REVISTA DE LA ASOCIACIÓN GEOLÓGICA ARGENTINA

VOLUMEN 79(2022)

# Recording of multiple lake-marsh paleoenvironments during the middle Holocene in the Quebrada del Toro, NW Argentina

**Juan G. VEIZAGA SAAVEDRA[1], María Cristina SÁNCHEZ[1], Olga MARTÍNEZ[2], Heiko PINGEL[3], Claudio G. DE FRANCESCO[4]**

[1]Cátedra de Estratigrafía y Geología Histórica, Universidad Nacional de Salta, Avda. Bolivia 5150, 4400 Salta

[2]Facultad de Ciencias Naturales, Herbario MCNS, Instituto de Bio y Geociencias del NOA (IBIGEO-CONICET)

[3]Institut für Geowissenschaften, Universität Potsdam, 14476 Potsdam, Germany

[4]Instituto de Investigaciones Marinas y Costeras (IIMyC), CONICET, UNMdP, Mar del Plata, Argentina

Corresponding Author: Juan Gonzalo Veizaga Saavedra. juangveizaga@gmail.com

Editor: Francisco Córdoba

Enviado: 10 de agosto de 2020

Aceptado: 23 de mayo de 2021



**ABSTRACT**

Quaternary lake systems have developed in many Andean intermontane valleys in northwestern Argentina in association with landslides, rock avalanches, and the development of large alluvial fans, caused either by tectonics, climate change, and/or increased rainfall. At the El Candado location, in the narrow, southern sector of the Quebrada del Toro (Salta Province, Argentina), fine-grained sedimentary deposits are recognized, which, based on their sedimentological and paleontological characteristics, are interpreted as the sedimentary infill of shallow lakes-marshes that were generated by the development of large alluvial fans that dammed the Río Toro. Based on AMS $^{14}C$ dating of gastropod shells and organic matter (ca. 8-4.8 ka), this region experienced multiple lacustrine-marsh paleoenvironments during the middle Holocene. Pollen analysis and paleobotanical investigations of these deposits suggest that the accumulation of the lake sediments occurred under relatively humid conditions that alternated with semi-arid periods as is typical for the Andean Holocene.

Keywords: Quaternary, Central Andes, Paleoflora, Molluscs, Paleoclimate

**RESUMEN**

*Registro de múltiples episodios lacustre-palustres durante el Holoceno medio en la Quebrada del Toro,* *noroeste argentino*

En el noroeste argentino durante el Cuaternario se desarrollaron sistemas lacustres asociados con deslizamientos, avalanchas de roca y desarrollo de grandes abanicos aluviales, generados por la actividad tectónica andina, los cambios climáticos y/o lluvias extraordinarias. En la localidad de El Candado, tramo inferior de la Quebrada del Toro (provincia de Salta, Argentina), se reconocen afloramientos pelíticos que son interpretados en base a sus características sedimentológicas y paleontológicas como acumulaciones lacustres-palustres someras. Estos depósitos se habrían producido a partir de la instalación de un ambiente lacustre-palustre como consecuencia del desarrollo de un gran abanico aluvial que obstruyó al río Toro. La sedimentación ocurrió durante el Holoceno medio de acuerdo con la datación de gasterópodos y materia orgánica que arrojaron edades entre 8-4.8 ka. Según los restos paleobotánicos y palinológicos así como los atributos sedimentológicos, la acumulación ocurrió en ambientes lacustre-palustre temporarios, somero bajo condiciones húmedas que habría alternado con las condiciones paleoclimáticas áridas y secas que caracterizaron al Holoceno medio de esta región de los Andes Centrales.

Palabras clave: Cuaternario, Andes Centrales, Paleoflora, Moluscos, Paleoclima



## INTRODUCTION

During the late Pleistocene- early Holocene, transient mountain lakes were formed in various locations and settings throughout the arid and semi-arid regions of northwestern Argentina associated with landslides, seismic events or the development of large alluvial fans during periods of increased rainfall (Hermanns and Strecker 1999, Wayne 1999, Bookhagen et al. 2001, Trauth et al. 2003, Colombo 2005, Hermanns et al. 2004, Savi et al. 2016). As a result, many intermontane river valleys have preserved remnants of lacustrine deposits, often recognizable by their typical ochre to yellow colors. One of these valleys is the Quebrada del Toro in the Eastern Cordillera of the southern Central Andes (Fig. 1). Along its main river (Río Toro), discontinuous outcrops of 10 to 50 m thick Quaternary lake deposits have been recognized that are laterally and vertically related to alluvial-fluvial accumulations of the same age (Robinson et al. 2005, Álvarez et al. 2012).

Sedimentary deposits of intermontane paleolakes are important but relatively rare repositories of proxy material to investigate and reconstruct past environmental conditions and their changes over time in orogenic landscapes (e.g. Trauth et al. 2000, Hermanns et al. 2004, Colombo et al. 2009, Piovano et al. 2014). Among these proxy data, sedimentary and geochemical compositions, floral and faunal fossil remains, and often pollen, are used to provide a snapshot of the paleoenvironment including climatic and biotic conditions during lake deposition (e.g. Garralla et al. 2001, De Francesco et al. 2007, 2009). For that matter, datable materials (e.g. organic carbon, fossils, volcanic ash) are just as helpful as their prominent appearance in the landscape. Of particular interest in this study are late Quaternary environmental changes in the Argentine Andes, which remain enigmatic (e.g. Tchilinguirian and Morales 2013, Tiner et al. 2018) due to various aspects such as the availability of suitable data and the complex interactions between climate systems and mountain topography (e.g. Strecker et al. 2007, Bookhagen and Strecker 2012, Barnes et al. 2012).

Our study focusses on the lower section of the Río Toro where the valley is considerably narrow and the adjacent mountain flanks are steep (Fig. 2). Recent studies showed that these slopes are unstable and prone to failure and generation of debris flows (Olen et al. 2020), while catchment-wide erosion rates from the flanking tributaries are high (Tofelde et al. 2018). As a consequence, at the outlets of these tributaries, many wide and asymmetric alluvial fans have developed, characterized by fan areas between 0.2 and 2 $km^2$ (on average 1 $km^2$), a surface slope of 5° to 10°, and a thickness of 10-15 m (Veizaga Saavedra 2012). Due to relatively large amounts of sediment added to the main river, active alluvial fans have often influenced the dynamics of the Río Toro by altering the local base level, which led to reduced run-off gradients, upstream aggradation, and potentially the damming of the river to form transient lake systems (Sánchez et al. 2005, 2010). Similar observations have been made throughout the Argentine Andes for the late Pleistocene-Holocene (e.g. Colombo 2005, Colombo et al. 2005, 2009, Pingel et al. 2013, Savi et al. 2016, May and Soler 2011).

At the confluence of the El Candado stream and the Río Toro (El Candado site) (Figs. 2, 3), we document several outcrops that show lacustrine beds with an average thickness of 2.5 m that are interbedded and interdigitated with alluvial fan sediments (Fig. 4). Despite their potential to provide valuable information on past climate changes, these deposits have not been studied in detail. Therefore, we present new chronostratigraphic (AMS $^{14}C$), sedimentological, mineralogical, geochemical, and paleontological data for preserved lacustrine beds from five stratigraphic sections along the lower section of the Quebrada del Toro and place them into a refined stratigraphic and paleoclimatic context. Based on this data, we show that during the middle Holocene this region experienced multiple lake-marsh episodes, which are most likely related to the development of an alluvial fan at the confluence of the El Candado stream and the Río Toro.

## GEOLOGICAL AND CLIMATIC SETTING

The studied El Candado area (ca. 24.8°S, 65.6°W) is located near the confluence of the El Candado stream and the Río Toro in the intermontane Quebrada del Toro, which is an integral part of the Eastern Cordillera morphotectonic domain (Fig. 1, 2). The Quebrada del Toro is a fault-bounded intermontane valley delimited by approximately NNW-SSE striking, bivergent reverse faults and associated mountain ranges (Marrett et al. 1994, and references therein). More specifically, the El Candado area is located in a narrow, structurally controlled basement gorge through which the Río Toro exits the valley to the south and along which several minor tributaries (e.g. El Candado and El Alisal streams) and one major tributary (Río Capillas) enter the river valley (Fig. 2). A major fault crossing the valley in the study area is the east-dipping Incamayo Fault (Fig. 2). Adjacent mountain ranges to the east and west exceed 3,000 m a.s.l. and their valley flanking slopes average around 30° (e.g. Tofelde et al. 2018). The basement rocks exposed in the study area mainly comprise Neoproterozoic to early Cambrian meta-sediments of the Puncoviscana Formation (Turner 1960) that are unconformably overlain by mainly fluvial and alluvial Quaternary sediments (Fig. 3). The latter comprise occasional intercalation of lacustrine beds (this study).

The eastern flanks of the southern Central Andes of Argentina are characterized by pronounced orographic rainfall gradients (Fig. 1b, Bookhagen and Strecker 2008). Water vapor transport from the Atlantic Ocean and Amazon Basin is mainly governed by the South American Monsoon system (SAMS), in which the South American low-level jet (SALLJ) funnels air masses southward along the Andes into (sub-) tropical South America (Castino et al. 2016, Vera et al. 2006). The Quebrada del Toro receives rainfall ranging from ~900 mm/yr at the outlet to <200 mm/yr in the interior of the intermontane basin (Figure 1). Moisture supplied to the Central Andes has varied significantly over the past several tens of thousands of years (Baker and Fritz 2015). Variability in the intensity of SAMS precipitation on precessional timescales (21 kyr) has been documented by paleo-lake studies on the Puna Plateau of Argentina and Chile and the Bolivian Altiplano (Bobst et al. 2001, Godfrey et al. 2003, Fritz et al. 2010, Fritz et al. 2004, Placzek et al. 2006).

On interannual timescales, El Niño/Southern Oscillation (ENSO) is the main source of variability in precipitation and circulation over South America, this system would have influenced the South American continent during the Quaternary in a dissimilar way (Markgraf et al. 1986, Villagrán and Varela 1990, Markgraf and Seltzer 2001, Villa Martinez et al. 2003). Many studies have shown that during El Niño events, precipitation is suppressed over central-eastern Brazil and enhanced over southeastern South America (southern Brazil, Uruguay, and northern Argentina), while opposite anomalies are observed during La Niña events (Grimm 2011). Also, the subtropical rainfall anomalies during El Niño are related to a stronger SALLJ and enhanced pole ward moisture transport to southeastern South America (Zhou and Lau 2001), therefore the interannual variability of the jet's strength and frequency is significantly modulated by the El Niño Southern Oscillation, especially during spring (Montini et al. 2019).

## METHODOLOGY

We used traditional sedimentological and stratigraphic techniques to characterize five individual alluvial stratigraphic sections containing intercalated lacustrine beds (El Alto, La Cirila, Los Cardones, El Candado West and El Candado sections, Fig. 2) using the lithofacies classification of Miall (1996) and the lake classification of Fregenal Martinez et al. (2010). In addition, we collected 11 bulk lake-sediment samples from the El Candado section for geochemical analyses by energy-dispersive X-ray spectrometry (EDS). For this purpose, samples were air-dried, gold-coated, and analyzed using an FEI Quanta 200 SEM microscope and an EDAX Phoenix 40 (acceleration voltage 20 keV, spot size 3 to 4 mm) at the Faculty of Engineering, La Plata, Argentina. Each sample was studied at varying magnification up to 25,000 to determine the major and minor mineralogical components. In addition, clay mineral compositions were determined by EDS and their morphologies were identified by scanning electron microscopy (SEM).

Four samples were analyzed by X-ray diffractometry (XRD) to determine the mineral composition of lake sediments. Samples were gently ground with a rubber mortar and repeatedly washed in distilled water until deflocculation occurred. The <2 mm fraction was separated by suspension and gravity decantation, and oriented samples were prepared on glass slides. Clay mineralogy was determined from diffraction patterns obtained using samples that were air-dried, solvated with ethylene glycol, and heated to 550°C for 2 hours (Brown and Brindley, 1980). The diffractograms were performed in an X'Pert PRO model X PANalytical (CIG) diffractometer, using Cu/Ni radiation and 40 kV and 40 mA generation settings.

The weighting (semi-quantitative) of the minerals present in the total rock was carried out from the intensity of the main peak for each mineral (Schultz 1964, modified with own standards; Moore and Reynolds 1997). The estimation of the mineralogical components has a methodological error ca. 10%. The semi-quantitative estimates of the relative concentrations of clay minerals were based on the peak area method following the Biscaye (1965) methodology. The response of mineral species to sedimentation depends on the shape of the particles (Pierce and Siegel 1969). For that reason, each mineral proportion is not directly proportional to the defined areas. The relative percentages of each clay mineral were determined by applying empirical factors (Moore and Reynolds 1997).

In the El Alto, La Cirila, and Los Cardones sections, we collected fossil plant remains that were identified at the Herbarium of the National University of Salta. Observations, measurements and photographs were made using an Optika SZM-LED2 stereoscopic magnifying glass with a Motic-MotiCAM BTU10 camera and a JEOL JSM6480LV scanning electron microscope.

To determine the correlation of the lake deposits in the El Candado locality with other recognized lacustrine deposits, we dated gastropod shells and organic matter using the AMS $^{14}C$ method. The samples were extracted and cleaned in the mineral separation laboratories of the University of Potsdam (Germany) and then sent to the Radiocarbon Laboratories in Poznan (Poland) for radiocarbon analysis.

For the mapping of Quaternary deposit within the southern sector of the Quebrada del Toro and a

2D reconstruction of the paleotopography of the abandoned fan surface (Fig. 2), we used a combination of field- and satellite-based mapping and DEM-processing tools in QGIS software and TopoToolbox, a Matlab-based toolset for topographic analysis (Schwanghart and Kuhn 2010). The base for these analyses is a TanDEM-X digital elevation model (DEM) with 12 m spatial resolution (https://gdk.gdi-de.org/geonetwork/srv/api/records/5eecdf4c-de57-4624-99e9-60086b032aea).

## RESULTS

### Stratigraphy and sedimentology

Eight lithofacies of alluvial-fluvial (gravel: Gmc, Gm, Gng, Gig and sand: Sm, St, Sr, Sh) and two lithofacies of lacustrine origin (clay: Clm and silt: Lm) have been defined. A summary of lithofacies and interpretations used in this study is shown in Table 1.

(1) In general, the greenish-grey gravel facies (G) are poorly sorted and consist of medium to coarse gravel that are either, clast-supported (Gmc) or matrix-supported (Gm), with normal (Gng) or inverse (Gig) gradation (Fig. 6a). Clasts exclusively meta-graywackes, slates, and phyllites from Puncoviscana Formation are angular to subangular, oblate, prolate, and laminar. The matrix is composed of silts to silty clay and sand. The stratification is diffuse, tabular and lenticular, with erosive or planar base and the thickness of the beds is between 0.5 and 1 m.

(2) Sand facies (S) are represented by moderately sorted, medium to coarse, and sub-rounded sand with either planar-cross lamination (St), massive appearance (Sm), parallel lamination (Sh) or with current ripple-lamination (Sr). The stratification is tabular, with a planar base and top and the thickness of the beds is between 0.5 and 1 m. Occasional fine-grained, lenticular sandy levels are 3 to 5 cm thick with planar and parallel lamination (Sh) are interbedded with pelitic facies and contain abundant carbonate cement. In addition, these sandy beds contain oxidized parts.

(3) Two pelitic facies have been identified: massive silt (Lm) and massive clay (Clm). Both form tabular beds with sharp and flat base between 1 and 2.5 m thick (Fig. 6b). The clay levels contain abundant black and reddish-ocher plant remains, gastropod shells, and show abundant bioturbation.

These lithofacies were grouped into two facies associations that are identified in some levels of the stratigraphic sections considered (Fig. 5):

(1) Facies association A-F: It consists of the aggradation of gravel bodies (Gmc and Gm) mantiform, tabular, up to 2 m thick, with poor selection and poor textural maturity, generally massive, although at the finest levels a certain normal gradation is recognized. The sedimentary features of the G lithofacies such as the presence of fine interstitial matrix, the angular and monomictic character of the individuals, the absence of stream structures and the chaotic fabric suggest a massive flow of debris along a very steep slope during episodes of large discharge of water and sediment. Thus, these facies would have

been deposited by high-kinetic energy, high-density and high-viscosity flows of the debris flow type (Coussot and Meunier 1996, Blikra and Nemec 1998). On the other hand, if it considers: 1) the slope of the alluvial fans (15° average; Veizaga Saavedra 2012), 2) the proximity of the source areas and 3) the high availability of material to be mobilized due to the nature of the source areas, it is possible that the fine-grained G lithofacies could be the result of intermediate flows, between hyper-concentrates and fluids (Suriano and Limarino 2009).

The Gmc and Gm facies grade vertically and laterally to lithofacies composed of tabular beds of coarse to medium massive sand (Sm) with abundant plant remains. These are interpreted as sheet flood deposits generated by hyper-concentrated flows (Blair and McPherson 1994) produced by low-frequency and high-intensity rainfall (Gutiérrez et al. 1988) that are typical of the Holocene of the arid to semi-arid region of the Central Andes (Tofelde et al. 2017).

In the El Candado West and El Candado sections, lenticular levels of medium sand with planar-cross lamination (St) are recognized associated with the Sm facies (Fig. 5). These are the result of the migration of small sand waves under the influence of fluid, tractional and unidirectional currents (Collinson and Thompson 1989) that occur when the intensity of precipitation is greater than the infiltration capacity of the soil (Gutiérrez Elorza 2001).

(2) Facies association of L-M facies: In all the studied sections, it is characterized by monotonous clastic successions of massive clays with desiccation cracks. In the El Candado and El Candado West sections (Fig. 5), tabular levels of massive silt are interbedded. In the five sections considered, fine tabular beds of fine sand, with a planar to wavy base, with parallel lamination (Sh) and ripple lamination (Sr) are intercalated. The pelites contain abundant black and reddish-ocher plant remains with bioturbation (Fig. 6b) and remains of gastropod shells (Fig. 7a-b) in the sections of La Cirila, Los Cardones and El Candado.

The sedimentological characteristics of the Clm/Lm association suggest that sedimentation occurred under conditions of low flow regime and with a predominance of suspension-fallout processes in a water body. Among the pelitic beds, tabular levels of fine sand with carbonate cement (Sh/Sr) are recognized that would be linked to sporadic tractive flows produced by the entry of a river course into a lentic water body (Spalletti 2001). This means that the El Candado lake levels described in this study would have been shallow, ephemeral, and vegetated as suggested by sedimentary structures and fossil content.

**Mineralogy and geochemistry**

The samples analyzed are homogeneous and display small compositional variations; contents of major elements were determined: O (44-48%), Si (23-32%), Al (5-12%), minor amounts of Fe (4-9%), K (1-

5%), Ca (1-3%) and Mg (1-2%) (Fig. 8a-b). Likewise, Na, Co, Ba, Cl, I, P and Mn were identified in trace concentrations. It should be noted that the samples bearing abundant plant and gastropod remains showed high values of K (3.61%), Ca (2.73%), Mg (1.78%) and Na (1.29%). The mineralogy of lake sediments is characterized by quartz (50-75%), plagioclase (5-15%), potassium feldspar (1-5%) and clay minerals (15-30%) (Fig. 8). Clay mineral assemblages defined by X-ray diffraction consist of illite (45-60%), smectite (5-20%), illite/smectite mixed-layer (5%), chlorite (20-30%), and kaolinite (5%) (Fig. 8c-d). SEM analyses reveal that illite show as high fragmented clays with variable size, irregular borders and without a preferential order. Their EDS analysis show in descending order Si, Al, Na, Mg, K, and Fe (Fig. 8a). Smectite shows as curled flakes with open-air voids having small interfacial zones and as flaky particle morphology (Fig, 8b). EDS shows that Si is the major cation, followed by Al, Na, K, Mg and Fe in order of abundances (Fig. 8b), and in some cases, minor Ca.

**Paleontology**

In the Los Cardones section, a 1.5 m thick level of massive clay is recognized; the paleobotanical record consists of dicotyledonous remains exhibiting the lignified tissues of a woody plant, in which the growth rings were preserved, with conducting vessels and the supporting tissue of erect plants. In the La Cirila section, a 0.9 m thick clay bank bears plant remains of a large leathery leaf in which the veins, petioles of leaves, leaves of tapered sheets characteristic of grasses, fruit imprints of dicotyledons are identified and seeds similar to the modern *Aeschynomene* (Fabaceae) (Fig. 7c-h). In 2.5 m thick massive clay and silt levels of the El Alto section, black and red dicotyledonous remains were collected in which conducting vessels with secondary growth are recognized.

In the La Cirila section, remains of shells of the genus *Biomphalaria* (represented mainly by *B. peregrina*) are recognized (Figs. 7a and b). Shells have an average diameter of 4 mm, they are very fragmented and exhibit a poor state of preservation, characterized by surface dissolution. Shells have been dated by AMS $^{14}$C and results indicate that the molluscs and, therefore, the sedimentary deposits that host them have a middle Holocene age of 6,440 ± 40 cal. years BP (Table 2). In addition, fragments of indeterminable gastropod shells were collected at different stratigraphic levels. Moreover, organic matter from the El Alto section has been dated by AMS $^{14}$C, results indicate that the paleontological remains, and thus the sedimentary deposits they host, are of middle Holocene age: 8,030 ± 60 and 7,420 ± 80 cal. years BP for the lower section; and 4,790 ± 40 and 4,825 ± 35 cal. years BP for the upper section (Table 2).

In all sections, samples were collected for palynological analysis at the Palynology Laboratory of the National University of Jujuy; some samples were productive in the content of palynomorphs. The assemblage is diverse and consists of pollen types with species of marsh plants (Cyperaceae), terrestrial

(Poaceae, Asteraceae, Celtidaceae (*Celtis*), Betulaceae (*Alnus*) and trilete and monolet spores of ferns.

**Geomorphological analyses**

Based on our geomorphological analyses of the southern sector of the Quebrada del Toro we were able to reconstruct the paleotopography of the abandoned/non-active El Candado paleofan surface in 2D. These analyses show that the paleofan surface is approximately 60 m above the present-day stream (Fig. 2d). At its confluence with the Río Toro, this surface is located at an altitude of 2,000 m above sea level and must have extended at a similar altitude towards the western flank of the valley. Thus, the upstream projection of the 2,000 m contour line outlines the maximum extent of a potentially dammed lake environment.

Another intriguing observation from our Río Toro profile analysis is a notable change from a convex river profile above and a concave profile below the confluence of the Río Capillas (Fig. 2c), where the main valley floor also widens downstream from less than 100 m near El Candado to up to 450 m near El Alisal.

## DISCUSSION

**Paleoenvironmental interpretation**

In the El Candado region, multiple shallow lacustrine-marsh episodes are documented. These lakes had a maximum area of about 1 km$^2$ (Fig. 2b) and were hydrologically open according to Collinson's (1978) classification. Its deposits are exclusively characterized by detrital facies and are vertically related to alluvial-fluvial systems (Fig. 5).

Sedimentation began in marginal positions of the lake (coastal zone; Fregenal Martinez et al. 2010) with the installation of a fining-upward alluvial system characterized by debris flows. This pattern is well developed in the El Alto, El Candado West, and El Candado sections (Fig. 5). Towards the center of the basin, the thickness of the coarse-grained facies is significantly reduced, so that the supralittoral zone is predominantly characterized by psammitic levels with medium to fine grain sizes (Fregenal Martinez et al. 2010). These psammitic levels were derived by unconfined flows and are deposited as massive or parallel laminated beds. In some cases, these beds grade to sand facies with cross-lamination that corresponds to ephemeral river systems such as flood beds generated during periods of increased rainfall that would have affected the entire study area.

In the middle of the valley, a lacustrine body formed, which is documented by the massive clay facies (Clm). The periphery of the lake constitutes a mud plain of siltstones (Lm) interstratified with the massive clays (Clm). These fossiliferous beds show all characteristics of a flooded marsh environment populated by grasses or poaceae, fabaceae, and shrubs. The suspension-fallout processes would have been interrupted by tractive flows responsible for the accumulation of fine sandstone beds with carbonate cement and high regime parallel-lamination coinciding with a period of increased rainfall within the drainage area. Source of the carbonate cement are either Cretaceous limestones of the Yacoraite Formation (e.g. Marquillas et al. 2005) or reworked material from abundant Quaternary conglomerates (e.g. Pingel et al. 2020) exposed in the central and upper sections of the Quebrada del Toro. Finally, in this lake-marsh environment, sedimentological features have been identified that indicate subaerial exposure by lake level fluctuations: desiccation cracks, discontinuous calcic horizons (<0.5 cm), oxidized plant remains, suprastratal trace fossils, and vertical bioturbation.

**Mineralogy and geochemistry**

Based on similarities in the geochemical and mineralogical composition it is inferred that all the lake records recognized in the study area would be genetically related during an episode prone to lake formation. The geochemical composition of lacustrine deposits with abundant plant and gastropod remains suggest alkaline waters, in line with the lentic water bodies composition, which represents low or zero flow velocity (≤ 0.7 m/s), low conductivities (0.1-1.7 mS/cm) and relatively high pH values (7.1-9.4) (De Francesco and Hassan 2009).

Clay minerals consist mainly of illite, chlorite, and smectite with small amounts of kaolinite. While illite and chlorite are the product of low-grade metamorphism and occur mainly in the Puncoviscana Formation, smectite is formed from chlorite by groundwater interaction under oxidizing conditions (Do Campo and Nieto 2003). Another smectite source may be the alteration of volcanic glass (Chamley 1997), a very rich source considering the abundance of volcanic deposits in the Quebrada del Toro (e.g. Molina 2006, Mazzuoli et al. 2008, Vezzoli et al. 2009, 2012, Pingel et al. 2020).

Finally, kaolinite may result from alteration of feldspar and mica from the Precambrian to Lower Paleozoic Tastil batholith (Kilmurray and Igarzábal 1971), the above mentioned volcanics from the central and southern Quebrada del Toro, and the weathering of micaceous siltstones of the Puncoviscana Formation (Zeballos et al. 2016, Do Campo and Nieto 2003). Kaolinite is stable under subaerial/near-surface conditions and is often correlated with temperate and humid paleoclimatic conditions (Do Campo et al. 2018).

**Paleontology**

The paleobotanical and palynological assemblage is diverse and consists of plants remains and pollen types that suggest a lake/marsh environment surrounded by woodland vegetation under humid conditions. The monolet spores of ferns described are characteristic of epiphytic Polyopodiaceae from the Yungas biogeographic region, predominant in the Selva Montana, a vegetation zone found on eastern flanks of the NW Argentine Andes between 900 and 1,600 m a.s.l. with an average annual rainfall of up to 1,800 mm (Malizia et al. 2012).

The snails of the genus *Biomphalaria* documented in this study suggest the coeval existence of lentic, vegetated, and very shallow water bodies within lotic systems such as streams and rivers, with abundant submerged vegetation (De Francesco and Hassan 2009). The high degree of fragmentation and wear of the shells suggests an important taphonomic alteration, likely caused by sediment reworking. According to the sedimentological context, the lake environment would have been subject to episodic flows of water from the main fluvial system, i.e. the Río Toro. This situation would have promoted adverse conditions for the fossilization of the molluscs, which could have been subjected to reworking as well as bioturbation. Some recent taphonomic studies indicate that freshwater environments with the presence of abundant aquatic vegetation (and high concentrations of organic matter) significantly affect the preservation of molluscs, mainly through the dissolution of carbonate shells (De Francesco et al. 2020). The presence of various remains of indeterminable gastropod shells supports this interpretation.

## Geomorphological considerations

As the concavity of the Río Toro changes at the confluence with the Río Capillas, it is likely that the additional discharge facilitates downstream sediment transport. Sediment entering the Río Toro north of the confluence does not seem to be transported as easily, leading to a rather convex stream profile. Indeed, a recent InSAR (synthetic aperture radar interferometry) study has shown that the landscape in this low-vegetated part of the valley is relatively unstable and susceptible to failure and the generation of debris flows (Olen et al. 2020). These findings are consistent with modern catchment-wide erosion rates from in situ-produced cosmogenic $^{10}$Be, which, in contrast to the drier and less steep northern sectors of the valley, document relatively high rates (approximately 1-1.5 mm/yr) and hillslope dominated sediment transport processes within tributary catchments in the southern part of the Quebrada del Toro (Bookhagen and Strecker 2012, Tofelde et al. 2018). Hence, in times of increased intermontane rainfall large amounts of debris may be generated and fed into the Río Toro, however, exporting this material may still be difficult, causing river damming. In fact, when projecting the 60 m high alluvial fan surface from the El Candado fan across the Quebrada del Toro suggests a prominent barrier to dam the Río Toro.

## Paleoclimatic considerations

Since the middle Holocene lake/marsh episodes of El Candado may have been formed as a result of the development of the El Candado alluvial fans and the subsequent damming of the Toro River, the question now arises as to the conditions that may have led to it.

The El Candado catchment is located along the western slopes of the tectonically active Sierra Pascha Sur and intersected by the Incamayo Fault (Fig. 2, Sánchez et al. 2010), therefore a tectonic control of alluvial fans in this area cannot be excluded. However, due to the lack of geological evidence, such as deformed layers or syn-sedimentary landslide deposits associated with the investigated outcrops, we consider this control to be insignificant and focus on the paleoclimatic conditions during the middle Holocene.

Based on our paleobotanical and palynological evidence, the studied sector of the Quebrada del Toro may have been relatively more humid during the middle Holocene (8.2 to 4.2 ka) than today. As a consequence, significant amounts of sediment must have been mobilized to give rise to the formation of thick alluvial fans with the potential to dam temporary lakes. This is especially true for areas with steep channel gradients such as those from our study area (Bookhagen and Strecker 2012, Tofelde et al. 2018, Olen et al. 2020).

Although the Holocene of the Central Andes is considered relatively arid (Tchilinguirian and Morales 2013; and references therein), numerous studies have locally documented episodes of higher humidity during the last 10 ka (Morales and Schittek 2008, Morales 2011, Tchilinguirian et al. 2014, Alcalde and Kulemeyer 1999, Olivera et al. 2006, Tchilinguirian 2009, Betancourt et al. 2000, Rech et al. 2002, Latorre et al. 2006, Yacobaccio and Morales 2005). In northwestern Argentina, another sedimentary record of similar age and humid conditions (ca. 10-4 ka BP) is that of Lake El Rincón in the Tafí del Valle region (26.9°S; Garralla et al. 2001).

The described humid conditions during the middle Holocene may be related to dynamics of the South American Monsoon system and/or ENSO activity, which would have influenced the variability of precipitation during this period in northwestern Argentina (Zhou and Lau 2001, Grimm 2011, Novello et al. 2017, Montini et al. 2019).

## CONCLUSIONS

In this study, we investigated the origin and evolution of late Quaternary lacustrine beds intercalated with alluvial fans deposits in the southern sector of the Quebrada del Toro (Eastern Cordillera, NW Argentina). Our results suggest that during the middle Holocene (ca. 8-4.8 ka BP) the development of large alluvial fans and the consequent damming of the Toro River created exclusively clastic lakes events.

Combined facies characteristics, paleontological content, and clay mineral compositions indicate that deposition took place in multiple temporary shallow lake-marsh environments with alkaline water under humid conditions. This suggests a wet period in an otherwise mainly dry area of northwestern

Argentina during the middle Holocene that may have been related to the dynamics of the SASM system, possibly influenced by ENSO activity. We suspect that these climatic conditions favored the mobilization of abundant coarse-grained sediments from adjacent steep mountain slopes, which provided the material for the construction of sufficiently large alluvial fans to dam the Río Toro.

**Acknowledgements**

The authors wish to thank Prof. Alonso for insightful discussions and logistical support and Prof. Manfred R. Strecker and Dra. Stefanie Tofelde for sample collection of organic matter and constructive discussions. We acknowledge Dr. Francisco E. Córdoba (editor), Dr. Luis R. Horta, and an anonymous reviewer for their evaluations that improved the manuscript. In addition, the authors would like to thank Luis Veizaga for digitizing some of the illustrations and the CONICET and the Universidad Nacional de Salta for their financial support.



## REFERENCES

Alcalde, J.A. and Kulemeyer, J.J. 1999. The Holocene in the south-eastern region of the province Jujuy, northwest Argentina. Quaternary International 57-58: 13-116.

Álvarez, L.M., Sánchez, M.C. and Salfity, J.A. 2012. Los depósitos cuaternarios lacustres del tramo medio de la Quebrada del Toro, noroeste argentino.13° Reunión Argentina de Sedimentología, Relatorio, p. 25-36. Salta.

Baker, P. and Fritz, S.C. 2015. Nature and causes of quaternary climate variation of tropical South America. Quaternary Sciences Review 124: 31–47.

Barnes, J. B., Ehlers, T. A., Insel, N., McQuarrie, N., & Poulsen, C. J. (2012). Linking orography, climate, and exhumation across the central Andes. Geology 40(12): 1135-1138.

Betancourt, J.L., Latorre, C., Rech, J.A., Quade, J. and Rylander, K. 2000. A 22,000-year record of monsoonal precipitation from northern Chile's Atacama Desert. Science 289: 1542-1546.

Biscaye, P. E. 1965. Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. Geological Society of America Bulletin 76(7): 803-832.

Blair, T. C. and McPherson, J. G. 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. Journal of Sedimentary Research 64(3a): 450-489.

Blikra, L.H. and Nemec, W. 1998. Postglacial colluvium in western Norway: depositional process, facies and paleoclimatic record. Sedimentology 45: 909-959.

Bobst, A.L., Lowenstein, T.K., Jordan, T.E., Godfrey, L.V., Ku, T. L. and Luo, S. 2001. A106 ka paleoclimate record from drill core of the Salar de Atacama, north-ern Chile. Palaeogeography, Palaeoclimatology, Palaeoecology 173: 21–42.

Bookhagen, B., Haselton, K. and Trauth, M. H. 2001. Hydrological modelling of a Pleistocene landslide-dammed lake in the Santa Maria Basin, NW Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology 169(1-2): 113–127.

Bookhagen, B. and Strecker, M. R. 2008. Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes. Geophysical Research Letters 35(6).

Bookhagen, B. and Strecker, M. R. 2012. Spatiotemporal trends in erosion rates across a pronounced rainfall gradient: Examples from the southern Central Andes. Earth and Planetary Science Letters 327: 97-110.

Bronk Ramsey, C. 2001. Development of the radiocarbon calibration program. Radiocarbon, 43(2A), 355-363.

Castino, F., Bookhagen, B. and Strecker, M.R. 2016. Rainfall variability and trends of the past six decades (1950–2014) in the subtropical NW Argentine Andes. Climatic Dynamics 1–19.

Chamley, H. 1997. Clay mineral sedimentation in the ocean. In: Soil and sediment. Springer-Verlag, 269-302, Berlin.

Collinson, J. D. 1978. Lakes. Sedimentary Environments and Facies, 61, 79.

Collinson, J. D. and Thompson, D. B. 1989. Sedimentary Structure (2nd cd.). Uniwin Hyman, London.

Colombo, F. 2005. Quaternary telescopic-like alluvial fans, Andean Range, Argentina, en Harvey, A.M., Mather, A.E. y Stockes, M. (eds.), Alluvial Fans: Geomorphology, Sedimentology Dynamics. Geological Society, Special Publications, 251: 69-84.

Colombo, F., Limarino, C., Busquets, P., Solé de Porta, N., Heredia, N., Rodríguez-Fernández, R. and Alvarez-Marron, J. 2005. Primeras edades absolutas de los depósitos lacustres holocenos del río Jachal, Precordillera de San Juan. Revista de la Asociación Geológica Argentina 60(3): 606-608.

Colombo, F., Limarino, C., Busquets, P., Solé de Porta, N., Heredia, N., Rodríguez-Fernández, R. and Alvarez-Marron, J. 2009. Holocene intramontane lake development: A new model in the Jáchal River Valley, Andean Precordilleran, San Juan, Argentina. Journal of South American Earth Sciences 28: 229-238.

Coussot, P. and Meunier, M. 1996. Recognition, classification and mechanical description of debris flows. Earth Sciences Reviews 40: 209-227.

De Francesco, C. G., Zárate, M. A. and Miquel, S. E. 2007. Late Pleistocene mollusc assemblages and inferred paleoenvironments from the Andean piedmont of Mendoza, Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology 251(3-4), 461-469.

De Francesco, C.G. and Hassan, G.S. 2009. The significance of molluscs as paleoecological indicators of freshwater system in central-western Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology 274: 105-113.

De Francesco, C. G., Tietze, E., Cristini, P. A. and Hassan, G. S. 2020. Actualistic taphonomy of freshwater molluscs from the Argentine Pampas: an overview of recent research progress. In: S. Martínez, A. Rojas, F. Cabrera (eds.), Actualistic Taphonomy in South America. Springer Nature Switzerland AG 2020. Topics in Geobiology 48: 69-88.

Do Campo, M. and Nieto, F. 2003. Transmission electron microscopy study of very low-grade metamorphic evolution in Neoproterozoic pelites of the Puncoviscana formation (Cordillera Oriental, NW Argentina). Clay Minerals 38(4): 459-481.

Do Campo, M., Bauluz B., Del Papa C., White T., Yuste A. and Mayayo M.J. 2018. Evidence of cyclic climatic changes recorded in clay mineral assemblages from a continental Paleocene-Eocene sequence, northwestern Argentina. Sedimentary Geology 368: 44-57.

Fregenal Martínez, M. A., Meléndez, N. and Arche, A. 2010. Lagos y sistemas lacustres. Sedimentología. Del Proceso Físico a la Cuenca Sedimentaria: Madrid, Consejo Superior de Investigaciones Científicas, 299-395.

Fritz, S.C., Baker, P.A., Ekdahl, E., Seltzer, G.O. and Stevens, L.R. 2010. Millennial-scale climate variability during the Last Glacial period in the tropical Andes. Quat. Sci. Rev. 29: 1017–1024.

Fritz, S.C., Baker, P.A., Lowenstein, T.K., Seltzer, G.O., Rigsby, C.A., Dwyer, G.S., Tapia, P.M., Arnold, K.K., Ku, T.L. and Luo, S. 2004. Hydrologic variation during the last 170,000 years in the southern hemisphere tropics of South America. Quaternary Research 61: 95–104.

Garralla, S., Muruaga, C. and Herbst, R. 2001. Lago El Rincón, Holoceno del Departamento de Tafí del Valle, Provincia de Tucumán (Argentina): palinología y facies sedimentarias. Ameghiniana 8: 91–99 (Publicación Especial).

Grimm, A. M. 2011. Interannual climate variability in South America: Impacts on seasonal precipitation, extreme events, and possible effects of climate change. Stochastic Environmental Research and Risk Assessment, 25(4): 537–554.

Godfrey, L.V., Jordan, T.E., Lowenstein, T.K. and Alonso, R.L. 2003. Stable isotope constraints on the transport of water to the Andes between 22◦and 26◦S during the last glacial cycle. Palaeogeography, Palaeoclimatology, Palaeoecology 194: 299–317.

Gutiérrez, F., Gutiérrez, M. and Sancho, C. 1988. Geomorphological and sedimentological analysis of a catastrophic flash flood in the Arás drainage basin (Central Pyrenees, Spain). Geomorphology, 22: 265-283.

Gutiérrez Elorza, M. 2001. Geomorfología Climática. Ediciones Omega, 642 p. Barcelona.

Hermanns, R. L. and Strecker, M. R. 1999. Structural and lithological controls on large Quaternary rock avalanches (sturzstroms) in arid northwestern Argentina. Geological Society of America Bulletin 111(6): 934–948.

Hermanns, R. L., Niedermann, S., Ivy-Ochs, S. and Kubik, P. W. 2004. Rock avalanching into a landslide-dammed lake causing multiple dam failure in Las Conchas valley (NW Argentina)—evidence from surface exposure dating and stratigraphic analyses. Landslides 1(2): 113–122.

Hogg, A., Heaton, T., Hua, Q., Palmer, J., Turney, C., Southon, J., Bayliss, A., Blackwell, P., Boswijk, G., Bronk Ramsey, C., Petchey, F., Reimer, P., Reimer, R., & Wacker, L. 2020. SHCal20 Southern Hemisphere calibration, 0–55,000 years cal BP. Radiocarbon 62(4): 759-778.

Kilmurray, J. and Igarzábal, A. 1971. Petrografía y rasgos geomórficos del batolito granítico de Santa Rosa de Tastil, provincia de Salta, Rep. Argentina. Revista de la Asociación Geológica Argentina 26(4): 417-438.

Latorre, C., Betancourt, J.L. and Arroyo, T.K. 2006. Late Quaternary vegetation and climate history of a perennial river canyon in the Río Salado basin (22°S) of Northern Chile. Quaternary Research 65: 450-466.

Malizia, L., Pacheco, S., Blundo, C. and Brown, A. D. 2012. Caracterización altitudinal, uso y conservación de las Yungas Subtropicales de Argentina. Revista Ecosistemas 21(1-2): 53-73.

Markgraf, V., Bradbury, J.P. and Fernández, J. 1986. Bajada de Rahue, province of Neuquen, Argentina: An interstadial deposit in northern Patagonia. Palaeogeography, Palaeoclimatology, Palaeoecology 56: 51-258.

Markgraf, V. and Seltzer, G. O. 2001. Pole-Equator-Pole paleoclimates of the Americas integration: toward the big picture. In: Markgraf, V., (ed.) Interhemispheric Climate Linkages. Academic Press, San Diego, CA, 433-442.

Marrett, R. A., Allmendinger, R. W., Alonso, R. N. and Drake, R. E. 1994. Late Cenozoic tectonic evolution of the Puna Plateau and adjacent foreland, northwestern Argentine Andes. Journal of South American Earth Sciences 7(2): 179-207.

Marquillas, R. A., Del Papa, C. and Sabino, I. F. 2005. Sedimentary aspects and paleoenvironmental evolution of a rift basin: Salta Group (Cretaceous–Paleogene), northwestern Argentina. International Journal of Earth Sciences 94(1): 94-113.

May, J. H. and Soler, R. D. 2011. Late Quaternary morphodynamics in the Quebrada de Purmamarca, NW Argentina. E&G Quaternary Science Journal 59(1-2) : 21-35.

Mazzuoli, R., Vezzoli, L., Omarini, R., Acocella, V., Gioncada, A., Matteini, M., Dini, A., Guillou, H., Hauser, N., Uttini, A. and Scaillet, S. 2008. Miocene magmatism and tectonics of the easternmost sector of the Calama–Olacapato–El Toro fault system in Central Andes at~ 24 S: Insights into the evolution of the Eastern Cordillera. Geological Society of America Bulletin 120(11-12): 1493-1517.

Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer-Verlag, 582 p., Berlin.

Molina, J.I. 2006. Estratigrafía de los depósitos volcaniclásticos neógenos entre Ingeniero Maury y San Bernardo de las Zorras, quebrada del Toro, Salta. Universidad Nacional de Salta, Tesis Profesional, 202 p., Salta.

Montini, T. L., Jones, C. and Carvalho, L. M. 2019. The South American low-level jet: A new climatology, variability, and changes. Journal of Geophysical Research: Atmospheres, 124(3): 1200-1218.

Moore, D.M. and Reynolds Jr., R.C. 1997. X-ray diffraction and the identification and analysis of clay minerals. Oxford University Press, 332 p., Oxford.

Morales, M.R. 2011. Arqueología ambiental del Holoceno Temprano y medio en la Puna Seca Argentina. Modelos paleoambientales multi-escalas y sus implicancias para la arqueología de cazadores-recolectores. In: British Archaeological Research 2295, South American Archaeology Series, vol. 15. Archaeopress, Oxford, UK.

Morales, M. and Schittek, K. 2008. Primeros resultados paleoambientales del Holoceno medio en Alto Tocomar (Puna Salteña): interpretación local e implicancias regionales. In: Primeras jornadas del área puneña de los Andes Centro-Sur, Tucumán, Argentina, 109-110.

Novello, V. F., Cruz, F. W., Vuille, M., Stríkis, N. M., Edwards, R. L., Cheng, H., Emerick, S., de Paula, M. S., Li, X., Barreto E. de S., Karmann, I. and Santos, R. V. 2017. A high-resolution history of the South American Monsoon from Last Glacial Maximum to the Holocene. Scientific reports 7(1): 1-8.

Olen, S. and Bookhagen, B. 2020. Applications of SAR Interferometric Coherence Time Series: Spatiotemporal Dynamics of Geomorphic Transitions in the South-Central Andes. Journal of Geophysical Research: Earth Surface 125(3).

Olivera, D.E., Tchilinguirian, P. and De Aguirre, M.J. 2006. Cultural and Environmental Evolution in the Meridional Sector of the Puna of Atacama during the Holocene. In: International Prehistoric Congress. En Change in the Andes: Origins of Social Complexity Pastoralism and Agriculture. Acts of the 14° UISPP Congress. University of Liege, Belgium. 1-7.

Pierce, J. W. and Siegel F.R. 1969. Quantification in clay mineral studies of sediments and sedimentary rocks. Journal of Sedimentary Research 39(1): 187-193.

Pingel, H., Strecker, M. R., Alonso, R. N. and Schmitt, A. K. 2013. Neotectonic basin and landscape evolution in the Eastern Cordillera of NW Argentina, Humahuaca Basin (~ 24 S). Basin Research 25(5): 554-573.

Pingel, H., Strecker, M. R., Mulch, A., Alonso, R. N., Cottle, J. and Rohrmann, A. 2020. Late Cenozoic topographic evolution of the Eastern Cordillera and Puna Plateau margin in the southern Central Andes (NW Argentina). Earth and Planetary Science Letters 535.

Piovano E., Córdoba, F. y Stutz, S. 2014. Limnogeology in Southern South America: an overview. Latin American Journal of Sedimentology and Basin Analysis 21 (2): 65-75.

Placzek, C., Quade, J. and Patchett, P.J. 2006. Geochronology and stratigraphy of late Pleistocene lake cycles on the southern Bolivian Altiplano: implications for causes of tropical climate change. Geology Society American Bulletin 118: 515–532.

Rech, J. A., Quade, J. and Betancourt, J. L. 2002. Late Quaternary paleohydrology of the central Atacama Desert (lat 22–24 S), Chile. Geological Society of America Bulletin 114(3): 334-348.

Robinson, R. A. J., Spencer, J. Q. G., Strecker, M. R., Richter, A. and Alonso, R. N. 2005. Luminescence dating of alluvial fans in intramontane basins of NW Argentina. Alluvial Fans: Geomorphology, Sedimentology, Dynamics 251: 152–168.

Sánchez, M.C., Caba, R.E. and Salfity, J.A. 2010. Geología Ambiental del tramo inferior de la Quebrada del Toro, provincial de Salta. Revista de Geología Aplicada a la Ingeniería y al Ambiente 25: 77-88.

Sánchez, M.C., Lucena, L.L., Rivelli, F.R. and Salfity, J.A. 2005. Geología y geomorfología de la cuenca del río Pascha-Incamayo, Quebrada del Toro, Salta. 16° Congreso Geológico Argentino, Actas 3: 529-536, La Plata.

Savi, S., Schildgen, T. F., Tofelde, S., Wittmann, H., Scherler, D., Mey, J., Alonso R.N. and Strecker, M.R. 2016. Climatic controls on debris-flow activity and sediment aggradation: The Del Medio fan, NW Argentina. Journal of Geophysical Research 1–22.

Schultz, L. G. 1964. Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale. US Geological Survey of Professionals. Papers, 391-C.

Schwanghart, W. and Kuhn, N. J. 2010. TopoToolbox: A set of Matlab functions for topographic analysis. Environmental Modelling & Software 25(6): 770-781.

Sobel, E. R. and Strecker, M. R. 2003. Uplift, exhumation and precipitation: tectonic and climatic control of Late Cenozoic landscape evolution in the northern Sierras Pampeanas, Argentina. Basin Research 15(4): 431-451.

Spalletti, L.A. 2001. Modelo de sedimentación fluvial y lacustre en el margen pasivo de un hemigraben: el Triásico de la Precordillera occidental de San Juan, República Argentina. Revista de la Asociación Geológica Argentina 56(2): 189-210.

Strecker, M. R., Alonso, R. N., Bookhagen, B., Carrapa, B., Hilley, G. E., Sobel, E. R. and Trauth, M. H. 2007. Tectonics and climate of the southern central Andes. Annual Reviews Earth Planetary Sciences 35: 747-787.

Suriano, J. and Limarino, C.O. 2009. Sedimentación pedemontana en las nacientes del río Jachal y Pampa de Gualilán, Precordillera de San Juan. Revista de la Asociación Geológica Argentina 65(3): 516-532.

Tchilinguirian, P. 2009. Paleoambientes Holocenos en la Puna Austral (27°S): implicancias geoarqueológicas, Argentina. Tesis doctoral, Universidad de Buenos Aires (inédita), Buenos Aires.

Tchilinguirian, P. and Morales, M. R. 2013. Mid-Holocene paleoenvironments in Northwestern Argentina: Main patterns and discrepancies. Quaternary International 307: 14-23.

Tchilinguirian, P., Morales, M. R., Oxman, B., Lupo, L. C., Olivera, D. E. and Yacobaccio, H. D. 2014. Early to Middle Holocene transition in the Pastos Chicos record, dry Puna of Argentina. Quaternary international 330: 171-182.

Tiner, R. J., Negrini, R. M., Antinao, J. L., McDonald, E. and Maldonado, A. 2018. Geophysical and geochemical constraints on the age and paleoclimate implications of Holocene lacustrine cores from the Andes of central Chile. Journal of Quaternary Science 33(2): 150-165.

Tofelde, S., Schildgen, T. F., Savi, S., Pingel, H., Wickert, A. D., Bookhagen, B., Wittmann, H., Alonso, R.N., Cottle, J. and Strecker, M. R. 2017. 100 kyr fluvial cut-and-fill terrace cycles since the Middle Pleistocene in the southern Central Andes, NW Argentina. Earth and Planetary Science Letters 473: 141-153.

Tofelde, S., Duesing, W., Schildgen, T. F., Wickert, A. D., Wittmann, H., Alonso, R. N. and Strecker, M. 2018. Effects of deep-seated versus shallow hillslope processes on cosmogenic $^{10}Be$ concentrations in fluvial sand and gravel. Earth Surface Processes and Landforms 43(15): 3086-3098.

Trauth, M. H., Alonso, R. A., Haselton, K. R., Hermanns, R. L. and Strecker, M. R. 2000. Climate change and mass movements in the NW Argentine Andes. Earth and Planetary Science Letters 179(2): 243-256.

Trauth, M.H., Bookhagen, B., Marwan, N. and Strecker, M. 2003. Multiple Landslides clusters record Quaternary climate change in the NW Argentine Andes. Paleogeography, Palaeoclimatology, Palaeoecology 194: 109-121.

Turner, J.C.M. 1960. Estratigrafía de la sierra de Santa Victoria y adyacencias. Boletín de la Academia Nacional de Ciencias de Córdoba 41(2): 163-196.

Veizaga Saavedra, J.G. 2012. Los abanicos aluviales cuaternarios de la Quebrada del Toro, noroeste argentino: tramo inferior y medio. Tesis Profesional, Universidad Nacional de Salta (inédita), 126 p., Salta.

Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C.R., Nogues-Paegle, J., Silva Dias, P.L. and Zhang, C. 2006. Toward a unified view of the American monsoon systems. Journal of climate 19(20): 4977-5000.

Vezzoli, L., Acocella, V., Omarini, R. and Mazzuoli, R. 2012. Miocene sedimentation, volcanism and deformation in the Eastern Cordillera (24° 30′ S, NW Argentina): tracking the evolution of the foreland basin of the Central Andes. Basin Research 24(6): 637-663.

Vezzoli, L., Matteini, M., Hauser, N., Omarini, R., Mazzuoli, R. and Acocella, V. 2009. Non-explosive magma–water interaction in a continental setting: Miocene examples from the Eastern Cordillera (central Andes; NW Argentina). Bulletin of volcanology 71(5): 509-532.

Villagrán, C. and Varela, J. 1990. Palynological evidence from increased aridity on the central Chilean coast during the Holocene. Quaternary Research 34: 198-207.

Villa Martínez, R., Villagrán, C. and Jenny, B. 2003. The last 7500 cal yr B.P. of westerly rainfall in Central Chile inferred from high-resolution pollen record from Laguna Aculeo (34°S). Quaternary Research 60: 284-293.

Yacobaccio, H. D. and Morales, M. 2005. Mid-Holocene environment and human occupation of the Puna (Susques, Argentina). Quaternary International 132(1): 5–14.

Wayne, W.J. 1999. The Alemania rockfall dam: a record of Mid-Holocene earthquake and catastrophic flood in northwestern Argentina. Geomorphology 27: 295-306.

Zeballos, A., Weihed P., Blanco M. and Machaca V. 2016. Geological, mineralogical and chemical characterization of Devonian kaolinite-bearing sediments for further applications in the ceramic (tiles) industry in La Paz, Bolivia. Environmental Earth Sciences 75(7): 546.

Zhou, J. and Lau, K. M. 2001. Principal modes of interannual and decadal variability of summer rainfall over South America. International Journal of Climatology, 21(13): 1623–1644.

**TABLES**

Table 1. Lithofacies described for fluvial, alluvial, and lacustrine deposits of the southern sector of the Quebrada del Toro.

Table 2. Calibrated $^{14}C$ ages and sample locations

# FIGURE CAPTIONS

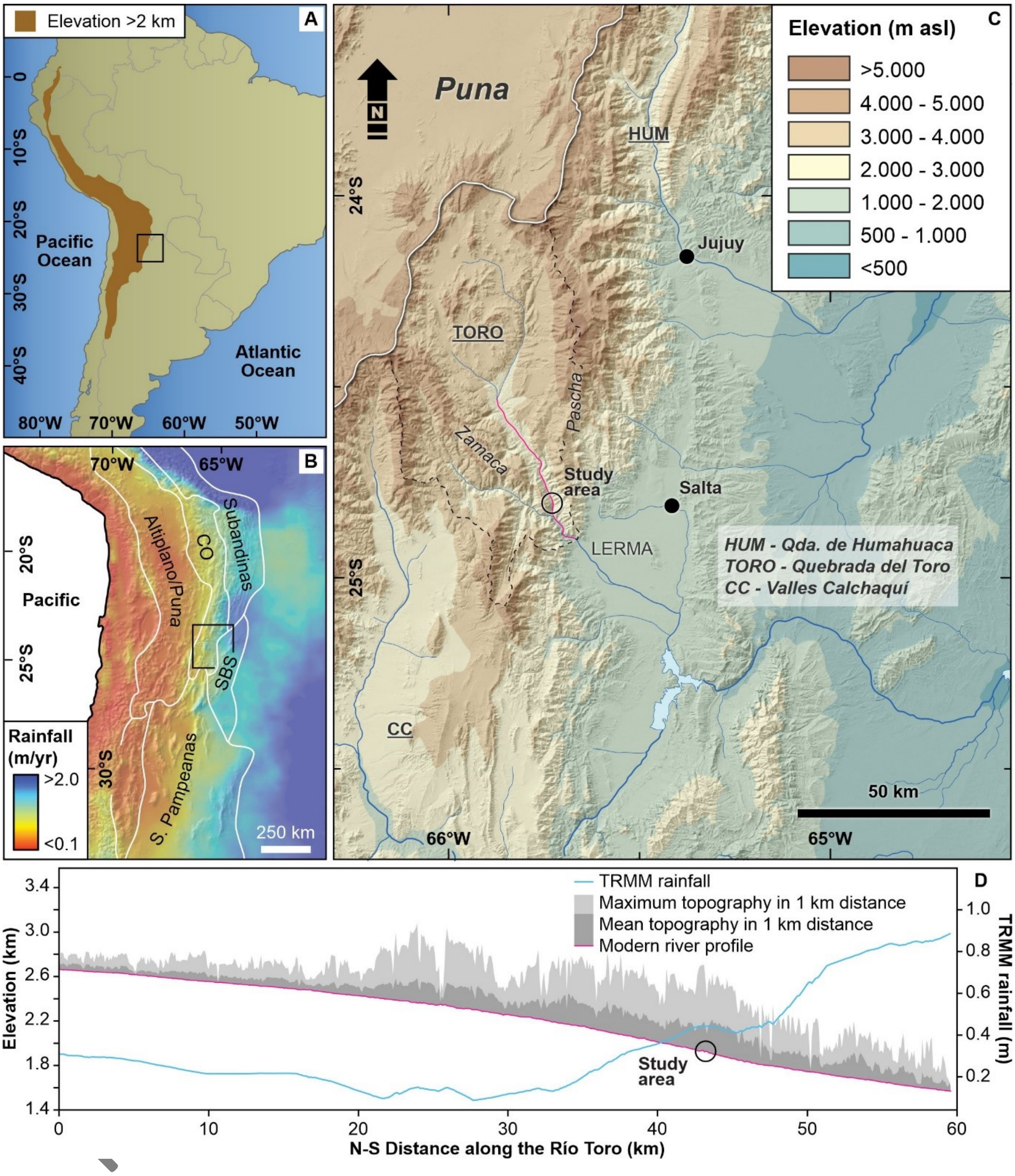


**Figure 1.** a) Overview map of South America showing Andean topography (>2 km a.s.l.) and extent of Fig. 1c (black box). b) Morphotectonic map of southern Central Andes showing mean annual rainfall derived from NASA's (National Aeronautics and Space Administration) TRMM mission (Tropical Rainfall Measurement Mission) and extent of Fig. 1c (black box). EC—Eastern Cordillera, SFTB—Subandean fold-and-thrust belt; SBS—Santa Bárbara System. c) Digital elevation model of the southern central Andes of NW Argentina (extracted from 90 m SRTM elevation data) showing the intermontane

Quebrada del Toro (dashed outline), adjacent sedimentary basins, and their drainage systems. A bold white line delineates the internally drained Puna Plateau from the externally drained areas of the Andes. d) Longitudinal river profile of the Río Toro (magenta line in Fig. 1c) showing the annual mean rainfall amounts (from NASA-TRMM), the modern river profile, and the mean and maximum topography within 1-km distance along the river. (a-c) modified from Pingel et al. (2020)

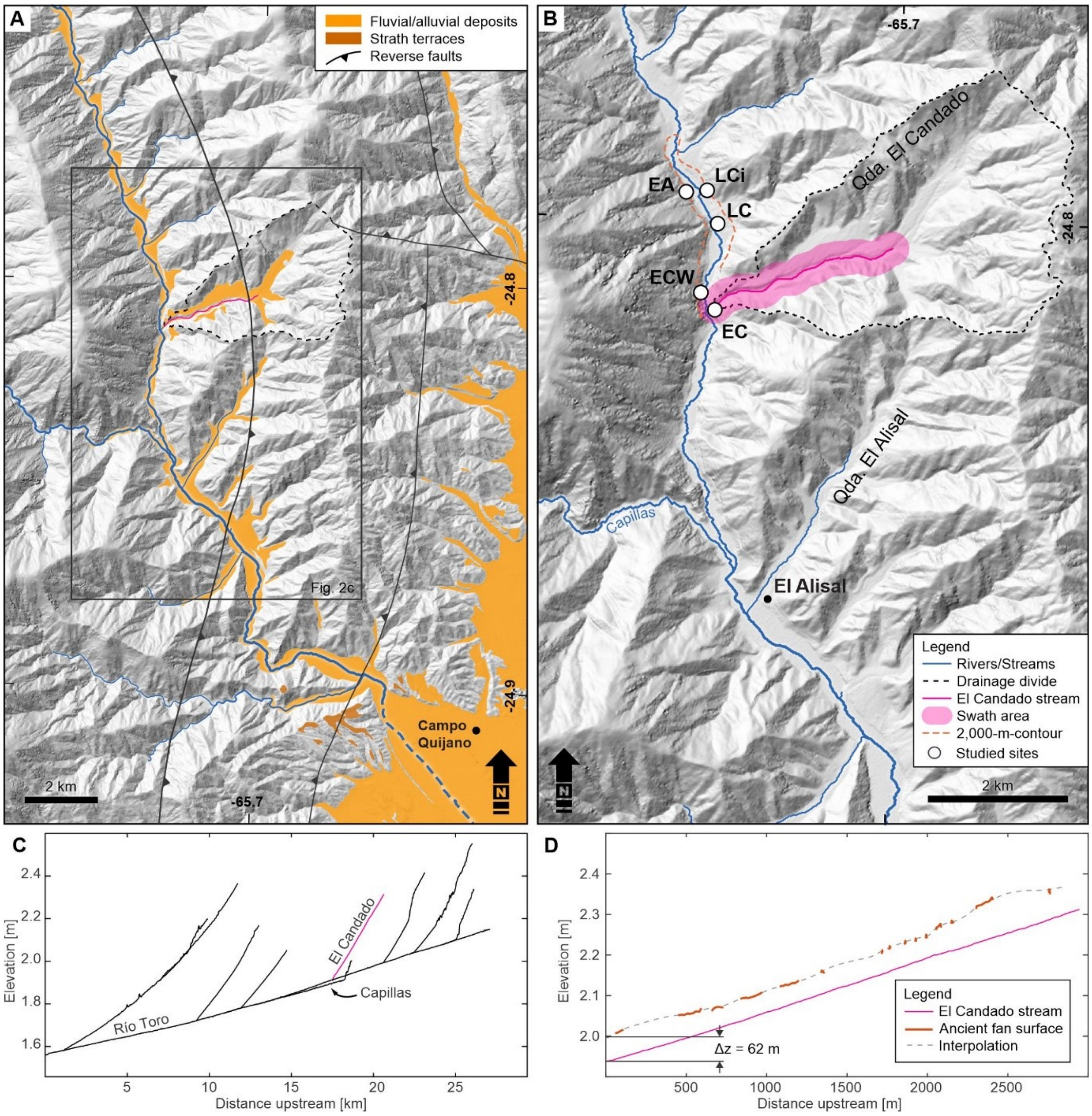


**Figure 2.** a) Shaded relief map from the southern sector of the Quebrada del Toro showing river network and flat topography (slope ≤ 15°) mainly associated with late Quaternary fluvial/alluvial lithologies (using TanDEM-X-Digital Elevation Model, 12 m); b) Longitudinal river profiles of the lower reach of the Río Toro and its tributaries. Studied sections: EA-El Alto, LCi-La Cirila, ECW-El Candado West,

and EC-El Candado; c) Shaded relief map of the El Candado area showing sampling locations, the El Candado catchment, and an upstream 2,000-m contour line; d) Longitudinal profile of the modern El Candado stream and the maximum elevation of the adjacent low relief surface, i.e. ancient alluvial fan surface (within 250 m distance). Note the elevation difference between the fan surface and the modern stream (62 m).

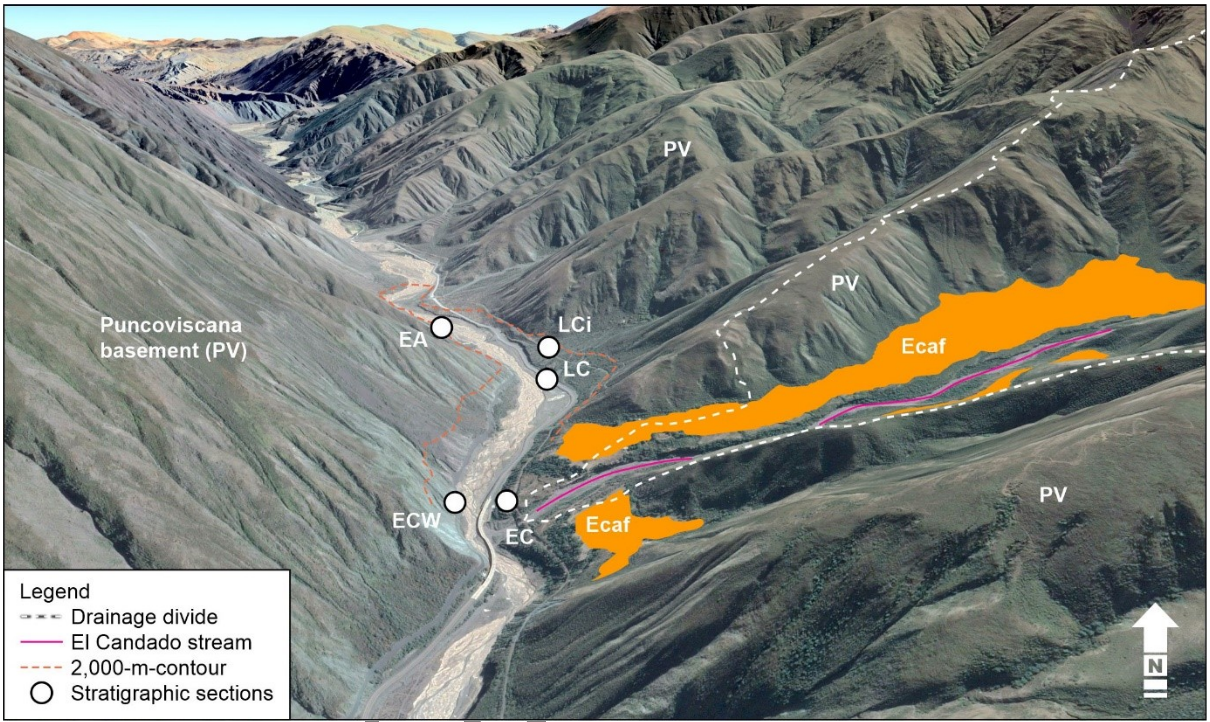


**Figure 3.** Oblique view to the north along the basement gorge of the Quebrada del Toro (Google Earth) illustrating the field relationship between the El Candado catchment area (outlined with dashed white line), its incised vestiges of the ancient El Candado alluvial fan (ECaf, the surface is shown in orange), the location of stratigraphic sections, and the south draining Río Toro. The dashed orange line is a 2,000-m contour line representing the upstream projection of the fan surface, i.e. the maximum possible extent of a dammed paleolake.

REVISTA DE LA
ASOCIACIÓN GEOLÓGICA
ARGENTINA
VOLUMEN 79(2022)

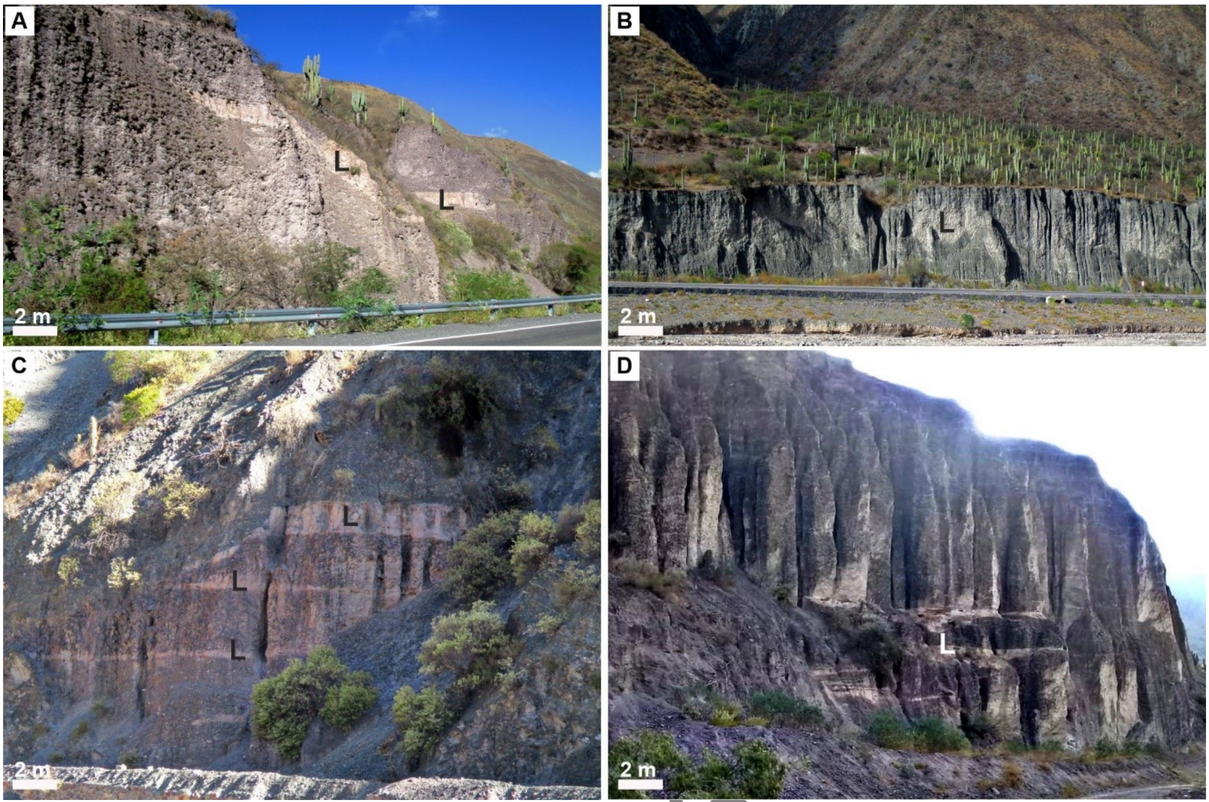


**Figure 4.** Field photographs of alluvial-fluvial deposits interdigitated with the lake deposits at the studied sites: a) El Candado; b) Los Cardones; c) El Candado West; d) El Alto. The tabular and/or lenticular levels of lighter color correspond to lacustrine beds (L).

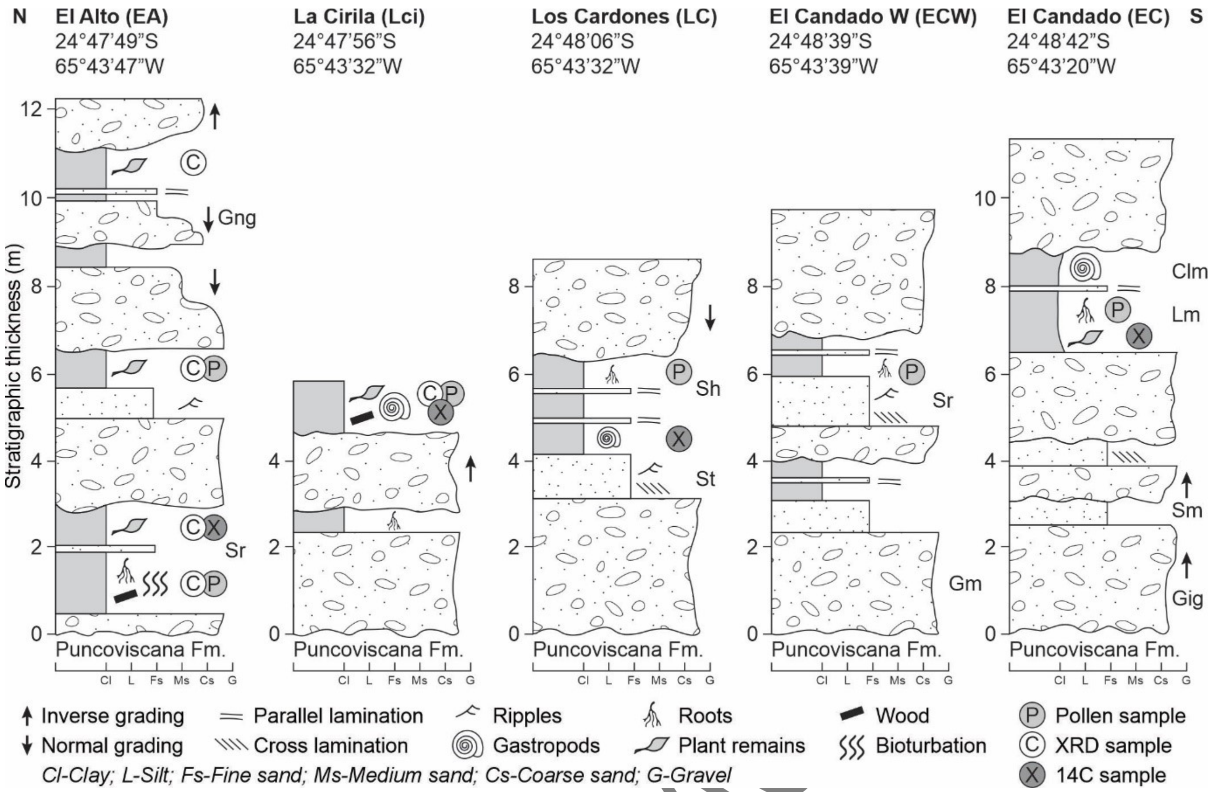


**Figure 5.** Measured stratigraphic sections of alluvial/lacustrine sections exposed along the Río Toro in the El Candado area, showing additional paleontological and sedimentological information, as well as sampling locations for our AMS $^{14}C$ geochronology, pollen, and geochemical analyses. Locations are shown in Figures 2 and 3.

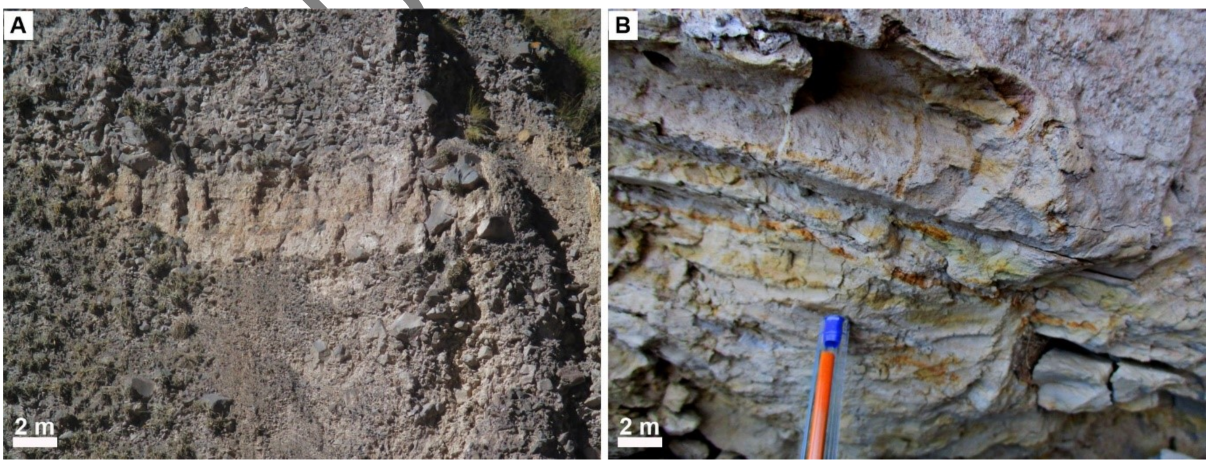


**Figure 6.** a) Massive lacustrine deposits (Clm) of the El Candado section concerning fluvial facies (SM - massive sand and ST - sand with cross-lamination) and alluvial (Gm - massive gravel and Ggn - gravel with normal gradation); b) Massive clay facies (Clm) with plant remains and with very fine levels of

charred plant remains (indicated by the white arrow) from the El Alto section.

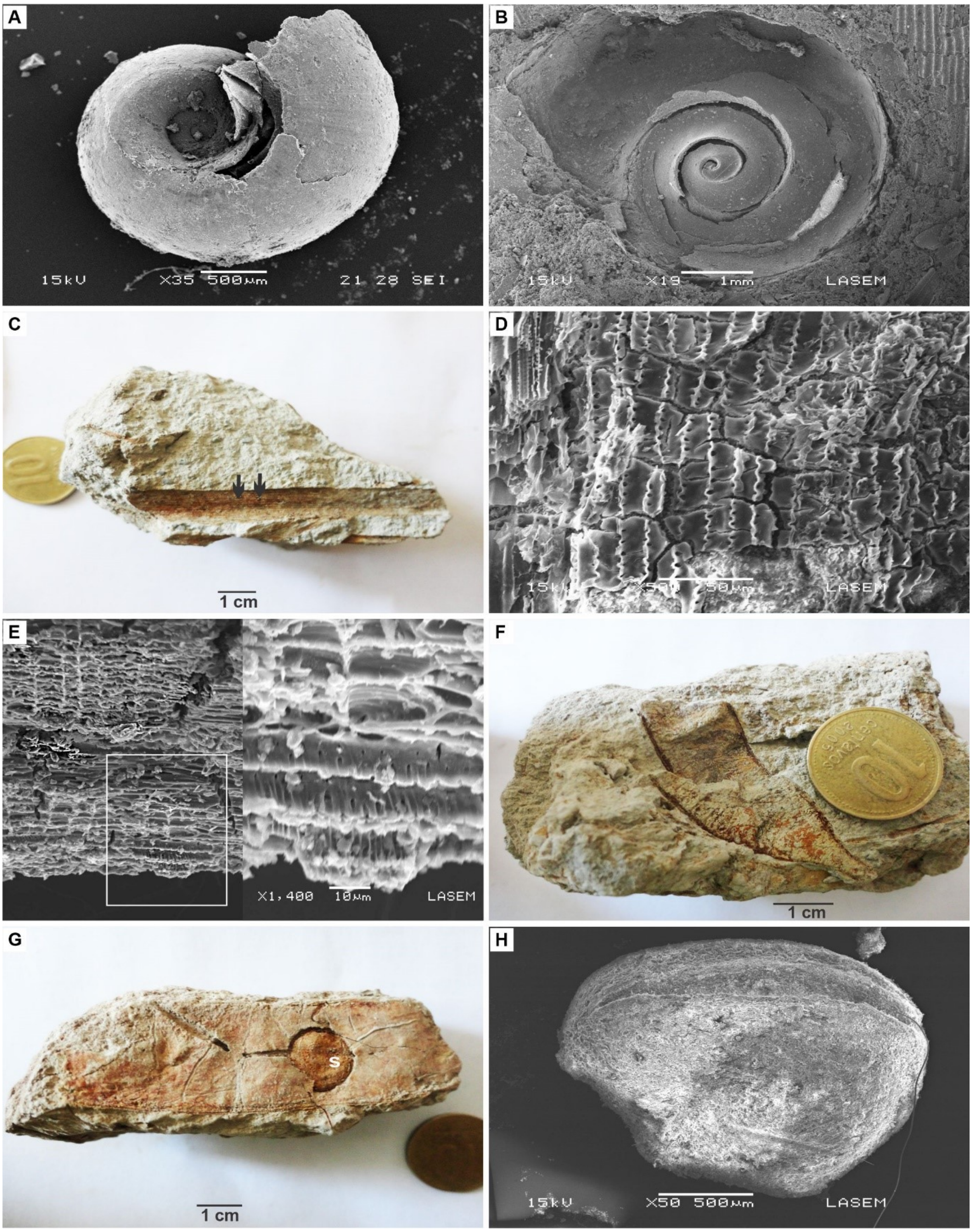


**Figure 7.** a-b) SEM images of *Biomphalaria* sp. from the lacustrine beds of the La Cirila section; c-f) Plant remains samples of the La Cirila section; c) Hand sample of sandy/clay unit containing grass leaf

with stomata (arrows); d) SEM image of the epidermis of a grass leaf; e) Dicot stem with detail of conduction tissue; f) Fruit, legume type; g) Fruit showing legume seed; h) Legume seed.

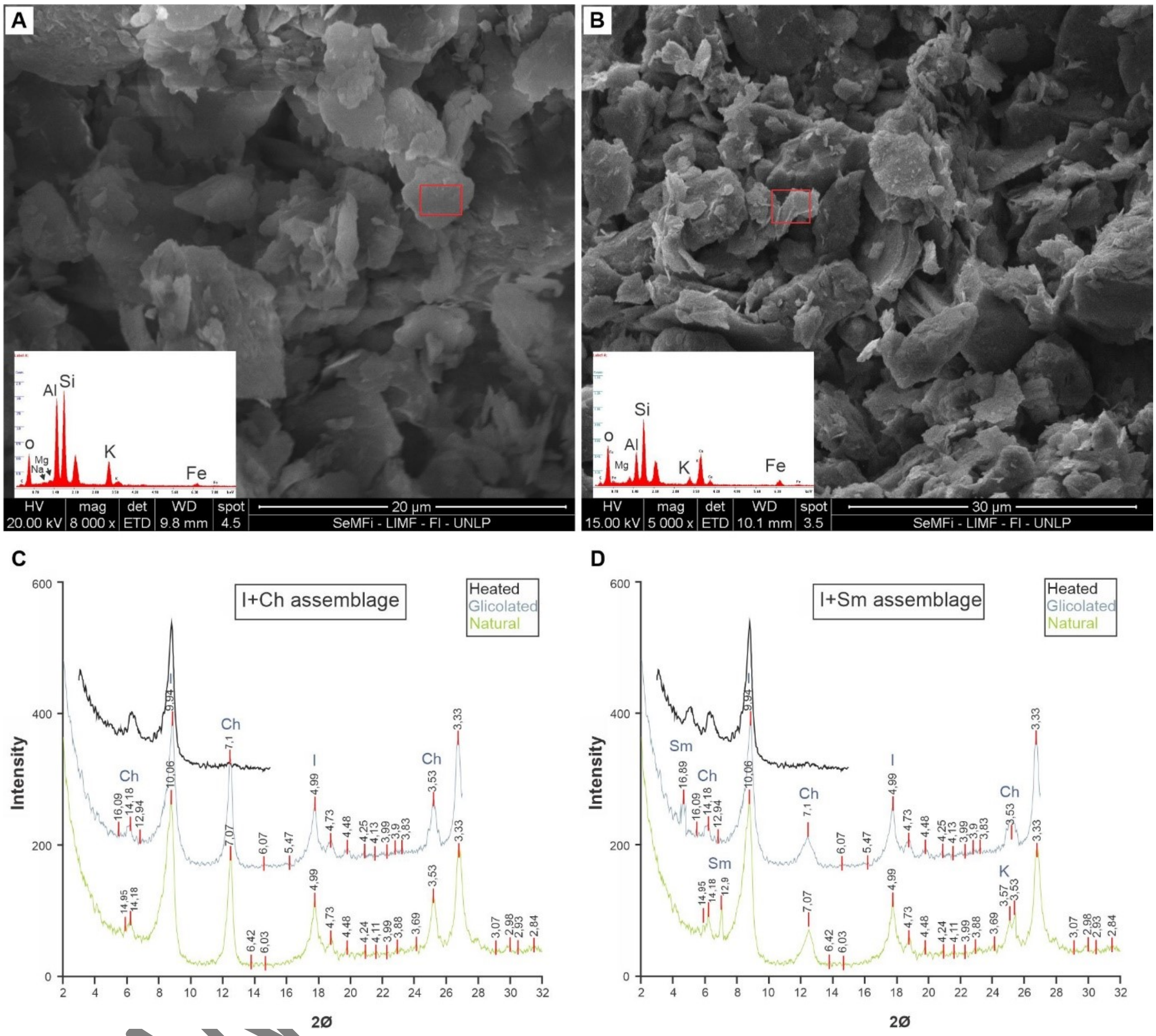


**Figure 8.** a-b) SEM microphotographs and EDS results from middle Holocene lake deposits of the studied sections. a) Illite: high fragmented clays with variable size, irregular borders, without a preferential order. b) Smectite: curled flakes with open-air voids having small interfacial zones, flaky particle morphology. The red area indicates the area measured by EDS analysis of major elements. c-d) X-ray diffractograms of (c) illite+chlorite (I+Ch) and (d) illite+smectite (I+Sm) assemblages.

# TABLES

Table 1. Lithofacies described for fluvial, alluvial, and lacustrine deposits of the southern sector of the Quebrada del Toro.

| Lithofacies code | Description | Interpretation |
|---|---|---|
| Gmc and Gm | Coarse gravel, clast-support (Gmc) and matrix-support (Gm), with silty sand to silt-clay matrix. Poor selection. Composed exclusively by angular and subangular clasts of the Puncoviscana Fm. With poorly defined tabular and lenticular stratification, with planar and erosive bases. Massive. | Debris flow with high kinetic energy, high viscosity, high density, with tractional transport. |
| Ggi | Fine gravel, matrix-support, with inverse gradation. Thin tabular beds. | Intermediate flows, between hyperconcentrates and fluids based on high availability and the slopes of the alluvial fans. |
| Gng | Medium gravel, matrix-support, with normal gradation. Medium tabular beds. | High energy, high density and high viscosity debris streams. |
| Sm | Medium to fine sandstone, grayish-brown. Planar-based tabular beds. Massive. | Sheet-flood, unconfined ephemeral streams. |
| St | Medium sandstone, brown to gray. With low angle planar cross lamination | Migration of small sand waves (2D type). |
| Sr | Fine sandstone, brown to yellowish-brown. Ripple lamination. | High flow rate stream. |
| Sh | Fine, grayish-brown sandstone. Thin tabular layers with parallel lamination. | High rate flows in planar bed phases associated with near supercritical high rate flows in response to laminar flood periods. |
| Am | Yellowish-brown clays. Tabular beds of 2 to 0.5 m thick. Massive. With desiccation cracks. With remains of gastropod shells, plant remains and bioturbation. | Very low energy lake deposit with periods of subaerial exposure. |
| Lm | Yellowish-brown silts. Massive. | Deposit generated by suspension-fallout in marginal positions of a body of water. |

Table 2. Calibrated $^{14}C$ ages and sample locations

| Sample | Site | Material | Lab ID | Latitude | Longitude | $^{14}C$ age ± 1σ (yr BP) | $^{14}C$ age ± 1σ (cal yr BP)* |
|---|---|---|---|---|---|---|---|
| QT-02032014-01 | El Alto | Charcoal | Poz-63278 | -24.797976 | -65.729083 | 4790 ± 40 | 5480 ± 80 |
| QT-02032014-02 | El Alto | Charcoal | Poz-63279 | -24.797976 | -65.729083 | 4825 ± 35 | 5520 ± 60 |
| ST14-46-C14 | El Alto | Charcoal | Poz-63435 | -24.798120 | -65.729020 | 8030 ± 60 | 8840 ± 110 |
| ST14-47-C14 | El Alto | Organic matter | Poz-63283 | -24.797590 | -65.729080 | 7420 ± 80 | 8190 ± 100 |
| Gastropods Toro | La Cirila | Gastropod shells | Poz-62843 | -24.799011 | -65.725642 | 6440 ± 40 | 7330 ± 60 |

*converted from conventional ages using OxCal v4.4.3 (Bronk Ramsey 2001) and the SHCal 20 calibration data (Hogg et al. 2020).