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The Quequén Salado river basin: Geology and biochronostratigraphy of the Mio-Pliocene boundary in the southern Pampean plain, Argentina

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ABSTRACT

The Quequén Salado river basin has been the focus of several contributions since the first decades of the XX century, namely dealing with the general geological features of the deposits and with the vertebrate remains. In this paper, the Neogene geological history documented by the Quequén Salado river exposures is reconstructed by means of stratigraphic, sedimentological and paleomagnetic studies along with the paleontological analysis of vertebrate remains. The study area is a crucial setting not only to better understand the evolution of the southern Pampas basin during the late Miocene-early Pliocene interval, but also to test the validity of the biochronologic and biostratigraphic schemes, especially the "Irenense". A geological model for the Quequén Salado river valley is proposed: a case of downcutting and headward erosion that contributes with a coherent interpretation to explain the spatial distribution of facies and fossil taxa: the younger in the distal sector of the Quequén Salado middle basin and the older in the lower basin. The sedimentary record is believed to represent the distal reaches of a distributary fluvial system that drained from the Ventania ranges. The stratigraphic section of Paso del Indio Rico results a key stratigraphic site to fully understand the stratigraphic nature of the boundary between the Miocene and the Pliocene (the Huayquerian and Montehermosan stages/ages). In this sense, two stratigraphically superposed range zones have been recognized in the area: *Xenodontomys ellipticus* Range Zone (latest Miocene-early Pliocene; late Huayquerian), and *Eumysops laeviplicatus* Range Zone (early Pliocene; Montehermosan). Taking into account the available geological and paleontological evidences, the "Irenense" would not represent a valid biostratigraphic unit, since, according to the geological model here proposed, it would be represented by elements of the *Xenodontomys ellipticus* Range Zone in the lower QS basin and by elements of the *Eumysops laeviplicatus* Range Zone in the middle QS basin.

1. Introduction

The Pampean plain of central eastern Argentina comprises several morphostructural units that determine a complex and heterogeneous environment. As a result, the region is divided into different geomorphological settings, one of which is the Pampa Interserrana that extends across the Claromecó basin between the Ventania and Tandilia ranges of southern Buenos Aires province (Fig. 1A). In this area, the late Cenozoic stratigraphic record consists of late Miocene and Pliocene deposits mostly made up of Andean-derived volcaniclastic material capped by a calcrete crust, which is in turn covered by an extensive Late Pleistocene and Holocene

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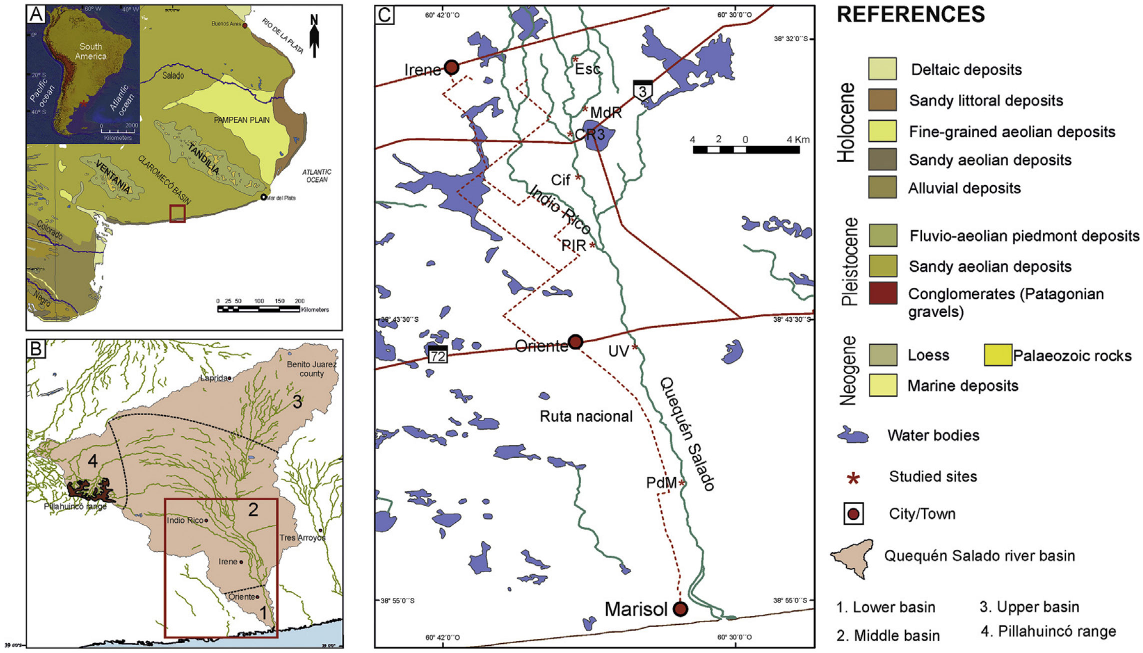

Fig. 1. Location map. **A.** Geological map of the Buenos Aires province. **B.** Quequén Salado river basin showing the upper, middle and lower reaches and the study sites. Abbreviations: **Esc**, Cascada Escondida; **MdR**, Molino de la Rosa; **CR3**, Cascada de la Ruta 3; **Cif**, Cascada Cifuentes; **PIR**, Paso del Indio Rico; **UV**, Usina Vieja; **PdM**, Paso del Médano.

aeolian mantle. The Neogene deposits were accumulated in the southern Pampas basin, a shallow (200 m average) and extensive distal foreland sedimentary basin. According to Folguera and Zárate (2011), the occurrence of Pliocene (*sensu lato*) deposits is related to the eastward migration of the Andean arc and deformation front (*circa* 6-5 Ma; Ramos and Folguera, 2005), that generated the corresponding eastwards migration of Pliocene depocenters across the southeastern part (i.e. Pampa Interserrana of Buenos Aires province).

The discontinuous nature and reduced thickness of the exposures is a major hindrance to reconstruct the stratigraphic relationships of the record, and consequently to fully understand the Neogene evolution of the basin. The chronological calibration of the Mio-Pliocene sequence is mainly based on fossil vertebrate remains recovered from numerous localities of the Pampa Interserrana area, pertaining to various stages/ages (Huayquerian, Montehermosan and Chapadmalalan) (e.g. Cione and Tonni, 1995, 2005; Verzi et al., 2008 Tomassini et al., 2013a). Recently, impact glasses recovered from two localities yielded numerical ages (Schultz et al., 2006) which allow a refinement of the chronology. This regional context of fragmentary and sparse exposures makes correlation difficult. The Quequén Salado river basin (Fig. 1B) is a key setting to solve these issues, since it is a small area where abundant remains of Neogene mammals were recovered from several sites along the riverbanks of the stream and its tributary Indio Rico (Fig. 1C). Because of this, the area has been the focus of several contributions since the first decades of the XX century, namely dealing with the general geological features of the deposits (e.g. Frenguelli, 1928; Fidalgo et al., 1975; Isla et al., 2014), and with the vertebrate remains (Kraglievich, 1927, 1934; Reig, 1955, 1958; Pascual and Herrera, 1973; Goin et al., 1994). In addition, from a biostratigraphic viewpoint, some lineages of fossil rodents (e.g. Octodontidae) from the Neogene record of the southern Pampas basin have been proposed as potential biochronological tools because of their particular evolutionary pattern (Verzi et al., 2003, 2008). Different species of the Neogene genus *Xenodontomys* (Rodentia, Octodontidae) were found at several localities of the southern Pampas basin. *Xenodontomys* was replaced sometime in the early Pliocene by the genus *Actenomys*, commonly found in *sensu lato* Pliocene beds (Deschamps et al., 2012; Tomassini et al., 2013a; Verzi et al., 2004). The major hindrance to eventually support and reinforce the biostratigraphic significance of the lineage is the lack of stratigraphic superposition in a sequence, a key evidence to support the proposal. In this regard, both *Xenodontomys* and *Actenomys* have been reported from the outcrops of the Quequén Salado fluvial system. Additionally, some previous biochronostratigraphical interpretations, including the informal "Irenense", were based on specimens with either uncertain taxonomic determination or unclear geographical and stratigraphical provenance (see Tonni et al., 1992; Marshall et al., 1983; Goin et al., 1994; Verzi et al., 2008). Why was the fossil record was assigned to different biostratigraphic units? Is there a fossil bias? Are the *Xenodontomys-Actenomys* remains coming from different or the same stratigraphic levels? Does the stratigraphic sequence record the late Miocene-Pliocene transition? Is there a geological explanation to account for the several biochronostratigraphic interpretations? In order to answer these questions, the goal of this paper is to contribute to the reconstruction of Neogene geological history documented by the Quequén Salado river exposures by means of stratigraphic, sedimentological and paleomagnetic studies along with the paleontological analysis of vertebrate remains. The study area is a crucial setting not only to better understand the evolution of the southern Pampas basin during the late Miocene-early Pliocene interval, but also to test the validity of the biochronologic and biostratigraphic schemes.

2. Environmental and geological setting of the study area

The headwaters of the Quequén Salado (QS) fluvial system drains the Pillahuincó ranges of Ventania and the distal northwestern piedmont of Tandilia (Benito Juárez-Laprida area; Fig. 1B). The study area includes several sites along the lower basin and the distal sector of the middle-basin following the subdivision by Marini and Piccolo (2005). The landscape is characterized by a gentle relief with a hilly topography close to the transition between the lower and middle basins, and a relatively flat plain sloping to the Atlantic Ocean across the lower basin. The altitude of the plain drained by the QS fluvial system decreases from 87 m a.s.l. (terminal sector of middle basin) at Irene, to 10 m a.s.l. by the coastal sand dune system, with a general gradient of 1.73 m/km (Fig. 2). Accordingly, the relative relief of the valley increases downstream, with a maximum difference of around 20 m downstream from Usina Vieja (Fig. 2), along the lower reaches of the QS valley. The QS and Indio Rico valleys are excavated into Neogene deposits, discontinuously exposed at various sites along the riverbanks. Rapids and 1–4 m high waterfalls, some of them formed on Neogene outcrops, occur along the river channels. Beilinson et al. (2015) studied several sites (Cueva del Tigre, Usina Vieja, Paso del Indio Rico and Cascada Irene, here known as Cascada Escondida), and informally described two Neogene sections for the exposed deposits. They identified the *Xenodontomys ellipticus* Range Zone in the lower stratigraphic section, and the *Eumysops laeviplicatus* Range Zone in the upper stratigraphic section. The sedimentary filling of the QS River consists of fluvial, lacustrine and marine deposits assigned to the late Pleistocene-Holocene interval (Alberdi et al., 1989; Pardiñas et al., 1996; Grill, 2003; Schillizzi et al., 2005 and literature therein); it is well exposed along the lower basin. Older fluvial deposits of unknown age (Pleistocene *sensu lato*?) have also been identified during this study. In addition, the lower reach of the QS valley exhibits an internal stepped topography due to the occurrence of fluvial terraces. Beilinson et al. (2015) pointed out that the incision of the QS valley occurred before the last interglacial. According to these authors, the fluvial-alluvial nature of the late Cenozoic deposits of this area was temporarily interrupted by the marine ingression of MIS 5e, and ended with the establishment of well-developed lacunar systems.

3. Previous work and biostratigraphic framework

Frenguelli (1928) was the first to report and describe Neogene deposits and vertebrate fossils of the QS. Kraglievich (1927, 1934) stated that all, or almost all, of the sequence exposed at the riverbanks (~15 m height) of the QS middle basin is formed by what he called "Arauco-entrerrianos" sediments, which are covered in turn by a relatively thick and tough limestone. He referred to the vertebrate assemblage recovered as "fáunula Irenense", older than the "Chapadmalense" (*sensu* Ameghino, 1908) from the Mar del Plata-Miramar area, but younger than the "Hermosense" (*sensu* Ameghino, 1908) of Farola Monte Hermoso locality (Fig. 3). By the mid-twentieth century, Mignone (1949) revisited the "Irenense" (*sensu* Kraglievich, 1927, 1934), including a brief description of the Cascada Grande (=Cascada Cifuentes of this paper) exposures. Later, the oldest deposits were grouped into the Irene "Formation" and assigned to the Upper Pliocene (Montehermosan) (Reig, 1955). Two decades later, Fidalgo et al. (1975) stated that the mammal remains found between the village of Irene and the QS outlet were not quite different from those found in the "Hermosense" from Farola Monte Hermoso. From there on, the Irene "Formation" fauna was mostly correlated with the assemblages recorded in the Montehermosan (Late Miocene-Early Pliocene) and early Chapadmalalan (Early Pliocene) stages/ages (*sensu* Cione and Tonni, 1995), as defined in the Monte Hermoso Formation (Farola Monte Hermoso locality) (Fig. 3). Recently, the exposures of the Monte Hermoso Formation were included in a single unit, the *Eumysops laeviplicatus* Range Zone (ElRZ), Montehermosan Stage/Age (Early Pliocene) (see Deschamps et al., 2012, 2013; Tomassini et al., 2013a).

Verzi et al. (2008) recognized the *Xenodontomys ellipticus* Range Zone (XeRZ) (Late Huayquerian Stage/Age, Late Miocene) based on

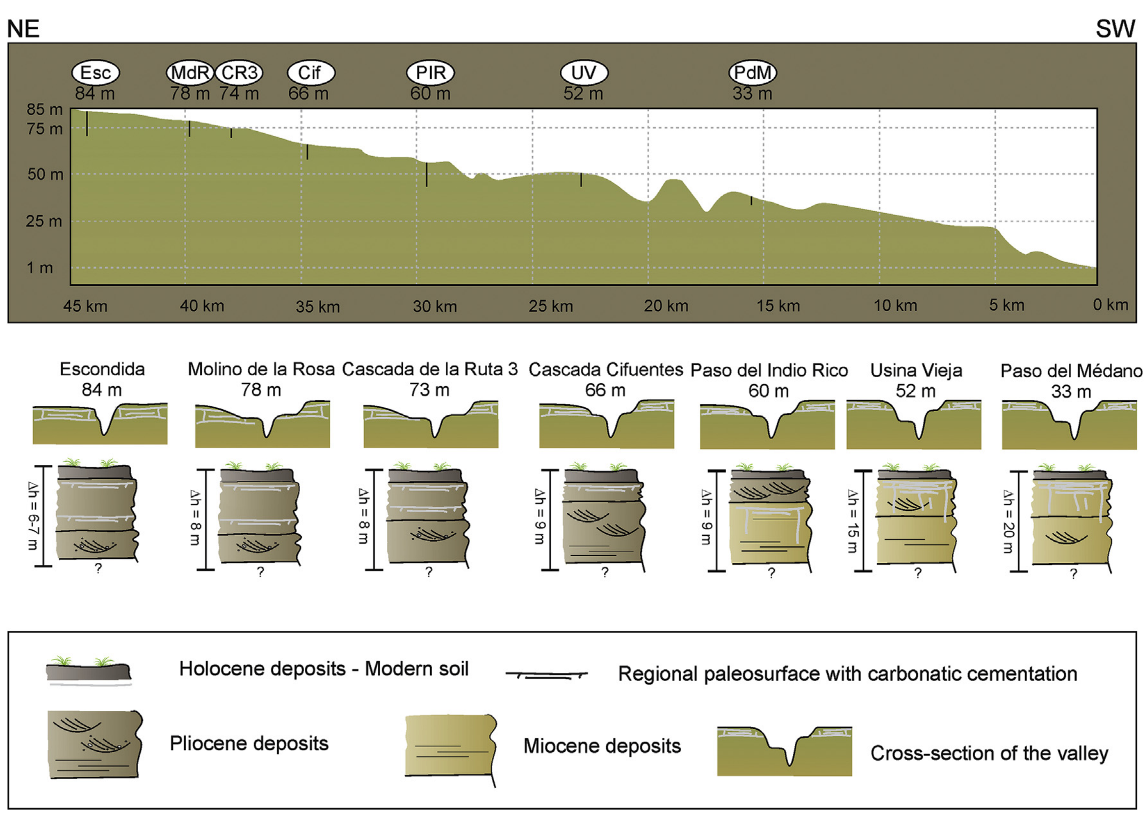

Fig. 2. Top figure, longitudinal profile of the middle and lower Quequén Salado river valley showing the regional gradient. Lower figure, cross sections of the river valley in the different study sites and schematic sedimentological profiles. Note that downstream the age of the deposits become older, and the valley becomes wider. Site abbreviations as in Fig. 1.

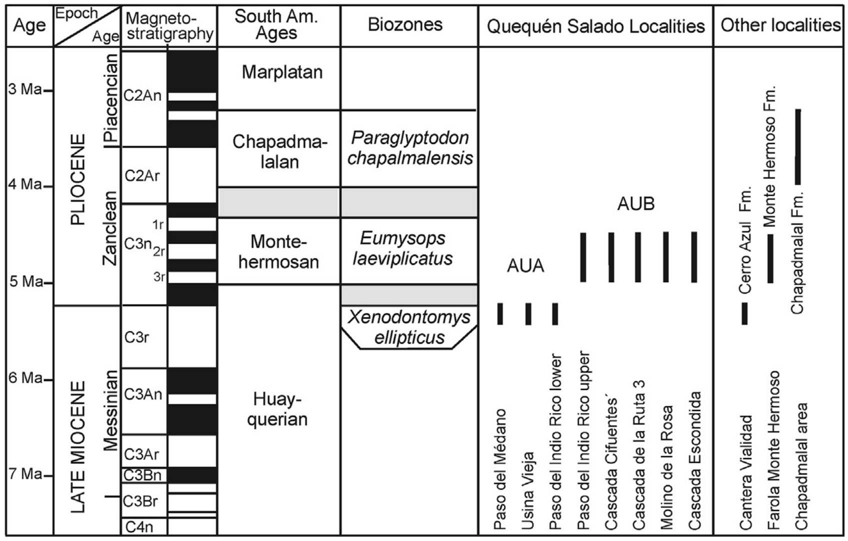

Fig. 3. Stratigraphic chart showing the levels exposed at the studied localities correlated with International and South American ages, and the global magnetostratigraphic scale. Other localities and formations mentioned in the text are also shown. Note that the different assemblages represent brief intervals. Gray areas, inferred hiatus; South American Ages and Biozones follow Cione and Tonni (1995, 2005; but see also Cruz et al., 2016), Verzi et al. (2008) and Tomassini et al. (2013a).

the presence of this taxon in several localities (Arroyo Indio Rico, Irene, Paso del Médano and Oriente) along the QS river. The XeRZ was originally defined by Deschamps (2005) for the assemblage recovered from the Saldungaray Formation deposits (Cerro Azul Formation *sensu* Folguera and Zárate, 2009) exposed in the outskirts of Bahía Blanca city (Cantera Seminario locality) (Fig. 3). In addition, according to the record of rodents typical of younger units and the thickness of the exposure, Verzi et al. (2008) stated that the existence of more than one Stage/Age could not be discounted for the QS basin.

Oliva et al. (2010) recognized two faunal assemblages, one in Paso del Indio Rico and the other in Cascada Cifuentes. Because of the presence of *X. ellipticus*, the assemblage of Paso del Indio Rico was attributed to the Huayquerian Stage/Age (Late Miocene); the Cascada Cifuentes assemblage was assigned to the Montehermosan-Early Chapadmalalan stages/ages (Early Pliocene), considering the occurrence of *Hyperdidelphys inexpectata*, *Actenomys priscus*, *Pithanotomys* sp. and *Eumysops laeviplicatus*, among others.

Deschamps et al. (2012, 2013) suggested that the assemblages with *X. ellipticus* correspond to the Late Huayquerian Stage/Age (Late Miocene), whereas those with *A. priscus*, *E. laeviplicatus*, *Pithanotomys columnaris* and *Phugatherium cataclisticum* could be correlated with the Montehermosan Stage/Age (Early Pliocene). Tomassini et al. (2013a) stated that the assemblages with *E. laeviplicatus* could be assigned to the ElRZ, Montehermosan Stage/Age (Early Pliocene).

4. Materials and methods

The Neogene record was studied following an interdisciplinary approach that included geomorphic, stratigraphic, sedimentologic and magnetostratigraphic analysis, as well as taphonomic and taxonomic analyses of the fossil record. Fieldwork comprised a regional survey on the general geological and geomorphological setting of the mid-lower basin of the QS river complemented with DEM images and Google Earth. Stratigraphic and sedimentological sections were described in detail at the localities of Cascada Escondida (formerly known as Cascada Irene), Molino de la Rosa, Cascada de la Ruta 3, Cascada Cifuentes (formerly known as Cascada Grande or Cascada Aldaya), Paso del Indio Rico, Usina Vieja (1500 m downstream of the old power plant) and Paso del Médano (Figs. 1C and 4). At each site, high-resolution sedimentological profiles were surveyed (scale 1:20; Fig. 4) and sampled for petrographical, compositional and micromorphological studies. In order to define sedimentary facies, the stratigraphical logging focused on grain size, lithology, primary sedimentary structures, bioturbation, fossil content, scale and geometry of the lithosomes. Depositional facies were described according to the scheme of Miall (1978, 2006), which was modified to facilitate the description and interpretation (Table 1). The architectural elements and the hierarchy of bounding surfaces were defined according to Miall (2006) (Table 2). They were deduced from the interpretation of sedimentological profiles and analysis of laterally continuous sedimentary bodies and discontinuities.

Oriented samples were collected for paleomagnetic analysis from each of the major units at the study sites. The objective was to determine the magnetic susceptibility of sediments and rocks, and to establish a magnetostratigraphy.

Paleomagnetic field sampling was carried out by horizontally inserting poly-carbonate plastic cylinders into cleaned vertical faces of sediment, or by drilling into rock faces with a portable drill. For unconsolidated sediments, insertion azimuths of cylinders were measured using a magnetic compass corrected for the declination of the study sites. Drilled core samples were oriented before they were removed from the exposures, using an orienting device equipped with magnetic compass and inclinometer, which allowed the dip and down-dip azimuth of each core to be measured in situ. Samples were generally selected from sorted, fine-grained sediments. Where fine-grained sediments were not present, samples were taken from sorted coarser deposits containing a sufficiently fine-grained matrix. As far as was possible, sediments containing pebbles were avoided. In this manner, it was possible to sample all major units in the QS river basin reported in this study. Within study sites, samples were collected from each of the major subunits identified, typically from the base, middle and top (Fig. 4). Sample cylinders were sealed to prevent drying and oxidation, and stored in a magnetic shield following field collection and during laboratory measurements.

To help constrain the age of the sediments, paleomagnetic

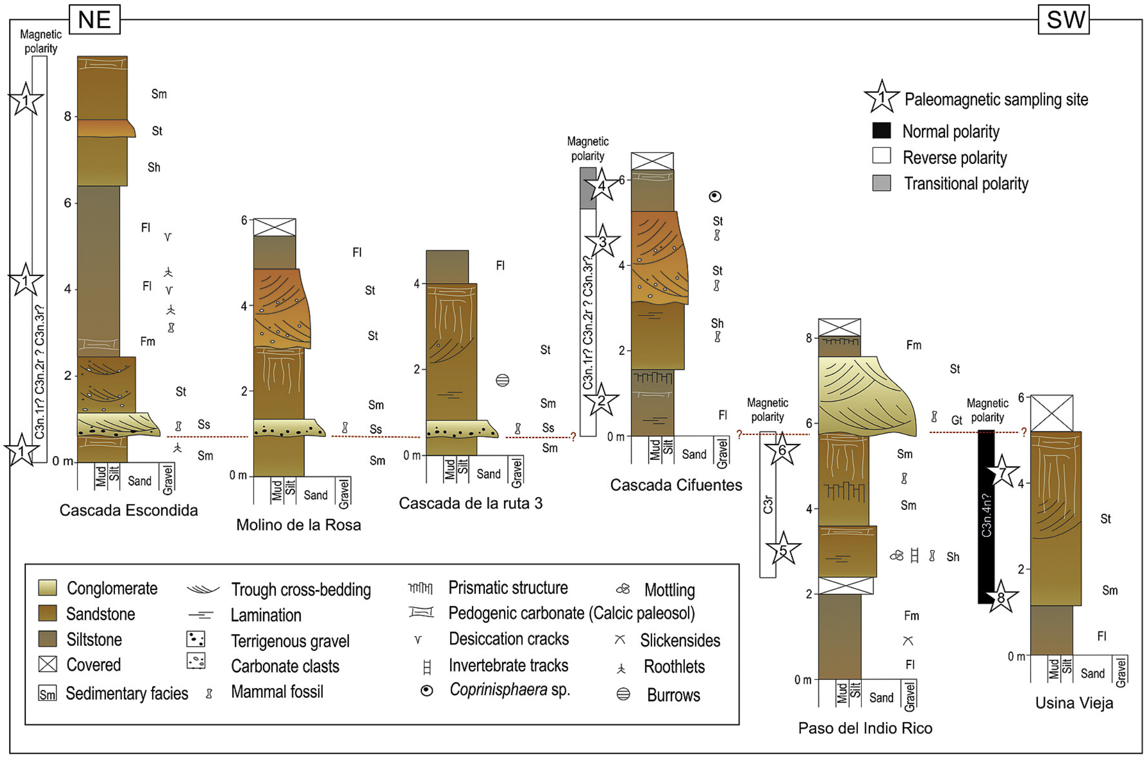

Fig. 4. Sedimentological and magnetostratigraphic profiles of the study sites.

Table 1
Sedimentary facies of the Quequén Salado succession (modified from Miall's, 1978; 2006 schemes).

Facies	Features	Interpretation
Gt	Polymictic, matrix-supported, trough-cross-bedded gravel or coarse to very coarse sandstones.	Sinuous-crested dunes, lag deposits
Ss	Coarse to very coarse, poorly-sorted sand. Seldom normal grading. Abundant intraclasts.	Scour-fill sand. Rapid deposition of bed load; lag deposits
St	Fine to medium sandstone, sometimes pebbly. Trough cross-bedding.	Sinuous-crested and linguoid (3D) dunes
Sp	Fine to medium sandstone; silty sandstone. Planar cross-bedding. Tabular to concave-up based bodies with flat tops.	Transverse (2D) dunes
Sh	Fine to medium sandstone; silty sandstone. Horizontal bedding. Tabular bodies with erosive base.	Plane-bed flow (critical flow)
Sm	Fine silty to medium sandstone. Massive or with faint lamination. Tabular bodies.	Plane-bed flow (lower flow regime)
Fl	Interlamination of siltstone and very fine sandstone.	Deposition from suspension and from weak traction currents.
Fm	Mudstone and siltstone. Massive or with faint lamination. Sometimes with desiccation cracks. Tabular bodies.	Suspension fallout in still-stand water

measurements were carried out on oriented samples to obtain a polarity record. Remanence measurements were carried out at the Environmental Paleomagnetics Laboratory at the University of Lethbridge, using a JR-6A spinner magnetometer (AGICO, Brno, Czech Republic). We measured the natural remanent magnetization (NRM) of each of the 80 samples collected, and re-measured the remanence after stepwise demagnetization in alternating fields (typically 5–12 steps ranging from 5 to 100 mT) using an ASC Scientific D-2000 alternating-field (AF) demagnetizer with three axis manual tumbler. Characteristic remanent magnetization (ChRM) directions were determined by principal component analysis (PCA, Kirschvink, 1980) using at least 3 points on the demagnetization curve directed toward the origin, when plotted on an orthogonal projection (Fig. 5). Only points with a maximum angular standard deviation (MAD) $\leq 5°$ were selected. Mean remanence directions of sampled subunits were determined from PCA results of individual samples (Table 3, Fig. 6A). Overall means were calculated for all the reversed units and all the normal units (Fig. 6B) obtained from the four study sites combined. AGICO's Remasoft v. 3.0 paleomagnetic data analysis software was used in these calculations. Magnetic susceptibility (a measure of the bulk magnetite content) was measured using a Sapphire Instruments (SI-2B) susceptibility meter.

Detailed paleontological prospection yielded numerous vertebrate remains. All the materials are housed at the Vertebrate Paleontological collection of Museo de La Plata (La Plata, Buenos Aires Province, Argentina), under the acronym MLP. In addition, remains from previous collections with precise geographic and

Table 2
Architectural elements of the Quequén Salado succession. These were identified with the aid of facies associations, geometry, palaeocurrents, unit dimensions and determination of the hierarchy of the bounding surfaces (modified from Miall, 1978, 2006).

Architectural element	Principal facies assamblage	Geometry and relationships	Interpretation
AE 1 (Multistorey fluvial channels)	Gt, St or St, Sp, Sm ± Ss	Sandbodies with concave-up to irregular erosional base (5th order surface) and sheet geometry (W/T: 15–35); internally laterally shifted stories. Internal concave-up and lateral-accretion 3rd order surfaces.	Low-sinuosity, fixed channel deposits
AE 2 (Single fluvial channels)	St, Sp, Sm	Single ribbon sandbodies (W/T < 3.5) with low relief basal erosion surface (4th order surface). Encased in fine-grained deposits. Characteristic absence of lateral accretion surfaces.	Minor floodplain channels
Overbank (OV)	Sh, Sm, Fl, Fm	Tabular bodies (0.4–0.6 m thick, 10′s to 100′s m wide) stacked in 1.5–3 m successions with a 4th order basal surface. Pedogenic features such as vertical root traces, mottling and abundant calcium carbonate deposits. Trace fossils are common within beds in the form of vertical, cylindrical, unlined and lined, passively filled tubes.	Deposition from unconfined flow related to episodic overbank flows and flooding of the proximal and distal overbank areas followed by suspension fallout in very shallow-water. Abundance of pedogenic and biogenic processes.

stratigraphic data were also considered. The complete paleontological systematic list is given in Appendix 1.

In order to estimate the spatial and temporal resolutions (*sensu* Behrensmeyer and Hook, 1992) and improve the age of the assemblages, pre- and postburial taphonomic features were analysed according to the methodology proposed by Tomassini and Montalvo (2013).

Biostratigraphic analysis is based on the schemes proposed by Cione and Tonni (1995, 2005), Deschamps (2005), Verzi et al. (2008), Deschamps et al. (2013), and Tomassini et al. (2013a) for the Neogene of the southern Pampean Region. Formal definitions related to biostratigraphical issues are based on the International Stratigraphic Guide (ISSC, 1999).

5. Results and discussion

5.1. Stratigraphic and paleontological record

The gradient of the land surface, the altitude of the examined sites, and the general geomorphological features of the fluvial basin reveal that downstream (from Cascada Escondida to Paso del Médano) the QS valley is more deeply incised into relatively older stratigraphic levels of the Neogene bedrock (Fig. 2), reflecting a case of headward erosion and downcutting. A similar process has been described for the neighbouring Sauce Grande River (Zavala and Quattrocchio, 2001). Accordingly, the younger Neogene (Pliocene) sections crop out in the distal sector of the QS middle basin (Cascada Escondida) up to the immediate vicinity of Paso del Indio Rico, in the lower basin. Other Pliocene outcrops, such as Molino de la Rosa, Cascada de la Ruta 3 and Cascada Cifuentes, can be found along 14 kms of river valley (Fig. 2). Downstream from Paso del Indio Rico, the QS valley becomes gradually wider and deeper, with discontinuous outcrops of the older Neogene stratigraphic sections exposed at the river banks. In the lower QS basin, the Pliocene levels are barely exposed at the upper slope segment of the valley wall (plain rim), 0.1–0.2 km away from the main stream channel, and are mostly covered by a late Quaternary aeolian mantle (Fig. 2).

The Neogene sedimentary succession of the QS has an approximate thickness of 10 m and is dominantly composed of fine to medium sandstones, silty sandstones and siltstones (Fig. 4). These sedimentites show a variety of primary structures, from horizontal bedding to planar or trough cross-bedding; in the latter pebbles are common. The occurrence of mudstones is less common (recorded mainly at Cascada Escondida), and they characteristically show horizontal lamination or a massive appearance with desiccation cracks. The participation of coarse sedimentites is also limited, as they are restricted to lenticular bodies of gravel or coarse to very coarse sandstones with a characteristic erosional base. In spite of this, they crop-out in almost all of the studied sites (Fig. 4).

Due to the relative lithological homogeneity of the Neogene deposits, the sedimentary record has been subdivided into two allostratigraphic units, informally named A (lower) and B (upper) on the basis of the identification of a discontinuity surface (erosional surface) between the two units. This allostratigraphic boundary is well-exposed at Paso del Indio Rico section.

The allostratigraphic unit A (AUA) crops out at Paso del Médano, Usina Vieja and in the lower levels of Paso del Indio Rico with a thickness of ~2–4 m (Figs. 2 and 4); the basal contact is not exposed. Silty sandstones primarily occur as tabular bodies either exhibiting horizontal bedding (Sh), faint lamination (Sm) or massive (Sm) (Table 1); lenticular bodies with trough cross-bedding (St), faint lamination or massive (Sm) are also present. The finer sediments are represented by siltstones and very fine sandstones (Fl) or by mudstones and siltstones with faint to massive lamination, and occasional desiccation cracks (Fm). Pedogenic features are frequently present, including very common carbonate accumulations, usually found in the form of pervasively cemented calcretes (Stage IV and V of Machette, 1985) (Fig. 7). These lithofacies are usually bioturbated; the most common traces are those of invertebrates (namely vertical passively filled tubes), and to a lesser extent burrows (Usina Vieja) of ~15 cm in diameter attributed to micromammals.

Tabular sandstones and sheet-like mudstones and siltstones 0.4–0.6 m thick, and 10′s to 100′s m wide, dominate the architectural elements of the AUA and are stacked in 1.5–3 m successions (Fig. 7). These sedimentary bodies are interpreted as the result of deposition from unconfined flow in proximal and distal overbank areas (OV element, Table 2), later modified by pedogenesis. Lenticular sandstone facies were interpreted as fluvial channel-fill deposits (AE2 element, Table 2). These ribbons (W/T < 3.5) have a low-relief basal erosion surface and are often encased in fine-grained deposits (Fl and Fm). The absence of lateral accretion surfaces is characteristic.

The identified taxa for AUA include *Xenodontomys ellipticus* (Fig. 8A–B), *Lagostomus* sp., *Argyrolagus* sp., *Paedotherium minor* and Caviidae indet. Their record in each locality is given in Appendix 1. Taphonomic features were similar in the different facies. All the remains were disarticulated and isolated. The breakage degree was very high (>90%); longitudinal, stepped and transversal fractures were identified. Few remains (~15%) showed evidences of weathering (e.g. slight splitting). Signs of abrasion were absent. Most of the remains (~65%) presented impregnation

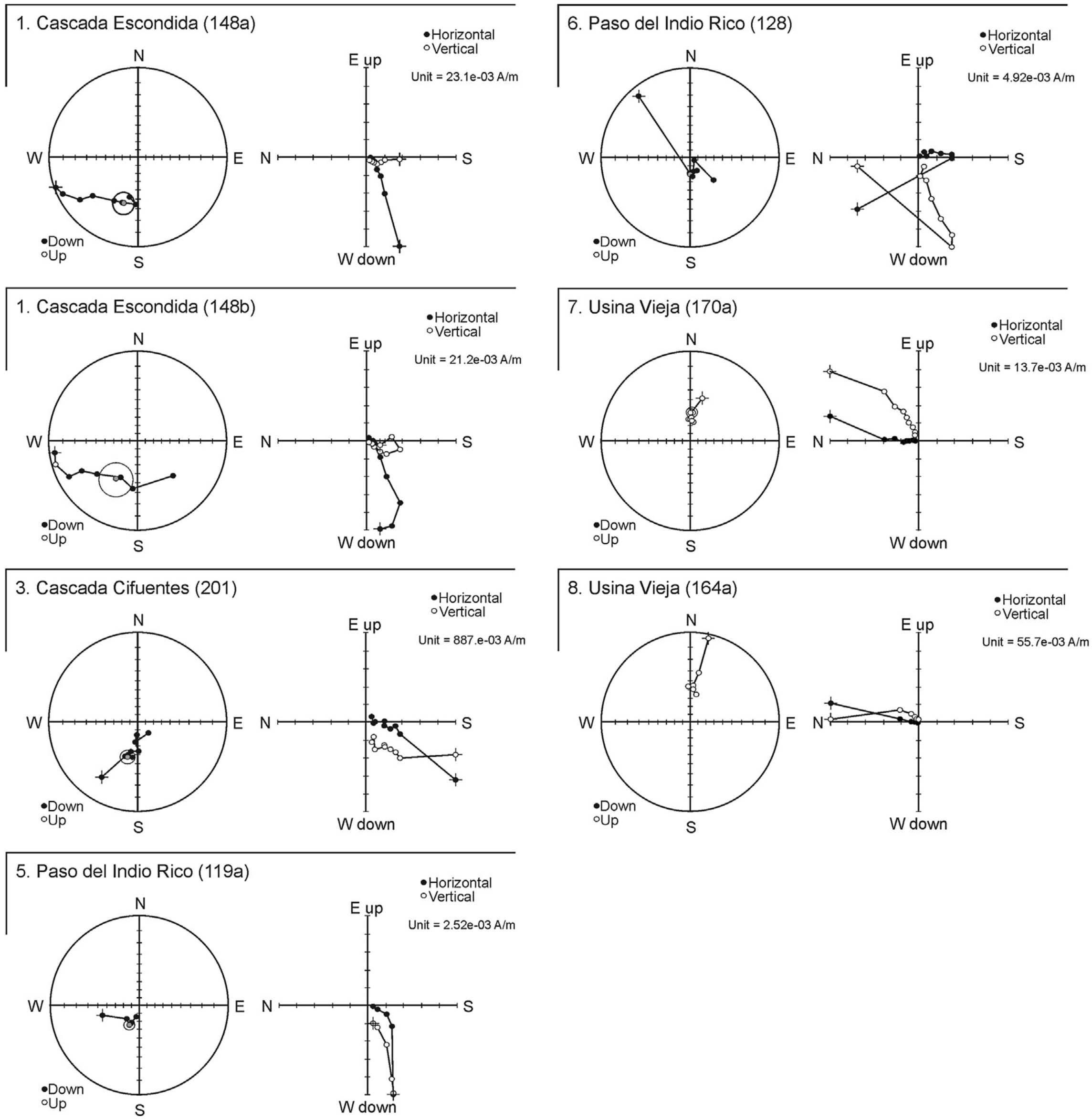

Fig. 5. Representative orthogonal plots and equal area stereographic projections obtained from stepwise alternating field and thermal demagnetization (sample 148B) of sediments and rocks from each of the major stratigraphic units listed in Table 3. Open and closed circles on orthogonal plots represent vertical and horizontal planes, respectively. Open and closed circles on stereographic plots are upper and lower hemisphere projections, respectively. NRM is open or closed circle with cross-hair. Demagnetization increments are 10 mT for AF treatment and 100° C increments, up to 500° C followed by 550 and 575° C for thermal demagnetization. Mean directions for each sample were obtained through principle component analysis (Kirschvink, 1980) using AGICO's Remasoft version 3.0 software, and are plotted with a red circle.

with manganese oxides (e.g. dark spots with dendritic habits, covering the outer surface).

The allostratigraphic unit B (AUB) is exposed at the upper levels of Paso del Indio Rico, Cascada Cifuentes, Cascada de la Ruta 3, Molino de la Rosa, and Cascada Escondida (Figs. 2 and 4) and has a thickness of ~3–5 m. At Paso del Indio Rico, the basal contact is a well-defined erosive surface followed by a 2 m thick polimictic conglomerate with a sandy matrix (Gt) (Fig. 9A, B). In other sites (Cascada Escondida and Cascada de la Ruta 3), this high-energy, tractive event is represented by decimetre-thick lenses of coarse to very coarse sandstones (Ss) (Fig. 9C and D). Fine sandstones appear as lenticular bodies with calcareous clasts, trough cross-bedding (St), planar cross-bedding (Sp) horizontal lamination or massive (Sm). Silty sandstones and siltstones occur as tabular bodies with horizontal bedding (Sh), faint lamination (Sm) or massive with desiccation cracks (Sm and Fm) (Table 1) and frequent calcic pedogenic features. Invertebrate traces (vertical passively filled tubes, *Coprinisphaera* isp. chambers) were found in the upper levels of AUB (Cascada Cifuentes) along with ~15 cm in diameter burrows assigned to micromammals (Cascada Cifuentes and Cascada de la Ruta 3).

The architectural elements of AUB are somewhat similar to those of the underlying AUA. Channel-fill deposits, however, are represented by a more complex internal arrangement (AE1 element, Table 2). Lenticular sandstone facies are ribbon to sheet-like lithosomes with a basal erosion surface that removed 1–2 m of the underlying fine-grained deposits (Sm and Fm facies, Table 1). Internal concave-up and lateral-accretion surfaces are present, suggesting laterally shifted stories (Fig. 9E). Tabular sandstones and siltstones, 0.4–0.6 m thick, are stacked in 1.5–3 m thick successions (Fig. 9F). These bodies assigned to the OV element (Table 2) were modified by pedogenesis (paleosols).

Table 3
Summary of paleomagnetic directions and means. Ns, total number of specimens used from each section; D and I, declination and inclination of the mean direction; k, precision parameter; α_{95}, circle of confidence (P = 0.05); P, polarity (N-normal; R-reversed; Tr-transitional). **based on polarity data, paleontological records, and meteoritic impact glass ages (Schultz et al., 2006).

Sampled allostratigraphic units - site	Lithology	Ns	*D*	*I*	*k*	α_{95}	P	Chron**
1. AUB (QSA 141–163). Cascada Escondida (3 horizons: 1, 3 and 8 m above river)	Sandstone, siltsone (Sm, Fl)	9	222	35	22	11	R	C3R
2. AUB (QSA 188–197). Cascada Cifuentes, 3 m above river	Siltstone, very fine sandstone (Fl)	8	202	66	202	4	R	C3n.2r/C3n.3r
3. AUB (QSA 198–203). Cascada Cifuentes, 4 m above river	Fine-medium sandstone (St)	5	184	46	10	10	R	C3R
4. AUB? (QSA 204–209). Cascada Cifuentes, 6 m above river	Sandstone (Sm)	6	339	16	84	7	Tr	??
5. AUA (QSA 101–121). Indio Rico, sandstone (2 horizons: 3 and 4 m above river)	Fine-medium sandstone (Sh)	20	230	66	35	6	R	C3R
6. AUA (QSA 122–129). Indio Rico, 5.5 m above river	Fine silty sandstone with paleosol (Sm)	8	173	70	27	11	R	C3R
7. AUA (QSA 172–179). Usina Vieja (calcrete), 3 m above river	Fine sandstone (St)	8	360	−57	167	4	N	C3n
8. AUA (QSA 164–171). Usina Vieja (paleosol), 5 m above river	Fine silty sandstone with paleosol (Sm)	9	6	−46	47	8	N	C3n
9. Mean of reversed units		5	204	58	18	19	R	
10. Mean of normal units		2	3	−52	101	25	N	
Geocentric Axial Dipole Field for sampling latitude (38.5°S), normal field		0	−58					
Present Earth's Field direction at sampling localities (38.5° S and 60° W)		−5	−42					

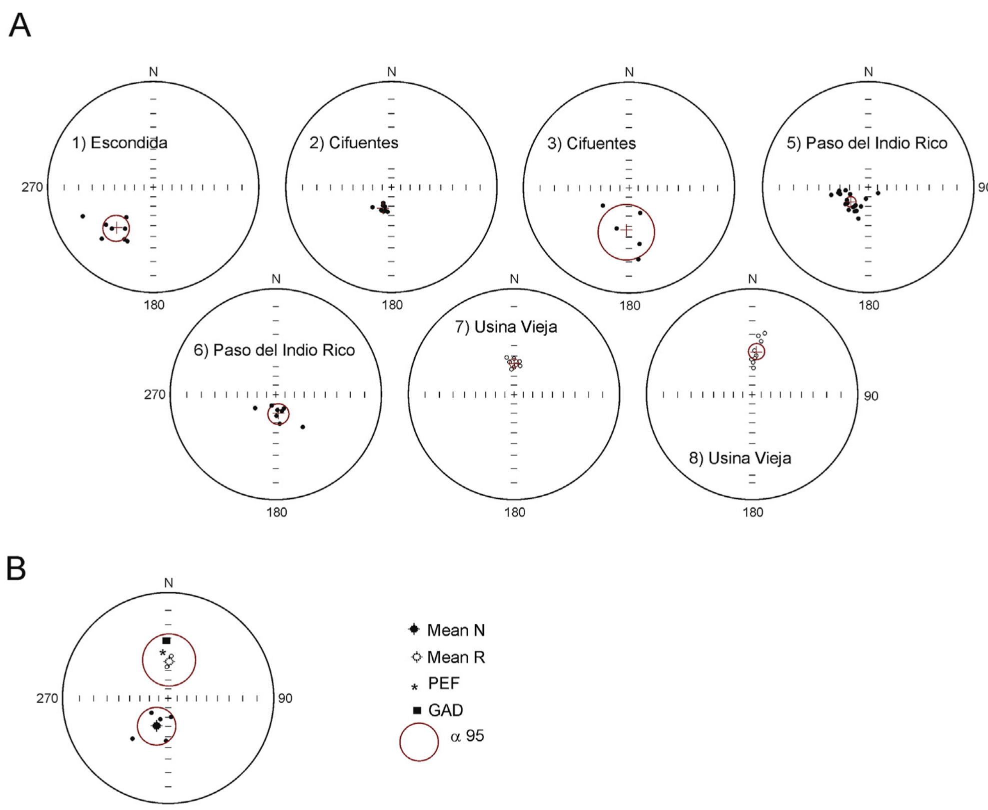

Fig. 6. (**A**, **B**). Stereographic plots of all coherent and PCA-fitted sample directions and their means, given for each of the 4 study sites (Fig. 4). Directional means (cross) and circles of confidence (α_{95}) are plotted, and values are listed in Table 3. GAD, Geocentric Axial Dipole position for a normal field at sampling latitude (51.25° N. latitude). PEF, Present Earth's Field [(decl. = -5° (westerly), incl. = −42°].

Fossil vertebrate remains were exhumed from different lithofacies of AUB, but mainly from Gt and Ss. The vertebrate fossil record includes *Actenomys priscus* (Fig. 8C–D), *Eumysops laeviplicatus* (Fig. 8E), *Paramyocastor diligens* (Fig. 8F), Phyllotini indet. (Fig. 8G–H). The complete list of taxa together with their record in each locality is given in Appendix 1. In addition, *E. laeviplicatus*, *Pithanotomys columnaris* and *Hyperdidelphys inexpectata* were reported by other authors for Cascada Cifuentes in levels assigned to the "Irenense" (Goin and Pardiñas, 1996; Oliva et al., 2010; Olivares et al., 2012; Deschamps et al., 2012).

All the remains recovered from Gt and Ss facies were disarticulated and isolated. The breakage degree was very high (>95%); transversal fractures were predominant. Few remains (~5%) showed evidences of weathering (e.g. slight splitting). Several remains (~55%) displayed signs of intense abrasion (e.g. rounding on the edges and polishing of the outer surface). Impregnation with

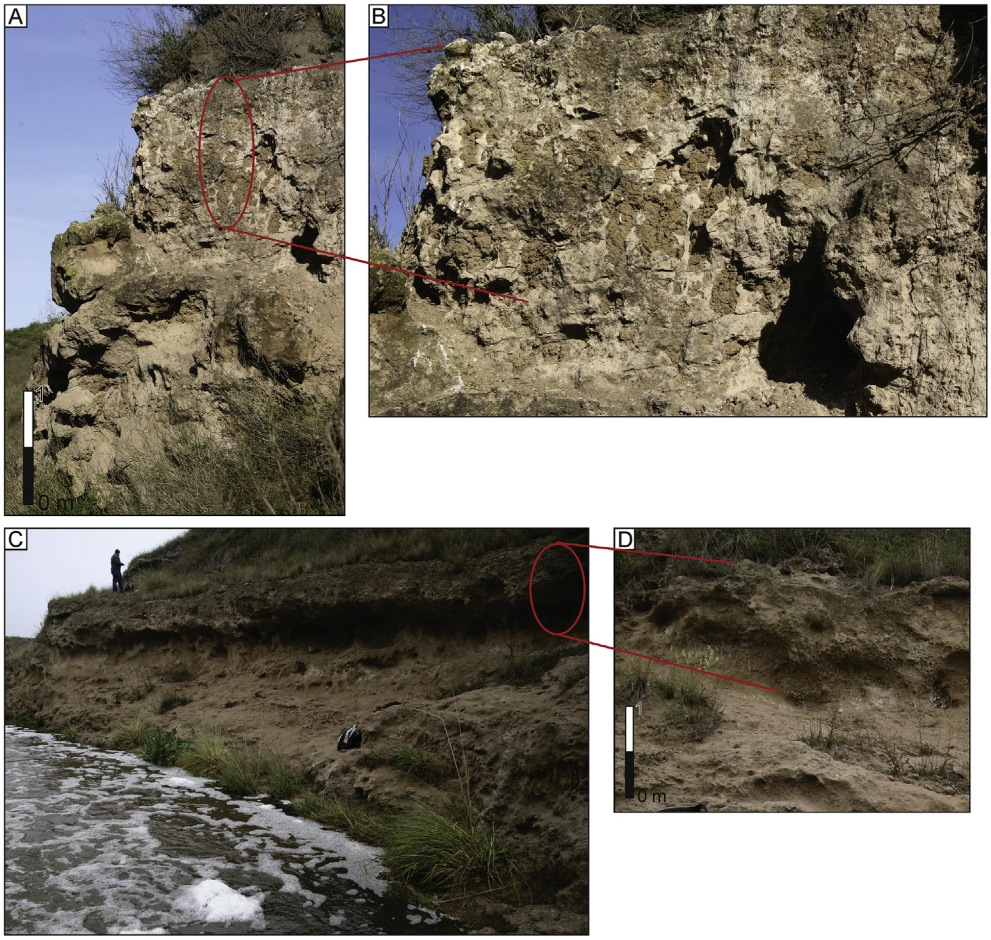

Fig. 7. Photos of the allostratigraphic unit A (AUA). **A.** General view of AUA at Usina Vieja. **B.** Detail of the calcic paleosol developed on top of the succession. **C.** General view of AUA at Paso del Indio Rico. **D.** Detail of the calcic paleosol developed on top of the succession.

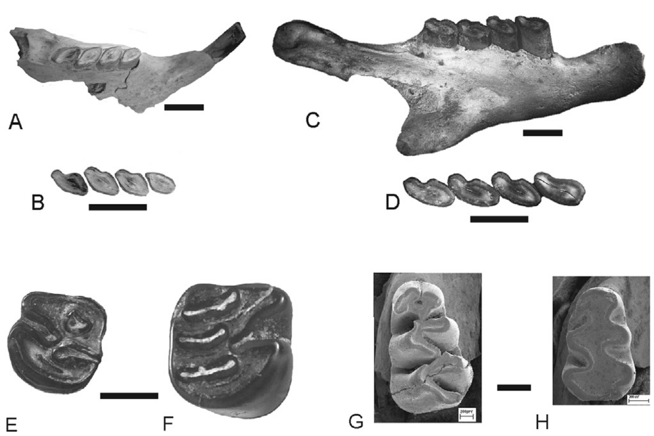

Fig. 8. Rodent remains found in AUA (A–B) and AUB (C–H). **A-B.** *Xenodontomys ellipticus* MLP 14-V-1-17. **A.** Left mandible; **B.** Detail of cheek teeth in occlusal view. **C-D.** *Actenomys priscus* MLP 16-III-20-5. **C.** Right mandible. **D.** Detail of cheek teeth in occlusal view. **E.** *Eumysops laeviplicatus* MLP 14-V-1-12, right second lower molar. **F.** *Paramyocastor diligens* MLP 16-III-20-18a, right first lower molar. **G-H.** Phyllotini indet. **G.** MLP 14-V-1-31, first lower molar. **H.** MLP 14-V-1-10, first lower molar. Scale equals 5 mm (A–D), 2 mm (E–F), and 0.5 mm (G–H).

manganese oxides (e.g. dark spots with dendritic habits, covering the outer surface) was observed in most of the remains (~80%). It is worth highlighting that in the facies St of the Cascada Cifuentes locality, complete and articulated skeletal elements of *P. bonaerense* and *A. priscus* were recovered inside the burrows or associated with them.

5.2. Paleoenvironmental and paleoclimatic interpretation

The general features of the Neogene deposits in Quequén Salado basin support previous general interpretations of their fluvial nature (Frenguelli, 1928; Reig, 1955; Fidalgo et al., 1975; Isla et al., 2014). However, the detailed analysis of the facies associations and of the architectural elements permitted a more comprehensive reconstruction of the fluvial system characteristics.

The AUA is dominated by fine-grained deposits assigned to the OV element. These lithosomes were generated by unconfined flows connected to episodic overbank flows that flooded the proximal and distal floodplain areas and ended with suspension fallout during the wanning period of the flood. These sedimentary processes took place in a highly dynamic, high-accommodation context (environment), where non-channelized or poorly-channelized flows prevailed, and few low-sinuosity minor channels drained the floodplain. The uppermost section of AUA is marked by the development of a mature calcic paleosol (Fig. 7), with dominance of pedogenesis over sedimentation and erosion, which indicates a relative prolonged interval of geomorphological stability across the fluvial basin.

The accumulation of the AUB started with an erosive surface and was followed by deposition of Gt or Ss facies, which indicates the

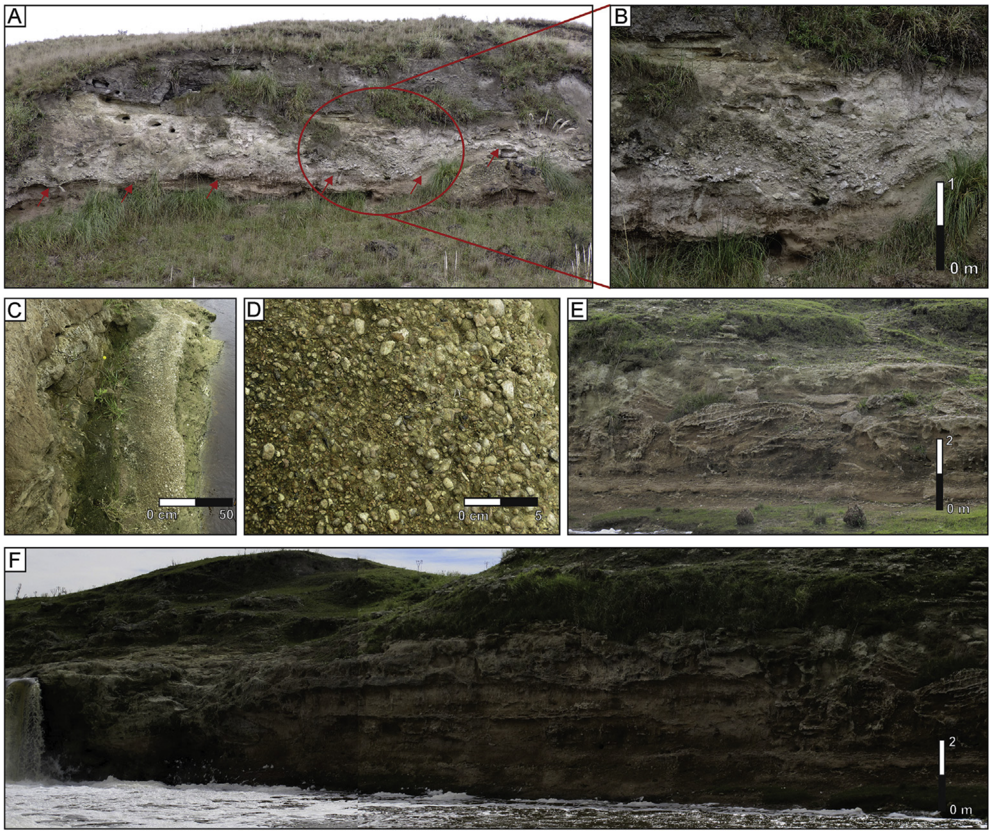

Fig. 9. Photos of the allostratigraphic unit B (AUB). **A.** General view of the left margin of the Indio Rico creek at Paso del Indio Rico; the arrows show the erosional contact between AUA and AUB. **B.** Detail of the AUB: Gt facies (AE1 element) eroding paleosol of AUA. **C-D.** Cascada de la Ruta 3: Ss facies (AE1 element). **E-F.** Left margin of the Quequén Salado river at Cascada Cifuentes. **E.** AE1 element, macroform with lateral accretion. **F.** Vertical stacking of OV and AE1 elements.

occurrence of a high-energy, erosive episode. The participation of quartzitic sabulites and basement blocks of Ventania in these facies points to a regional reactivation of the fluvial basin. These coarse facies are followed by 1.5–3 m of fine-grained, tabular bodies of the OV element modified by little pedogenesis. The upper strata document the development of erosive, relatively sinuous and mobile fluvial channels, with laterally accreting macroforms and laterally-stacked channels. In general, the AUB deposits record a repetitive pattern of destruction-generation of accommodation space, as recorded by the vertical succession of AE1 deposits, OV deposits and AE1 deposits once again. When compared to AUA, it could be assumed that AUB was deposited during a period of more geomorphological instability, when alternating depositional and erosional processes prevailed over pedogenesis. The architectural arrangement of the Neogene deposits of the QS basin (both AUA and AUB deposits) indicates that the sedimentary record might represent the distal reaches of a distributary fluvial system (*sensu* Nichols and Fisher, 2007) that drained from the Ventania ranges.

The presence of pedogenic carbonates has been related to a non-humid climate (Retallack and Alonso-Zarza, 1998), usually to soils of arid or semi-arid regions with sparse vegetation (Bellosi and González, 2010). Mack et al. (1993) noted that Calcisols are indicative of a dry subtropical palaeoclimate zone (MAP <1000 mm) and Birkeland (1999) estimated that for the development of this pedofeature a MAP <500 mm in cool climates, or a MAP <600 mm in warm climates, is needed (i.e. subhumid to semiarid-arid conditions). In addition, it has been suggested that unconfined, non-channelized or poorly channelized flows reflect arid or semi-arid conditions, a period when surface vegetation is sparse or conforming grasslands (North and Davidson, 2012). In these environments, superficial flow is favoured not only following overbank spill, but also as Hortonian overland flows, collecting and transporting rain water down the topographic surface.

Taphonomic and sedimentologic features suggest that vertebrate remains were gradually accumulated in different fluvial subenvironments (e.g., channels, floodplains) and were affected by diverse processes directly linked to the type of depositional context in which they were preserved. Based on the results obtained a local/regional spatial resolution (see Behrensmeyer and Hook, 1992) is inferred.

5.3. Biostratigraphy and chronological calibration

The QS river basin sediments exhibit magnetic susceptibility values ranging from 3–5 x 10^{-3} SI units/vol. with a median value of 3.2×10^{-3} SI units/vol. indicating a high magnetite particle content in both sediments and rocks (sandstones and calcretes), typical for the surficial deposits of Argentina. Paleomagnetic remanence measurements made after alternating field demagnetization, typically in the range of 10–60 mT, in 10 mT increments, indicate that most of the samples (73/80 = 91%) reveal a single (primary) stable reversed or normal component of remanent magnetization. Median destructive fields (MDF) are in the range of 20–60 mT (Fig. 5: e.g. samples 148A, B, 201), typical of magnetite-bearing sediments. While most samples appear to contain predominantly single-domain magnetite, about 30% exhibit softer magnetization indicative of multi-domain magnetite (MDF <20 mT; Fig. 5: sample 164A). Seven samples, not from any particular unit or site, reveal poor quality records, probably due to coarser textures (multi-domain magnetite grains). The mean inclination (all samples) is very close to the value of the Geocentric Axial Dipole (GAD) field at this latitude (58° for a reversed field at 38.5° south latitude). All study sites of the QS river basin, for which fossil data are reported here, are reversely magnetized (Table 3; Fig. 6B) and, based on stratigraphic and geochronological evidence, can be assigned to the Chrons indicated in Table 1. Since all of the fossil-bearing sedimentites are reversely magnetized, and come from a variety of sedimentary facies, it is likely that these sediments were deposited over timespans of the order of 10^4 or more likely 10^5 years, and given that there are erosional contacts, and periods of geomorphic stability, as well as instability, the sediment sequence can be seen as a punctuated (episodic) record of the magnetic field during this reversed Chron.

According to the faunal assemblages found in both allostratigraphic units (AUA and AUB), two range zones could be recognized.

The *Xenodontomys ellipticus* Range Zone (see Deschamps, 2005; Verzi et al., 2008) was recognized in the AUA at the lower levels of Paso del Indio Rico and Paso del Médano (Fig. 10). It was defined at Cantera Seminario (S 38° 44′ 08″, W 62° 12′ 19"; Deschamps, 2005; Verzi et al., 2008), and recognized in other localities of the southern Pampean Region including Barrancas de Sarmiento (S 38° 42′ 6″, W 62° 14′ 54″), Cantera Relleno Sanitario (S 38° 46′ 29″, W 62° 09′ 28″) and Cantera Vialidad (S 38° 45′ 16″, W 62° 09′ 38″) (Deschamps, 2005; Verzi et al., 2008; Deschamps et al., 2013) (Fig. 3). Bearing in mind the numerical age obtained in the levels with *X. ellipticus* of Cantera Vialidad (5.28 ± 0.04 Ma; Schultz et al., 2006), and the paleomagnetic data obtained in the present study for the stratigraphic interval represented by the faunal assemblage, this unit likely records an interval during the C3r chron (5.23–5.89 Ma; Fig. 3; Appendix 1), and therefore in this area, is latest Miocene-earliest Pliocene, Late Huayquerian Stage/Age.

The *Eumysops laeviplicatus* Range Zone (see Tomassini et al., 2013a) was recognized in the AUB at Cascada Escondida, Cascada de la Ruta 3 and Cascada Cifuentes (Fig. 3; Appendix 1). Other common taxa of this biozone in the type area are *Actenomys priscus*, *Pithanotomys columnaris*, *Phugatherium cataclisticum* and *Hyperdidelphys inexpectata*, all of them important biostratigraphic indicators (see Deschamps et al., 2013; Tomassini et al., 2013a). In Molino de la Rosa and Paso del Indio Rico (upper levels), *E. laeviplicatus* has not been found yet, but the record of *Actenomys priscus* allows referring the assemblages of these sites to the *Eumysops laeviplicatus* Range Zone.

The absence of *X. ellipticus* and the abundance of *A. priscus*, the most derived representative of the *Xenodontomys-Actenomys* (X-A) lineage, suggests that the faunal assemblage of the AUB is more modern than AUA. The specimens of *A. priscus* from AUB (Fig. 8C–D) and the Monte Hermoso Formation have similar dental morphology, and are less derived than those from the Chapadmalal Formation which are more elongated and narrow (see Deschamps, 2003; Deschamps et al., 2012; Tomassini et al., 2013a; Verzi, personal communication). In addition, the presence of *Paramyocastor diligens* (Fig. 8F) indicates a Pliocene *sensu lato* age (see Deschamps et al., 2013; Tomassini et al., 2013a). It is worth highlighting that no characteristic taxa (e.g. *Eumysops chapalmalensis*, *E. gracilis*, *Phugatherium novum*) of the Chapadmalalan Stage/Age have been found. Thus, taking into account the paleomagnetic data obtained in this work for the AUB, this unit may record an interval during chrons C3n.1r (4.29–4.48 Ma), C3n.2r (4.62–4.80 Ma) or C3n.3r (4.89–4.98 Ma), Early Pliocene, Montehermosan Stage/Age (Fig. 3; Table 3).

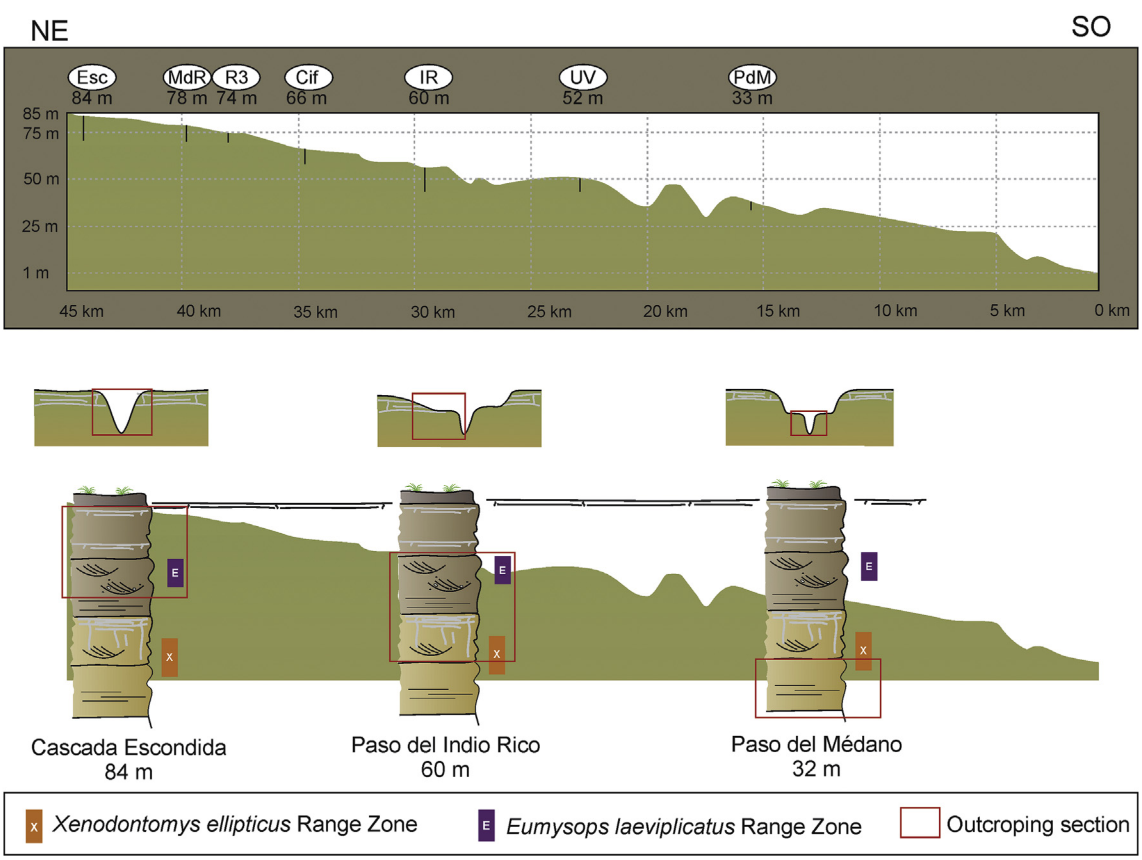

Fig. 10. Top figure, longitudinal profile of the middle and lower Quequén Salado river valley showing the regional gradient. Lower figure, Composite profiles of the Neogene succession and cross sections of the river valley. The red boxes show the outcropping levels with the corresponding range zones (XeRZ and ElRZ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

It is worth noting that, at the Paso del Indio Rico site, AUA and AUB deposits are in stratigraphic superposition; hence, the stratigraphic superposition of *Xenodontomys ellipticus* Range Zone and *Eumysops laeviplicatus* Range Zone is documented for the first time.

The taphonomic features and the environmental contexts of preservation (see Behrensmeyer and Hook, 1992) support the paleomagnetic estimate of a maximum time resolution of approximately 10^5 years for these assemblages, representing brief timespans ("temporal windows", *sensu* Tomassini et al., 2013b).

The phyletic sequence X-A is characterized by non-reversible grades (anagenetic evolutionary pattern) with rapid changes in short intervals (e.g. Verzi et al., 2004, 2008). This fact implies two significant issues. On the one hand, it supports the proposal that the assemblages represent brief intervals. On the other hand, it identifies polarity, which makes this lineage useful in correlation, even without superposition of the bearing levels (Verzi et al., 2008). The scheme proposed on the basis of these taxa is supported by other rodents (e.g. *Reigechimys* and *Neophanomys*; see Verzi et al., 2011; Sostillo et al., 2014). In this regard, the presence of the X-A lineage in the QS Neogene deposits clearly suggests a stratigraphic pattern when their occurrences are examined in the context of the two allostratigraphic units identified (Fig. 10).

6. Conclusions

- The occurrence or absence of biostratigraphically significant taxa (e.g. *Xenodontomys*, *Actenomys*) in the QS sites has been previously interpreted as the result of an erratic pattern that precludes their use as biostratigraphic tools (Prevosti and Pardiñas, 2009). Notwithstanding, the interdisciplinary approach followed in this paper provided a stratigraphic control to analyse the mammalian fossil record and rejects the previous conclusion.
- The initial geomorphological approach to the problem resulted in a proposal of a geological model for the QS river valley: a case of downcutting and headward erosion. Our model contributes a coherent interpretation to explain the spatial distribution of facies and fossil taxa: the younger in the distal sector of the QS middle basin and the older in the lower basin.
- The sedimentary record is believed to represent the distal reaches of a distributary fluvial system that drained the Ventania ranges. This was a highly dynamic environment, where non-channelized or poorly channelized flows alternated with relatively sinuous and mobile fluvial channels. The development of paleosols reflects another cyclic pattern, indicating alternating intervals of geomorphological stability/instability.
- The stratigraphic section of Paso del Indio Rico now becomes a key stratigraphic site to fully understand the geological and paleontological record of the Mio-Pliocene boundary interval. Therefore, the section becomes of major relevance to define the extension, boundaries of stratigraphic units, and the paleoenvironmental conditions of the latest Miocene/early Pliocene in the southern Pampean basin, and thus, refine the current schemes.
- Until now, the major challenge to verifying the biochronological and biostratigraphic significance of the *Xenodontomys-Actenomys* lineage was the lack of a superposed stratigraphic sequence of the fossil bearing levels, a key requirement to support the proposal. The Paso del Indio Rico site provides this evidence: the *Xenodontomys* and *Actenomys* remains come from different stratigraphic levels of the section, AUA and AUB respectively.
- The short interval ("temporal windows") represented by each assemblage (XeRZ and ElRZ) suggests that the schemes for the late Cenozoic are in need of revision, particularly the extension and boundaries of the biostratigraphic units. In this regard, the "Irenense" would not represent a valid biostratigraphic unit, since, according to the geological model proposed here, it would be represented by elements of the *Xenodontomys ellipticus* Range Zone in the lower QS basin and by elements of the *Eumysops laeviplicatus* Range Zone in the middle QS basin. Further studies will hopefully continue to shed light on this matter.

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APPENDIX 1

Systematic list. Records in the studied localities. X, specimens found by the authors of this paper; 0, specimens from previous collections with precise stratigraphic and geographic provenance. Abbreviations: AUA, Allostratigraphic Unit A; AUB, Allostratigraphic Unit B; Cif, Cascada Cifuentes; CR3, Cascada de la Ruta 3; Esc, Cascada Escondida; MdR, Molino de la Rosa; PdM, Paso del Médano; PIRl, Paso del Indio Rico lower level; PIRu, Paso del Indio Rico upper level; UV, Usina Vieja.

Taxa	Localities							
	AUA			AUB				
	PdM	UV	PIRl	PIRu	Cif	CR3	MdR	Esc
Class Mammalia								
Order Polydolopimorphia								
Argyrolagus sp.			X		X			
Order Didelphimorphia								
Hyperdidelphys inexpectata					0			
Order Cingulata								
Plohophorus figuratus						X		
Glyptodontidae indet.					X			X
Order Tardigrada								
Proscelidodon patrius					X			
Order Rodentia								
Pithanotomys columnaris					0			
Pseudoplataeomys sp.					X			
Xenodontomys ellipticus	0		X					
Actenomys priscus				X	X	X	X	
Eumysops laeviplicatus					0	X		X
Paramyocastor diligens						X		
Lagostomus incisus					X	X		
Lagostomus sp.		X						
Caviidae indet.			X		X		X	X
Orthomyctera sp.					X		X	
Phyllotini indet.								X
Order Notoungulata								
Paedotherium bonaerense					X	X	X	X
Paedotherium minor			X					
Order Carnivora								
Parahyaenodon argentinus						X		

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