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HIGH-RESOLUTION ANALYSIS OF AN ERG-MARGIN SYSTEM FROM THE CRETACEOUS CANDELEROS FORMATION (LA BUITRERA PALEONTOLOGICAL AREA, RÍO NEGRO PROVINCE, ARGENTINA): AN APPROACH TO DIFFERENT SCALES OF FLUVIAL-AEOLIAN INTERACTIONS

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ABSTRACT

Several studies have emphasized the complexity of the interaction between fluvial and aeolian processes at *erg* margin settings, and their importance in the resulting geological record. The Cretaceous Candeleros Formation in the “Cañadón de Las Tortugas” site which is located in “La Buitrera Paleontological Area” (Neuquén Basin, Argentina) provides excellent outcrops where the record of a variety of interactions between the aeolian and fluvial processes can be observed. Therefore, the aim of this project was to reconstruct the accumulation systems and the spatial and temporal relations of their associated sedimentary processes. The methodology included the logging of sedimentary sections, a facies and architectural analysis and the identification of the different hierarchies of unconformities. The different architectural elements identified are related both to aeolian and fluvial genesis as mentioned before. The first ones comprise aeolian dune deposits and wet interdune deposits, whilst the second ones are channelized deposits, non-channelized proximal fluvial deposits and non-channelized distal fluvial deposits. These architectural elements were identified in three different evolutive stages of the depositional model made. Hence, the studied interval has a complex pile of overlapping units that represents the contraction/expansion of an *erg*-margin system as a result of variations of the water table position to climatic conditions. Therefore, this study enhances current understanding of the stratigraphic record of *erg* margin systems at different time-space scales. This high-resolution study provides a detailed account of the processes that operated in the Kokorkom paleodesert and relevant information for the reconstruction of the accumulation systems in the southern part of the Neuquén Basin during the Late Cretaceous.

INTRODUCTION

In desert regions, and particularly at *erg* margins, fluvial and aeolian processes do not operate independently (Langford, 1989; Al-Masrahy and Mountney, 2015). Typically, complex interactions between fluvial and aeolian processes have a direct impact in the geomorphology, sedimentation and the resulting sedimentary succession transferred to the geologic record (Langford and Chan, 1989; Bullard and Livingstone, 2002). Therefore, it must be noted that the common classification of conceptual models of accumulation systems in “fluvial” and “aeolian”, intending to reflect the dominant suite of processes that characterize a system, can be misleading in many cases (Mountney, 2006). Although the importance of fluvial-aeolian interaction at different temporal and spatial scales over the geological record has been documented since the early studies of Langford (1989) and Langford and Chan (1989), recent contributions expose the striking variety of such interactions in modern systems around the planet (Al-Masrahy and Mountney, 2015). The diverse ways in which these interactions are registered in the geological record, through depositional and erosional features, are still relatively unexplored and are an additional motivation to study *erg*-margin successions.

La Buitrera is an exceptional, Upper Cretaceous, vertebrate paleontologic site (Apesteguía *et al.*, 2016), without a fairly good understanding of the continental accumulation system that generated its deposits and its link to (i) the conditions in which its varied fauna might have lived; and (ii) the preservation quality of such findings. Previous studies relate the origin of the fossil’s host sediment in the area to an *erg*-margin setting within the so-called Kokorkom desert (Apesteguía *et al.*, 2016; Candia Halupczok *et al.*, 2018). In this context, a detailed sedimentological and stratigraphic study, based on facies analysis and considering the particular characteristics of such settings, is needed to unravel the formerly expressed relationships.

This work performs a sedimentological characterization of the middle and upper sections of the Candeleros Formation (Neuquén Basin, Argentina) in the “Cañadón de Las Tortugas” site, within the La Buitrera locality, one of the five localities of the La Buitrera Paleontological Area (LBPA), to gain new perspectives that can contribute the understanding of how the accumulation systems operated in the past. This sector is particularly adequate due to the exceptional nature of the outcrop, in terms of vertical and lateral extent and continuity of exposure. Specific aims were (i) to perform a detailed facies analysis, identifying individual accumulation processes; (ii) to define architectural elements and major bounding surfaces, interpreting the spatial and temporal relations that existed between accumulation processes; and (iii) to present the likely ancient depositional systems along with their temporal evolution at different scales. Hence, this can be useful to analyze the ecological conditions and preservation conditions of the Mesozoic fauna.

GEOLOGICAL SETTING AND PREVIOUS WORK

The Candeleros Formation (Cazau and Uliana, 1973) forms part of the Neuquén Group of the Neuquén Basin (Fig. 1A, B) and is Upper Cretaceous (Cenomanian) in age (Leanza, 2009). This unit lies above the Patagonidean Unconformity (Leanza, 2009) and underlies the Huincul Formation; together comprising the Río Limay Subgroup (De Ferrariis, 1968). The contact between the Candeleros and the Huincul Formations is a regional erosional unconformity (Sanchez, 2004; Sanchez *et al.*, 2008; Asurmendi and Sanchez, 2014; Sanchez and Asurmendi, 2015). The main lithological components of this unit are quartz-lithic sandstones, greywacke sandstones and greywackes (Garrido, 2010). These deposits have been interpreted as the accumulation of diverse continental sedimentary environments. Although the predominant environment is interpreted as fluvial, both aeolian and terminal fluvial-fan deposits have also been documented (Garrido, 2010).

In the “Río Limay” region, which includes the LBPA, the deposits of the Candeleros Formation were interpreted as aeolian (Spalletti and Gazzera, 1989; Candia Halupczok *et al.*, 2018) and belonging to the ancient Kokorkom desert (Apesteguía *et al.*, 2016). The Candeleros Formation was described in the Río Limay’s eastern sector as constituted mainly by medium- and fine-grained sandstones with subordinated mudstones (Candia Halupczok *et al.*, 2018). These deposits were interpreted as accumulated by ephemeral fluvial systems and migration of aeolian dunes. The vertical and lateral association of these facies is thought to indicate migrating dunes and interdunes in the wind direction affected by ephemeral fluvial flows, pointing to a semi-arid climate with intermittent water availability. Consequently, the depositional system is characterized as a wet aeolian system in which the water level or its capillary fringe was near the surface (Candia Halupczok *et al.*, 2018). This ancient system with aeolian dunes of big dimensions

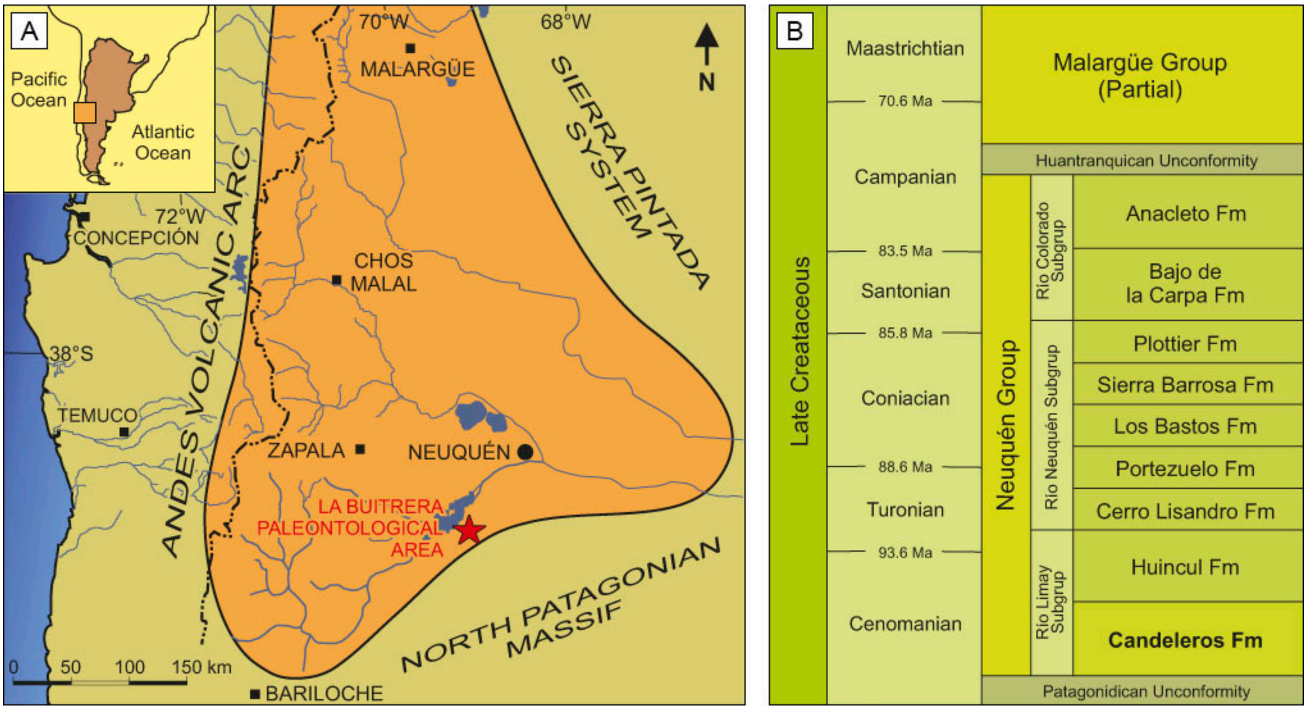


Figure 1. a) Map of the Neuquén Basin. The red star indicates the location of La Buitrera Paleontological Area (modified from Howell *et al.*, 2005). **b)** Chronostratigraphic column for the Late Cretaceous of the Neuquén Basin, in which the studied unit is highlighted (modified from Garrido, 2011).

covered at least an area of 800 km^2 in the southern sector of the Neuquén Basin.

Similar deposits were found in the Rio Limay's western sector by Spalleti and Gazzera (1989). In this sector, large-scale, cross-stratified sandstones were interpreted as the result of transverse dune migration, while massive siltstone and massive fine-grained sandstone intervals were associated with the accumulation in aeolian interdunes. Also mudstones and sandstones with planar stratification, parting lineation, bioturbation and small-scale trough cross-bedding were related to upper-flow regime ephemeral currents; and heterolithic facies composed by mudstones and chert interlaminations were assigned to playa-lake environments.

As for the prolific paleontological record of the Candeleros Formation in the LBPA, the unit is well-known for the variety of its vertebrate findings. These include a rich fauna in tetrapods, (Apesteguía, 2001), rhynchocephalian lepidosaurs, limbed snakes (Garberoglio *et al.*, 2019), uruguaysuchid crocodyliforms (Pol and Apesteguía, 2005), a dromaeosaurid (Makovicky *et al.*, 2005), an alvarezsaurid (Makovicky *et al.*, 2012), theropod dinosaurs, fragmentary sauropods, dryolestoid mammals (Rougier *et al.*, 2011), ceratodontiform dipnoans (Apesteguía *et al.*, 2007) and more recently a new species of turtle (Maniel *et al.*, 2020). Moreover, specifically in the studied location, dinosaur tracks have been recognized in the aeolian sandstones (Candia Halupczok *et al.*, 2018).

STUDY AREA AND METHODS

The selected area for this high-resolution study was the "Cañadón de Las Tortugas". It is a 0.16 km^2 sector located in the westernmost part of the LBPA (Fig. 2A), constituted by cliffs and small canyons that allowed a detailed vertical identification of facies changes, as well as a lateral tracking of sedimentary units and bounding surfaces (Fig. 2B). The rocks that constitute the sedimentary succession in the studied area are mostly fine- to medium-grained sandstones that are well to very well-sorted, except in some cases where sorting is moderate. The matrix is absent in all the cases. In lesser proportions, relatively thin mudstones and heterolithic intervals were also identified.

A workflow consisting of a sedimentary facies analysis, followed by a sedimentary architecture

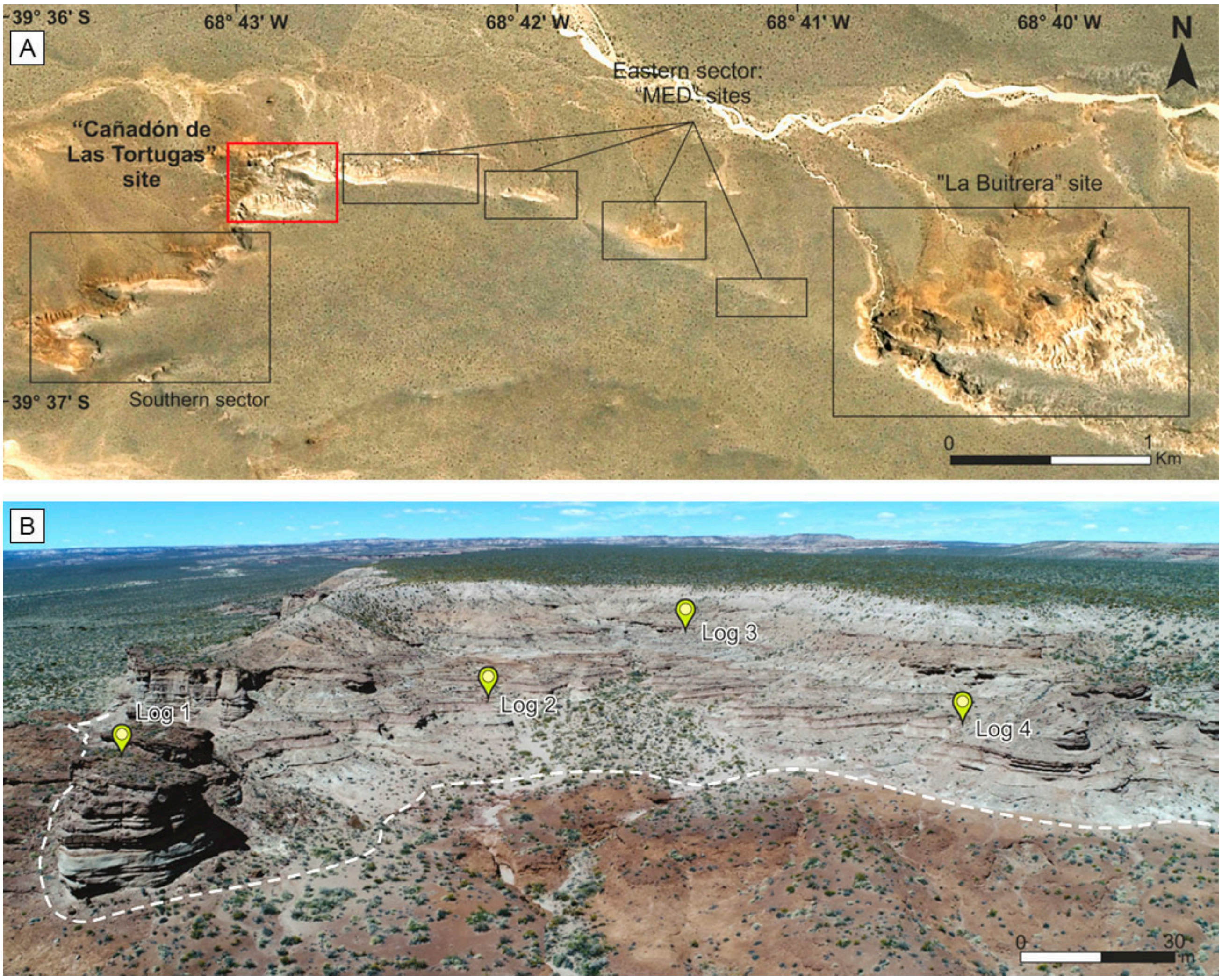


Figure 2. a) Satellite image showing the different sites that constitute the La Buitrera Paleontological Area. The "Cañadón de Las Tortugas" site is highlighted in red. **b)** Panoramic view of the "Cañadón de Las Tortugas" locality. The base of the studied interval, as well as the location of the logged sections, is indicated.

analysis, was implemented. Four sedimentary logs were measured in the outcrop and then used for the construction of a sedimentary facies scheme and the understanding of the vertical facies relationships. The textural properties of the rocks were determined using a magnifying glass and a comparative grain-size chart. Afterwards, the characterization of the lateral relationships of facies and sedimentary units was added, supported by the sedimentary logs, physical tracking of the sedimentary units in the field and the construction of virtual outcrop models. These models were constructed using photogrammetry from geo-referenced photographs obtained employing a drone, which allowed a better characterization of the different sedimentary bodies and bounding surfaces (Argüello Scotti and Veiga, 2015). As a result, it was possible to appreciate the spatial variability and the heterogeneities of the deposits, including the development of different scales of stratigraphic boundaries (sensu Brookfield 1977, Langford and Chang 1989; and Clemmensen and Tisgaard, 1990) and the distribution of the facies and architectural elements. Hence, a stratigraphic scheme was elaborated based on the analysis of the distribution of architectural elements and the integration of the surfaces that link them.

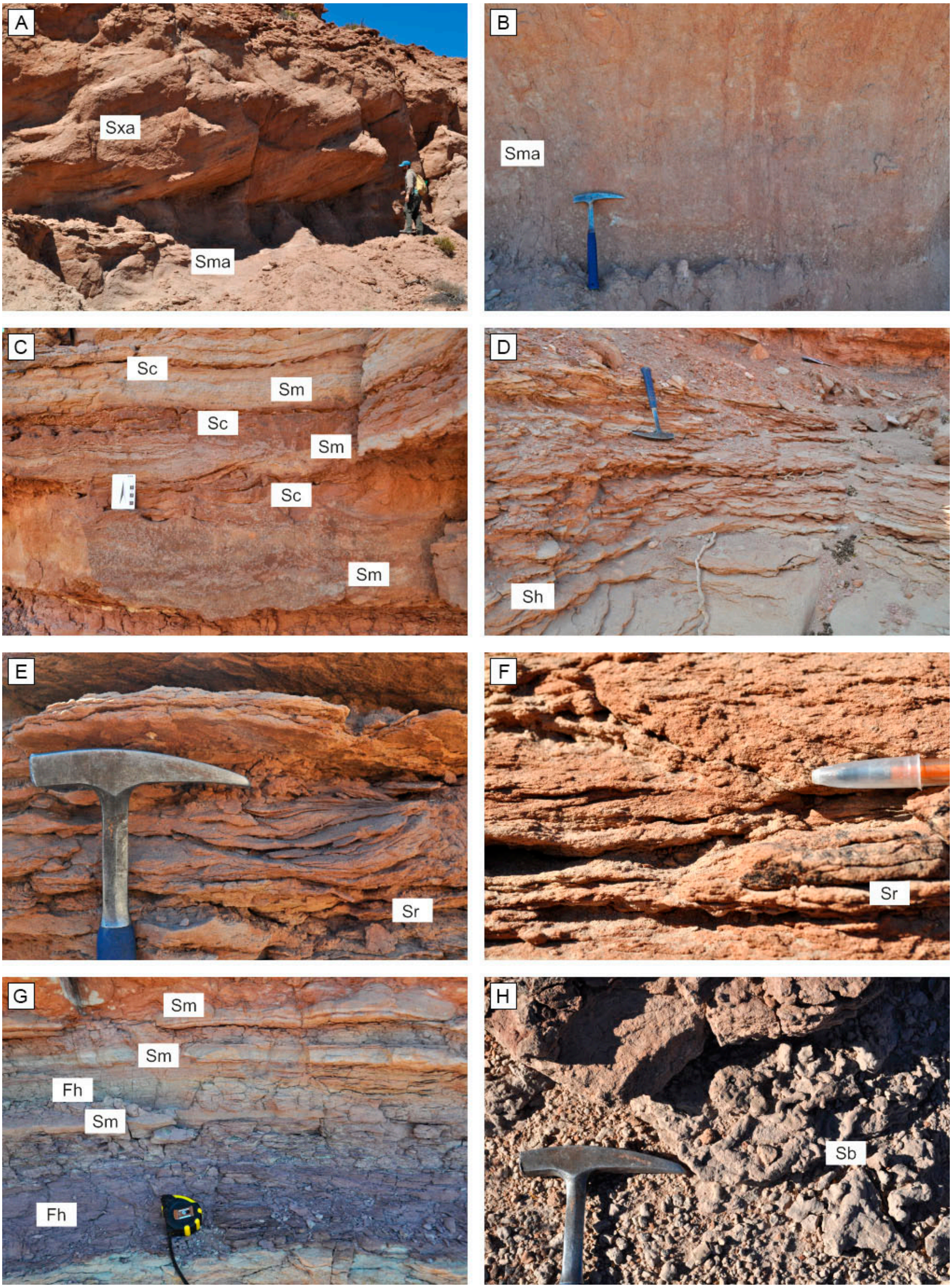
SEDIMENTARY FACIES AND ARCHITECTURAL ELEMENTS

Nine sedimentary facies were recognized in the Candeleros Formation in the study area (Table

Code	Texture	Sed. structure	Boundaries	Thickness	Interpretation
Sxa	Very well-sorted, fine-grained sandstones	Tangential-planar and trough cross-stratification.	Net boundaries. In some cases, the upper one erosive	Sets between 1.5 and 3 m	Migration of aeolian dunes via continuous avalanching in the dune´s lee slope
Sma	Well sorted, fine-grained sandstones	Massive	Net boundaries. In some cases, the upper one erosive. Also, in some cases, lateral transition to Sxa	Individual beds 0.4 to 3 m thick	Massive due to secondary processes that erased the structures or homogeneous grain size that hinders their preservation
Sh	Moderate to well sorted, fine-grained sandstone. Small mudstone rip-up clasts	Horizontal lamination with occasionally parting lineation	Net boundaries. Base can be erosive and locally irregular	Packages from 0.05 to 0.4 m thick	Deposition under plane bed condition related to upper flow regime unidirectional currents
Sr	Well-sorted, fine-grained sandstones	Planar and trough, small-scale, cross lamination	Transitional boundaries	Individual beds 0.05 to 0.1 m thick, grouped in packages of 0.4 to 0.8 m	2D and 3D sub-aqueous ripples migration under unidirectional low-flow regime currents
Sc	Well sorted, fine-grained sandstones.	Convolute lamination	Lower boundary transitional from Sm facies and erosive upper boundary	From 0.1 to 0.3 m	Deformation due to fluid scape related to sedimentary loading
Sm	Moderate to well-sorted, fine-grained sandstones with frequent intraclasts	Massive	Lower boundary is erosive. Upper one can be transitional to Sc facies or erosive	From 0.1 to 0.5 m	Rapid deposition associated to high energy sediment laden flow. Alternatively, absence of structure related to soft sediment deformation
Sb	Well-sorted, fine-grained sandstones	Massive bioturbation	Lower boundary transitional from Sr facies. Net upper boundary	From 0.1 to 0.2 m	Substrates subject to intense bioturbation
H	Sandstones and mudstones	Heterolithic	Lower boundary is net and horizontal. Upper boundary is usually erosive	Beds of 0.2 to 0.35 m thick with internal strata less than 3 cm thick	Alternation of tractive conditions and settling from suspension
Fl	Mudstones	Horizontal lamination	Lower boundary is net. The upper one is transitional to Sm facies	Individual beds 0.2-0.3 m thick	Settling from suspension in low-energy setting

Table 1. Sedimentary facies in the “Cañadon de Las Tortugas” site of the La Buitrera locality within La Buitrera Paleontological Area. Dynamic interpretation based on Hunter, 1977; Bridge, 1993; Mountney, 2006; and Collinson *et al.*, 2006.

1) based essentially on texture and mechanical sedimentary structures. In some cases, other features were used to separate similar facies (e.g., bioturbation). Two of the facies are interpreted as the result of subaerial processes, while the rest is related to subaqueous processes (Fig. 3). The most common transport mechanism (in terms of facies recurrence) was related to unidirectional subaerial currents, although there was a considerable contribution related to subaqueous unidirectional currents and settling in low-energy environments, with a variable degree of bioturbation.


A
Sxa
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Fh
Sm
Fh
H
Sb

Sedimentary facies have been grouped into five different architectural elements based on its internal facies arrangement, external geometry and bounding surfaces following Langford and Chan (1989), Bridge (1993) and Mountney (2006). These are (I) Aeolian Dune Elements, (II) Wet Interdune Elements, (III) Non-channelized Proximal Fluvial Elements, (IV) Non-channelized Distal Fluvial Elements; and (V) Channelized Fluvial Elements (Table 2).

Aeolian Dune Elements

Description. Dune elements are characterized by large-scale sets of cross-bedded sandstone (facies Sxa, Table 1), and occasionally with cross bedded-sandstones with a gradual and diffuse lateral transition to massive sandstones (facies Sma, Table 1). This transition, and the textural, compositional and geometric features between the two facies, indicates the aeolian origin of the massive sandstones. Aeolian dune elements are bodies with tabular geometry whose upper and lower boundaries are planar and sharp (Fig. 4A, B). In some cases, the upper boundary can have an irregular shape due to erosive processes that are related to overlying sedimentary bodies. On the other hand, the lower boundary can show an interdigitation relation with subaqueous deposits interpreted as wet interdune elements.

Two different types of dune elements were recognized depending on the features of their internal surfaces and their scale: simple dune elements and compound dune elements. In simple dune elements, all internal surfaces dip in the same direction as cross-strata, with a lower angle. In compound dune elements, some internal surfaces dip in the same direction as cross-strata. However, another group of internal surfaces dips with a very low angle in the opposite direction, making the entire element a coset. Simple dune elements are 2 to 3 m thick, and are found in the lower part of the studied section, while compound dune elements reach up to 7 m thick and are found in the upper part of the studied section.

Interpretation. These elements are interpreted as the result of the migration of aeolian dunes preserved in the rock record. The tabular geometry of these units is a consequence of the movement and erosion inherent to dune migration and climbing (Kocurek, 1981). The flat and sharp lower and upper boundaries of the dune elements are interpreted as first-order or interdune surfaces (Brookfield, 1977). The presence of massive sandstones within the dune elements is interpreted as a result of the homogeneous grain size that hinders the preservation of original structures, and/or as the result of diagenetic processes (Collinson *et al.*, 2006).

The internal surfaces that dip in a similar direction to the cross-strata, but with a lower angle, can be interpreted as third-order or reactivation surfaces (*sensu* Brookfield, 1977). These are product of erosion at the leeward slope with subsequent sedimentation associated with a change in the migration direction, speed of migration, asymmetry of the bedform and/or inclination of the leeward slope (Mountney, 2006). On the other hand, the internal surfaces that dip approximately opposite to the cross-strata, can be interpreted as second-order or superimposition surfaces (*sensu* Brookfield, 1977). These are a consequence of the superimposition of dunes over a host *draa* or mega-dune bedform (Mountney, 2006). Therefore, simple dune elements are interpreted as the result of simple dune bedform migration, while compound dune elements are interpreted as the product of *draa* or mega-dune bedform migration.

Wet Interdune Elements

Description. Wet interdune elements have facies associated in two different ways. In some cases, they form packages of convolute laminated sandstones (Sc, Table 1) at the base and massive subaqueous sandstones (Sm, Table 1) on the upper part. In other cases, ripple cross-laminated sandstones (Sr, Table 1) and bioturbated sandstones (Sb, Table 1) are associated in strata with 0.1 to 0.2 m thick that

Figure 3. Sedimentary facies identified for the Candeleros Formation at the "Cañadón de Las Tortugas" site. **a)** Well-sorted, fine-grained sandstones with large-scale, cross-stratification (Sxa). 1.8 m person for scale. **b)** Fine-grained, massive sandstone of aeolian origin (Sma). 33-cm-long hammer for scale. **c)** Massive sandstones (Sm) and convolute laminated sandstones (Sc). **d)** Fine-grained, horizontally laminated sandstones (Sh). 33-cm-long hammer for scale. **e)** Trough, crossed-laminated sandstones (Sr). 33-cm-long hammer for scale. **f)** Planar, crossed-laminated sandstones (Sr). Pen cap is 3.3 cm long. **g)** Horizontally laminated mudstones (Fl), intercalated with massive, fine-grained sandstones (Sm). 7.5 cm long measuring tape for scale. **h)** Intensely bioturbated sandstones (Sb). 33-cm-long hammer for scale.

Arquitectural Element	Boundaries and Geometry	Dimentions and Extension	Facies	Interpretation
Aeolian Dune Elements	Elements with tabular aspect across the entire outcrop. Both boundaries are horizontal and sharp. The upper one sometimes can be locally irregular and erosive	Thickness between 2 and 7 m. Their lateral extension surpasses the study area (160000 m^2)	Sxa, Sma	Migration of aeolian dunes and *draa*
Wet Interdune Elements	Lenticular section. Lower boundary sharp and non-erosive. The upper boundary can be interdigitated with aeolian dune elements	Lenses of 1 to 2 m thick, and a lateral extension that ranging from 30 m to a few hundreds of meters	Sm, Sc, Sr, Sb, Sma	Fluvial invasion or a rise in the water table in the interdune corridors.
Non-channelized, Proximal Fluvial Elements	Rectangular section. Elements with tabular aspect across the entire outcrop. Both limits are horizontal and net o irregular	Thicknesses range between 1 to 3 m. Their lateral extension surpasses the study area	Sm, Sc, Sr, Sh, Sb	Short-lived, non-channelized flows whose transport mechanism is tractive
Non-channelized, Distal Fluvial Elements	Rectangular section and tabular-like aspect across the entire outcrop. Both limits are horizontal and sharp	Thickness varies between 1 and 1.5 m. Their lateral extension surpasses the study area	Fl, H, Sm	Non channelized flows that feed semi-permanent/ permanent water bodies and deposit sandstones in a tractive way and mudstones by settling
Channelized Fluvial Elements	Lenticular geometry. Its upper boundary is horizontal and sharp. Conversely, its lower boundary is concave upwards, irregular and erosive	Wide ranges between 10 and 14 m. Maximum thickness varies from 1 to 1.5 m	Sm, Sc	Channelized unidirectional currents

Table 2. Architectural elements identified at the studied sector in the Candeleros Formation with a brief characterization and genetic interpretation based on Langford & Chan, 1989; Bridge, 1993; and Mountney, 2006.

alternate with massive aeolian sandstones (Sma).

These elements have a lenticular section and are found laterally and vertically associated to the aeolian dune elements (Fig. 4B). The maximum thickness of these bodies varies between 1 and 2 m, and their lateral extension ranges from 30 to a few hundreds of meters. The element boundaries are sharp, with the upper ones commonly showing an interdigitation with aeolian dune deposits. Conversely, the lower boundaries are planar on top of aeolian dune elements or channelized fluvial deposits (Fig. 4B).

Interpretation. The presence of facies related to deposition from subaqueous currents (Sm, Sr, Sc and Sb), interdigitated with aeolian dune elements, represents the fluvial invasion of the low areas between successive aeolian dunes (Cain *et al.*, 2009). At the same time, the presence of the convolute lamination (Sc) at the base of some deposits indicates the water presence that led to partial liquefaction and deformation of the sediments (Collinson et al., 2006) once they are loaded following dune migration. The lateral and vertical relation with the aeolian dune deposits that these elements show, in addition to the similar grain size in comparison to the dune elements allow us to interpret them as coeval to aeolian dune migration and thus wet interdune deposits. Interdune elements constituted by ripple cross-laminated sandstones (Sr) and bioturbated sandstones (Sb), associated to massive aeolian sandstones (Sma), can be interpreted as the re-working of aeolian sand deposits in water bodies within the interdune space (Kocurek, 1981). Also,

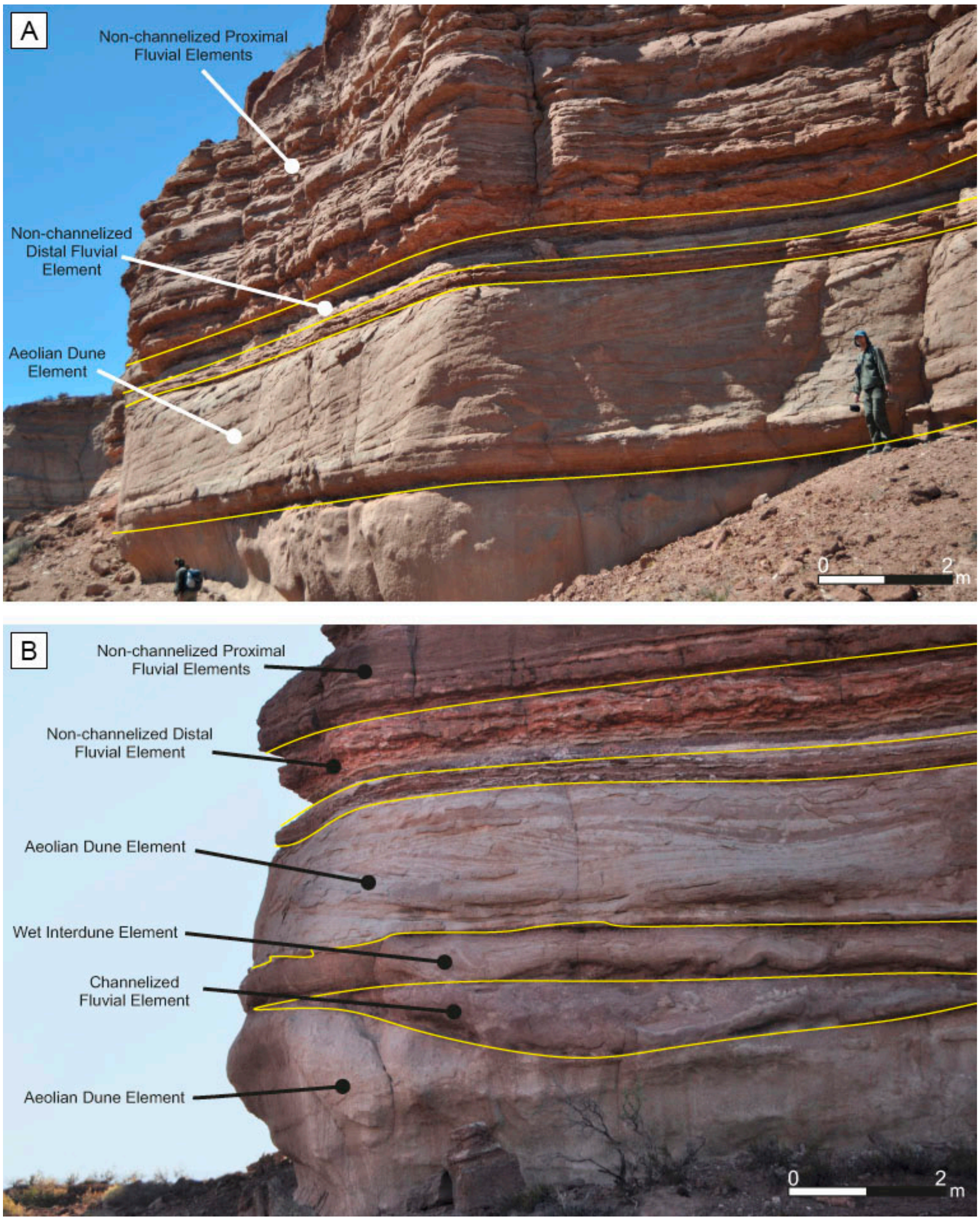

Figure 4. Architectural elements identified in the "Cañadón de Las Tortugas" site. **a)** Aeolian dune element underlying non-channelized proximal and distal fluvial elements. 1.8 m person for scale. **b)** Channelized fluvial element section overlying aeolian dune elements and beneath wet interdune elements. This alternation underlies non-channelized proximal and distal fluvial elements.

the occurrence of facies indicating current ripples (Sr) can be linked to wetter periods in which the water could flow through the interdunes or by the rise of the water level.

Non-channelized Proximal Fluvial Elements

Description. Non-channelized proximal fluvial elements have a tabular geometry with both of their limits being planar and parallel at outcrop scale (Fig. 4A, B). These elements can reach up to 2.5 m thick and their lateral extension exceeds the studied area.

The individual beds that constitute this architectural element can be grouped into two types (erosive and non-erosive) according to the nature of their lower boundary. The erosive ones are formed by massive sandstones (Sm) passing upwards into convolute laminated sandstones (Sc), in beds 0.2 to 0.4 m thick. These are vertically stacked; therefore, their upper limits are also irregular. The non-erosive beds have both of their boundaries planar and sharp. They are constituted by horizontally laminated sandstones with parting lineation (Sh, Table 1), planar or trough cross-laminated sandstones (Sr), thin horizontal layers of massive sandstones (Sm) and bioturbated sandstones (Sb). In general, there is no fixed arrangement in the order in which these facies occur within the architectural element, but a relatively frequent disposition is the planar or trough cross-laminated sandstones overlying horizontally laminated sandstones with parting lineation. The individual beds are 0.05 to 0.2 m thick and the entire succession has a thickness that varies between 2 and 2.5 m.

Interpretation. The constitutive facies disposed in bodies with tabular geometry is compatible with the accumulation from non-channelized flows (Bridge, 2003). These deposits are related to sporadic, high-energy floods that carry sediments until its dissipation (Cain *et al.*, 2009). On the other hand, the grain size and the textural features of the sediments are similar to the one in rocks of aeolian origin which leads us to think in the reworking of pre-existing material.

The massive sandstones (Sm) associated with the convolute laminated sandstones (Sc) can be interpreted as the consequence of rapidly decelerating ephemeral flows with high sediment load (Coronel *et al.*, 2020). Water saturation in the deposit at the moment of sedimentation could have led to partial liquefaction that generated syn-sedimentary deformation (Collinson *et al.*, 2006). At the same time, the element's irregular to planar lower boundary suggests that, at least in their beginnings, the flows that deposited them had relatively high energy and were under-saturated in sediments, being slightly erosive (Fisher *et al.*, 2007)

The horizontally laminated sandstones with parting lineation (Sh) suggest upper-flow regime accumulation conditions (Leeder, 1982). Conversely, the record of planar and trough cross-laminated sandstones (Sr) represents an energy decrease and the transition to lower-flow regime conditions (Leeder, 1982). The vertical arrangement of these facies implies a decrease in the flow´s energy during a single flood event (Bridge, 2003). Thereby, these bodies are constituted by overlapping beds accumulated by successive ephemeral flows (Bridge, 2003).

Non-channelized Distal Fluvial Elements

Description. Non-channelized distal fluvial elements are formed by laminated mudstones (Fl, Table 1) whose maximum thickness is about 0.4 m; massive sandstones (Sm) of about 0.1 to 0.2 m thick; and heterolithic deposits (H, Table 1) up to 0.3 m thick. The occurrence of these fine-grained bodies is associated with non-channelized proximal fluvial deposits. These elements have a tabular geometry, with planar and sharp upper and lower limits (Fig. 4A, B). The thickness of these varies from 1 to 1.5 m and their lateral extension exceeds the studied area.

Interpretation. The dominance of the laminated mudstones (Fl) indicates deposition in a zone where settling of material in suspension was a more common process (Collinson *et al.*, 2006). Moreover, the heterolithic facies (H) that also are characteristic of these elements indicate alternate sedimentation from low to very low energy flows and suspended sediments linked to energy variations from successive flow events. On the other hand, the presence of massive sandstones implies that during certain periods of time, tractive deposition existed associated with higher energy conditions.

Based on the facies, the tabular geometry of these bodies, and their close occurrence to non-channelized proximal fluvial deposits, it is likely that these elements are the result of permanent or semi-permanents, pond-like, water bodies located in the distal parts of non-channelized flows (Fisher *et al.*, 2007). Alternatively, these elements can also be regarded as a product of the sedimentation of suspended load not deposited by the proximal flows with higher energy (Fisher *et al.*, 2007).

Channelized Fluvial Elements

Description. The facies present in these bodies are mainly massive sandstones (Sm) and sandstones with convolute lamination (Sc) (Fig. 5). These bodies are characterized by a symmetric lenticular section with planar and sharp tops, and concave upwards, sharp, and erosive bases (Figs. 4B, 5). These are 10 to 14 m in real wide and 1 to 1.5 m thick, resulting in a relatively low width/thickness ratio (~10). The lower part of these bodies frequently contains rip-up clasts of very fine-grained, red sandstone whose B axes are up to 0.5 cm.

In the analyzed sector, these elements are stratigraphically related to aeolian dune elements. Channelized fluvial deposits overlie and cut into the aeolian dune elements (Figs. 4B, 5). The contact between them is a sharp surface that has small-scale irregularities, indicating its erosive origin. On the other hand, these elements can be also found underlying the Wet Interdune Elements.

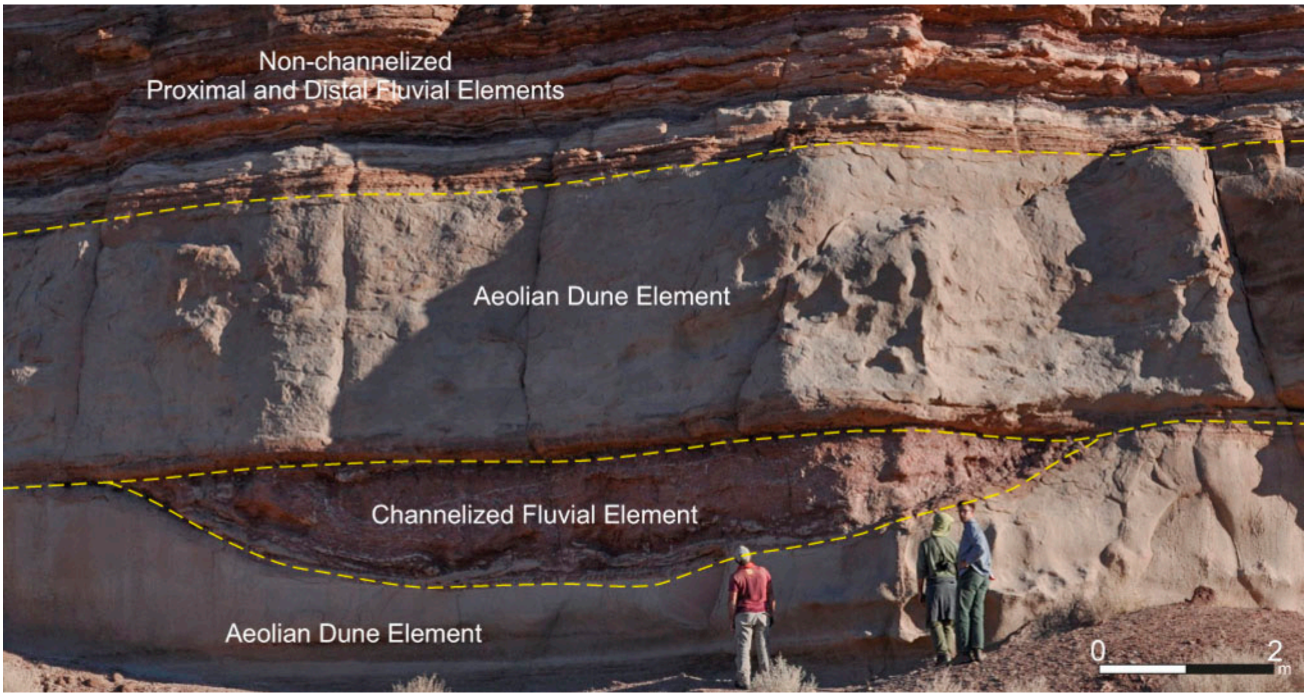

Figure 5. Reddish fluvial channel deposit interbedded with aeolian dune elements. Note the flat top and concave-upward base as well as the low width/thickness ratio. 1.8 m person for scale.

The boundary between both bodies is also a sharp contact, but planar in this case.

Interpretation. The lenticular shape that these sandstones elements have in cross-section, in association to the erosive lower boundary and the presence of rip-up clasts in the base, allowed us to interpret these elements as deposits resulting from the accumulation of unidirectional channelized currents (Bridge, 1993). The erosive base suggests that the channelized flow that deposited these elements was initially diluted (Fisher *et al.*, 2007). The uniformity in the grain size and the apparent absence of sedimentary structures likely indicates that these elements were the consequence of rapid decelerating flows with relatively high sediment concentration (Gibling, 2006; Fisher *et al.*, 2007). These elements can be identified as single symmetric channel bodies (Gibling, 2006).

CHANGES IN SEDIMENTARY ARCHITECTURE: EVOLUTIONARY STAGES

Three informal stratigraphic intervals were defined for the studied section, characterized by a lateral and vertical relationship between different architectural elements and bounded by key surfaces that point to an abrupt change in the depositional style (Fig. 6). These stratigraphic intervals are regarded as three main stages in the evolution of sedimentary systems in the "Cañadón de Las Tortugas" site. In addition, surfaces within the stratigraphic intervals have lower hierarchy and are considered as the result of different processes inside the same depositional system.

Stage I: Dry-to-Wet Aeolian System

General description and boundaries. The lower stratigraphic interval is characterized by aeolian dune elements, wet interdune elements and channelized fluvial deposits (Figs. 6, 7). The aeolian dune elements make up the largest portion of the succession, while the other two are subordinated. The interval has a thickness of 6-8 m that increases slightly towards the northeast sectors of the studied area.

This interval is defined by two sharp surfaces that are relevant across the entire studied sector due to their defined and notorious facies contrast. The surface that constitutes the base of the interval can be well recognized due to a change in coloration and grain size in the rocks beneath and below

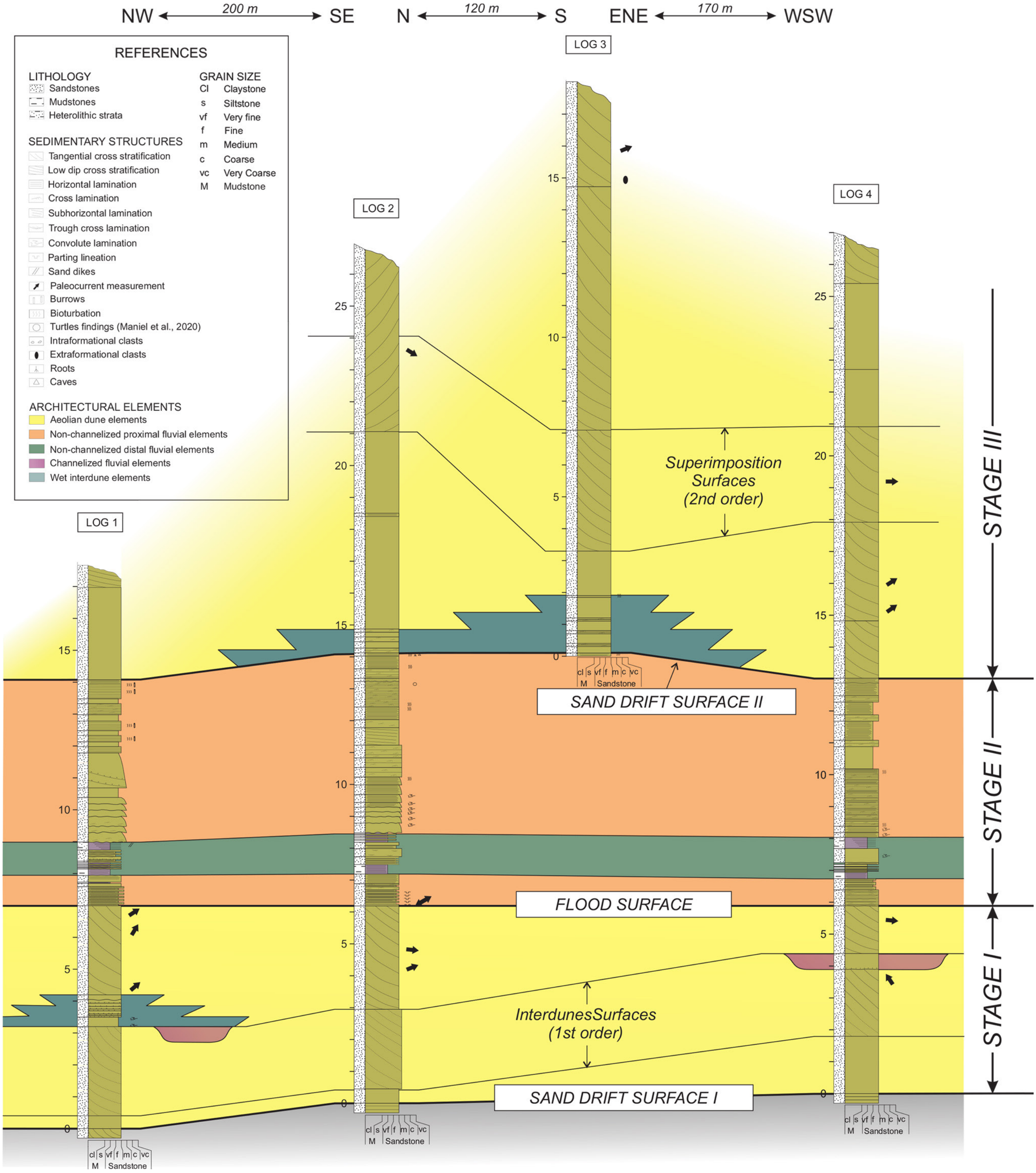

Figure 6. Correlation panel of the architectural elements and surfaces for the Candeleros Formation in the "Cañadón de Las Tortugas" site within the La Buitrera Paleontological Area.

the surface, and it marks the base of the analyzed succession. Because it is a sharp planar surface, it is identifiable across the whole region. Units below the surface, and outside the study interval, are medium-grained, red sandstones, usually small-scale cross-stratified, which have been interpreted as of fluvial origin (Candia Hapluczok *et al.*, 2018). Conversely, the rocks directly above the surface are very well sorted, fine-grained, white sandstones related to an aeolian genesis. The development of aeolian dune elements on top of fluvial deposits allows considering this unconformity as a sand-drift surface (*sensu* Clemmensen and Tirsgaard, 1990).

On the other hand, the surface that bounds the upper part of the interval involves the contact of aeolian dune elements with non-channelized proximal fluvial deposits above and it is also well-defined along the entire studied outcrop. This unconformity, which has a net and planar shape and is associated with a transition to fluvial deposits, is interpreted as a flood surface (*sensu* Langford and Chan, 1989).

On top of the basal surface (Sand-Drift Surface I), two different aeolian dune elements are found, separated by a planar surface dipping southwest (Fig. 6). These sedimentary bodies are constituted by very-well sorted, massive sandstones so it was impossible to measure paleocurrents. Above both of these deposits, there is a third dune element constituted by cross-stratified sandstones whose paleocurrents mark a sense of dune migration in an ENE direction (N77°E). The surface that relates this last deposit with the other dune elements below is planar and net-shaped across most of the studied sector. But there are some cases, where channelized fluvial elements are identified below this surface (Fig. 6). On the other hand, on top of the surface, wet interdune elements are found interdigitating with aeolian dune elements.

Paleo-environmental Interpretation. The development of the Sand Drift Surface I, before the accumulation of the first interval, indicates a deflation period of the underlying fluvial sediments and a posterior initiation of the aeolian accumulation (Clemmensen and Tirsgaard, 1990). In contrast, the aeolian dune elements that lay above this surface represent periods in which there were capture, transport and accumulation of fine-grained sandstone (Mountney, 2006)

The combination of dominant aeolian dune elements, along with wet interdune elements and subordinated interbedded fluvial channels, indicates that this interval was the result of the accumulation in a wet aeolian system. The bounding surfaces of the aeolian dune elements are interpreted as interdune surfaces (Mountney, 2006) given their erosive nature, low dipping angle, and dip direction opposite to paleocurrent direction. The lack of interdune deposits associated with the surfaces between the first two aeolian dune elements indicates the presence of dry interdunes characterized by local deflation (Mountney, 2006) and dryer conditions at the beginning of the accumulation of this interval.

Although in a period of aeolian dominance, the presence of channelized fluvial elements and wet interdune elements towards the top of interval suggest wetter conditions and the action of sporadic fluvial activity with the capacity to invade interdune corridors while eroding the underlying aeolian deposits (Langford and Chan, 1988). Moreover, the channelized nature of the fluvial currents forming narrow channels, indicates that floodwaters were forced to circulate through narrow interdune corridors promoting channelization (Al-Mashary and Mountney, 2015)

Since the only surfaces bounding these aeolian dune elements are interdune surfaces, and record of these elements is only punctuated by the development of reactivation surfaces it can be inferred that the bedforms that migrated during this stage were simple dunes (Kocurek, 1981). On the other hand, if we take the paleocurrent measured in the last set of cross-stratified sandstones into account, it can be interpreted that at least for this interval, these simple dunes were of transverse dynamics and had its crests perpendicular to the wind transport direction (Mountney, 2006).

The horizontal nature of the Flooding Surface at the top of this interval suggests that the aeolian depositional system that was functioning up to that moment ceased its accumulation and suffered a period of erosion that removed any potential topography associated to the *erg* (Veiga *et al.*, 2002; Mountney, 2006). According to these features, the surface can be further defined as a Stokes Surface. These are caused by the wind erosion of unconsolidated material down to the water table, leaving a relatively plain surface (Stokes, 1968). On top of that surface, deposits related to non-channelized fluvial flows are identified, suggesting a drastic change in depositional conditions.

Stage II: Ephemeral Fluvial System

General description and boundaries. This stratigraphic interval is formed by dominant proximal and subordinated distal non-channelized fluvial deposits. The geometry of the interval is relatively tabular across the studied sector and its

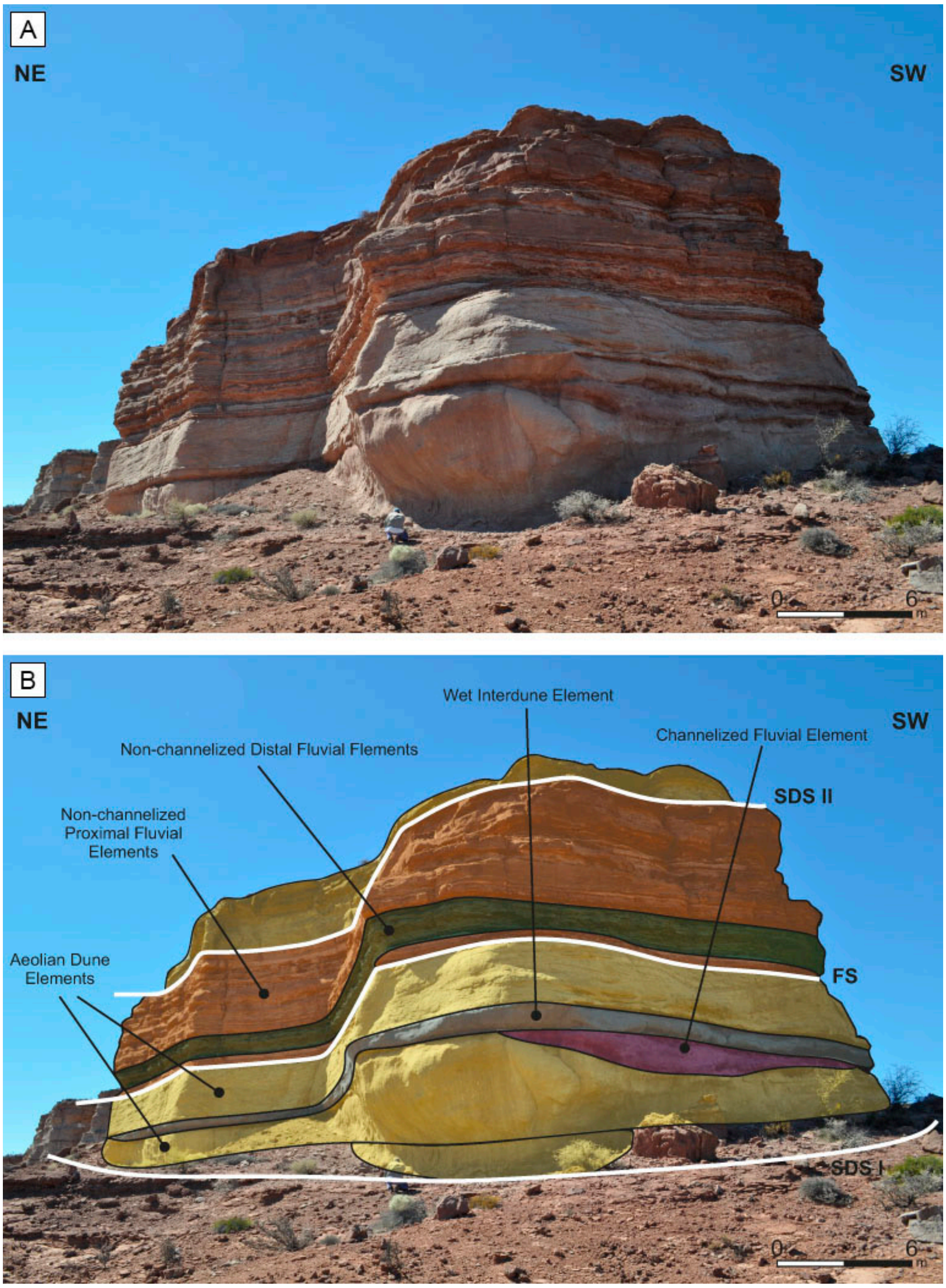

Figure 7. Stage I. **a)** Outcrop's panoramic view in the NE-SW direction. **b)** Interpretation of the architectural elements and indication of the major hierarchy surfaces. Stage I is delimited by the SDS I (Sand-Drift Surface I) at the base and FS (Flooding Surface) at the top. Stage II is limited by this FS and the SDS II (Sand-Drift Surface II).

thickness varies between 6 and 7 m (Figs. 7, 8).

This interval directly overlies the Flooding Surface previously described. The upper section of the interval is distinctly marked by a hard, highly bioturbated interval with root traces, thus indicating a stability period with reduced to null deposition (Collinson *et al.*, 2006). Since that surface lies beneath aeolian deposits, it is possible to define it as a new sand-drift surface (Sand-Drift Surface II) (Clemmensen and Tirsgaard, 1990)

The first deposits above the flooding surface across the entire analyzed area are non-channelized proximal fluvial elements dominated by non-erosive type of bodies. A planar surface separates these sandy elements from sediments interpreted as non-channelized distal elements representing the stabilization of permanent or semi-permanent, pond-like water bodies that allowed the settling from suspension (Collinson et al, 2006).

Towards the top of the interval, non-channelized proximal flow deposits are developed on top of the distal flow element across a sharp and irregular

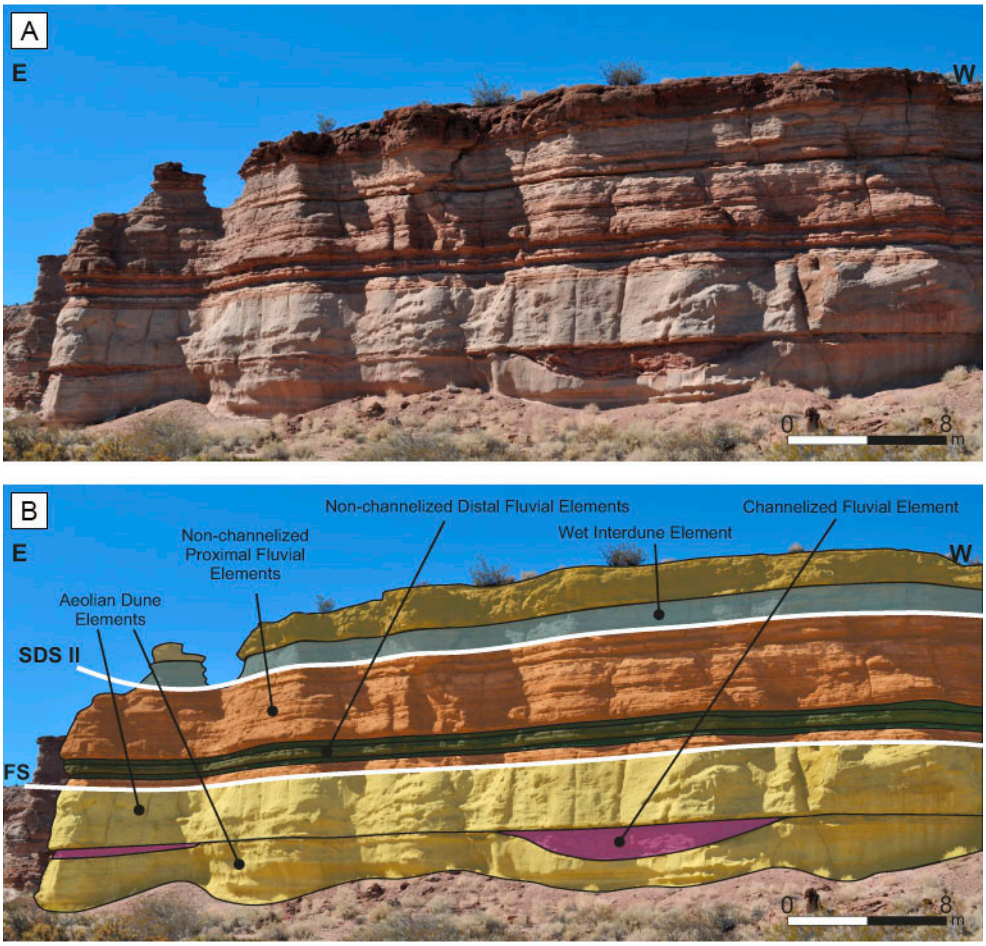

Figure 8. Stage II. **a)** Outcrop's panoramic view in the East-West direction. **b)** Interpretation of the architectural elements and indication of the major hierarchy surfaces. The stage I is delimited by the SDS I (Sand-Drift Surface I) and FS (Flooding Surface) surfaces. The interval II is limited by the FS and SDS II (Sand-Drift Surface II) in the base and the top, respectively.

contact. This facies change and contact is traced beyond the study area for at least 3 km. These units are constituted mainly by erosive non-channelized proximal fluvial elements. These are formed by individual beds with massive sandstones with convolute lamination at the top of them. Moreover, their bases have a very marked erosive nature, also given to the presence of rip-up clasts of very fine-grained red sandstone on top of irregular contacts at the base of the beds. The dominance of erosive beds in these proximal elements likely represents more proximal conditions to the source in comparison to the basal proximal deposits. In the uppermost portion of the interval, the non-channelized proximal flow deposits are non-erosive, characterized by planar or trough cross-laminated, fine-grained sandstones or horizontally laminated sandstones associated with a higher frequency of bioturbated facies.

Paleo-environmental Interpretation. The combination of proximal and distal, non-channelized fluvial elements indicates that an episodic or ephemeral fluvial system was related to the accumulation of Stage II. Given the interbedding and close occurrence of these two element types, we can argue that the vertical stacking in the record is an expression of lateral relationships, and that fluvial sheet floods passed laterally from high energy, slightly erosive and rapid sand accumulation conditions, into low energy conditions and finally to settling from suspension as they reached lower areas where the flows became stagnated (Fisher *et al.*, 2007). The presence of sandy deposits interbedded in the distal elements suggests that some high-energy floods reached the more distal parts of the system and could have affected the finer-grained substrate (Cain *et al.*, 2009).

The vertical stacking of proximal and distal fluvial deposits can be interpreted as the result of autogenic processes within the fluvial system, as the non-channelized flows may switch positions in time (Coronel *et al.*, 2020). However, the presence of erosive proximal flow deposits on top of a laterally-traceable sharp erosive surface over non-channelized distal elements might also indicate an allogenic forcing over the stacking. The greater proportion of low regime flow deposits and the rise in the frequency of bioturbated levels towards the top may also indicate gradual reduction in the energy and frequency of the flows suggesting a stabilization of the system in its late stage. Finally, the development of a second sand-drift surface on the top of this interval marks the initiation of a new stage of accumulation of an aeolian system in the area and another shift in depositional conditions.

Stage III: Wet to Dry aeolian system

General description and boundaries. The last studied stratigraphic interval at the "Cañadón de Las Tortugas" site is constituted in all its extension by aeolian-related deposits. While the overwhelming majority of the interval is made up of stacked dune elements, some wet interdune elements are also present at the base (Fig. 9). This interval is developed on top of the Sand-Drift Surface II and its upper limit is not exposed in the study area due to modern erosion. For this reason, the interval's geometry is hard to determine, and the observed thickness varies from 5 m in the most reduced parts to up to 20 m in sectors where the record has endured recent erosion (Fig. 6).

Aeolian dune elements identified for this section have large dimensions and their thicknesses are between 6 to 8 m (Fig. 9). The main dip direction of the slipfaces in these sandstones is N100°. Southeast-dipping surfaces bound the different aeolian dune elements with an angle of 2° to 3°. These surfaces could be defined as superimposition surfaces due to the fact their dip direction makes an acute angle with the dip direction of the slipfaces and because of their low angle of dip (Brookfield, 1977; Mountney *et al.*, 1999; Mountney, 2006).

Wet interdune elements from 0.5 to 2 m thick, are characterized by massive, fine-grained sandstones 0.5 to 1.5 m thick interbedded with bioturbated sandstones and cross-laminated, fine-grained sandstones 0.1 m thick. Tracing these elements in a virtual outcrop model reveals their intertonguing relationship with aeolian dune elements. Also, it showed that the thickness of the wet interdune is lower in the northeast and southwest direction, increasing their thick in the southeast direction.

Paleo-environmental Interpretation. This interval is interpreted as the result of the accumulation of an aeolian system. Due to the scale of the architectural elements and the presence of superimposition surfaces, this system was likely more developed and had a greater complexity than the dune system developed during Stage I. Superimposition surfaces indicate that individual dunes migrated above a parental bedform of greater size, a *draa* or megadune (Mountney *et al.*, 1999; Mountney, 2006). The study of the paleocurrent measured from slipfaces in the cross-stratified sets, indicates that the migrating dunes were of transverse type, with the superimposed dunes having a rather straight crestline, given the low dispersion of the dip direction data (N100° +/- 16° with 95% of confidence). On the other hand, the planar shape and similar dipping direction of the bounding surfaces compared to the slipfaces indicate a transverse *draa* type (overall sand transport perpendicular to *draa* crestline; McKee, 1979). Thereby, given that both host and superimposed dunes are of the same type, they were a compound form (*sensu* Mountney, 2006).

The presence of wet Interdune elements at the base of this interval indicates that the aeolian system that was operating at the beginning was a wet aeolian system (Mountney, 2006). Then, as the major bedforms developed the conditions had to be drier making a transition to a dry aeolian system (Mountney, 2006).

DEPOSITIONAL MODEL

The overall vertical stacking of the three stages of the study section and their bounding surfaces allows for the reconstruction of the evolution and relationships of the fluvial and aeolian sedimentary systems in the study area. The described succession can be best explained by current facies models for *erg*-margins (Mountney, 2006). In these models, *erg* systems are characterized by a progressive shift from a dry *erg* center, through a damp *erg*-margin zone, to a wet, outer *erg*-margin location, where interdune areas are periodically flooded and dune accumulation is controlled by the water table (Langford and Chan, 1989; Havholm and Kocurek, 1993; Mountney and Jagger, 2004; Mountney, 2006). In this sense, the following depositional model suggests that vertical variations in sedimentary architecture of the study section are driven by contractions and expansions of an *erg*-system.

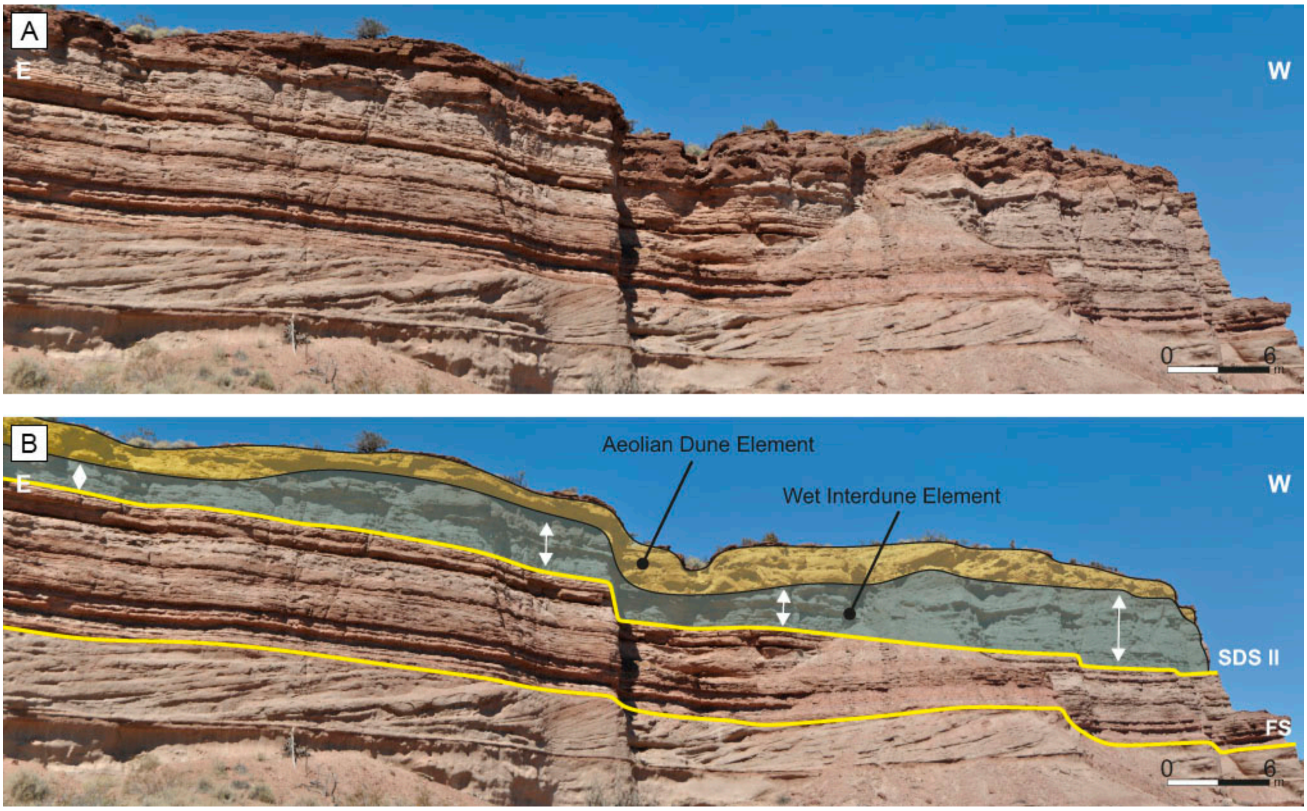

Figure 9. Stage III. **a)** Outcrop's panoramic view in the East-West direction. **b)** Interpretation of the upper deposits. Notice the change in wet interdune element's thickness (Sky-Blue) below the aeolian dune element (Yellow). References: SDS II: Sand-Drift Surface II, FS: Flooding Surface.

The construction and accumulation of a climbing, dry aeolian dune system, initiated the accumulation of stage I of the study section after a period of deflation that produced Sand-Drift Surface I (Fig. 10A). As the system evolved, the conditions were wetter and wet interdunes started to develop, often acting as corridors for channelized fluvial incursions (Al-Mashary and Mountney, 2015). This represents a shift from a dry to a wet aeolian system, where accumulation was controlled by the relative position of the water table (Kocurek, 1999; Mountney and Jagger, 2004, 2004). Dunes in this wet stage were of simple transverse type and migrated towards the E-NE.

The *erg* stopped accumulation and went into deflation/bypass conditions after accumulating the wet stage, being afterwards flooded and replaced by an ephemeral fluvial system which accumulated stage II. As a result, the flooding surface was formed and a major contraction of the *erg* is interpreted. The ephemeral fluvial system was characterized by episodic, non-channelized flows, with dominant high-energy sheetflows, depositing sand, and subordinated distal very low energy/stagnated flows, with settling silt and mud from suspension (Fig. 10B). The appearance of proximal, high-energy and erosive sheetflows, accumulating the upper stage II marks a forced progradation of the ephemeral fluvial system (Fig. 10C). Eventually, this system had a decrease in fluvial activity, allowing for an increase in the settlement of plant and animal organisms that bioturbated the uppermost deposits of stage II.

The *erg* expanded once more over the study area after the stage of fluvial activity, accumulating stage III and completing the studied succession (Fig. 10D). Although this *erg* initially had wet interdunes, no evidence of channelized accumulation or high energy fluvial flows was recorded in these deposits. As the *erg* started to climb and accumulate, large, compound transverse *draa* bedforms developed (Mountney, 2006), and the system shifted into dry conditions. These *draa* migrated towards the East.

Overall, the evolution of the accumulation systems can be summarized in a first "Kokorkom

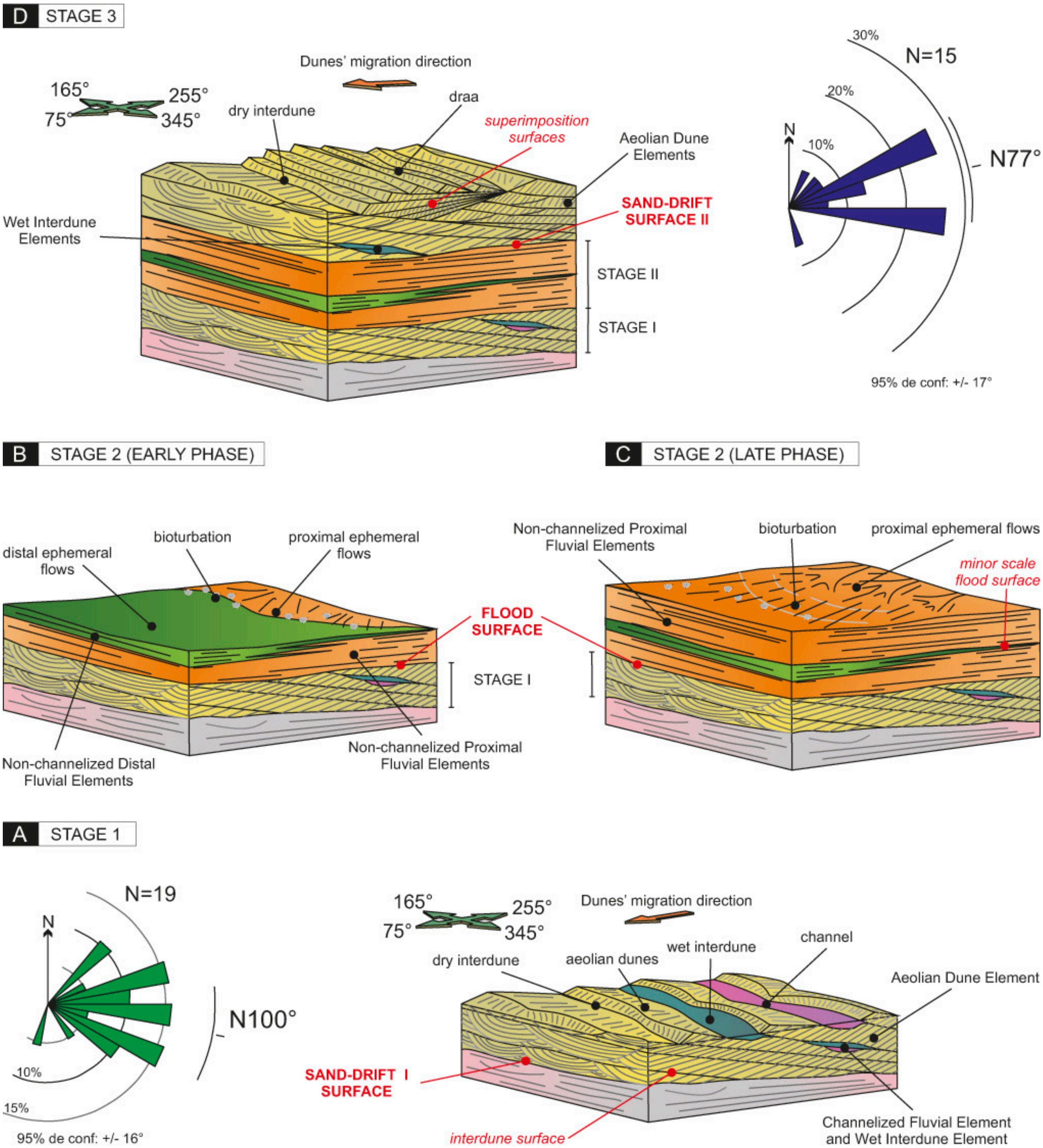

Figure 10. Depositional models **a)** Depositional model for the Stage I deposits. Wind rose indicates the dip direction of the cross-bedding within dune elements. Note that different types of interdunes can be observed: wet, damp and dry interdunes. **b)** Depositional model for the Stage II deposits: early stage. **c)** Depositional model for the Stage II deposits: late stage. **d)** Depositional model for the Stage III deposits. Wind rose indicates the dip direction of the cross-bedding within dune elements. Note the transition from a wet aeolian system to a dry one reflected in the expansion of the *erg* and development of *draa*.

erg" expansion, followed by *erg* contraction coupled with an invasion of a fluvial ephemeral system, and finally a new expansion of the *erg* system, along with the retreat of the fluvial system, culminating in the development of large-scale bed forms in dry conditions (Fig. 11).

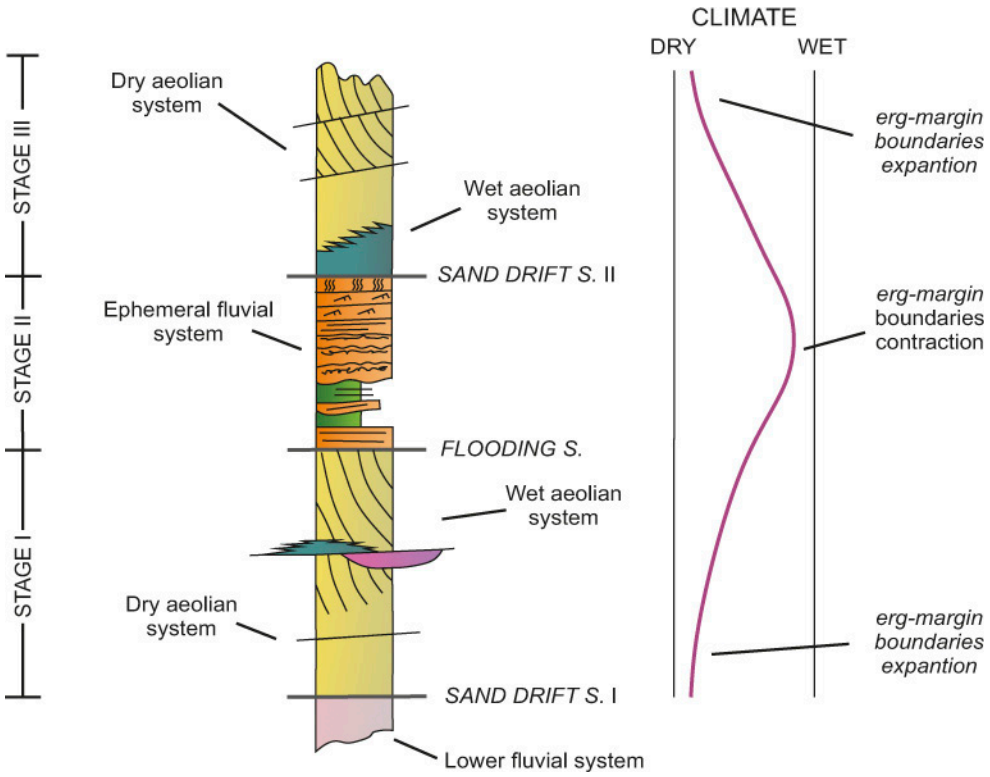

Figure 11. Schematic sedimentary log from the "Cañadón de Las Tortugas" site with the different evolutionary stages pointed. The inferred climate variations between dryer and wetter conditions at also indicated.

DISCUSSION

Controls on sedimentation

With the presented depositional model, the relative position between the accumulation surface and the water table can be inferred. A Barrell diagram (Barrel, 1917) provided a suitable method to visualize this relationship in detail (Fig. 12).

The onset of Stage I accumulation is marked by a positive slope of the accumulation surface. The shift from a dry to a wet aeolian system, as observed in the record of this stage, is linked to a rise in the water table illustrated by the approximation of both curves. Then, a period where deflation and/or bypass had taken place is shown by a decline due to absence of accumulation. During this temporal interval, the Strokes Surface was generated. After that, a Flooding Surface was created, represented by the intersection between the lines. From this moment, a period of fluvial erosion was installed starting the Stage II. Then, a time of ephemeral fluvial system accumulation is marked by the positive slope of the accumulation curve. A new erosion period is generated with accumulation after reflected by the oscillations that the lines have during this stage. The Sand-drift surface that tops these deposits is shown by another curves' intersection. Again, this marks the beginning of the third stage of accumulation. Given that during this period a transition between a wet aeolian system to a dry one happened, the phenomenon is represented by a distancing between the accumulation curve and water table curve during a period of accumulation with positive slope.

Consequently, periods of relative water table rise can be associated to *erg* contraction, and alternatively, periods of water table lowering can be linked to *erg* expansion. With a notion of the relative height of the water table, the control parameters upon construction, accumulation and preservation of the studied record can be discussed. Given the tectonic context of the unit, within a foreland basin far from the orogenic wedge, a relatively constant subsidence is assumed (Garrido, 2011). Having this consideration, inferred variations in the position of the water table can be linked to climate change, and wetting and drying upwards trends to climate forcing of the *erg* margin system.

Erg construction is controlled by the supply of the sediment, the sediment available for entrainment by the wind, and the transport capacity of the wind (Kocurek and Lancaster, 1999). In dry

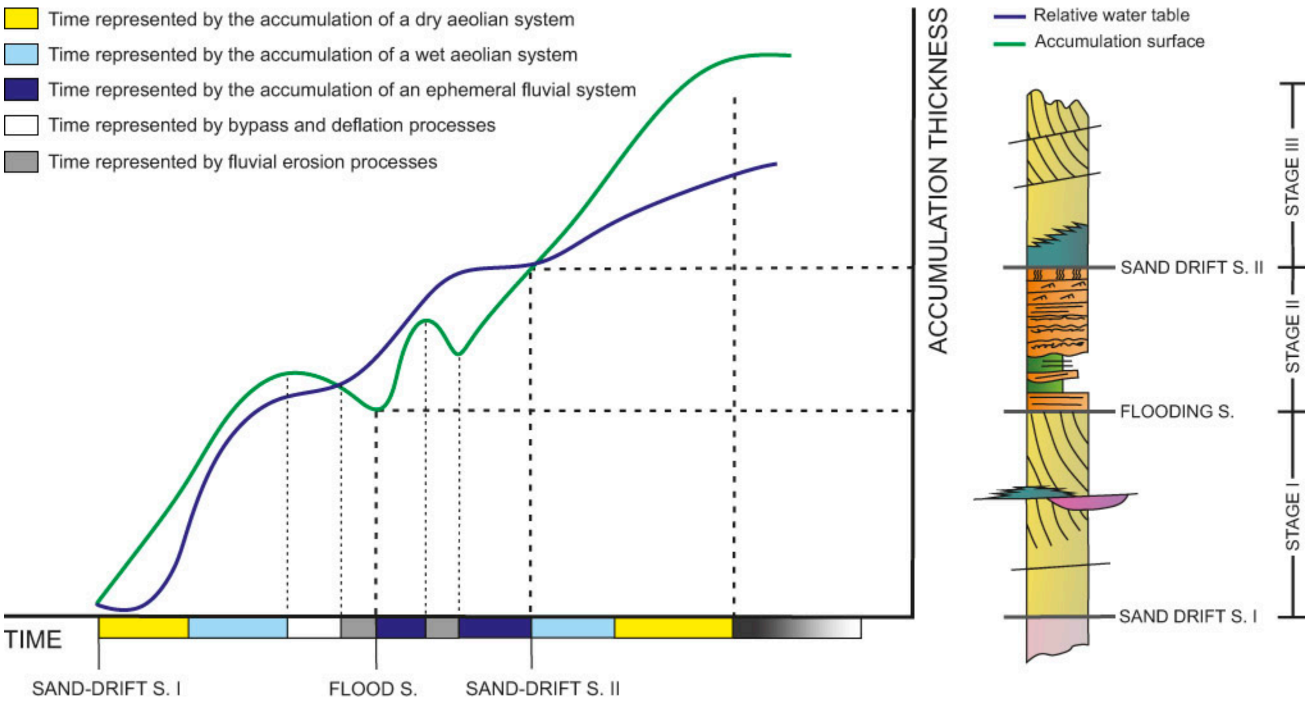

Figure 12. Barrel diagram (Barrell, 1917) showing a possible combination of the accumulation surface (green line) and water table variation (blue line) for the preservation of the geologic record found in the "Cañadón de Las Tortugas" site.

aeolian systems, accumulation occurs when there is a positive net sand budget in a particular sector, usually when the saturated wind suffers a loss in transport capacity (e.g. as the result of the flow expansion when entering a topographic basin). Hence, the bedforms grow until a point where they start to climb (Kocurek and Lancaster, 1999). Given that the initial construction of the Kokorkom *erg* after a deflation period was related to a low water table and arid climate, construction most likely occurred given an increase in sediment availability in the sediment source area. It is likely that an increment in arid conditions over the area made more dry sediment available for transport. Furthermore, wind dynamics was evidently favorable not only for transport, but also for accumulation of a dry sedimentary column.

The later shift of the initial Kokorkom *erg* towards a wet aeolian system indicates the start of a wetting upwards trend. The accumulation of a wet aeolian system is controlled mainly by a progressive rise in the water table that happens at the same time of dune migration (Mountney and Jagger, 2004). The generation of a Stokes Surface indicates that further rise of the water table and humidity in the area likely caused the contrary conditions to early *erg* construction, given a drop in sediment availability, deflation down to the water table and *erg* contraction, and eventually flooding the study area (Fryberger *et al.*, 1988). This water table rise also allowed for the preservation of the initial aeolian accumulation. In order to pass into the geologic record, leaving aside exceptional mechanisms, preservation of aeolian successions is controlled by the temporal and spatial variations of the relative water table (Havholm and Kocurek, 1993). Finally, the wetting upwards trend likely continues during the accumulation of stage II, being the probable cause for initial *erg* contraction as the fluvial system expanded.

Following the same reasoning, a drying upwards trend controls accumulation of the upper stage II and the second expansion of the Kokorkom *erg* at stage III (Fig 11), by lowering the water table, gradually increasing sediment availability, and providing the proper conditions for *erg* construction and accumulation. Regarding preservation however, there is yet no evidence as to the mechanisms that allowed stage III to pass into the geological record.

Fluvio-aeolian interaction

Fluvial and aeolian systems rarely operate independently in desert regions, and both fluvial and aeolian processes typically occur and interact within these systems (Bullard and Livingstone, 2002; Mountney and Jagger, 2004; Al-Masrahy and Mountney, 2015). Having this in consideration, to understand the ancient environmental conditions at La Buitrera Paleontological Area, and add new insights to the ecological conditions of the ancient fauna, we must consider how interdependent the identified fluvial and aeolian processes and accumulation systems were.

The interpreted accumulation systems, and their geological record, were categorized as “aeolian” or “fluvial”, denoting the dominant processes within the system. However, within aeolian intervals for instance, architectural elements related to a suite of fluvial processes are usually interbedded. This is most evident in Stage I, where channelized fluvial elements were found interbedded with aeolian dune and sometimes interdune elements. In addition, wet interdune elements usually display an alternation between massive aeolian sandstone, and beds of current-ripple laminated sandstone, indicating aeolian-fluvial process interaction even within architectural elements. In the case of the interbedded channelized fluvial elements, their presence indicates not only the influence of the water table upon accumulation in a wet aeolian system, but also the action of channelized flows across their interdunes, observed to be recurrent laterally across the study area. This record is therefore most likely the result of fluvial incursions, a typical fluvial-aeolian interaction, in which fluvial currents from outside the *erg*, penetrate for considerable distances within it, constrained and channelized in open interdune corridors (Al-Masrahy and Mountney, 2015). On the other hand, an aeolian influence within dominantly fluvial stage II is suggested by the overall grain size of the interval, which is very similar to the aeolian intervals above and below. Therefore, fluvial sheetflows that accumulated stage II both pass over and eroded previous aeolian deposits or the currents took the sediment from the margins of the protracted, but still active dunefield.

This leads to the discussion of the interdependence between the accumulation systems. In the study area, the record of fluvial and aeolian systems is separated by major unconformities (flooding and sand-drift surfaces). This would give the impression that the fluvial and aeolian systems were independent, never coevally active. However, there is evidence that indicates otherwise. As we discussed earlier, the aeolian and fluvial systems form integral part of the same wetting upward or drying upwards trends, likely linked to climatic changes. As presented in the depositional model, current facies models of *erg* margins contemplate a lateral shift from marginal ephemeral fluvial systems, to wet *erg* margins, to dry *erg* centers; therefore major surfaces in the succession don’t represent a fundamental break from these transitions. And finally, there is evidence of interaction of fluvial-aeolian processes within each stage. Hence, it is most likely that the aeolian and fluvial systems identified were strongly interdependent systems, interbedded laterally at a regional scale.

Although documenting lateral transitions between these systems would require a further regional study, we can grasp a preliminary notion of the lateral extensions of the system and subsystem from the present study. This is especially relevant to understand the ecological conditions in which the animal species found within this interval lived. For instance, at the most humid stage in the fluvial system in which record the fossilized turtle (Maniel *et al.*, 2020) remains were found, the settling from suspension domain of distal flow elements had at least 3 km lateral extension at the NE-SW direction.

CONCLUSIONS

Detailed facies analysis allowed the identification of fluvial and aeolian processes in the Cretaceous Candeleros Formation at “Cañadón de Las Tortugas” site, within La Buitrera locality, Neuquén Basin, Argentina. The definition of five architectural elements revealed how the fluvial and aeolian sedimentary processes interacted within the accumulation system. At a stratigraphic-scale of analysis, the result of these interactions was registered in the geological record in three evolutive stages that could be easily separated and recognizable. Two of them, the first and third one, were aeolian dominated, while the second one is clearly fluvial dominated. Moreover, the identification of key surfaces, such as the flooding surface and both sand-drift surfaces, were crucial for the recognition of important shifts in the accumulation systems. These indicate that other processes apart from accumulation have been registered such as deflation, bypass and fluvial erosion.

The geological record studied is consistent with the accumulation of an *erg* margin system that experienced expansions and contractions through time. Water table position, likely linked to climatic conditions, controlled not only how the *erg* margin expanded or contracted its boundaries, but also the type of aeolian system developed. Hence, the analysis of *erg*-margins depositional systems is an important tool to help understand the different conditions in which interaction processes occur and to enhance the paleogeographical reconstructions of aeolian systems.

On the other hand, the understanding of temporal evolution reaffirms the influence that the water table has, under wet conditions, on the development of aeolian dune systems. As conditions turned wetter the ephemeral fluvial systems became more active. In this way, the studied deposits reflect the transition of a dry aeolian system, probably located near the *erg* center, which shifted to a wet one. Then it was replaced by a fluvial system due to wetter climate conditions. Finally, once arid conditions returned, triggering a decrease in the water level, a new aeolian system was developed. This means that with the aeolian dune system contraction, the area is exposed to other events such as ephemeral flows invasions. This work is an example of how different fluvial and aeolian systems never operate independently but always coexisting, showing interactions at different temporal and spatial scales.

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REFERENCES

Al-Masrahy, M. A., and Mountney, N. P. (2015). A classification scheme for fluvial-aeolian system interaction in desert-margin settings. *Aeolian Research*, 17, p. 67-88.

Apesteguía, S., de Valais, S., González, J.A., Gallina, P.A. and Agnolin, F.L. (2001). The tetrapod fauna of 'La Buitrera', new locality from the basal Late Cretaceous of North Patagonia, Argentina. *Journal of Vertebrate Palaeontology*. Abstracts 21 29A.

Apesteguía, S., Agnolin, F. L. and Claeson, K. (2007). Review of Cretaceous dipnoans from Argentina (Sarcopterygii: Dipnoi) with descriptions of new species. *Revista del Museo Argentino de Ciencias Naturales*, nueva serie 9 (1): 27-40.

Apesteguía, S., Veiga, G.D., Sanchez, M.L., Argüello-Scotti, A. and Candia-Halupczok, D.J. (2016). *Kokorkom, el desierto de los huesos: Grandes dunas eólicas en la Formación Candeleros (Cretácico Superior), Patagonia Argentina.* XI *Congreso de la Asociación Paleontológica Argentina*. General Roca. Actas: 7.

Argüello Scotti, A. and Veiga, G.D. (2015). Morphological characterization of an exceptionally preserved eolian system: the cretaceous Troncoso inferior member in the Neuquén Basin (Argentina). *Latin American Journal of Sedimentology and Basin Analysis* 22 (1): 29-46.

Asurmendi, E. and Sánchez, M.L. (2014). *Análisis petrográfico y procedencia de las sedimentitas de las Formaciones Candeleros y Huincul (Cretácico Inferior-Superior), región occidental de Cuenca Neuquina, provincia de Neuquén, Argentina*. IX Congreso de Exploración y Desarrollo de Hidrocarburos. Mendoza. Actas: 161-168.

Barrell, J. (1917). Rhythms and the measurements of geologic time. *Bulletin of the Geological Society of America* 28: 745-904.

Bridge, J.S. (1993). Description and interpretation of fluvial deposits: a critical perspective. *Sedimentology* 40: 801-810.

Bullard, J.E. and Livingstone, I. (2002). Interactions between aeolian and fluvial systems in dryland environments. *Area* 34.1: 8-16.

Cain, S.A. and Mountney, N.P (2009). Spatial and temporal evolution of a terminal fluvial fan system: The Permian Organ Rock formation, South-east Utah, USA. *Sedimentology* 56: 1774-1800.

Candia Halupczok, D.J., Sánchez, M.L., Veiga, G.D. and Apesteguía, S. (2018). Dinosaur tracks in the Kokorkom Desert, Candeleros Formation (Cenomanian, Upper Cretaceous), Patagonia Argentina: Implications for deformation structures in dune fields. *Cretaceous Research* 83: 194-206.

Cazau, L.B. and Uliana, M.A. (1973). El Cretácico superior continental de la Cuenca Neuquina. *5° Congreso Geológico Argentino*. Buenos Aires. Actas 3: 131-163.

Clemmensen, L.B. and Tirsgaard, H. (1990). Sand-drift surfaces: A neglected type of bounding surface. *Geology* 18: 1142-1145.

Collinson, J.D., Mountney, N.P. and Thompson, D.B. (2006). Sedimentary structures. *Terra Publishing*. 292 pp.

Coronel M.D., Isla M.F., Veiga G.D., Mountney N.P. and Colombera, L. (2020). Anatomy and facies distribution of terminal lobes in ephemeral fluvial successions: Jurassic Tordillo Formation, Neuquén Basin, Argentina. *Sedimentology* 67: 2596-2624.

De Ferrariis, C. (1968). El Cretácico del norte de la Patagonia. *III Jornadas Geológicas Argentinas*. Actas 1: 121-144.

Fisher, J.A., Nichols, G.J. and Waltham, D.A. (2007). Unconfined flow deposits in distal sectors of fluvial distributary systems: Examples from the Miocene Luna and Huesca Systems, northern Spain. *Sedimentary Geology* 195(1-2): 55-73.

Fryberger, S.G. (1993). A review of aeolian bounding surfaces, with examples from the Permian Minnelusa Formation, USA, In C.P. North and Prosser, J.D. (Eds.), *Characterization of Fluvial and Aeolian Reservoirs.* Geological Society of London, Special Publication 73: 167-197.

Fryberger, S.G., Schenk, C.J. and Krytinik, L.F. (1988). Stokes surfaces and the effects of near surface groundwater table on Aeolian deposition. *Sedimentology* 35(1): 21-41.

Garberoglio, F.F., Gómez, R., Apesteguía, S., Caldwell, M.W., Sánchez M L. and Veiga, G.D. (2019). A new specimen with skull and vertebrae of Najash rionegrina (Lepidosauria: Ophidia) from the early Late Cretaceous of Patagonia. *Journal of Systematic Palaeontology* 17: 1313-1330.

Garrido, A.C. (2010). Estratigrafía del Grupo Neuquén Cretácico Superior de la cuenca Neuquina (Argentina): nueva propuesta de ordenamiento litoestratigráfico. *Revista del Museo Argentino de Ciencias Naturales* 12 (2):121-177.

Garrido, A.C, (2011). *El Grupo Neuquén (Cretácico Tardío) en la Cuenca Neuquina*. Relatorio Del XVIII Congreso Geológico Argentino, p. 231-244.

Gibling M. R. (2006). Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. *Journal of Sedimentary Research* 76: 731-770.

Havholm, K.G. and Kocurek, G. (1993). Eolian sequence stratigraphy e a conceptual framework. In: Weimer, P. and H.W. Posamentier, (Eds.), *Siciliclastic Sequence Stratigraphy.* American Association of Petroleum Geologists Memoir 58: 393-409.

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

Hunter, R.E. (1977). Terminology of cross-stratified sedimentary layers and climbing ripple structures. *Journal of Sedimentary Petrology* 47: 697-706.

Kocurek, G. (1981). Significance of interdune deposits and bounding surfaces in aeolian dune sands. *Sedimentology* 28: 753-780.

Kocurek, G. and Lancaster, N. (1999). Aeolian system sediment state: theory and Mojave Desert Kelso dune field example. *Sedimentology* 46 (3): 505-515.

Langford, R.P. (1989). Fluvial–aeolian interactions: part 1, modern systems. *Sedimentology* 36: 1023-1035.

Langford, R.P. and Chan, M.A. (1989). Fluvial–aeolian interactions: part 2, ancient systems. *Sedimentology* 36: 1037-1051.

Leanza, H.A. (2009). Las principales discontinuidades del Mesozoico de la cuenca Neuquina según observaciones de superficie. *Revista del Museo Argentino de Ciencias Naturales*, nueva serie 11 (2): 145-184.

Leeder M.R. (1982). *Sedimentology*: Process and Product. *Springer* 344 pp.

Makovicky, P.J., Apesteguía, S. and Agnolín, F.L. (2005). The earliest dromaeosaurid theropod from South America. *Nature* 437: 1007-1011.

Makovicky, P.J., Apesteguía, S. and Gianechini, F.A. (2012). A new coelurosaurian theropod from the La Buitrera fossil locality of Río Negro. Argentina. *Fieldiana Life and Earth Sciences* 5: 90-98.

Maniel, I J., de la Fuente, M.S., Apesteguía, S., Pérez Mayoral, J., Sánchez M.L., Veiga, G.D. and Smales, I. (2020). Cranial and postcranial remains of a new species of Prochelidella (Testudines: Pleurodira: Chelidae) from 'La Buitrera' (Cenomanian of Patagonia, Argentina), with comments on the monophyly of this extinct chelid genus from southern Gondwana. *Journal of Systematic Palaeontology* 20 (12): 1033-1055.

Mountney, N.P. (2006). Eolian facies Model. Facies Models Revisited. *SEPM Special Publication* 84: p. 19-83.

Mountney, N.P., Howell, J., Flint, S. and Jerram, D. (1999). Relating eolian bounding-surface geometries to the bed forms that generated them: Etjo Formation, Cretaceous, Namibia. *Geology* 27(2): 159-162.

Mountney, N.P. and Jagger, A. (2004). Stratigraphic evolution of an aeolian erg margin system: The Permian Cedar Mesa Sandstone, SE Utah, USA. *Sedimentology* 51(4): 713-743.

Pol, D. and Apesteguía, S. (2005). New Araripesuchus remains from the Early Late Cretaceous (CenomanianeTuronian) of Patagonia. *American Museum Novitates* 3490, 38 pp.

Rougier, G.W., Apesteguía, S. and Gaetano, L.C. (2011). Highly specialized mammalian skulls from the Late Cretaceous of South America. *Nature* 479: 97-102

Sánchez, M.L. (2004). Paleoambientes sedimentarios de la Formación Candeleros (Subgrupo Río Limay), Cretácico Superior, sudeste del Neuquén. *IV Congreso Uruguayo de Geología y II Reunión de Geología Ambiental y Ordenamiento Territorial del MERCOSUR*, 20 pp.

Sánchez, M.L. and Asurmendi, E. (2015). Stratigraphy and sedimentology of the terminal fan of Candeleros Formation (Neuquén Group), Lower Cretaceous, Neuquén basin, provinces of Neuquén and Mendoza, Argentina. *Andean Geology* 42 (3): 329-348.

Sánchez, M L., Rossi, J., Morra, S. and Armas, P. (2008). Análisis Estratigráfico secuencial de las formaciones Huincul y Lisandro del Subgrupo Rio Limay (Grupo Neuquén - Cretácico tardío) en el departamento El Cuy, Rio Negro, Argentina. L*atin American Journal of Sedimentology and Basin Analysis* 15 (1): 1-26.

Spalletti, L.A. and Gazzera, C.E. (1989). Eventos eólicos de capas rojas cretácicas (Fm. Río Limay, Grupo Neuquén), sector sudeste de la Cuenca Neuquina, Argentina. *Contribuciones de los Simposios sobre Cretácico de América Latina* Parte A: 89-100.

Stokes, W.L. (1968). Multiple parallel-truncation bedding planes a feature of wind deposited sandstone formations. *Journal of Sedimentary Petrology* 38: 510-515.

Veiga, G.D., Spalletti, L.A., and Flint, S. (2002). Aeolian/fluvial interactions and high-resolution sequence stratigraphy of a non-marine lowstand wedge: the Avilé Member of the Agrio Formation (Lower Cretaceous), central Neuquen Basin, Argentina. *Sedimentology* 49(5): 1001-1019.