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Stratigraphy and sedimentology of the terminal fan of Candeleros Formation (Neuquén Group), Lower Cretaceous, Neuquén Basin, provinces of Neuquén and Mendoza, Argentina

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ABSTRACT. The Candeleros Formation is represented by a succession of deposits that represent terminal fans starting to fill a foreland basin (back-arc) during the Albian. The different sub-environments of the terminal fan suggest low gradients during the onset of deposition of the Río Limay Subgroup (Neuquén Group). The terminal fan system is represented by distributary zone (TF-DZ), distributary zone-base zone (TF-DZBZ) and base zone deposits (TF-BZ). Its most notable feature is the presence of bitumen in "pockets" and scattered in the sandstone channel fill and crevasse splays deposit. In this system the feeder zone of the terminal fan system has not been identified, however, the distribution of architectural elements and paleocurrent data allow us to infer that the catchment area of the backbone would have been located to the NNW/NW. Distributary zone deposits are characterized by thick deposits of low sinuosity channel, with a high degree of connectivity and strong vertical aggradation of channel belts. Deposits of distributary zone-base zone are characterized by a higher density of channel deposits/distributary plain, but with belt channel less thick, longer laterally, greater width/thickness ratio and connectivity in the braided deposits. The distal parts of the terminal fan are well represented and vary only in the channelized deposits and mantle/floodplain ratio, which is abruptly reduced towards the flood basin connection. The importance of Candeleros Formation deposits is that they are remnants of accommodation that preserved the original architecture and represent exhumed reservoirs.

Keywords: Candeleros Formation, Neuquén Basin, Terminal fan.

RESUMEN. Estratigrafía y sedimentología del abanico terminal de la Formación Candeleros (Grupo Neuquén), Cretácico Inferior, Cuenca Neuquina, provincias de Neuquén y Mendoza, Argentina. La Formación Candeleros se encuentra representada por una sucesión de depósitos de megabanicos terminales que representan el inicio del relleno de la cuenca de antepaís (retroarco) durante el Albiano. La identificación de los distintos subambientes del abanico terminal permite inferir bajos gradientes regionales topográficos durante el inicio de la depositación del Subgrupo Río Limay (Grupo Neuquén). El sistema de abanico terminal está representado por depósitos de la zona distributaria (TF-DZ), zona distibutaria-zona base (TF-DZBZ) y zona base (TF-BZ). Su rasgo más destacable es la presencia de bitumen en "bolsones" y de manera dispersa en las areniscas del relleno de canal y en los depósitos de abanicos de desborde. En este sistema no se ha identificado un sistema de alimentación del abanico terminal, sin embargo, la distribución de los elementos arquitecturales y datos de paleocorrientes permiten inferir que el área de captación de la red troncal se habría ubicado al NNW/NW. Los depósitos de la zona distributaria están caracterizados por potentes depósitos de canales de baja sinuosidad, con escasa participación de canales sinuosos, con un alto grado de conexión y fuerte agradación vertical de los cinturones de canal. Los depósitos de la zona distributaria-zona base están caracterizados por una mayor densidad de depósitos de canal/planicie distributaria, pero con cinturones de canal menos potentes, más extensos lateralmente, mayor relación ancho/espesor y alta relación de conección en los depósitos entrelazados. La importancia de estos cinturones de canal es la presencia de abundante bitumen que inclusive induce una coloración oscura de los afloramientos y la abundante dispersión en los depósitos de desborde. Los sectores distales del abanico terminal están bien representados y varían solamente en la relación depósitos canalizados y manto/planicie de inundación, los cuales se reducen abruptamente hacia la cuenca de inundación. La importancia de los depósitos de la Formación Candeleros es que constituyen remanentes de acomodación que conservan la arquitectura original y representan reservorios exhumados.

Palabras clave: Formación Candeleros, Cuenca Neuquina, Abanico terminal.

1. Introduction

The Neuquén Basin (Fig. 1) is a localized ensialic depression occuring in positions of an intra-arc (Chile) and retro-arc (Argentina). The tectonic history of the basin involves different stages, such as the development of rift basins during the Late Triassic-Jurassic (Legarreta and Gulisano, 1989; Ramos and Folguera, 2005). During the Cretaceous, as a result of the growth of the volcanic arc, the basin was completely isolated from the sea due to changes in the dynamics of the continental margin at the western edge of South America. Various factors, particularly changes in the expansion rate of the South Atlantic Ocean, the reorganization of the Pacific Plate and the decrease in the angle of subduction led to the development of compressive tectonics that caused the reversal of extensional and flexural basin structures in the Neuquén Basin region (Cobbold and Rossello, 2003). This back-arc foreland basin was controlled by compressive tectonics, tectonic inversion and the uplift of the area located to the west. The Agrio Fold -and- Thrust Belt (Fig. 1) foreland phase and position controlled the distribution of major depocenters, which include the Neuquén and Malargüe Groups, and their migration to the east (Howell *et al.,* 2005; Ramos and Folguera, 2005). By the end of the Cretaceous, the Atlantic marine transgression, associated with high sea level on a global scale, affected the Neuquén Basin and

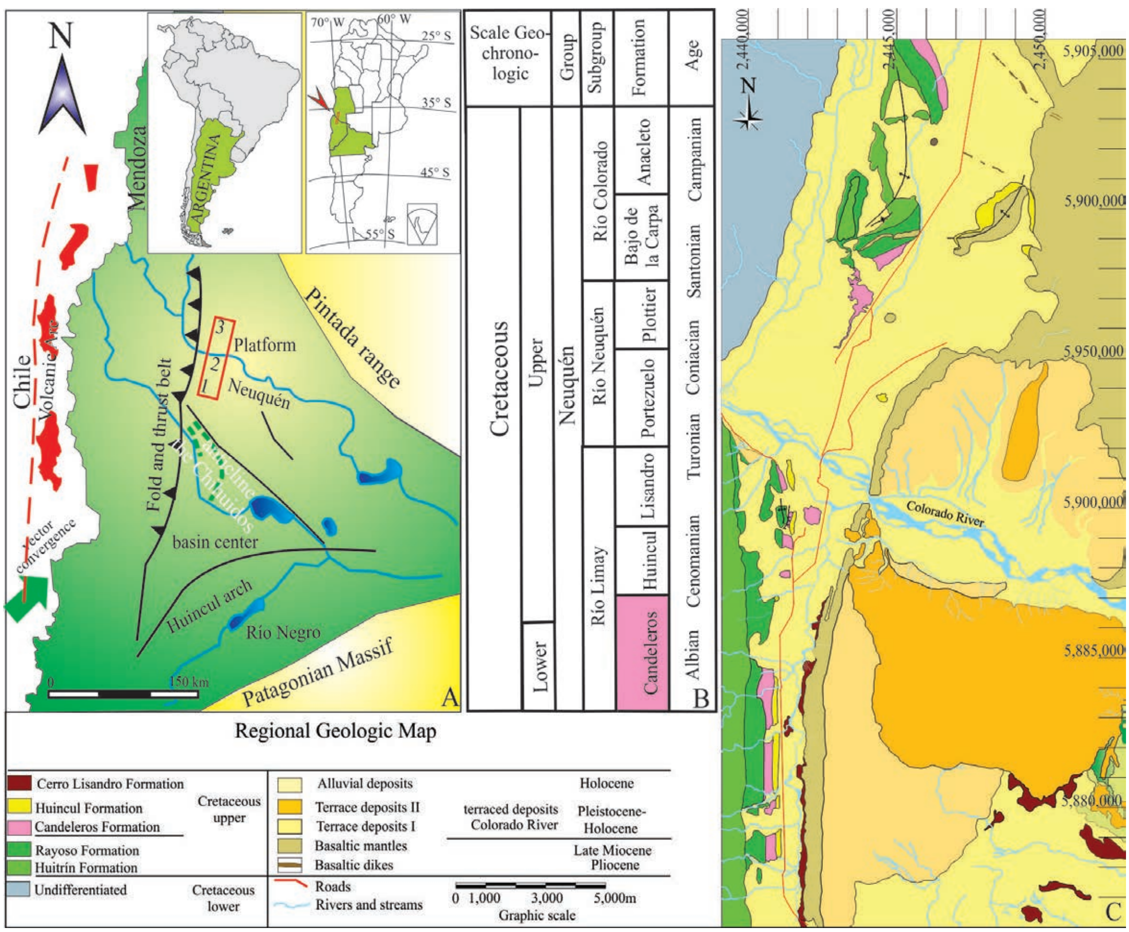

FIG. 1. **A.** Map of Neuquen Basin (modified from Cobbold and Rosello, 2003; Manacorda *et al.,* 2004; Ramos and Folguera, 2005), with major structural features. To the west the volcanic arc and Fold - and - Thrust Belt NE verging to the Cretaceous; to the south, the Huincul arch. The study area is indicated by the red rectangle in the center of the figure and signalled by arabic numerals (1-3); **B.** Table of chronostratigraphic Neuquen Group (in pink stratigraphic unit studied); **C.** Geological map of the study area.

allowed the deposition of shallow marine sediments over large areas (Cobbold and Rosello, 2003).

The Río Limay Subgroup (De Ferrariis, 1968) is the basal unit of the Neuquén Group (Fig. 1) consisting of fluvial, aeolian, lacustrine and deltaic deposits accumulated in the Neuquén Foreland Basin. This basin includes the Candeleros, Huincul and Cerro Lisandro Formations and has a minimum thickness of 350 m. It ranges from the Albian to early Turonian and crops out in the southwestern Mendoza Province, the eastern and southe astern Neuquén Province and the northwestern Río Negro Province (Hugo and Leanza, 2001).

Although there have been studies in certain localities, concerned with the depositional architecture and auto- and allocyclic mechanisms that controlled sedimentation (Sánchez *et al.,* 2008), there is a notable absence of studies level developing an evolutionary model at basin level.

This paper aims to characterize and interpret, at different scales, the architecture of the terminal fan depositional system of the Candeleros Formation range by identifing and correlating discontinuities in the development of the stratigraphic sequence of the Río Limay Subgroup (local and regional). This will be a contribution to the tecto-sedimentary evolution of the subgroup in the central Neuquén Basin. For this purpose we selected continuous exposures of an up to 8 km long sector at the foot of the Agrio Fold - and - Thrust Belt in the region of Sierra de Reyes and the Cara Cura Belt. We present here the first map showing the formations that make up the Río Limay Subgroup, which have been identified and mapped for the first time in this region (Fig. 1c).

The importance of defining the depositional system and its relationship with autocyclic and allocyclic processes during their formation, is that they constitute depositional remnants of accommodation (Martinsen, 2003), which preserve the original architecture and represent exhumed reservoirs (Sánchez and Asurmendi, 2011; Asurmendi and Sánchez, 2014a; Asurmendi and Sánchez, 2014b).

2. Tectonic framework

The Neuquén Group corresponds to the synorogenic deposits of the Andean Foreland Basin (Cretaceous-Tertiary), and since the Cenomanian it has been affected by a complex history of deformation that peaked during the late Campanian (Silvestro and Zubiri, 2008). The start of the red sediments of the Neuquén Group begins with the deposition of the Candeleros (Keidel in Wichmann, 1927) Formation after the Diastrophic Phase of Patagonides Movements, which is expressed in the intercretaceous or intercenomanian unconformity (Ramos, 1981; Leanza, 2009; Tunik *et al.,* 2010) aged 97±3 Ma. The Candeleros Formation has its type locality east of the hill Lotena in the southern Province of Neuquén and its maximum thickness is approximately 300 m. The sequence in the type locality is interpreted as deposits of braided river systems associated with muddy floodplain deposits with development of paleosols (Herrero Ducloux, 1946; Leanza and Hugo, 1997; Garrido, 2000; Rodríguez *et al.,* 2007). While near the damming of El Chocón, Spalletti and Gazzera (1994) mencionated an environment corresponding to eolian and beach-lake deposits.

There is general consensus that the depositional basin systems were strongly controlled by the beginning of compressive tectonics during the Late Jurassic (Vergani *et al.,* 1995; Pángaro and Bruveris, 1999; Silvestro and Zubiri, 2008). The foreland basin stage (120-75 Ma - Vergani *et al.,* 1995; Howell *et al.,* 2005) is associated with the inversion of the compressional regime of the Andean margin, which controlled the size, shape and eastward migration of depocenters, thus resulting in the deposition of the Neuquén and Malargüe Groups (Cobbold and Rosello, 2003, Howell *et al.,* 2005; Aguirre Urreta *et al.,* 2011). Orogenic events in western Gondwana coincided with the start of the opening of the Atlantic Ocean and the absolute motion of the South American Plate to the west. The main stress vector, oriented NNW to NW during the Jurassic, rotated to a more orthogonal orientation during the late (Ramos and Folguera, 2005).

Early Cretaceous, which controlled the development of the Agrio Fold -and- Thrust Belt, forming the Late Cretaceous orogenic front. The shortening and lifting of the Agrio Fold -and- Thrust Belt (Fig. 1a) started at about 100 Ma with the inversion of the structurs of previously developed semi-grabens and continued its late Miocene migration of deformation toward the foreland (Zapata and Folguera, 2005; Zamora Valcarce *et al.,* 2007).

The Huincul Arch (Fig. 1a) is a first-order morphostructural feature in the Neuquén Basin with a general east-west orientation and extention of more then 270 km, constituting a structural barrier that exerted a strong control on sedimentation during the Jurassic and Cretaceous in the southern part of the Neuquén Basin. The geometric complexity and evolution of structures on a regional scale is explained by the oblique convergence between two regions of different mechanical behaviors (Silvestro and Zubiri, 2008; Pángaro *et al.,* 2009; Naipauer *et al.,* 2012).

Evidence for the beginning of compression in the andean basin was preserved in the Huincul Arch and along EW, NE and NE lineaments in the Albian, when the arch was very active, and persisted until the Tertiary. In the central sector of the basin, major anticlinal structures and lineaments are related to the trend of the most important inversion of semi-graben depocenters of previous extensional tectonics, inverting only in sections of extensional faults. These strain systems are of major importance in the structural features identified in the deposits of the Neuquén Group (Silvestro and Zubiri, 2008).

The compressive regime also affected the Chihuidos anticlinal structure with an area extending 70 km (Fig. 1a), elongated in the north-south direction. Subsurface information shows that this structure is of a low structural complexity, and its source would be linked to the oblique subduction of the tectonic compression between the Early Jurassic and Valanginian (Mosquera and Ramos, 2005). The deformational events associated with this structure, which played an important role in the tectonic basin, occurred from the Jurassic to late Miocene (Zamora Valcarce *et al.,* 2009). The hinterlad of the Chihuidos structure has already been considered by some authors (Cobbold and Rosello, 2003) as a topographic high that could have actued as a peripheral bulge from the Aptian, conditioning the distribution of the different depocenters during the evolution of the foreland basin. The Neuquén Group includes three full overfilled-underfilled cycles of a foreland basin (Sánchez and Asurmendi, 2011), limited by discontinuities that are associated with the activity of the orogenic front and the subsequent stages of flexural subsidence. The discontinuities that limit Albian-Cenomanian sequences correspond to the Peruvian phase and the beginning of compressive tectonics in the Turonian and Santonian (Cobbold and Rosello, 2003; Rodríguez *et al.,* 2007; Tunik *et al.,* 2010).

During the late Campanian, the orogenic front migrated eastward, reaching the area of the Neuquén River (Aguirre Urreta *et al.,* 2011). The expansion and migration of the volcanic arc took place toward the foreland (Ramos and Folguera, 2005). The compressional stage and subsequent flexural loading controlled the general tilting to the east of the basin and the first Atlantic transgression. The latter was widely distributed in the central part of Neuquén Province and north of the Río Negro, and the age and paleogeography is represented by rocks of the Campanian-Maastrichtian of the Río Colorado Subgroup and Maastrichtian-Danian of the Malargüe Group (Uliana and Dellapé, 1981; Barrios, 1990; Sánchez *et al.,* 2006; Armas y Sánchez, 2008; Sánchez and Armas, 2008; Sánchez *et al.,* 2008; Sánchez *et al.,* 2009; Aguirre Urreta *et al.,* 2011).

3. Methodology

The outcrops in this study (Fig. 1) represent both types of a terminal fan basin margin, and were selected based on the quality and continuity of exposure, abundance of sandstone, accessibility, and their potential for expanded, detailed studies. The methods used for the collection and analysis of data from the Candeleros Formation in the west-central Neuquén Basin follow a stratigraphic and sedimentological approach: a survey of 3 sections over 15 km with identification of the different integrating sedimentary units (Figs. 1a and c). Facies analysis and mapping was completed on photomosaic outcrop maps. This technique was used to define lithosomes and their bounding surfaces. We identified the lithology, sedimentary structures (Table 1), geometry of the deposits and paleocurrent data, which were then analyzed statistically. Also, extensive outcrops were photographed in order to identify and document any architectural elements (Table 2) present in accordance with the methodology proposed by Miall (1985). In addition, we carried out an integrated profile development at a scale of approximately 1:20 (Fig. 2) in order to provide detailed documentation of the facies profiles. Their identification and interpretation, together with the analysis of associations and architectural elements at meso-macro scale allowed the identification of processes involved in the development of the terminal fan units.

4. Architectural elements of terminal fan

4.1. Distributary zone deposits

Distributary zone deposit (TF-DZ) consists of fine massive conglomerates (Gm), as well as cross-

TABLE 1. FACIES CODE DESCRIPTIONS (MODIFIED AFTER MIALL, 1978; MIALL, 1996).

Facies Code	Description	Interpretation	
Gm	massive conglomerate	Depositional load as bed sheets or lag channel floor.	
Gh	horizontally stratified conglomerates	High flow regime deposits.	
Gp	planar cross-stratified conglomerates	Unidirectional migration of subaqueous two-dimensional dunes	
Gt	trough cross-stratified conglomerates	Unidirectional migration of subaqueous three-dimensional dunes	
Sm	massive sandstone, structureless	Bioturbated sand, or deposition by suspension fallout	
Sh	horizontally bedded sand	Streams high speed flat bed	
Sp	planar cross-stratified sandstone	Unidirectional migration of subaqueous two-dimensional dunes	
St	trough cross-stratified sandstone	Unidirectional migration of subaqueous three-dimensional dunes	
Sr	rippled sandstone	Unidirectional migration of subaqueous small scale bedforms (sand)	
Fm	massive mudstone	Suspension load fall-out of mud bioturbated	
Fl	laminated mudstone	Suspension load fall-out of mud	
Tlpm	laminated tuff-lapilli	Ash-fall deposits	
Tlpe	low-angle planar cross-stratified tuff-lapilli	Reworking of pyroclastic flows in distal environment	

stratified and planar cross-stratified conglomerates (Gt, Gp, respectively), followed either by horizontally bedded medium-grained sandstones or trough cross-stratified sandstone (St), then by planar cross-stratified sandstone, and in a subordinate manner, by massive sandstone (Sm). The facies associations are laterally extensive, interconnected bodies of up to 250 m (Fig. 2), with erosive basal surfaces. Individually, the association shows considerable variation in arrangements and spatial relationships. The association comprises a compound amalgamated channel (Table 2), with lateral assemblages of more

TABLE 2. ARCHITECTURAL ELEMENT DESCRIPTION (MIALL, 1985; MIALL, 1996). FACIES CODES ARE SUMMARIZED IN TABLE 1.

Lithofacies Assamblage	Description	Environmental interpretation	Depositional environmental
Gm-Gt-St-Sp-Sm-Sh-Sr	10 cm to 2 m thick beds; medium grained; red to reddish in colour; tabular or lenticular beds; basal bedding surfaces are primarily sharp and erosive; mud chips and mud clast.	unidirectional migration of subaqueous bedforms of varying sizes and flow regimes (St, Sr and Sp); bioturbation or rapid suspension load fall-out of sand (Sm) high energy deposition indicated by the presence of Sh. Channel width fluctuates spatially and temporally in response to variations in mass and energy input.	Distributary channel
Sr-St-Sh-Sm-Fm	10 cm a 1.5 m, thick beds; red to reddish in colour, fine to medium grains; lenses or lenticular beds; basal bedding surfaces are typically erosive; burrows and mud chips are common.	unidirectional migration of subaqueous sandy bedforms of varying sizes and flow regimes (Sr, St and Sh), bioturbated or rapid suspension load fall-out of sand and silt (Sm and Fm). Break in main channel margin.	Crevasse channel
St-Sh	20 cm a 0.50 cm, thick beds; red to reddish in colour, sandstones are fine to medium grained; lenses beds, stacked, cross-cutting channel forms.	multistorey channel scour and fill sandstones.	Low sinuosity channel complex
Sh	0.5 m a 2.5 m, reddish colour, thick-bedded, sandstone are fine-to medium- grained.	sheetfloods	Proximal sandy sheet-floods
Sr, Sh,Fl, Fm	0.10 cm a 0.20 cm, reddish colour, thin-bedded sheet sandstones and mudstones.	sheetfloods	Distal Sheetfloods
Fm-Fl-Pl-TLpm-Tlpe	20 cm to 3 m thick beds; red to purple in colour; laterally extensive and tabular beds, except where truncated by erosive sandstones and siltstones, burrow are common and volcanic deposits are present	suspension load fall-out of mud and silt in a low energy subaqueous environment; at times well oxygenated and subaerially exposed; palaosol horizons (Pl).	Overbank/floodplain

than 8 m thick, associated laterally with multistorey bodies 0.20 and 0.30 cm thick, respectively. These bodies are associated with deposits composed of Fl and Sr (Table 1). These often include abundant volcaniclastic material (Tlpm and Tlpe). It is common to find ferrous carbonate nodules of pedogenic origin, both in sand deposits and in those of very fine particle sizes, the latter associated with mudcracks.

Interpretation: These deposits are interpreted as channel belts of low sinuosity, showing the migration of 3D dunes and overlapping of vertical and lateral large dunes, simple, transverse or oblique complex bars, preserving the original morphology (Figs. 3 and 4). The channels often suffered avulsion and reinstallation processes or they are deeply incised into the floodplain (Table 2). The presence of small bars formed by lateral accretion suggests commonly coalesced downstream bars, a common process in braided systems (Jo and Chough, 2001). Since the bars have not suffered significant erosion processes and developed a complex pattern in the filling of individual belts, it is possible to estimate that they have been subjected to a high aggradation rate. Pedogenic bioturbation by the action of organisms or roots suggests a simultaneous hiatus of clastic deposition in surrounding floodplain areas and channel fills.

The distribution pattern of channel belts/floodplains is interpreted as a distributary system with mobile channels that migrated laterally, eroding their floodplains and periodically inhibiting the development of mature paleosols. The layout of the paleochannels

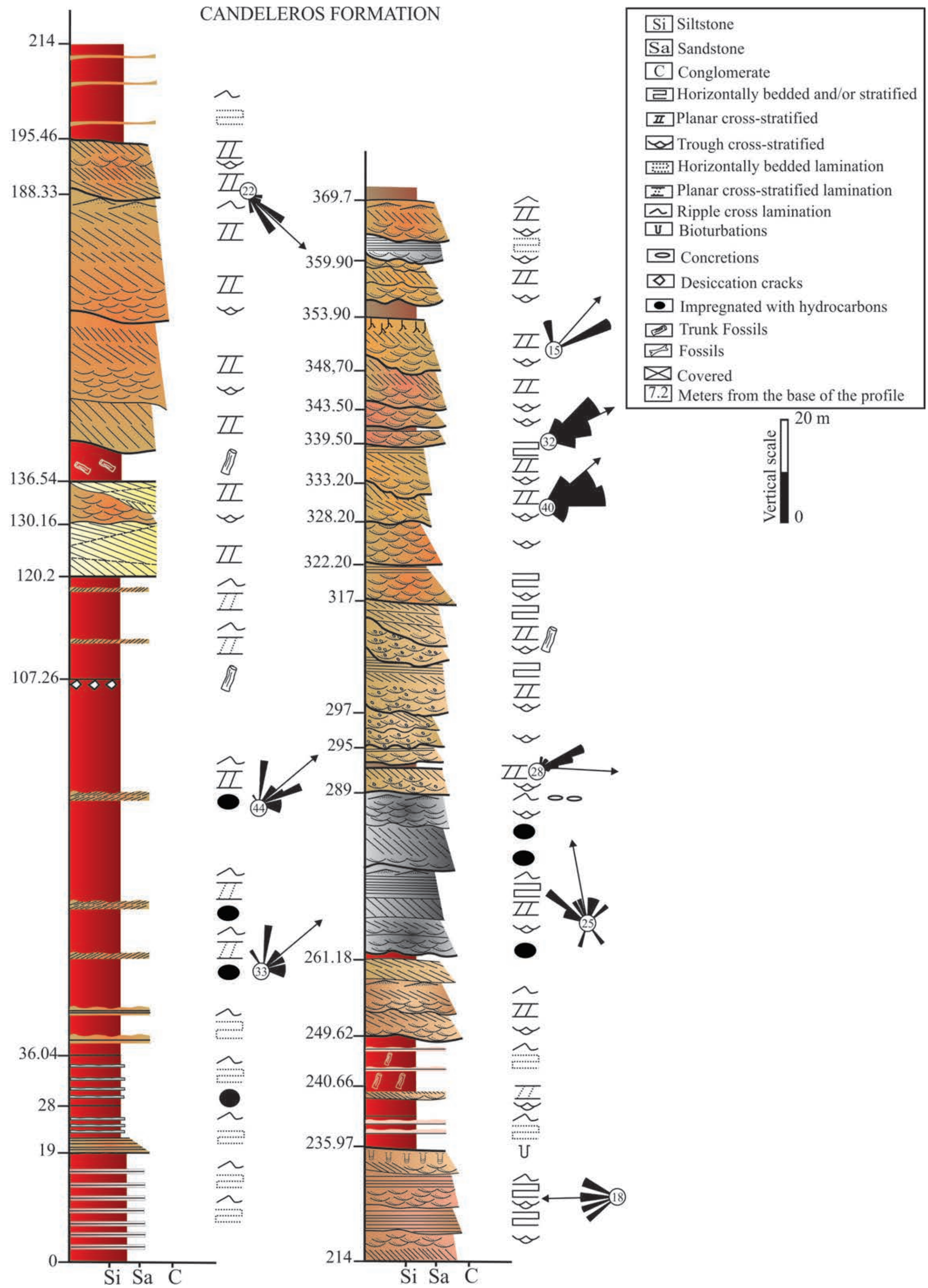

FIG. 2. Stratigraphic and sedimentological section for Candeleros Formation in the study area.

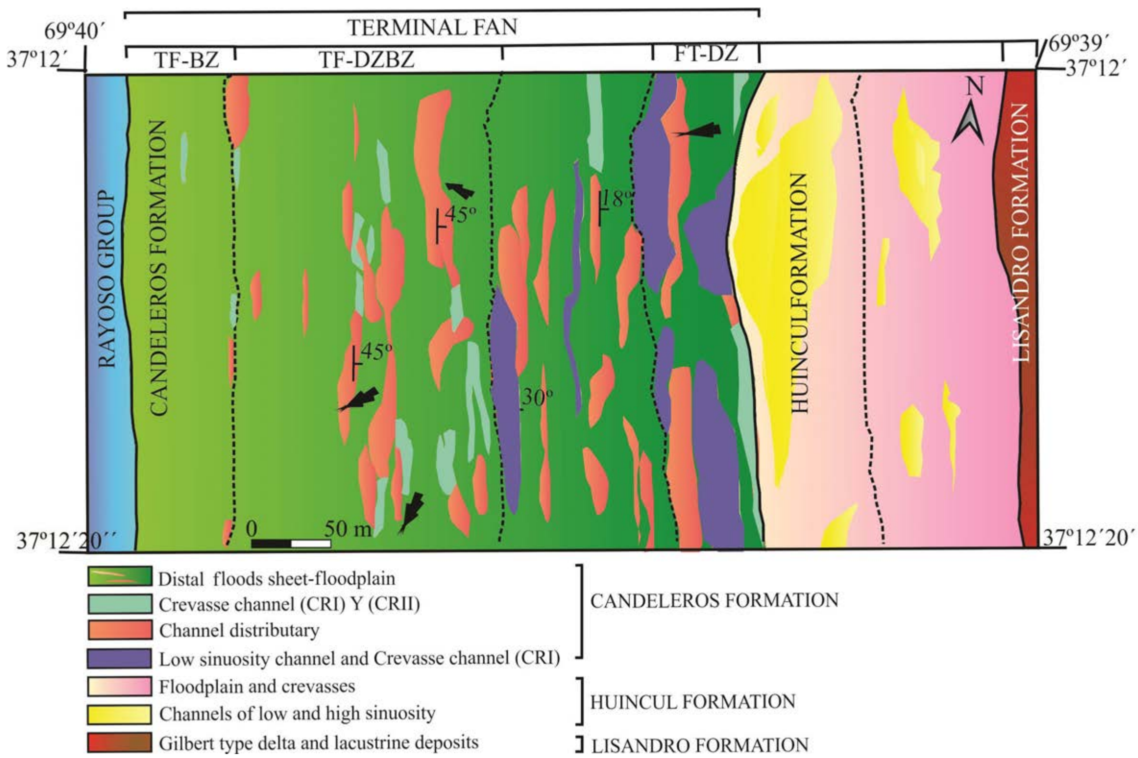

FIG. 3. Facies map of the terminal fan of the Candeleros Formation in the study area. The Huincul and Lisandro Formations also crop out.

allows to infer that many channels coexisted in the floodplain in the system. Channel belts have a high variability in their type of fill, suggesting in some cases that they originated from flows of high energy and low frequency (Parkash *et al.,* 1983; Paola *et al.,* 1989; Bridge and Best, 1997; Marshall, 2000; Alexander *et al.,* 2001; Fielding, 2006).

These characteristics suggest a distributary zone for the sediments of the terminal fan (MacCarthy, 1990; Sadler and Kelly, 1993; Kelly and Olsen, 1993; Nichols and Fisher, 2007).

4.2. Distributary zone-basinal zone deposits

Distributary zone-basinal zone deposits (TF-DZBZ) consist of fine-grained conglomerates (Se), massive conglomerates (Gm) and horizontally bedded medium-grained sandstones (Sh) or trough cross-stratified sandstone (St), planar cross-stratified sandstone (Sp) and massive sandstone (Sm). The association integrates large bodies of some hundreds of meters, interconnected along erosive bases. These bodies fill compound bodies with stacked channel geometry more than 5 m thick. The multistorey bodies are laterally associated with mantle or lobe type units, ranging between 0.20 cm and 0.50 cm thick. The sand bodies are associated with units comprising lithofacies Fl, Pl, Sr and volcaniclastic material (Tlpm and Tlpe-Table 1). The activity of organisms, roots and rhizoconcretions, ferruginous halos and developing pedogenic nodules is common in sand bodies or finer deposits.

Interpretation: This architectural element with a low ratio of suspended bedload indicates sedimentation within aggradational channel (Figs. 3 and 5). The tabular geometry and erosive bases indicate the existence of a network of low sinuosity channels with high textural variation, reactivation surfaces, bedload sediments and multiple scours. The lateral extent of the bodies, uniform paleocurrent direction and low width/thickness ratio are consistent with the deposits of braided rivers (Miall, 1977; Tunbridge, 1981; Rust and Jones, 1987; Gibling, 2006).Variations in grain size and sedimentary structures within sets are typical of migrating sand bars in rivers with a low to moderate sinuosity.

FIG. 4. **A-B.** Distributary channel deposits corresponding to distributary zone (TF-DZ) reflecting braidplain characteristics. Note stacking channels; **C.** Enlargement of the figure a; the yellow arrows indicate the lateral channel accretion; **D.** Detail of normal aggradation and lateral accretion channels.

It is interpreted that this element corresponds to low sinuosity channels that migrated within a large floodplain (Mjøs *et al.,* 1993; Jorgensen and Fielding, 1996; Bristow *et al.,* 1999; Jo, 2003).

The individual fluvial channels accreted obliquely by a combination of lateral migration and aggradation, generating a complex fill pattern, in which large-scale 3D dunes and oblique and lateral bars are stacked and overlapped laterally. Channel belts show numerous crevasse-splays at small to medium scale (Khan *et al.,* 1997; McCarthy *et al.,* 1997; Zaleha, 1997). Some tabular channels connect with other channel belts and show that they co-existed on the plain. The deformation of the avalanche faces of intrachannel macroforms suggests rapid deposition and exceptional discharge events. The aggradational character of the system can be inferred from the frequent preservation of sand wave tops and the form of the different bar units.

FIG. 5. Distributary zone-basinal zone deposits (TF-DZBZ). **A.** Low sinuosity channels that migrate in a large floodplain; **B.** Arrows indicate accretion and migration of transverse bars and linguoides.

The channels, in some cases, pass gradually over levee deposits and transitionaling to the floodplain. Channel belts exhibit traces, root traces, evidence of infaunal activity and redox effects produced by oxidation and reduction, which suggest breaks in operating systems. The evidence also suggests the development of truncated paleosols or compounds in the floodplain, allowing to infer long periods of inactivity suddenly altered by extraordinary flood events.

The distribution of geomorphic features reflect paleogeographic zonation in the development of interconnected channels that suffered frequent avulsion processes, acting in some cases simultaneously in different sections of a terminal fan. A floodplain with condensed sections (Pl) reflects periods of low supply. The abundance of tree fragments in the overflow elements suggests that an arboreal vegetation associated with the channel edge was eroded during events of high water discharge, and that there were sediments in suspension in the floodplain that were rapidly deposited during the decline in flow energy (Devaney, 1999). Larger trunks trapped in the channels deformed underlying sediment structures and their orientation is oblique to main paleocurrent direction. This allows to infer deposition from suspension during the final stages of a major flood event.

The alternation of flood events with long periods of inactivity of the river belt is registered in the pedogenic development in channel deposits: plant traces, rhizoconcretions, roots activity at the top of the macroforms, and the presence of pedogenic calcretes, which attest to the development of an edaphic floodplain deeply incised during the channel floods (Davies *et al.,* 1993; Müller *et al.,* 2004). The close relationship between the channel deposits and aeolian dunes (are not described in this manuscript) developed in the floodplain also allow to infer long periods of low channel supply.

These general characteristics allow us to infer palaeoclimate seasonality with a system of concentrated rainfall, while the paleogeography suggests the presence of elements common in sections of distal distributary fan systems (Sadler and Kelly, 1993; Marshall, 2000; Hornung and Aigner, 2002; Nichols and Fisher, 2007).

4.3. Basinal Zone

Basinal zone deposits (TF-BZ) consist of massive sandstone (Sm), planar cross-stratified sandstone at small scale (Sp), ripple cross-lamination sandstone (Sr), heterolithic successions, and siltstone and claystone with horizontal lamination (Fm, Fl). The sandy lithofacies composed of tabular or lobed multistorey units, with planar or erosive bases, lateral extensions between 10 and 100 m and thicknesses up to 30 cm. They were observed to be isolated or interconnected, sometimes tabular bodies of great thicknesses and lateral continuity. The sand multistorey bodies are associated with the FlF, SrF, PlF, Tlpm and Tlpe lithofacies. Also common are caliche covering the sandy units or interbedded between the very fine-grained lithofacies.

Interpretation: These lenticular sandstone units with erosive bases comprise multiple units of the order of a few centimeters (Figs. 3 and 6) and lithofacies deposited under a high flow rate followed by low regime successions indicating an abrupt decay in the energy of the flows. These are interpreted as distributary channels with little lateral accretion filled during flood events. Such deposits have been described as discrete units of low sinuosity channels in the of distributary plain environment (Parkash *et al.,* 1983).

The presence of small trunk fragments and root traces included in lobate bodies suggests that they are the result of flow disturbance due to the vegetation, which contributed to the deposition of sediments in the terminal portions of distributaries with lobed morphologies. A prominent feature of the distal zones is that much more sandstone is present as thin sheetfloods deposits than as channel-fill facies. These sheetsfloods have a sharp, sometimes erosive base, and this scouring at the base of sheetsfloods suggests local flow channelization (Marshall, 2000; Nichols and Fisher, 2007). Desiccation cracks and bioturbation at the top of the deposits are indicative of extensive periods of inactivity during which vertic paleosoils and caliche horizons developed (Sadler and Kelly, 1993). Changes in gradients after flood events caused the migration of depositional sites and alternated the distribution of section lobe, sheets and distributary channels. Floodplain deposits include horizons of compound and complex paleosols (Kraus and Wells, 1999) and an important contribution of reworked volcanic products. Paleosol horizons were associated with areas of low sedimentation rate and climatic seasonality periods controlling high accumulation ranges and frequent flooding episodes. The association of lithofacies and their distribution allows the assigning of these deposits to a distal floodplain-basin in a terminal fan (Parkash *et al.,* 1983; Kelly and Olsen, 1993; Sadler and Kelly, 1993; Newell *et al.,* 1999; Hampton and Horton, 2007; Hornung and Aigner, 2002; Wakelin-King and Webb, 2007; Wolela, 2009).

5. Stratigraphic architecture of the terminal fan system

This system is represented by the distributary zone (TF-DZ), distributary zone-basinal zone

FIG. 6. Basinal zone deposits. **A-B.** deposits of sheetflood sandstones; **C.** ephemeral stream channel sandstones.

(TF-DZBZ), and basinal zone (TF-BZ). This terminal fan system (Figs. 3 and 7) is the environment of greatest areal extent and development within the Candeleros Formation. Its most outstanding feature is the presence of bitumen in the form of pockets and dispersed in the sandstone of channel-fill and crevasse splay deposits.

Interpretation: In this system the proximal channel of the terminal fan has not been identified. However, the distribution of architectural elements and paleocurrent data allow us to infer that the catchment area of the hinterland was located to the NNW/NW (Fig. 2).

Deposits of the distributary zone are characterized by thick deposits of low sinuosity channels, with some deposits of sinuous channels, with a high degree of connectivity and strong vertical aggradation (Rajchl and Ulicny, 2005) of channel belts (Fig. 2). They remained fixed within the floodplain for long periods and generated pronounced stacking and vertical aggradation. Crevasse splays deposits are extensive, dominating the floodplain and connecting the main channel belts that co-existed. The avulsion process had an aggradational style that included reinstalling the channel belt on their previous deposits overflow and other active belts. This is consistent with a floodplain that was dominated by processes related to crevasse splays and suffered a high frequency of flooding (Jones and Hajek, 2007). The abundant carbonate concretions and rhizoconcretions present in the channel deposits originated from paleosols in sandy sediments rich in calcium and carbonate subjected to repeated cycles of wetting and drying (Esteban and Kappla, 1983; Retallack, 1990). High discharge events are also documented by the incorporation of large-scale tree trunks in the channel fills. The presence of trunks also suggests highly vegetated areas associated with the channel belts. Burrows, bioturbation and traces of scattered bushes provide evidence of intermittent exposure of the top of channel bars and rapid colonization. Halos were observed in the crevasse deposits, which indicate variations in redox conditions, suggesting a short-lived state of saturation after the event that gave rise to the state of saturation. Redox conditions are a common feature in the presence of strong climatic seasonality, where periods of heavy rainfall are followed by periods of drought and induce fluctuation of the water table, which generates changes in reducing to oxidizing conditions resulting in the formation of mottles (Daniels *et al.,* 1971). The interdistributary floodplain (TF-DZBZ) had a small proportion of clays and paleosols exhibiting no profuse root penetration. This is associated with poor exposure of floodplain sediments and permanence of the water table at the base of the paleosols. This is confirmed by the development of paleosols less than 1 m thick and the existence of a channel sandy substrate that may have acted as an aquifer (Therrien, 2005). The distal distributary plain is characterized by a higher density of channel deposits, but with less thick and laterally longer channel belts (slightly more than a hundred meters), greater width/thickness ratios and a greater connectivity ratio than in braided distributary channels. Channel belts are generally characterised by low sinuosity, although some are interspersed with some belts of high sinuosity with a good development of lateral accretion units. One common feature with in the upper reaches of the

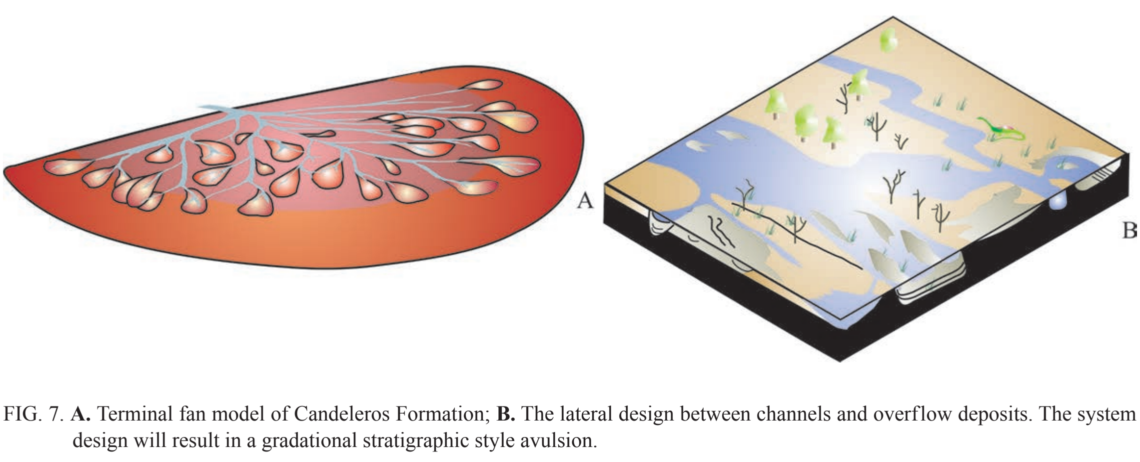

FIG. 7. **A.** Terminal fan model of Candeleros Formation; **B.** The lateral design between channels and overflow deposits. The system design will result in a gradational stratigraphic style avulsion.

terminal fan is the development of crevasse splays sequences extending laterally to reach other channel areas. These channel belts developed a typical pattern of oblique aggradation (Fig. 7; Rajchl and Uličný, 2005; Jones and Hajek, 2007). While avulsion triggers include tectonic factors and the paleoclimate mentioned above, locally they may have influenced by the low gradients that caused a great expansion of flood flows, generating differential gradients that controlled the new sites of channel belts. In addition to these extrabasinal factors, vegetation may have caused the blockage of flows. The evidence of this process are overflow horizons with preservation of abundant trunks fragments. Local avulsions were the product of migration of the upstream avulsion focus and included resettlement and lateral migration on crevasse deposits such as those observed in this sector of the distributary plain. The importance of these channel belts is the presence of abundant bitumen that induced a deep purple coloration of outcrops, abundantly present in crevasse deposits. The interdistributary plain is dominated by crevasse deposits. The presence of paleosols is a minor feature, as there is no noticeable development of paleosols. The absence of deep root traces combined with the activity of perforating organisms indicate that the water table was deep. An important element associated with this section of the terminal fan is the development of a dune field (Sánchez and Asurmendi, 2011) with barchanoid or transverse forms (not described in this paper), whose migration was strongly controlled by fluctuations in the water level and interference caused by channel avulsion. Its expression in the outcrops is locally reduced, however, it is likely that the dunes were widely distributed as discrete units throughout the development area of the terminal fan.

The distal parts of the terminal zone are well represented and vary only in the ratio between channelled deposits and mantle/floodplain deposits, which abruptly decreases toward the flood basin. This sub-enviroment presents local paleosol development incorporating a leached clay horizon (Bt), and in general, indicate that the rate of sediment accumulation during certain periods was lower and that the sub-enviroment was more stable (Therrien, 2005), without discarding the fact that paleosols on relative topographic highs are less susceptible to flooding, except in exceptional shock, since the development of a single paleosol is not generally recognized, but represents the compound type (Kraus, 1999). This style suggests pauses in sedimentation and prolonged stability in the floodplain that were succeeded by renewed pedogenesis phases (Davies *et al.,* 1993; Müller *et al.,* 2004).

The abundance of slickensides, rhizoconcretions and carbonate nodules along with ferruginous intergrowths shows the irregularity of the paleoprecipitation with, repeated wetting-drying cycles associated with alternation between wet and dry periods (Esteban and Kappla, 1983; Retallack, 1990).

The presence of more mature paleosols with well-developed calcrete horizons in certain areas of the floodplain indicates that the rate of sediment accumulation during certain periods was lower and indicates that the sub-enviroment was more stable (Therrien, 2005). The development of slickensides in paleosols confirms the sub-arid/sub-humid conditions in which paleoprecipitation may have exceeded a threshold of 760 mm/year (Horrell, 1991; Bush, 1997; Voigt *et al.,* 1999; Retallack, 1994; 2001).

Signs of erosion in the flood basin are not considered as depositional surfaces because flood sediments are deposited only during periods of high discharge. It is expected that less significant and higher frequency flood flows including those in which channels run from bank to bank, impose their own record on the channel (Stam, 2002). The cycles of recurrent flooding in this area of the basin generated a thick sequence with typical deposits produced by ephemeral streams in sheet flood events and the absence of clay-size components in the flood environments. These two characteristics are typical of current systems rich in sand where flooding covers hundreds of meters, with the development of low-amplitude dunes, about a few tens of cms in height, with large areas covered by fine sandstones or siltstones in flood deposits (Tanner and Spencer, 2007).

6. Discussion

Outcrop data presented here allow us to define a distributary and basinal zone which toward the top exhibits floodplain deposits constituting a continuous succession. Identifying terminal fan subenvironments (Figs. 3, 7 and 8) allows us to infer low regional topographic gradients during the onset of the deposition of the Río Limay Subgroup (Neuquén Group).

The Candeleros Formation is a succession of terminal megafan deposits (Fig. 9) representing the start of the filling of the foreland basin during the

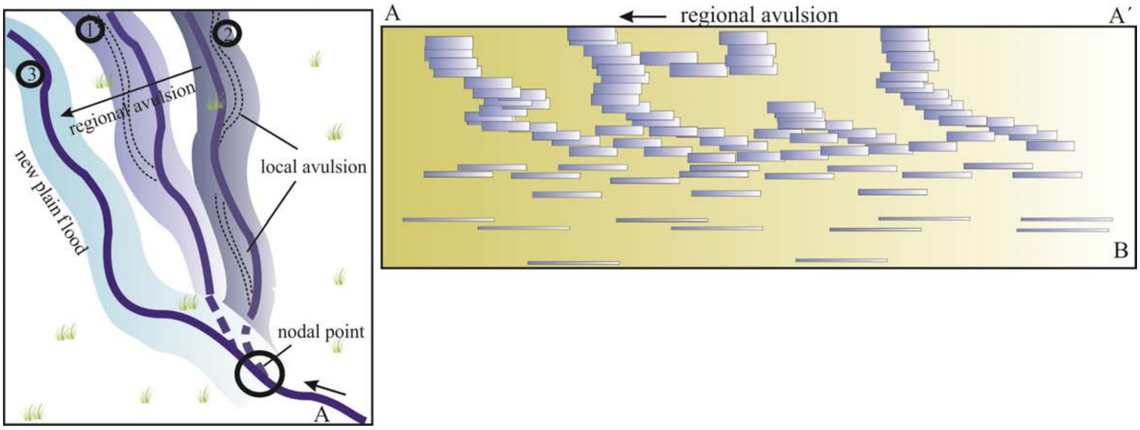

FIG. 8. **A.** Avulsion model system for distributary terminal fan of Candeleros Formation, a nodal point that is present in each of the distributary is recognized. Local avulsions are limited by the margins of the floodplain and reinstall of the active channel on the crevasse deposits (from Rajchl and Uličný, 2005); **B.** Models of regional avulsion for the terminal fan of Candeleros Formation from the distal zone, distal to distributary zone and distributary zone (Fig. 3). Note the changes in the ratio of connectivity, style aggrading channel belts, oblique aggradation in the central part of the image (middle seccion of the Candeleros Formation), and single aggradation at the top (top of the Candeleros Formation).

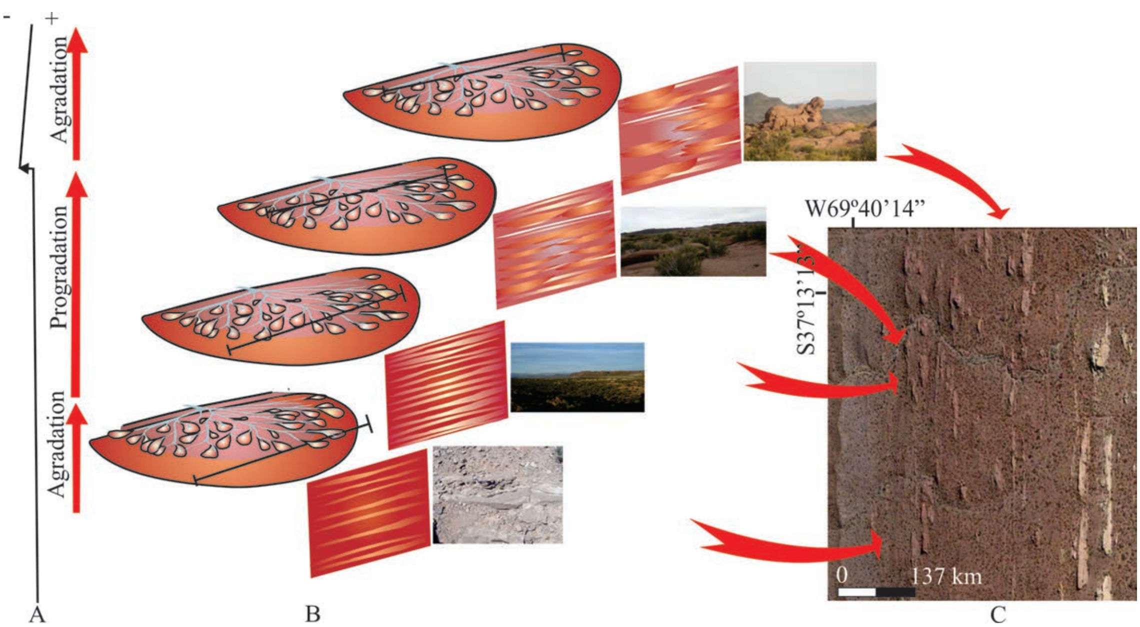

FIG. 9. **A.** Accommodation curve for each of the sections of the Candeleros Formation; **B.** Model of terminal fan adapted from Kelly and Olsen (1993) and Hampton and Horton (2007). Transects identified in the plan view with a straight and vertical panels; **C.** Satellite image of the workspace. The arrows indicate the correspondence with each of the schemes.

Albian (Ramos, 1999; Cobbold and Rossello, 2003; Sánchez *et al.,* 2004; Manacorda *et al.,* 2004; Howell *et al.,* 2005; Zapata and Folguera, 2005; Ramos and Folguera, 2005; Veiga *et al.,* 2005; Ramos *et al.,* 2008).

The terminal fan system at the base of the profile (Fig. 2) is represented by a flood basin environment that reflects a period of expansion of the system when the basinal zone was reworked by sheet floods. They were fed by three different mechanisms, shallow channels that lost their transport capacity under the influence of extremely low gradients, flow expansion phenomena related to topographic lows where the water eventually emerges and a spilling flow occurs (Tooth, 1999; Lang *et al.,* 2004) and small distributary channels during episodes of high discharge from headwater systems that allowed for the extension of flows in the flood basin. Channelized episodes covered limited distances in the floodplain because of the rapid loss of speed by friction that increased at the base of the channel, with increasing radial distance from the origin and laterally from the axis of the stream (Cuevas Gozalo and Martinius, 1993). The resulting large-scale architecture was formed by scatterd, and small channels and sheets and very fine sandstone/siltstones. The pedogenetic phases they might register only poorly developed paleosols, suggesting few periods of stability in the basin. The erosional surfaces within the plain are not considered to reflect significant discontinuities, as the dynamics of the system were controlled by the frequency of periods of high water discharge and sediments related to climatic conditions. In terms of paleoclimatic conditions, the paleosols of the terminal fan system reflect sub-humid/sub-arid conditions with paleoprecipitation that may have exceeded a threshold of 760 mm/year (Horrell, 1991; Bush, 1997; Voigt *et al.,* 1999; Retallack, 1994). This part of the Candeleros Formation represents a period of strong aggradation (Figs. 2 and 8), which is associated with high accommodation generated by a pulse of subsidence related to the activity of the Agrio Fold -and- Thrust belt, concomitant with the activity of the volcanic arc located to the west, which supplied ashfall deposits to the basinal zone. A slow progradation of the system started, resulting in the progressive installation of more proximal facies. The distal distributary fan system was characterized by braided stream flows with a high rate of aggradation, which caused frequent changes in the gradient of the channel floor, resulting in aggradation in the interdistributary floodplain by overflow deposits. The erodibility of plain deposits, given the low participation of clays and low topographic relief favored the development of avulsion by stratigraphically gradual annexation (Jones and Hajek, 2007). The system was characterized by a lateral aggradation style with a high connectivity between channels (Fig. 7). Channel belts have few incision features, many of which preserve bed form tops. However, channel belts alternate with high sinuosity channels that have an excellent preservation of their architecture.

The seasonal concentration of rainfall regulated periods of flooding and unusual sedimentation events. During the latter the vegetated interdistributary plain together with the high erodibility of the channel edges allowed flow dispersion over large areas and during the flood peak tree trunks were incorporated as fragments.

Large sections of the plain were occupied by aeolian dunes. However, they had limited migration controlled by the crevasse splays of the main channels, and were eroded during periods of channel avulsion.

Aggradation mechanisms suggest a large accommodation space. Subsidence is considered as the determining factor in the low channel/flood plain ratio. The domain of a high accommodation space and well-developed aggradation systems implies a period with a high subsidence rate (Martinsen *et al.,* 1999; Rygel and Gibling, 2006; López-Gómez *et al.,* 2010). The high contribution of sediments and frequency of floods in the basin produced channel incision and allowed the onset of progradation of the system.

The macroarchitecture shows a change during the development of the proximal braidplain. Initially a decrease is observed in the width/thickness ratio of channel units, having been mostly of low sinuosity. Although the style of avulsion remained the general trend was the reoccupation of existing channels and stacking, including the deeper incision of belts. This part of the Candeleros Formation is interpreted as a stage of progressive decrease in accommodation space accompanied by a slow progradation of the system. A more significant change in terms of stratigraphic architecture took place at the top of the unit. An abrupt change in grain-size, thickening of the sandstone bodies and the stacking design of channels indicate the sudden installation of distributary zone deposits. This suggests the development of a new terminal fan and a strong incision of proximal deposits related to the rapid migration of the feeder system. It follows that during this period changes in capture registered an event of lower reduction in accommodation space related to the autodynamics of the terminal fan. The marked aggradation pulses exceeded the threshold of creation of accommodation space, and the changing topography forced the rearrangement of the system.

The Candeleros Formation ends with deposits of a distributary zone containing three terminal fan sequences (Fig. 8), with continued participation of volcanoclastics components that suggest an intermittent activity of the arc.

7. Conclusions

- The Candeleros Formation at the foot of the fold and thrust belt is represented by a terminal fan system.
- Distributary channel patterns are characteristic of a terminal fan and reflect both loss of stream power and spatially/temporally fluctuating discharge events.
- The base of the Candeleros Formation is represented by a flood basin environment that reflects a period of system expansion during which the distal floodplain was reworked by sheet-channelled flows.
- The middle section of the formation is characterized by slow progradation of the system that led to the progressive installation of more proximal facies to the distal distributary system, which represented a period of high subsidence rate in the basin.
- The Candeleros Formation ends with the development of a new system of proximal fans that caused a strong incisión of underlying fan deposits.

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