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Research article

Cenozoic geologic evolution of the lower Colorado River Basin, Northern Patagonia, Argentina

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Abstract:

Climatic changes and eustatic sea levels have been assumed to be the most important controllers of the Colorado River alluvial fan in northern Patagonia. Although the alluvial fan occurs in a region considered tectonically stable, there are pieces of evidence that the Miocene Andean orogeny has reactivated inherited structures, with subsequent geomorphological changes that date back to the Pleistocene. Besides, the clear evidence of neotectonism in the region and their effects on the evolution of this fan, it has not been studied in detail yet. In this study, we map and analyze six sections outcropping in different terraces of the alluvial fan with the primary aim of disentangling the role of tectonism, climate and eustatic changes on the evolution of the alluvial fan. This study is part of a bigger project aimed to understand the origin of the shallow lakes occurring in northern Patagonia. Our results indicate that the alluvial fan of the Colorado River was established in the area around the Middle Pleistocene. Evidence of deformations in Miocene to Pleistocene units indicates significant neotectonism during the Upper Pleistocene. By the Pleistocene-Holocene transition, tectonism produced incision generating a set of terraces. After this time, an important climate change from semiarid to arid favored the calcretization of some terraces. By the Pleistocene-Middle Holocene, the terraces were covered by ancient eolian sediment accumulated during dry conditions. By the Middle Holocene, a broad alluvial fan developed in the region under a warmer and more humid climate generating the Alluvial Colorado River-III deposit at the T3 terrace. In the late Holocene, aggradation process was favored by a high sea level and temperate-arid climate, producing T4 terrace. At the same time, this climate condition favored the local deflation-sedimentation processes that resulted in the deposition of modern eolian deposits (mE) over the T3 terrace. The depressions generated by the deflation were, later on, occupied by shallow lakes when the climate turn more humid. Subsequently, during regressive sea level condition, ca. 2000 years BP, the T4 terrace was partially eroded and the modern alluvial plain formed.

Keywords: Cenozoic sediment, Neotectonic activity, Colorado river , Argentina.

1. Introduction

The study area is located in the morphostructural Colorado Basin (Fig. 1). It is a rift basin formed in the Upper Jurassic associated with the initial opening of the South Atlantic. Most of the Colorado basin develops offshore, roughly in an E-W direction (Folguera et al., 2015). The sedimentary basin fill includes sediments up to the Neogene, which have a maximum thickness of 7,000 m (Fryklund et al., 1996; Juan et al., 1996). Despite the location of the Colorado Basin in the extraandean area, a significant influence from the Andean orogeny has been recognized in these distal Upper Miocene and Pliocene synorogenic sequences, associated with subsidence occurring simultaneously with the Andean uplift (Folguera et al., 2015). Recently, Folguera and Zarate (2018) suggested that the mechanisms responsible for the deformation of these synorogenic sedimentary sequences are part of the dynamics of the Andean orogeny, as well as the forces associated with the mid-oceanic ridge activity (ridge-push).

The Colorado River has its headwaters in the Andes, and flow to the East, reaching finally the Atlantic Ocean (Fig. 1). Throughout its journey, it does not receive significant water contributions, and in its upper and middle course the river is confined (Melo, 2004). Near the limit of the provinces of La Pampa and Buenos Aires, in the lower part of the Colorado River basin, there is an alluvial fan, considered by some authors as an ancient delta. The existence of a complex system of terraces and paleochannels demonstrate high dynamism during its evolution. Etcheverría et al. (2009) and Martínez and Martínez (2011) suggest that deposits from this alluvial fan occurred simultaneously with the Lower Holocene eolian deposition. González Uriarte (2005) based on a geomorphological analysis assigned the oldest terrace of Colorado River to the Pleistocene.

The distal part of the ancient alluvial fan has been the focus of various geomorphological and geological studies aimed to understand its depositional dynamics and evolution (Spalletti and Isla, 2003; Martínez and Martínez, 2011). These studies concluded that the evolution of the Colorado alluvial fan has been the result of eustatic variations (sea level changes), tide and wave activity, terrigenous discharge from the fluvial system and watershed modification. Nevertheless, only few authors (Codignotto et al., 1992; Vogt et al., 2010) have considered the tectonic regime as an important agent in the evolution of the fan. Vogt et al. (2010) analyzed the genesis of the relief located to the North of the study area and concluded that changes in the hydrological patterns have been linked to a tectonic regime consisting in the activation of the major submeridian faults located to the North, during the Pleistocene (Fig. 1). Melo et al. (2003, 2013) inferred possible pre-quaternary faults on the basis of drainage control as being important in the development of a Colorado Paleo-river. Furthermore, the alternating arid and semi-arid conditions during the Holocene have generated intermittent morphological and pedological processes that have influence these deposits and are likely related to the formation of the several shallow water lakes present today in the area (Schäbitz, 1994, 2003; Abraham de Vázquez et al., 2000; Martínez and Martínez, 2011). So far, there are not detailed and integrated geological, and geomorphological analyses of this alluvial fan. This study is the first integrated study, based on the analysis of different terrace levels of the alluvial fan of the Colorado River. We have focused our study on the geologic processes that controlled the evolution of Colorado River alluvial fan mainly during the Pleistocene-Holocene and their relationship with the origin of shallow water lakes existing in the area, which, up to day, still remains unclear. Thus, the present study sheds light on the role of tectonics, climatic and eustatic changes in the evolution of the alluvial fan, and this is part of a bigger project aimed to understanding the origin of shallow water lakes present in northern Patagonia.

2. Study area

The study area is bounded by parallels 39.23° S-39.32° S and meridians 62.40° W-62.52° W, in Villarino County, Buenos Aires Province (Fig. 2). Its physiography is characterized by at least five levels of terraces of the alluvial fan of the Colorado River, namely T1, T2, T3, T4 and T5 from oldest to youngest (Fig. 3). Terrace T1 is capped by longitudinal dunes oriented in West-East direction. The eolian deposits are not always preserved. T2, contains closed depressions bounded to the West by barchan dunes. These depressions, located to the North of the town of Pedro Luro, are occupied by several shallow water lakes that included La Salada, La Dulce Chica and others unnamed lakes. The T3 is larger than the previous one and despite modern agricultural activities, the ancient drainage landforms are still preserved. Currently, the Colorado River is located at 6.5 km to the South of the studied area. This river is the main watercourse in the region and is a primary source for irrigation for agriculture and livestock, which are the main economic activities. The role of groundwater is still unknown, but water table is around 2-3 m deep (Aragon, personal communication, July 22th, 2015). La Salada is permanent and saline shallow water lake with 3 m of maximum depth, and since the groundwater is saline as well, a hydrological relation is suspected. By contrast, the very shallow water lakes located to the west of La Salada are non-permanent and saline and most likely not influenced by groundwater. La Dulce Chica shallow water lake is permanent but regulated by irrigation.

Climate is classified as "arid steppe" according to Köeppen classification and semi-arid mesothermal following the Thornthwaite's classification (Sánchez et al., 1998). According with the meteorological series for the period 1960-1990, the average annual temperature is 14.8 °C, and the average annual precipitation of 507.9 mm (Sánchez et al., 1998). Northwest winds prevail during March-June (Fall), whereas Northwest winds with a West tendency prevail in from June to September (winter), while from December to March (summer) is predominantly Southeast to Northwest (Sánchez et al., 1998). From September-December (spring) western winds are reduced.

3. Geological background

The study area (Fig. 1) is located within the geological province of the "Colorado Basin" (Ramos, 1999). The basin has an East-West elongated morphology bounded to the south by "Macizo Nordpatagónico#, to the north by "Positivo Bonaerense# and, to the west, the boundary with the 64°30' W meridian, defined by outcrops of the Colorado Formation (Casadío et al., 2000). This basin has an extensional origin and its evolution has been divided into four different stages (Yrigoyen, 1999) that include:

A Sin-rift stage (Lower Cretaceous): that consist of a continental sedimentary sequence of more than 7,000 m thickness grouped in the Fortín Formation (Zambrano, 1972; Lesta et al., 1978, 1980).

A Sag stage (Upper Cretaceous): characterized by thermal subsidence. It includes the Colorado Formation of alluvial origin (Yrigoyen, 1975; Casadío et al., 1999, 2000) and the Pedro Luro Formation of marine and transitional origin (Yrigoyen, 1999).

A Passive Margin stage (Eocene-Pliocene): represented by sedimentary rocks included in the Elvira and Ombucta formations, which are laterally equivalent and of alternating continental and marine origin of Eocene-Oligocene Age (Yrigoyen, 1999). These are overlain by the marine sedimentary rocks of the Barranca Final Formation of Middle Miocene Age.

On top of these rift related sedimentary units, and in discordant contact, there is a continental rock sequence (Etcheverría et al., 2009) including the Río Negro Formation (Upper Miocene-Lower Pliocene), characterized by medium to fine-grained sandstones, siltstones and claystones interbedded with tuff levels and powder limestone (Andreis, 1965). It is mainly of fluvial origin, with a few lacustrine and eolian sedimentary levels. Overlying the rocks of the Río Negro Formation, in discordant contact, there are coarse-grained fluvial deposits from the Middle Pliocene-Pleistocene, which extend widely in the area. Above these, in a discordant contact, overlies a calcrete crust from the Pleistocene (Folguera and Zárate, 2009) (Fig. 1A). This calcrete was generated by pedogenic processes with some groundwater influence (Etcheverría et al., 2009). Overlying this Pleistocene rock sequence, there are poorly-sorted fine eolian sediments composed of sandy silt, with dispersed gravel (0.3-1 cm) as result of local deflation (Frenguelli, 1925). These sedimentary deposits could be contemporary with the Pleistocene-Holocene Pampean Eolian System localized to the north of the study area (Iriondo and Kröhling, 1995; Etcheverría et al., 2009) (Fig. 1A).

According to Etcheverría et al. (2009) the terrace levels and the current alluvial plain were formed by the interaction between the river and changes in sea level and climate during the Lower and Middle Holocene (Etcheverría et al., 2009). (Fig. 3). Eolian deposits formed during the Upper Holocene when channels of the Colorado alluvial fan dried out and subsequently, eolian processes re-worked the sediment (Etcheverría et al., 2009). These sandy deposits constitute the parental material of the modern soils (Sbrocco and Carballo, 1995).

The main structural elements identified include (Fig. 1B) the Huíncul fault, a dextral transcurrent fault orientated W-E (Gregori et al., 2008, 2013). This fault is located south of the Colorado River, in the contact zone between the Brazilian and Patagonian shields (Orchuela et al., 1981; Chernicoff and Zappettini, 2003, 2004; Ramos et al., 2004). Grabens developed between the Colorado and Negro rivers (Criado Roqué and Ibáñez, 1979; Chernicoff and Zappettini, 2003; Ramos et al., 2004). Also, lineaments with dominant N-S to NNW-SSE trend that include the "Macachin fault" zone, which dip and kinematics are unknown (Vogt et al., 2010).

4. Methodology

Several field campaigns were carried out in 2014-2015 to map and sample sedimentary rocks units. Descriptions and sampling were done on fresh rocks exposures. Geographic location data was taken using a GARMIN eTrex Vista GPS, WGS84 datum.

Geographical and geological information was integrated into ArcGIS® 10.2.2 software by Esri. The cartographic data used for geological sketch map include the Colonia Julia y Echarren-Pedro Luro 3363-III/IV, 1: 250,000 geological chart (Etcheverria et al., 2009), the Hilario Ascasubi 3969-28-2, 1: 50,000 topographic chart (Instituto Geográfico Militar, 1968) and World Imagery Basemap of ArcGIS.

Granulometric analysis was performed at the Marine Geology Laboratory of Instituto Argentino de Oceanografía (IADO) in Bahía Blanca. The samples were dispersed in distilled water after cleaning the organic matter and carbonates and analyzed by laser diffraction particle size analyzer with the Mastersizer Malvern 2000 equipment. The samples with granulometry greater than 250 µm were sieved. Results were integrated into the GRADISTAT V 4.0 program (Blott and Pye, 2001). The granulometric parameters determined were Mean (x#), Sorting (σ), Skewness (Sk), Percentil 1% (Φ1%) and Kurtosis (K) through graphical methods proposed by Folk and Ward (1957). The grain-size distribution diagram, was performed with GRADISTAT V 4.0 program (Blott and Pye, 2001). The grain-size distribution graphs were analyzed following the methodology from Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011).

The interpretation of the sedimentary environment was made based on granulometry, sediment morphology and stratigraphic relationships. For the fine-grained sedimentary rocks of unknown origin, additional analyses were performed to discriminate between water and eolian flows. These include granulometric parameters, diagrams of grain-size distributions (cumulative curves at a probability scale and frequency curves) and bivariate diagrams. Complementary to the determination of sedimentary environment, bivariate diagrams using granulometric parameters were made and compared with the environmental fields defined by Friedman (1961), Spalletti (1980), Friedman (1979) later modified by Tripaldi et al. (1998) and Tripaldi (2001). The units were later correlated with those presented in Etcheverría et al. (2009).

5. Results

5.1. Stratigraphy

Six sedimentary stratigraphic columns were logged in the field and are presented below (Fig. 2).

5.1.1. Stratigraphic column I (39°27'34.00" S/ 62°43'4.80" W, 27 m a.s.l.)

The basal part of the lower unit is composed of sandstone with abundant calcareous cementation and plane-parallel lamination (Fig. 4). Above, in sharp planar contact, there is a very coarse-grained sandstone with calcareous cementation and dispersed gravel with fragment sizes of 1 to 3 cm; parallel laminated, and interbedded with a matrix-supported conglomerate with granule-pebble sized clasts and a sandy matrix.

A calcareous crust (laminar calcrete) blankets this lower unit. Above, in sharp irregular contact, there is a pebble conglomerate with a silty-sandy matrix, reddish brown color, with abundant calcareous cementation deposited in a paleochannel. The clasts are made up of sandstone and volcanic rocks. Here the calcareous blanket (laminar calcrete) and the reddish brown conglomerated will be refered as Calcretized alluvial deposits Level-I ("cACR-I").

The stratigraphic column is capped by a fine-grained sandstone, light brown to grayish in color, massive, with isolated calcareous nodules. In this work, this upper unit will be called ancient eolian deposits (aE).

5.1.2. Stratigraphic column II (39°28'23.0" S/ 62°42'54.6" W, 27 m a.s.l.)

From bottom to top, there is a well-sorted sandstone blue-gray in color, followed by a fine grained sandstone, with some dispersed gravels, with maximum clast sizes around 5 mm; isolated carbonate concretions are observed (Fig. 4). Overlying, on a sharp irregular contact, there is powdery calcrete. Above these units, in a sharp planar contact, there is a clast-supported conglomerate with sandy matrix, and calcareous cementation, which partially covers the clasts. Overlying, there is a laminar calcrete, with a 25 cm thick layer in the bottom, followed by nodular calcrete. Both laminar and nodular calcretes, especially the laminar, are brecciated. This unit is correlated with the cACR-I described in column I. this part of the sequence is folded by anisopachous folds with WSW-ENE axis (Fig. 5). Above this, in sharp erosive contact, there is a fine grained sandstone with some dispersed gravels, light brown color, equivalent to aE.

5.1.3. Stratigraphic column III (39°28'20.4" S/ 62°41'48.9" W, 23 m a.s.l.)

The basal part is composed of siltstone, reddish brown color (Figs. 6 and 7). Overlying, with a sharp contact, there is a 10 cm thick powdery calcrete. Above this, in sharp erosive contact, continues a well-sorted medium-grained to fine-grained sandstone with calcareous cementation, grayish blue color, and with a loose to friable consistency. Towards the top of this unit there is a well-developed paleosol with abundant roots, blocky structure, and abundant calcareous cementation. Above it, in sharp erosive contact, there is a unit divided into two subunits: the basal one is a clast-supported conglomerate, with a silty matrix, and calcareous cementation. The clasts are made up of volcanic rocks (basalts and rhyolites) and sandstones from the Río Negro Formation. The upper subunit consists of a matrix-supported conglomerate, with normal graded bedding. Towards the top, a calcareous crust blankets the clasts.

In sharp erosive contact, a 65 cm thick boulder calcrete covers partially the previous unit. In this work it is correlated with cACR-I. Above these units, there is a fine-grained sandstone with some dispersed gravels, considered equivalent to aE; it is of grayish brown color, loose consistency, with moderate carbonate content. In the upper part pedogenesis development is observed.

5.1.4. Stratigraphic column IV (39°26'57.19" S/ 62°40'34.82" W, 22 m a.s.l.)

From bottom to top there is a well-sorted medium to fine-grained sandstone, with calcareous cementation, grayish-blue color and friable consistency (Fig. 8). The sandstone is fractured in blocks, and its surface is covered by a calcareous crust. The block size varies from 1-15 cm. Above the previous one, a boulder rich calcrete is developed, the host material consists of very coarse-grained sandstone. In this work, the calcrete and its host sandstone will be refered as calcretized alluvial deposits level II ("cACR-II"). Overlying, in sharp erosive contact, there is a fine-grained sandstone with some dispersed gravels and calcareous nodules, this unit is considered equivalent to the ancient eolian deposits (aE). The clasts are composed of volcanic rocks.

5.1.5. Stratigraphic column V (39#25.525' S/ 62#40.438' W, 15 m a.s.l.)

The basal part is composed of a green-grayish mudstone, with high plasticity, and abundance of carbonates and mottled, with a wedge- lenticular shape (Subunit IV) (Fig. 8). Followed up, in sharp irregular contact, by poorly sorted very fine grained sandstone, light brown in color. Calcareous cementation at the top, gives it a friable consistency (Subunit II), while towards the base it is loose (Subunit III). It is overlied by matrix-supported conglomerates, with a silty matrix; the clasts are volcanic with abundant calcareous nodules (Subunit I matrix). The stratigraphic column V is located in the T3 terrace level of the alluvial fan and the sedimentary sequence will be referred as alluvial deposits level III ("ACR-III").

5.1.6. Stratigraphic column VI (39#27'48.1" S/ 62#42'48.8" W, 15 m a.s.l.)

From bottom to top, there is a fine, light brown sandstone with high carbonate content (Subunit VII, Fig. 9). Above this, in sharp-planar contact, there is a reddish brown siltstone, with high organic matter content (Subunit VI). A moderately-well sorted sandstone, dark brown color, mottled towards the top (Subunit V) is overlying Subunit VI, with sharp planar contact. On top, in sharp-planar contact, there is a poorly sorted fine-grained sandstone, light brown in color (Subunit IV) and, above it, in sharp-planar contact, there is a reddish brown siltstone (Subunit III). Overlying Subunit III, there is a reddish-brown very fine-grained sandstone (Subunit II), and, finally, a light brown fine-grained sandstone, with some dispersed gravels (Subunit I) constitutes the upper part of the sequence. This stratigraphic column is localized at the western shore of La Salada shallow lake, on terrace level T-2 and the sedimentary sequence will be referred as modern eolian deposits (mE). The deposits of the stratigraphic column VI overlies the Río Negro Formation. This is suggested by an outcrop of Río Negro Formation in the shoreline of La Salada.

5.2. Sedimentary analysis

In the case of stratigraphic columns V and VI, especially in the VI, the characteristic previously mentioned were not enough to assign the sediment to a particular sedimentary environment. Also, to confirm the influence of eolian processes over the T3 terrace level, of clearly alluvial origin, additional analyses based on the granulometry were needed to discriminate hydrologic from eolian environments. These analyses include diagrams of grain-size distributions (cumulative curves at a probability scale and frequency curves) and bivariate diagrams using textural parameters, contrasted to the environmental fields defined by Tripaldi (2001) (see also Friedmand, 1961, 1979; Spalletti, 1980; Tripaldi et al., 1998). The results of the interpretation of the sedimentary environment of deposition corresponding to stratigraphic columns V and VI are summarized in tables 1 and 2. The graphs of cumulative curves at a probability scale and frequency curves can be found in Appendix.

6. Discussion

6.1. Río Negro Formation

This formation is recognized at the bottom of the exposed sections in the stratigraphic columns II and III, located in the T1 terrace and in the stratigraphic column IV, in the T2 terrace. This unit is covered by coarse-grained fluvial deposits, except in the stratigraphic column IV where it is overlain, in unconformity, by a boulder calcrete. The rocks assigned to this formation thus expands in the central part of the mapped area, below 20 m.a.s.l (Fig. 1).

A fluvial-eolian origin has been suggested for the rocks included in this Formation outside of the study area (Andreis, 1965; Zavala et al., 2000; Zavala and Freije, 2005; Etcheverría et al., 2009). The well-sorted blue-gray sandstone interbedded with reddish fine-grained siltstone, and scarce conglomerates, observed in the study area are compatible with a similar origin. The interbedded powdery calcrete found in this unit is interpreted as the result of pedogenesis. Powdery horizons with thickness <2 m are commonly found in pedogenic calcrete (Chen et al., 2002), formed during soil drying when evapotranspiration exceeds precipitation (Gile et al., 1966; Birkeland, 1999; Rawlins et al., 2011; Hough et al., 2014). Therefore, alternating conditions between arid-semiarid are inferred for this time (Fig. 10). Etcheverría et al. (2009) assigned an Upper Miocene-Lower Pliocene age to the rocks of Río Negro Formation. This age is based on the dating of a volcanic glass concentrates from a tuff intercalated in the upper part of the stratigraphic equivalent marine Rionegrense (9.41 Ma) and a fission track age in rhyolitic volcanic ash, from the upper part of the formation, that give 4.41±0.5 Ma (Alberdi et al., 1997). Based on mammal fossils Aramayo (1987) assigned an Upper Miocene-Pliocene age for the upper part of this Formation.

6.2. Coarse-grained fluvial deposits

These deposits mainly consist of conglomerates; the conglomerate clasts are made up of volcanic rocks (basalts and rhyolites) and blanketed by a calcareous crust. This unit is overlying the rocks of the Río Negro Formation and has been recognized in the stratigraphic columns II and III, located in the T1 terrace, at the SW of the mapped area, between 20 and 20.5 m a.s.l. Similar conglomerates overlying the Río Negro Formation and crowning the plateau in the region have also been observed by other authors (De Ferraris, 1966; Etcheverría et al., 2009; Fernández, 2012). Then, based on the sedimentary features, such as type of clast observed in the conglomerates and its regional extension, this unit can be correlated with the coarse-grained fluvial deposit defined by Etcheverría et al. (2009) at a regional scale (Fig. 10).These authors suggest that this unit represent a high-energy fluvial environment that gave rise to the Colorado River alluvial fan, during Middle Pliocene-Lower Pleistocene. In the study area this event is recognized in the T1 terrace level (Fig. 3).

6.3. Calcretized alluvial deposits of the Colorado River (cACR-I; cACR-II)

Southern and Southwest of La Salada, the cACR-I unit was recognized above coarse-grained alluvial deposits, above 25 m a.s.l. To the North of La Salada, the cACR-II unit is overlying in unconformity the sedimentary units of the Río Negro Formation, above 20 m a.s.l. To the south of La Salada (Fig. 2) cACR-I and cACR-II generate two relatively levelled surfaces, at around 20 and 25 m a.s.l., which define the T1 and T2 terraces, respectively. Etcheverría et al. (2009) consider the terrace levels T1 and T2 as only one terrace level corresponding to the oldest deposit of Colorado River alluvial fan. However, in the study area, based on the areal distribution of cACR-I and cACR-II units and the topography, it is possible define the presence of two terraces. Furthermore, cACR-I and cACR-II units are capped by an unconformity over which aE deposit was accumulated. Based on the stratigraphic position, cACR-I and cACR-II units are equivalents to the calcrete levels defined by Etcheverría et al. (2009) at a regional scale (Fig. 10)

Etcheverría et al. (2009) recognize, westward of the study area, two levels of calcrete, equivalents to cACR-I and cACR-II units, overlying the coarse-grained fluvial deposits at different topographic levels (Fig. 10). They suggest, based on the stratigraphic relationships, a Pleistocene age. Furthermore, Etcheverría et al. (2009) observed alluvial deposits of the Colorado River-level I (14a), the name given by the authors to the oldest deposit of Colorado River alluvial fan (T1 in this work) in the area close to La Salada shallow lake. They found this unit in discordance over calcretized coarse-grained sandstone, which is correlated by these authors to the coarse-grained fluvial deposits (the calcretized coarse-grained sandstone, which is temporal equivalent to the coarse-grained fluvial deposits, is not represented in the Fig. 10 maintaining the stratigraphy of Etcheverría et al., 2009 who not distinguish it as a separate unit). Consequently, they assigned the alluvial deposits of the Colorado River-level I (14a) to the Lower Holocene. The spatial distribution of this unit is partially coincides with the cACR-I and cACR-II units defined in this work (Fig. 2). What we found in this work, differs from findings of the Etcheverría et al. (2009). We suggest, based on the geomorphological and geological context, and stratigraphic position, that these deposits should be older than the Holocene. Spalletti and Isla (2003), based on geomorphological features, proposed that the Colorado River alluvial fan would have drained the area around 120,000 years BP.

The presence of folding affecting the sedimentary units of the Río Negro Formation, coarse-grained fluvial deposits and probably the cACR-I unit (Fig. 5) suggests neotectonic activity in the area, which could have triggered the incision of the Colorado River and, probably, erosion before cACR-II deposition and development of a new terrace level, T2. During this period, there is a marine transgression and climate was semi-arid (Fig. 10), which would favor the deposition instead of erosion; this in turn suggests that local tectonism seems to be behind the generation of at less part of the terraces.

The well-differentiated horizons and the morphology of the cACR-I and cACR-II units suggest a pedogenic origin for the calcretization of these units. The same origin is also inferred by Etcheverría et al. (2009) for the calcretes in the region. The nodular and laminar morphology of the calcrete indicates different degrees of soil development, being lesser in the nodular than the laminar (Gile et al., 1966). Well-developed calcrete profiles form when the sedimentation rate is low and the residence time of the sediment in the active zone of soil formation is high (Wright, 1992). Tectonism also controls the developing of calcrete by its influence on the sedimentation rate and by generating different geomorphic settings (Alonso-Zarza, 2003). Probably, the calcretization of cACR-I and cACR-II units occurred during periods of tectonic stability, decrease in sediment supply and a climatic change from semi-arid to arid conditions (Fig. 10). Iriondo (1999) recognizes evidence of a regional Pampean climate improvement, with precipitation enough to mobilize carbonates, around 15,000-16,000 year BP based on radiocarbon and thermoluminescence dating of the concretion and eolian sand, respectively. In summary, based on stratigraphy, topography and deformation, we conclude that the cACR-I and cACR-II units would have formed during the Middle and Upper Pleistocene, and the calcretization occurred in the Upper Pleistocene. Subsequently, during the Pleistocene-Lower Holocene, the aE deposits would have covered the terraces as result of a dry and cold regional climate under possibly, predominantly westerly winds, as recognized by Iriondo (1999) to have prevailed from around 14,000 years BP to 8,500 years BP.

6.4. Alluvial-Eolian Deposits (ACR-III unit)

ACR-III deposits are recognized in the northern part of the mapped area and in the stratigraphic column V (Fig. 2). They have a larger areal extension than the alluvial deposits previously described, and have an elongated W-E distribution, with a slightly flat surface below 15 m a.s.l. ACR-III is part of T3 terrace of the alluvial fan of the Colorado River. The T3 terrace occurs ca. 5 m below the T2 terrace. The larger extension of the alluvial plain of the T3 terrace level, along with the upwards increase in the grain size of the sedimentary deposits in the stratigraphic column suggests an improvement in the climatic conditions, from arid to humid-warm condition (Fig. 10).

The results of the sedimentological analysis of the subunits of the stratigraphic column V indicate a fluvial and eolian origin for most of the cases, showing some inconsistencies (Table 2). The subunits I and IV belong to the third group of Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011), which includes sediments formed by relatively short-lived depositional processes or in an environment with high energy, but it also includes deposits resulting from various overlapping processes. The subunits II and III are included in the first group, which includes sediments of eolian origin but can also include beach and fluvial deposits (Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011). According to Sun et al. (2002) subunits I and IV are compatible with an eolian origin (6-7 Φ) and II and III with a fluvial transport (2.5-3.5 Φ). More over the bimodal character of the frequency curve displayed by subunits I and IV is indicative of complex evolution, for example a fluvial sediment reworked by eolian processes.

According to Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011) methodology, most of the subunits in stratigraphic column VI belong to the first group (Table 2), which included eolian deposits and, in some cases, beach and fluvial sediments. The subunit VI belongs to the third group that included sediments produced by short-lived depositional processes or in an environment with high energy but also adds deposits resulting from various overlapping processes. In this case the bimodal distribution of the particle sizes is compatible, for example with a combined fluvial-eolian origin (Sun et al., 2002).

Thus, we consider that the subunits II and III in column V, identified as of the first group of Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011), actually belong to fluvial deposits, according to the characterization of the fluvial deposits proposed by Sun et al. (2002). On the other hand, subunits I and IV in the column V and subunit VI in column VI have a fluvial-eolian origin due to the reworking of the fluvial sediments by the wind (Table 2). This, along with the geomorphological expression of the cACR-III suggest an alluvial origin for these sedimentary deposits. The mixed alluvial-eolian nature could be indicative that they were reworked by the wind, possibly during drier periods.

Based on its stratigraphic position ACR-III unit can be correlated with the alluvial deposits of the Colorado River-Level II (14b) of Etcheverría et al. (2009), the name given by those authors to the second oldest deposit of the Colorado River alluvial fan (T3 in this work). They associate this unit with the largest expansion of the river, later modified by eolian processes evidenced by interbedded eolian sediment. Etcheverría et al. (2009) further correlated this unit with the events described by Melo et al. (2003) for the evolution of Colorado River alluvial fan deposits which include the alternation of wet and dry periods, and sea level changes. Accordingly, Etcheverría et al. (2009) suggest that the Colorado River-Level II (14b) deposition would have started around 7,000 years BP, as a result of warm and humid climates that may have lasted until 3,000 years BP. After 3,000 years BP, when the climate changed to temperate-arid, the channels of the alluvial fan dried out and the fine-grained sediments were remobilized by the wind. Iriondo (1999) recognizes a climatic optimum around 6,000-7,000 years BP, which is also identified worldwide. Consequently, we consider ACR-III as equivalent to the alluvial deposits of Colorado River-Level II (14b) unit defined by Etcheverría et al. (2009).

Around 2,000 years BP, regressive sea level conditions started and the migration to the south of Colorado River took place (Melo et al., 2003). This migration generated another terrace level with its associated alluvial deposits of the Colorado River-Level III (14c) (in this works ACR-IV; T4). After this, the modern alluvial deposits of the Colorado River were formed (in this works ACR-V; T5 terrace) (Etcheverría et al., 2009). These sedimentary units and terrace levels are represented in the studied area by ACR-IV and ACR-V units (Fig. 2) and they are not analyzed in this work. Nevertheless, based on the geomorphological characteristics, we inferred that during the temperate-arid period the alluvial fan of the Colorado River was restricted to the south of the T1. Both sea level higher than present and temperate-arid climate favored aggradation and T4. This explains the fact that T4 is slightly higher than T3. Later, during following regression, T4 was partially eroded and the modern alluvial plain formed.

6.5. Ancient Eolian Deposits (aE)

These deposits capped cACR-IandII in T1 and T2 terrace levels. They were recognized in the area by Etcheverría et al. (2009) as fine eolian deposits and dated as Pleistocene-Middle Holocene because they overly Pleistocene units and are covered, near the coast, by transgressive marine sediments assigned to the Middle

Holocene (Weiler et al., 1987). Its provenance is interpreted by Frenguelli (1925) by the existence of clasts disseminated in the eolian sediment, as a result of local deflation. Also, Etcheverría et al. (2009) consider that these deposits are simultaneous with the "Sistema Eólico Pampeano" in the Pampean region (Fig. 1A). Zárate and Blasi (1993) and Etcheverría et al. (2005) proposed that the eolian sediments come from the wind erosion of alluvial plains of the Colorado and Negro rivers.

6.6. Modern Eolian Deposits (mE)

In the study area, the modern Eolian deposits (mE) occupy the depressions on top of the T3 terrace. These deposits are thickest on the west of the depression, following the barchan dune morphology. The extension of these deposits is limited, but they are surrounded by the T2 terrace sedimentary deposits, which may suggest that they have a local origin. The sedimentological analysis of the subunits identified in the stratigraphic column VI support an eolian origin, except for the subunit VI for which a fluvial-eolian origin is suggested according to Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011) method (Table 2). Sun et al. (2002) suggest that typical loess is fine skewed (0.1 to 0.3) with a primary modal size of 5-6 Φ, with a long tail on the fine side and steep for the coarse side. We suggest that mE were generated by local eolian erosion of the T3 terrace (Table 1). Therefore, during a period of aridity, the cACR-III deposits and sediments from the Río Negro Formation were reworked by the wind. For instance, Etcheverría et al. (2009) recognize eolian deposits in the Salitral de la Gotera (Fig.1B) that, based on Melo et al. (2003), suggests that these sediments were generated around 3,000 years BP when the climate changed to temperate-arid producing remobilization of the sediments by wind. This climatic condition prevailed up to ca. 1,000 years BP under dominant SW-NE and W-E winds (Iriondo, 1990; Tonni et al., 2001; Melo et al., 2003; González, et al., 2008; Iriondo and Kröhling, 2008). Therefore, we suggest that the mE unit is contemporary to the eolian deposits defined by Etcheverría et al. (2009). Severalshallow lakes occupy depressions localized on the third oldest terrace (T3) of the alluvial fan of the Colorado River, which were generated around 3,000 years BP.

Martínez et al. (2012), based on oxidizable carbon ratio, dated the sequence of eolian and lacustrine sediments alternating with pedogenized levels outcropping on the west coast of La Salada, close to the stratigraphic column VI, as Pleistocene-Holocene and Holocene. Our study suggests that this sequence formed later on in the Middle-Upper Holocene, based on topographic and stratigraphic relationships.

6.7. Neotectonic activity

The fold recognized in the figure 5 corresponds to a deformation event occurred during the Miocene-Middle-Upper Pleistocene. The WSW-ENE axis orientation suggests compressive stress NW-SE prevailing during the Pleistocene. Previously, Tapia (1939) and Groeber (1949) have recognized folds with W-E and NW-SE orientation, respectively, affecting the Río Negro Formation.

Other evidences of neotectonic activity in the area include a fast tectonic reactivation of the Macachin fault zone, which lowered the base level of Colorado River and, consequently, caused the deep and steep incisions in the Plateau located to the east (Fig.1B), during the Upper Pleistocene (Vogt et al., 2010). This reactivation could be a consequence of the Pleistocene N-S breaking and uplifting of the Miocene Sub-Andean piedmont (Vogt et al., 2010). In addition, this event could have modified the hydrological conditions of the Colorado River (Vogt et al., 2010). Furthermore, transgressive deposits, in the Patagonian Atlantic coast, analyzed by Codignotto et al. (1992) indicate a differential rise rate along the coast during the last 10,000 years as a result of neotectonism. Also, approximately 130 km north of the study area, Quattrocchio et al. (1994) recognized a deformation event affecting an Upper Pleistocene strata, possibly as a result of the modern activity of an E-W megafracture inferred by geophysical data.

7. Conclusion

The stratigraphic, structural and sedimentological information obtained in this study and their comparison with previous works, allowed to infer that the establishment of the Colorado River alluvial fan occurred around the Middle Pleistocene. The tectonic processes, dominant until the Pleistocene-Holocene transition, triggered the incision of the Colorado river alluvial fan generating several levels of terraces (T1 and T2). This is evident by deformations that affect the Miocene to Pleistocene units which indicate significant neotectonic activity during the Upper Pleistocene.

Later, during periods of tectonic stability, decrease in sediment supply, and probably climatic changes from semiarid to arid conditions generated the calcretization of the sedimentary deposits present in terraces T1 and T2 through pedogenic processes. Subsequently, in the Pleistocene-Middle Holocene, as consequence of regionally arid climates, the terraces were covered by eolian sediments (aE). Around 7,000 years BP a change to warmer and humid conditions favored the development of a wide alluvial fan, expressed in T3 and the ACR-III deposits. At around 3,000 years BP, climatic conditions switched to temperate-arid, causing the eolian reworking of the ACR-III deposit and its restriction toward the south of T1 terrace level. During this time, a higher sea level than at present and a temperate-arid climate favored the aggradation that generated T4 terrace level. Simultaneously, local deflation-sedimentation processes resulted in the deposition of mE sedimentary deposits over the terrace T3. The depressions generated by the deflation were, later on, occupied by the shallow water lakes once the climate turned more humid. Subsequently, during regressive sea level condition, ca. 2,000 years BP, T4 terrace level was partially eroded and the modern alluvial plain formed.

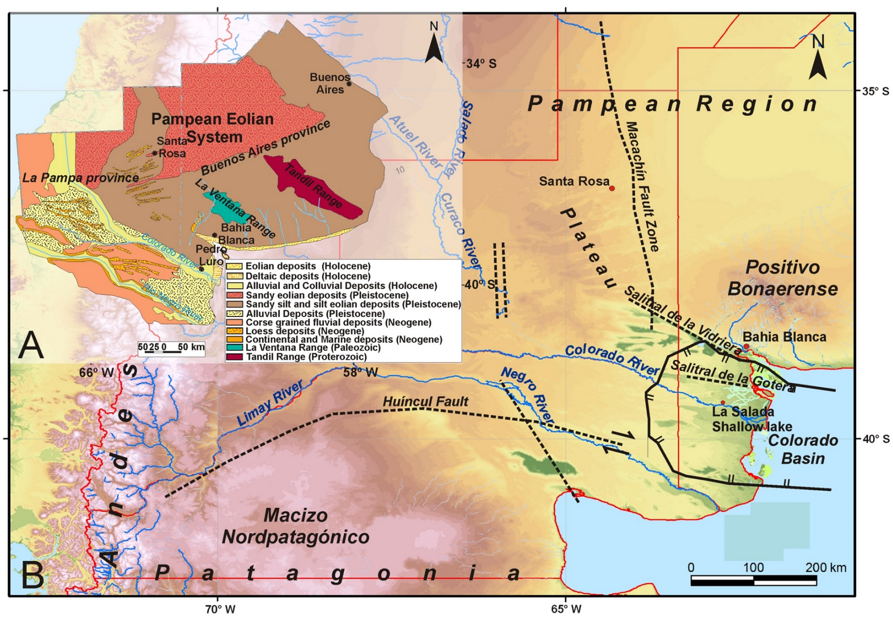

Fig. 1.

Fig. 1. A. Regional geological map (modified after Lizuaín et al., 1998); B. Structural sketch map showing the main faults in the study area and the Colorado Basin (modified after Vogt et al., 2010).

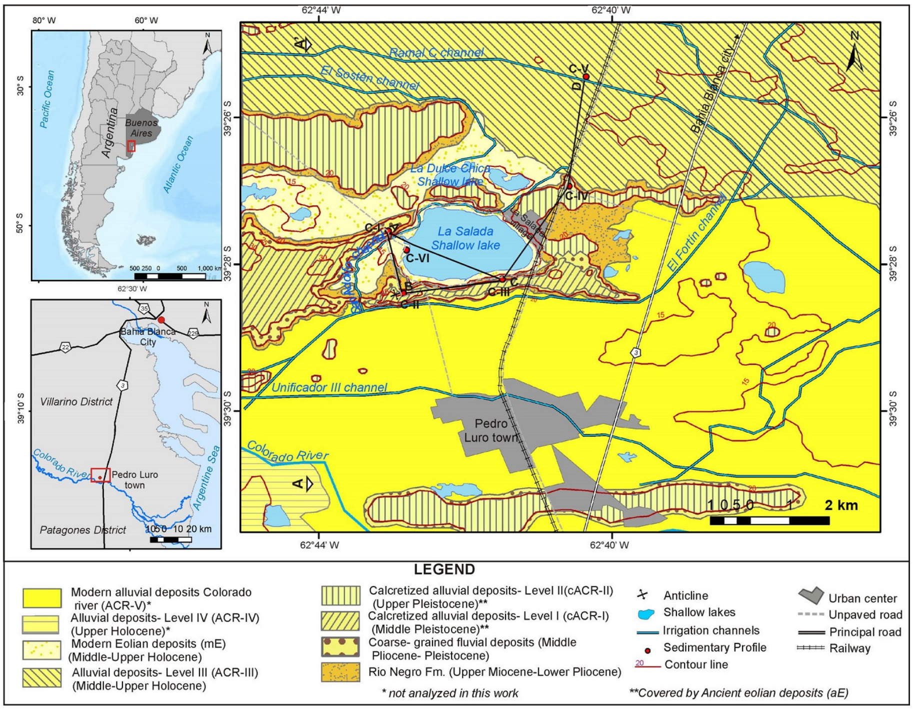

Fig. 2.

Fig. 2. Geological sketch map (modified after Etcheverría et al., 2009). The map show the location of the study area, stratigraphic columns and sections analyzed. C-I: Stratigraphic columns I; C-II: Stratigraphic columns II; C-III: Stratigraphic columns III; C-IV: Stratigraphic columns IV; C-V: Stratigraphic columns V; C-VI: Stratigraphic columns VI.

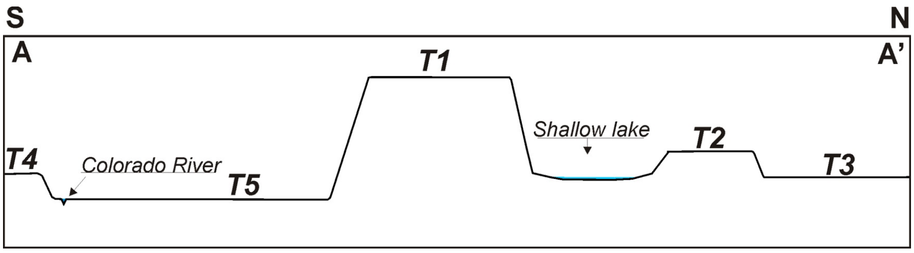

Fig. 3

Fig. 3. Schematic cross-section of the line showed as A-A' in the figure 2 representing the topographic relationship of the terraces in the alluvial fan of the Colorado River. These are mentioned as T1, T2, T3, T4, and T5 from oldest to youngest; is not to scale.

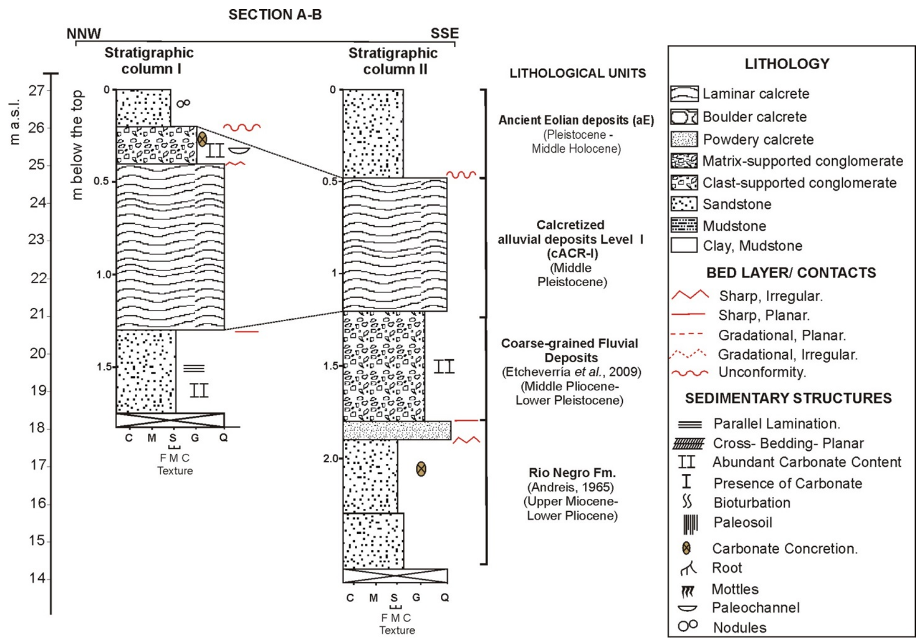

Fig. 4.

Fig. 4. Section A-B representing the integration of the stratigraphic columns I and II oriented in a NNW to SSE transect (see Fig. 2). The stratigraphic columns I and II are located according to their altitudinal position. The vertical scale has been exaggerated with respect to the altitudinal scale.

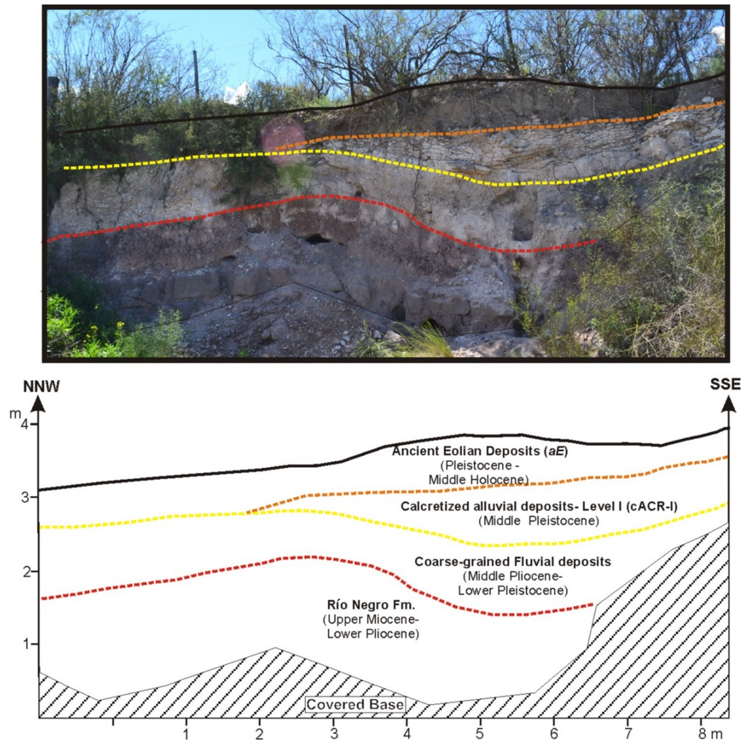

Fig. 5.

Fig. 5. Exposed section in the stratigraphic columns II locality. It is localized to the West of the La Salada shallow lake oriented NNW to SSE. It exposes the folding of the Miocene-Pleistocene units and the sharp erosive contact on which overlies aE deposits.

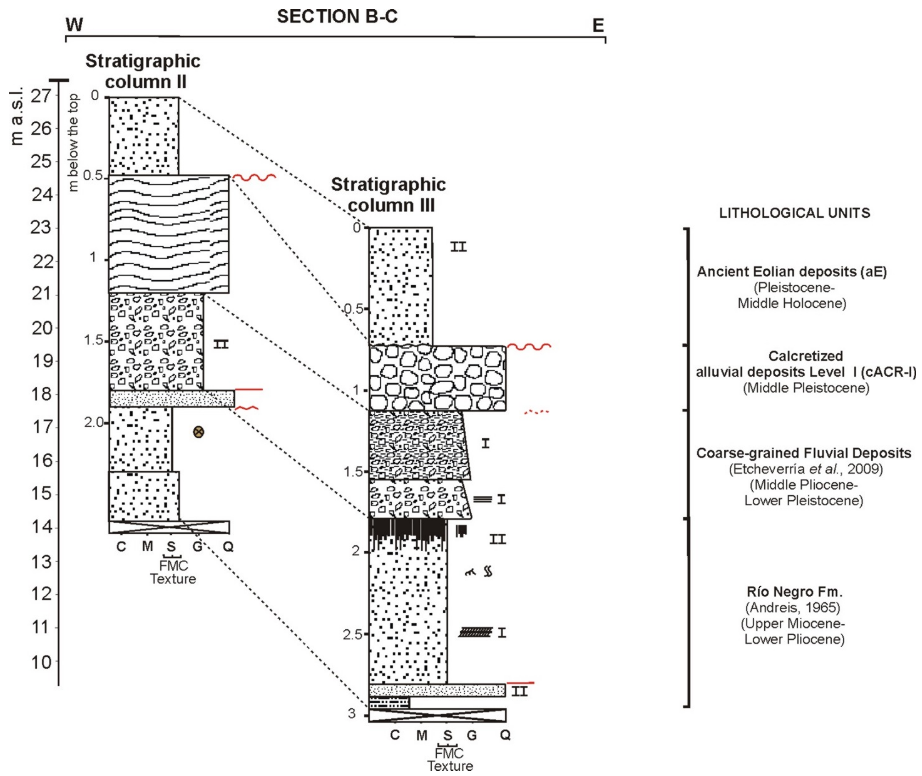

Fig. 6.

Fig. 6. Section B-C representing the integration of the stratigraphic columns II and III oriented in a W-E transect (see Fig. 2). The stratigraphic columns II and III are located according to their altitudinal position. The vertical scale has been exaggerated with respect to the altitudinal scale.

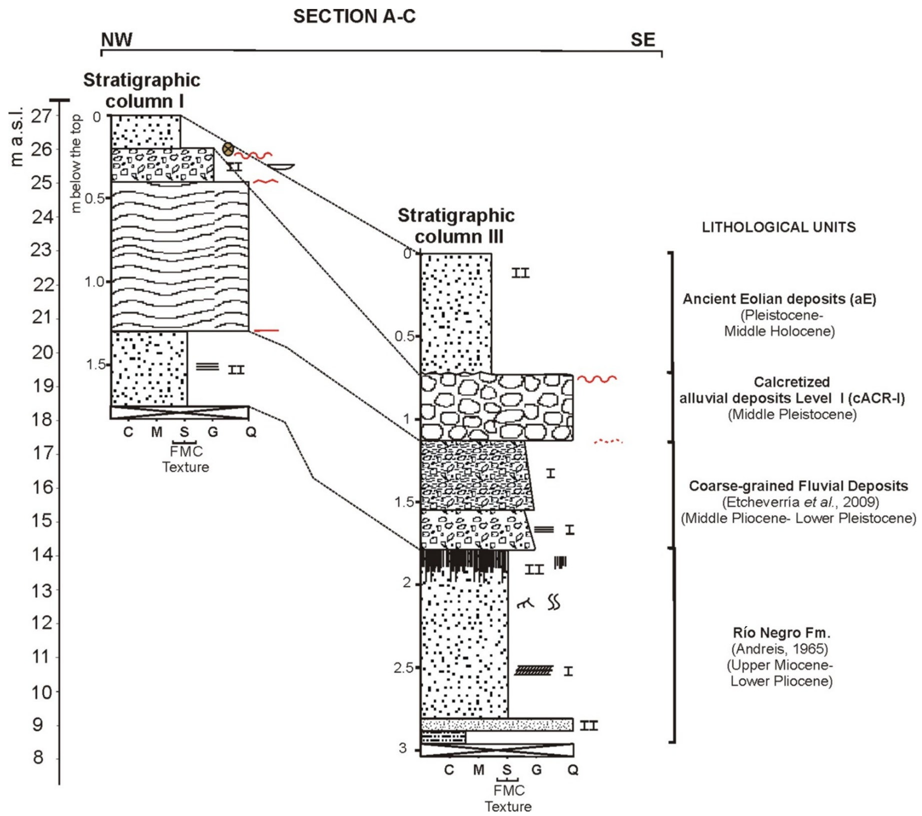

Fig. 7.

Fig. 7. Section A-C representing the integration of the stratigraphic columns I and III oriented in NW-SE transect (see Fig. 2). The stratigraphic columns I and III are located according to their altitudinal position. The vertical scale has been exaggerated with respect to the altitudinal scale. Observe the topographic difference among the stratigraphic columns I and III, localized at 27, and 23 m a.s.l. respectively.

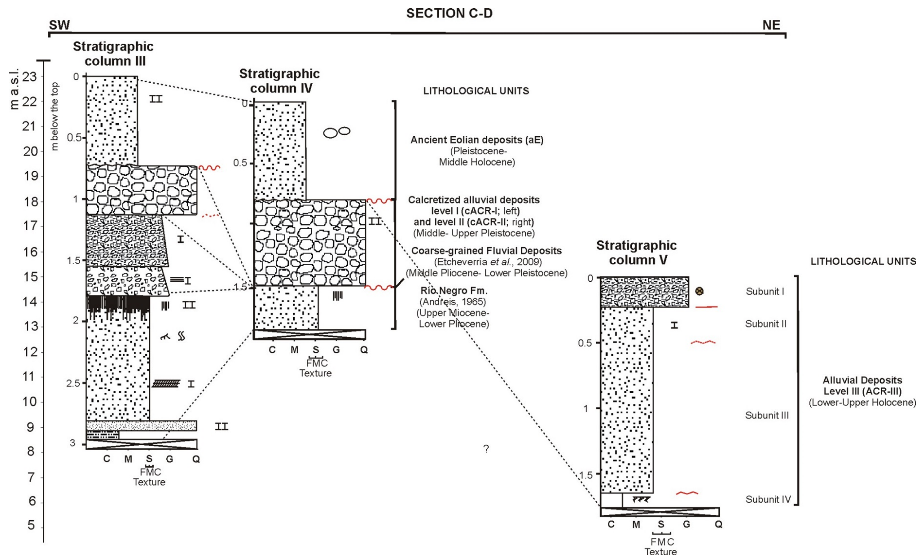

Fig. 8.

Fig. 8. Section C-D representing the integration of the stratigraphic columns III, IV and V oriented in SW-NE transect (see Fig. 2). The stratigraphic columns III, IV and V are located according to their altitudinal position. The vertical scale has been exaggerated with respect to the altitudinal scale. Observe the topographic difference among the stratigraphic columns III, IV and V, localized at 23, 22 and 15 m a.s.l. respectively, which are associated to three different terrace levels.

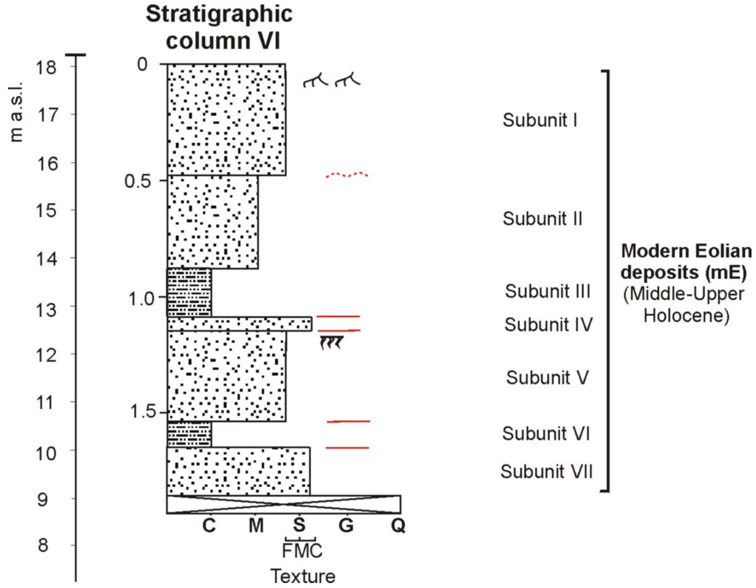

Fig. 9.

Fig. 9. The stratigraphic columns VI located west of La Salada shallow lake (see Fig. 2). The vertical scale has been exaggerated with respect to the altitudinal scale. This is localized at 18 m a.s.l. The deposits of the stratigraphic column VI overlies the Río Negro Formation. This is suggested by an outcrop of Río Negro Formation in the shoreline of La Salada.

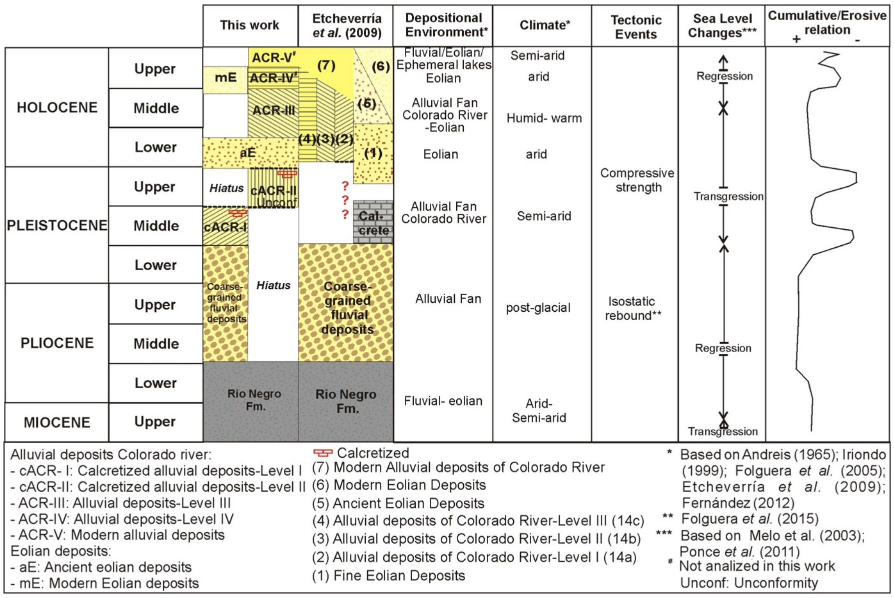

Fig. 10.

Fig. 10. Integrated stratigraphic column of the lithological units observed in this work and their environmental interpretation. Also, the figure shows the correlation with the units defined by Etcheverría et al. (2009) in the area.

TABLE 1. SUMMARY OF GRANULOMETRIC PARAMETERS DETERMINED FOR THE SUBUNITS OF THE STRATIGRAPHIC COLUMNS V AND VI.

	Subunit	Mean (x̄) (Φ)	Sorting (σ)	Skewnees (Sk)	Kurtosis (K)	Percentil 1% (Φ1%)
Stratigraphic Column-V	I	6.88	1.92	0.11	1.12	3.15
	II	3.12	1.16	0.33	1.55	1.56
	III	3.34	2.04	0.52	1.45	0.90
	IV	5.08	1.87	0.03	1.30	0.80
Stratigraphic Column-VI	I	3.53	1.78	0.36	0.99	1.00
	II	3.08	1.62	0.28	1.31	0.25
	III	4.96	1.77	0.25	1.22	2.00
	IV	2.33	1.06	0.34	1.83	1.00
	V	3.21	1.16	0.31	1.55	1.55
	VI	5.66	2.34	-0.12	1.11	0.70
	VII	2.21	0.61	0.02	0.93	1.00

Table 1

TABLE 2. SUMMARY OF DIFFERENT INTERPRETATIONS FOR THE SEDIMENTARY SUBUNITS RECOGNIZED IN STRATIGRAPHIC COLUMNS V AND VI. (*)

	Subunit	Friedman (1961)	Spalletti (1980)	Friedman (1979) later modified by Tripaldi *et al.* (1998)	Tripaldi (2001)	Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011)	This work
Stratigraphic Column-V	I	Fluvial	Fluvial-Eolian	Eolian	Eolian	Third group	Fluvial-Eolian
	II	Fluvial	Fluvial-Eolian	Eolian	Eolian	First group	Eolian
	III	Fluvial	Fluvial	Eolian	Eolian	First group	Eolian
	IV	Fluvial	Fluvial-Eolian	Fluvial	Fluvial	Third group	Fluvial-Eolian
Stratigraphic Column-VI	I	Fluvial-Eolian	Fluvial-Eolian	Eolian	Eolian	First group	Eolian
	II	Fluvial	Fluvial	Fluvial	Eolian	First group	Eolian
	III	Fluvial	Fluvial-Eolian	Eolian	Eolian	First group	Eolian
	IV	Fluvial-Eolian	Fluvial	Eolian	Eolian	First group	Eolian
	V	Fluvial	Fluvial-Eolian	Eolian	Eolian	First group	Eolian
	VI	Fluvial	Fluvial-Eolian	Fluvial	Fluvial	Third group	Fluvial-Eolian
	VII	Fluvial-Eolian	Eolian-Beach-Fluvial	Eolian	Eolian	First group	Eolian

(*) Based on Friedman (1961), Spalletti (1980), Friedman (1979) later modified by Tripaldi *et al.* (1998), Tripaldi (2001) and Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011) methodologies.

Table 2

Acknowledgements

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Appendix

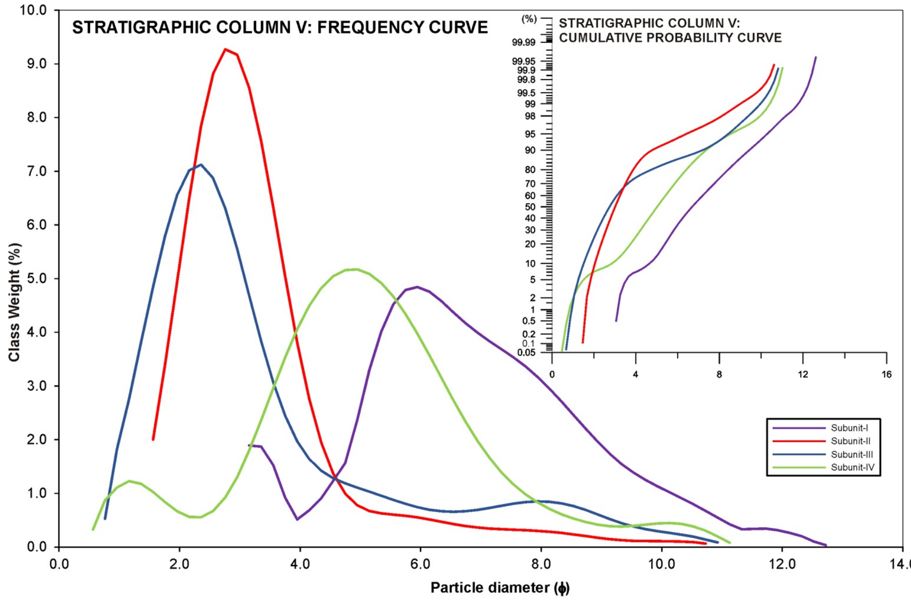

Fig. 1.

Fig. 1. Frequency and cumulative probability curves of each subunits in the stratigraphic column V. The cumulative probability curves according to (Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011) are third group for the subunits I and IV and the first group for subunits II and III, which indicate a Fluvial-eolian and eolian origin respectively. The frequency curves show a bimodal distribution for the subunits I and IV while for the subunits II and III are unimodal.

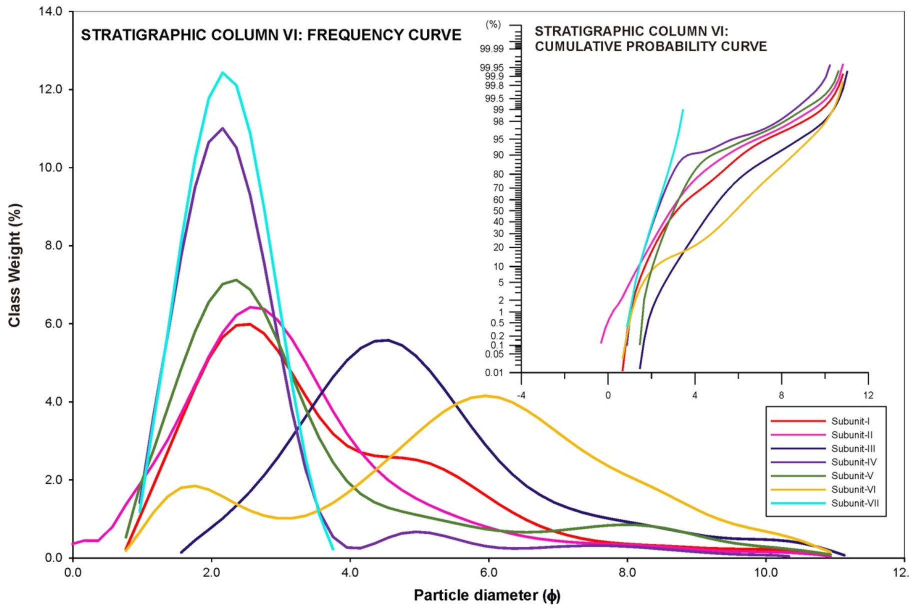

Fig. 2.

Fig. 2. Frequency and cumulative probability curves of each subunit identified in the stratigraphic column VI. The cumulative probability curves according to (Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011) are first group for all the subunit except for the subunits IV, which indicate an eolian and fluvial-eolian origin respectively. The frequency curves show a unimodal distribution for all subunits except for the subunit IV.