of the road to the Platanalito mine. **B.** Suggested interpretation showing a thick compound dune package in the upper part of Interval D2. The interpretation shows the lenticular, wedge-shaped, and sigmoidal cross-strata defining a progradational flow direction of the compound dune package toward NE. Note that the cross strata are dipping in the same direction as the main reactivation surfaces.

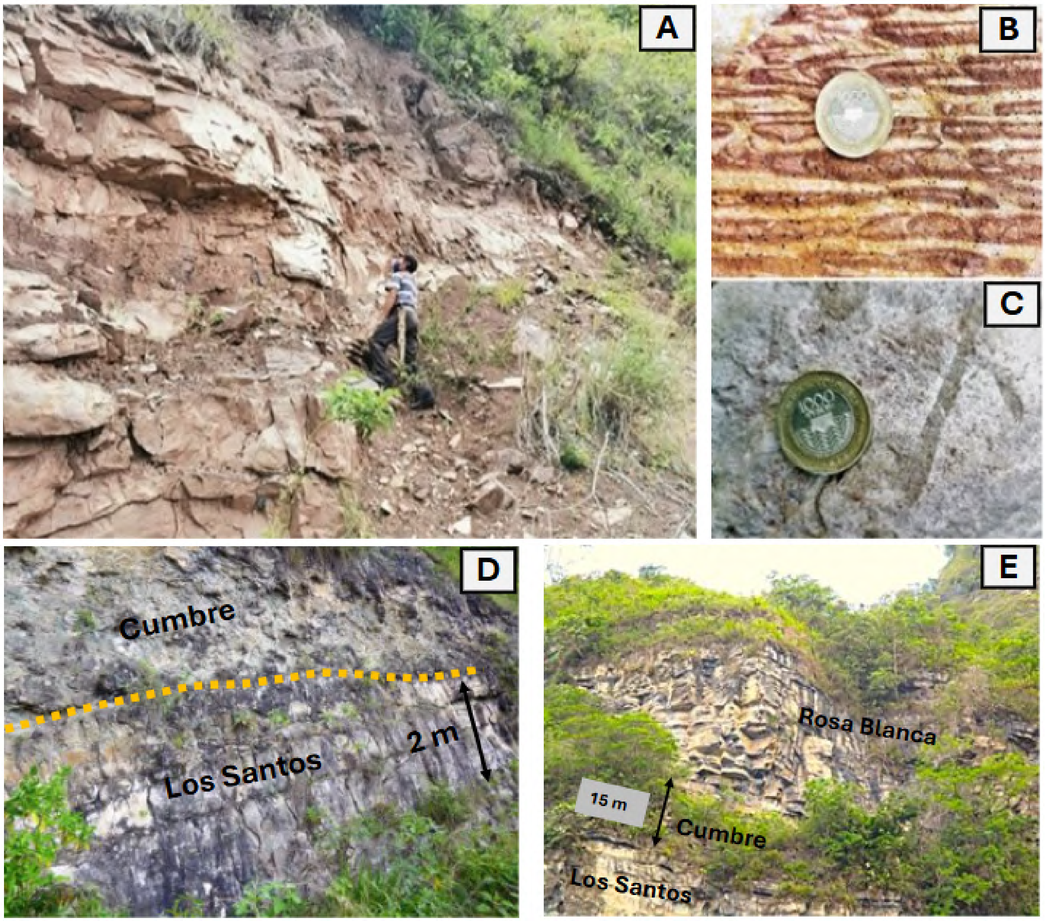

Figure 18. A. Outcrop of a very deformed, thick to very thick-bedded, fine to medium-grained quartzose sandstones reaching 10 meters in thickness. It has been correlated to the compound dune indicated in Figure 17. **B.** Abundant tubular-shaped and horizontally arranged burrows are widely distributed in a sector of the sandstone body shown in the previous figure. The coin is 27 mm in diameter. **C.** Elongated trace fossils developed on top of sandstone beds at the uppermost Interval D2, corresponding to *Scoyenia* ichnofacies. The coin is 27 mm in diameter. **D.** Gradational contact between the sandy facies of the Los Santos Formation and the finer siltstone facies of the Cumbre unit. **E.** Panoramic view showing the top of the Los Santos Formation, the exposure of the Cumbre unit, and the base of the Rosa Blanca Formation.

A regression episode is suggested by the rapid change from an intertidal deposits at the top of Interval C3 to supratidal and subaerial exposure facies of Interval D1, where the presence of pedogenic events is quite accentuated. The compound dune body at the base of Interval D2 (Figure 16) suggests a transgressive episode of a probable intertidal bar complex or even tidal dunes over the previous deposits of Interval D1. The overlying facies consists of lithological bodies showing a wide lateral extension (sheet-like), tabular geometry, erosive-based and sharp flat top, which are locally superimposed by canaliform and erosive bodies. Both tabular-sheet-like bedforms and canaliform bodies show lateral accretion surfaces, suggesting the presence of distributary channels spreading across a coastal plain.

The geometry, texture, and biogenic content of the uppermost sandbodies of Interval D2 seem to represent some distal tidal bar bodies reaching the shallow platform. According to Desjardins *et al*. (2011), tidal bars migrate through lateral accretion in association with channels. Tidal bars tend to occur in onshore areas bounded by channels or in brackish-water marginal-marine settings. Olariu *et al*. (2012) consider that such sand bars are common in the mouth of rivers in the outer part of estuaries.

Cumbre Formation

A coarsening upward succession consisting of a lower half of individual thin to medium beds forming a very thick-bedded or stacked interval (6 meters thick). These beds are completely bioturbated (BI=5-6) greenish gray

(5GY 6/1) massive siltstones overlying the sandbodies of Interval D2 in a predominantly transitional contact.

The upper half is composed of a medium to thick-bedded lens of medium-grained sandstone overlain by thin to very thick-bedded intercalations of very fine to fine-grained muddy and fossiliferous siltstones, with a total thickness of 11 meters. The tabular geometry and internal stratification are plane-parallel-laminated. The color ranges from dark yellowish orange (10YR 6/6) to light olive brown (5Y 5/6) to greenish gray (5GY 6/1) to medium gray (N5). A dolomitic sandstone is observable at the topset.

Trace fossil burrows, up to 4mm in diameter, are filled with oxide materials of bifurcated cylindrical shapes and greenish gray root remnants towards the top. The highly bioturbated dolomitic sandstone is identified by the presence of phosphatized micro-gastropods, disarticulated shells of small suspensive bivalves, and traces of echinoderm spicules.

Mendoza (1985) at the type section located north of Boyacá, found a succession 137 m thick, composed of olive gray sandstones, often with clay laminations developing flaser and wavy stratification. He interpreted this facies as deposited within the intertidal zone. Overlying, there are whitish to blackish siltstones and claystones showing monospecific bivalves, gastropods and fish remains. He thought to have been formed in a lagoon. Additionally, he describes a facies consisting of horizontally stratified sandstones, apparently formed in tidal environments. The fine-grained quartzose sandstones appear to represent a shallow barrier belt. For these reasons, he considers that the Cumbre Formation. represents oscillating deposits on an irregular coastal plain.

Renzoni (1985b) surveyed the Cumbre Formation at the Cordillera de Los Cobardes, north of the type section and southwest of the Platanalito area. He describes similar facies to those found by Mendoza (1985). He interpreted a shallow marine environment at the basal portion, followed by a deltaic progradation stage, whereas at the topset a shallow marine setting is suggested. Etayo-Serna and Guzmán (2019) consider that the Cumbre Formation in the Platanalito area documents a transitional deposit (from supratidal to subtidal).

Sedimentological model interpretation

Based on the results obtained and previously discussed, the sedimentological model of the Los Santos Formation corresponds to the initial deposit of a meandering fluvial system followed by the development of a transgressive river-mouth setting and its corresponding facies in an area subject to fluctuations at the base-level in response to probable tectonic activity (Figure 19).

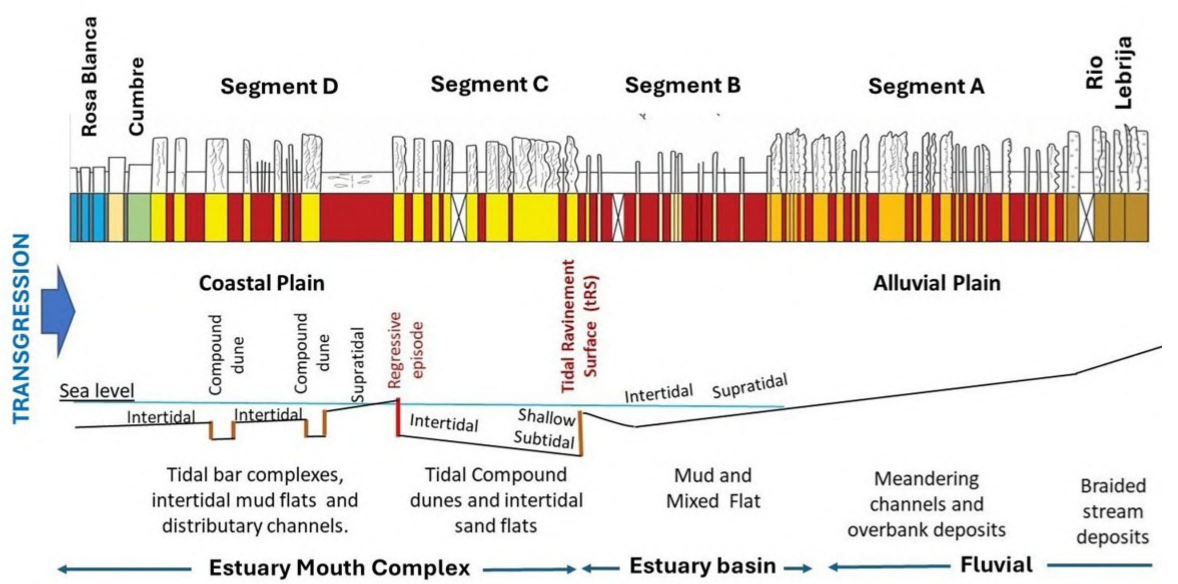

Figure 19. Illustrative profile representing the main geomorphic and sedimentological features of the Los Santos Formation at the Platanalito area. Fluctuations in the base level are observed in response to probable tectonic activity. The transgressive event converted the fluvial domain represented by the Segment A into an estuary basin and to estuary mouth complex (segments B, C, and D respectively).

Several important sedimentological events have been identified (Figure 20):

- The succession through the uppermost part of the Rio Lebrija and Los Santos formations is fluvial, with an abrupt decrease in energy levels across the contact between these two units. It is crucial to note the change in fluvial styles from an amalgamated braided stream system (dominant massive conglomeratic sandstones to sandy conglomerates of the Rio Lebrija Formation) to mature dominant muddy overbank deposits and remaining meandering fine-medium-grained sandstones at the lower part of the Los Santos Formation. This initial Los Santos deposition changed to distinctive amalgamated sandstones and a minor occurrence of overbank deposits at the upper part of Segment A.

- Allen and Posamentier (1994) consider that coarser amalgamated braided fluvial deposits in sharp contact with finer fluvial meandering deposits are indicative of a bay-line and constitute the first phase of transgression. In our study, this is represented by the contact between the Rio Lebrija and Los Santos formations. Moreover, tidal influences in fluvial systems indicate coeval shoreline proximity (Catuneanu, 2006).

- The contact between these two units seems to represent a migration of the "line of critical bypassing" *sensu* Christie-Blick (1991), which basically consists of changes of elevation with respect to the depositional base level, generating differential topography and changes in sediment supply. This is probably due to episodes of block tectonism accompanied by eustatic sea-level rise. Based on these characteristics and the data collected in our study, the Los Santos Formation may onlap in a low-relief surface onto the alluvial-fluvial profile of the Rio Lebrija Formation.

- Although there are a few indications of some tidal influence in the eminently fluvial sediments that constitute Segment A, and more solid evidence in part of Segment B, it is from the deposit of the sediments that constitute Segment C that the thick package of sandstones that make it up, their arrangement, and geometry where we more clearly identify a thick wedge of tidal sedimentation. This sedimentologic feature constitutes the first important transgression event in the latest Jurassic and earliest Cretaceous time in this area.

- During the initial transgression event (at least Segment B records more clearly this influence), a fluvial valley (Segment A of the Los Santos Formation) was progressively converted into a drowned river mouth estuary, with two major sources of sediments available to fill the new geomorphic area: fluvial sediments from the hinterlands (ancestral Santander Massif), and sediments sourced from the shelf by wave erosion and tidal currents coming from west or southwest.

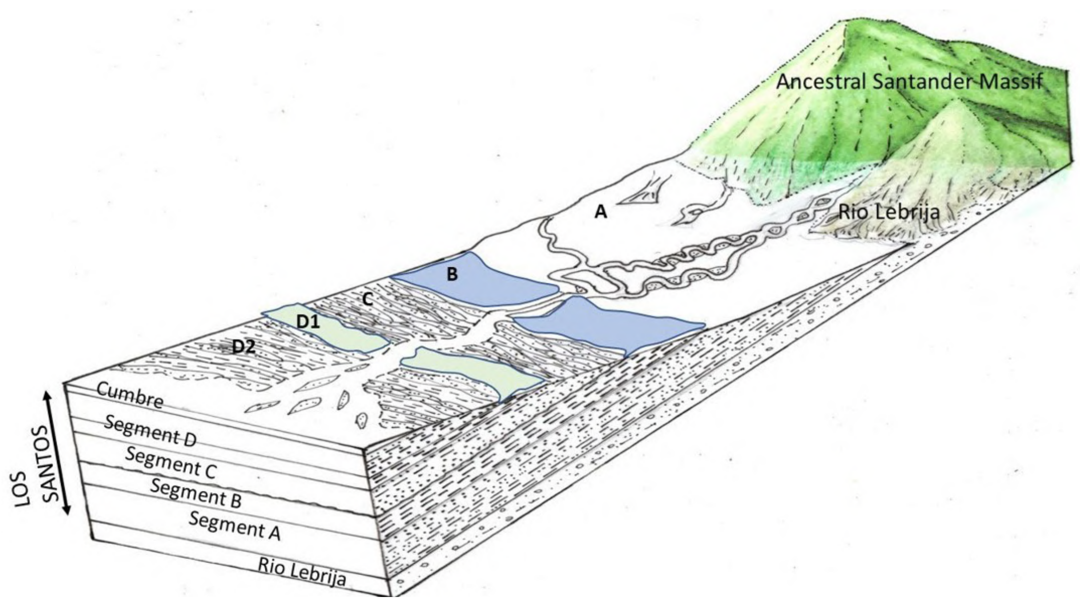

Figure 20. Sedimentological model of the Los Santos Formation in the Platanalito area.

- The landward-migrating event recorded in Segment C shows a well-defined erosional surface at Intervals C1 and C2, interpreted as the first tidal ravinement surface in the area.

The boundaries of the segments defined in this study seem to correspond to:

- Rio Lebrija Formation/Segment A of the Los Santos Formation. An incipient precursory transgressive episode in the basin.
- Segment A/B: Maximum regressive surface (Catuneanu, 2006) or transgressive surface (Posamentier *et al*., 1988).
- Segments B/C: First tidal ravinement surface (tRS1) and estuary mouth complex establishment in Segment C.
- Segments C/D: Regressive episode within Los Santos succession.
- Segment D/Cumbre facies: Probably a renewed transgressive episode.

All the sedimentological changes recorded in the Los Santos Formation suggest a direct response to fluctuations in the depositional base-level and consequently shifts in the shoreline, probably regulated by tectonic activity.

Conclusions

The facies variability of the Los Santos Formation is accompanied by several key stratigraphic surfaces indicating that a complex stage of events occurred during transgression. These events appear to be related to base-level changes that conditioned the mixed wave and tide processes as a direct consequence of tectonic pulses that predominated during transgression. For this reason, during transgression, two major sources of sediments were available to fill the area of deposition: fluvial sediments from the hinterlands (ancestral Santander Massif) and sediments sourced from the shelf and shorelines located westward or southwest. Consequently, during transgression, the latest Jurassic-earliest Cretaceous fluvial valleys were initiated to be filled from both ends. Based on this analysis, we conclude:

1. Segment A seems to reflect the development of a renewed fluvial system over the oldest one (Rio Lebrija Formation), generating, between, these two units at least an onlapping contact, which could be related to a paraconformity.
2. Segment B, is interpreted as a central estuary deposit.
3. Segment C seems to represent high-current velocities, where migration of large-scale bedforms (*i.e.*, two-dimensional and three-dimensional dunes) is the dominant process Dalrymple *et al*., 1994; Boyd *et al*., 2006; Dalrymple, 2010). On high-energy sandbodies, rapidly migrating bedforms generally preclude intense bioturbation.
4. In transgressive river-mouth settings like the Los Santos Formation, a transgressive ravinement surface (bottom of Segment C) is preserved as a distinct scoured contact (tRS1). This ravinement surface separates the dominant sandy deposits of the estuary-mouth complex (Segment C) from those of finer sediments (Segment B) that constitute the central basin.
5. In the case of Los Santos, after the deposition of Segment C, various small episodes of forced regressions and subsequent transgressive periods are recorded in the succession of Segment D. Interpreted forced regressions episodes in Segment D require fluvial systems to adjust to new settings, where fluvial processes are primarily controlled by depositional base-level changes.

Credit authorship contribution statement

Angela Torres: Polygonal survey measurement first part; stratigraphic column survey first part; investigation first part; formal analysis first part; writing – first original draft.

Georgina Guzman: Methodology; polygonal survey measurement first and second part; stratigraphic column survey first and second part; investigation first part; formal analysis first part; writing – first original draft.

Jairo Clavijo: Methodology; polygonal survey measurement first and second part; stratigraphic column survey first and second part; investigation first part; formal analysis first part; writing – first original draft; supervision first part.

Fabio Laverde: Methodology; investigation first and second part; formal analysis first and second part; supervision second part; writing – final draft.

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