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Geology and geochronology of type Chasicoan (late Miocene) mammal-bearing deposits of Buenos Aires (Argentina)

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Abstract

The late Miocene Chasicoan mammal-bearing deposits exposed along the lower reach of Arroyo Chasicó are composed of cross-bedded, very fine sandstones interpreted as a channel-bar deposit (lithofacies association 1) grading upward into sandy siltstones (lithofacies association 2), probably accumulated through relatively high-density flows in a marginal channel and/or floodplain environment. The uppermost levels are dominantly composed of mudstones and sandy siltstones (lithofacies association 3) deposited in generally low-energy conditions of sedimentation in a swampy environment. Several paleosols (lithofacies P) are present, indicating that the succession was the result of episodic fluvial sedimentation. The volcaniclastic composition (primary and reworked pyroclastics) suggests that the fluvial system drained the westward region by the Andean foothills. An impact event dated at 9.23 ± 0.09 Ma and recorded by impact glasses (escorias) during deposition of lithofacies Sp enables the fine tuning of the chronology of the deposits through high-resolution magnetostratigraphic profiles, which indicate that the approximately 9.4 m thick succession recorded by lithofacies association 1 and 2 accumulated between 9.43 and 9.07 Ma. The lithofacial arrangement of the succession does not support the current differentiation of the Arroyo Chasicó Formation into the Vivero and Las Barrancas members. Previous biostratigraphic interpretations contain significant inconsistencies in light of the revised stratigraphy proposed here.

Resumen

Los depósitos de edad mamífero Chasiquense (Mioceno tardío) expuestos en el tramo inferior del arroyo Chasicó están compuestos por areniscas muy finas con estratificación entrecruzada (asociación de litofacies 1) interpretadas como depósitos de barras de canal. Pasan transicionalmente hacia arriba a limolitas arenosas (asociación de litofacies 2) acumuladas probablemente por flujos relativamente densos en un canal marginal y/o ambiente de planicie de inundación. En los niveles superiores dominan las fangolitas y las limolitas arenosas (asociación de litofacies 3) depositadas en ambientes pantanosos. Los paleosuelos (litofacies P) intercalados en la sucesión sugieren un proceso episódico de sedimentación fluvial. La composición volcaniclástica señala un sistema fluvial que drenaba las cercanías del piedemonte andino. Un episodio de impacto, registrado por vidrios de impacto (escorias) datados en 9.23 ± 0.09 Ma durante la depositación de la litofacies Sp, permitió ajustar la cronología a través de perfiles magnetoestratigráficos de alta resolución. Los resultados señalan que el intervalo de aproximadamente 9.4 m de potencia de las asociaciones de facies 1 y 2, se acumularon entre 9.43 y 9.07 Ma. El arreglo litofacial de la sucesión no avala la diferenciación litoestratigráfica de la Formación Arroyo Chasicó en los Miembros Vivero y Las Barrancas. Por lo tanto, las interpretaciones

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biostratigráficas previas enfrentan inconsistencias significativas a la luz de la nueva interpretación estratigráfica propuesta en este trabajo.

Keywords: Late Miocene; Stratigraphy; Impact glass; Land mammal ages; Chasicoan; Argentina

1. Introduction

The late Miocene and Pliocene continental record of the southern Pampas comprises a vast sedimentary cover of relatively homogeneous sediments consisting of light reddish brown, massive sandy siltstones that are usually reported as loess and loess-like (loessoid) deposits (Zárate, 2003). Therefore, traditionally the stratigraphic subdivision of this record has been based on the relative degree of evolution indicated by the fossil vertebrate assemblages (South American Land Mammal Ages [SALMA]) recovered from the sediments at different localities across the region (Table 1). The type localities (Chasicó, Monte Hermoso, Chapadmalal) of three of SALMAS (Chasicoan, Montehermosan, and Chapadmalalan) occur in this region (Fig. 1), but until recently, no chronostratigraphic markers were available. Correlations were based on the fossil content, because paleomagnetic studies and radiometric dating were virtually absent for the Chasicoan and Montehermosan type sections. The recent identification and characterization of impact-generated glasses ("escorias") (Schultz et al., 1998, 2004) have provided a new strategy for chronologically calibrating these sequences.

The Chasicoan SALMA is the relatively oldest vertebrate assemblage found in the southern Pampas of central Argentina. The Chasicoan fauna assemblage has been characterized as recording a low number of pan-santacrucian mammals and dominantly primitive pan-araucanian elements (Pascual, 1965; Pascual et al., 1965). Despite its paleobiological relevance, no detailed stratigraphic analyses were carried out on the exposures where the Chasicoan was originally identified and defined as a separate unit of the late Cenozoic vertebrate fossil record of South America. Not only is its chronological control poorly documented (Flynn and Swisher, 1995), but its general stratigraphic setting is inferred from sections exposed in other distant regions using radiometric dating of younger units (NW Argentina) and assumptions regarding late Cenozoic Andean tectonism.

This article provides a comprehensive geological and paleoenvironmental framework of the Chasicoan-bearing deposits exposed at its Arroyo Chasicó type locality as a basis for contributing to the understanding of the late Miocene faunal evolution. With this purpose in mind, the stratigraphy of the sediments are reanalyzed and their environmental and main biostratigraphic implications discussed. Radiometrically dated impact glasses (escorias) provide new and critical chronostratigraphic benchmarks that enable fine tuning of the chronology of the sediments through high-resolution magnetostratigraphic profiles.

2. Materials and methods

Detailed stratigraphic surveys and sedimentological analyses were performed along 4 km of the lower reach of Arroyo Chasicó from the vicinity of the Bajada de los Toros (BDLT) site downstream (Fig. 2). Four representative sections, CH5, CH6, CH7, and CH8, were selected, lithologically described, and sampled for both sedimentological and paleomagnetic analyses. Other complementary sections were described for lateral correlation purposes. The analysis of the sections followed in general the approach of facies analysis (Miall, 1978), adapted to the characteristics of the exposures and deposits. Lithofacies were identified and coded on the basis of their primary lithological features and sedimentary structures and grouped into three lithofacies associations named 1–3. Paleosols (lithofacies P) were identified on the basis of morphological properties (i.e., color, texture, structure, consistency, and boundaries), complemented by thin section analyses of undisturbed blocks from selected samples. Laterally continuous paleosols, numbered from bottom to top of the sequence (P1–P5), were used as stratigraphic markers and

Table 1
Main lithostratigraphic units and their fossil mammal assemblages (late Miocene–Pliocene SALMA) identified in the southern Pampas following different authors: (1)Kraglievich (1952, 1953); (2)Pascual (1961); (3)Pascual (1965); (4)Pascual et al. (1965); (5)Fidalgo et al. (1978, 1987); (6)Linares et al. (1980); (7)Cione and Tonni (1995); (8)Cione et al. (2000)

Lithostratigraphic unit		SALMA(4)	SALMA chronology(8) Cione et al. (2000)
Barranca de los Lobos Formation, Vorohué Formation, San Andrés Formation(1)		Uquian (Marplatan(7))	*ca* 3.2 Ma–*ca* 1.8 Ma
Chapadmalal Formation(1)		Chapadmalalan	*ca* 3.2 Ma–*ca* 4 Ma
Monte Hermoso Formation		Chapadmalalan (?) Montehermosan	*ca* 6.8 Ma–*ca* 4 Ma
Epecuén Formation(3) Los Salitrales Formation(5)		Huayquerian	*ca* 8.7 Ma–*ca* 6.8 Ma
Cerro Azul Formation(6)		Huayquerian Chasicoan *sensu lato*	*ca* 8.7 Ma–*ca* 6.8 Ma, *ca* 10 Ma–*ca* 8.7 Ma
Arroyo Chasicó Formation(2)	Las Barrancas Member(5)	Chasicoan	*ca* 8.7 Ma–*ca* 9.5 Ma
	Vivero Member(5)		*ca* 10 Ma–*ca* 9.5 Ma

The numerical ages are estimated from the chronostratigraphic chart by Cione et al. (2000).

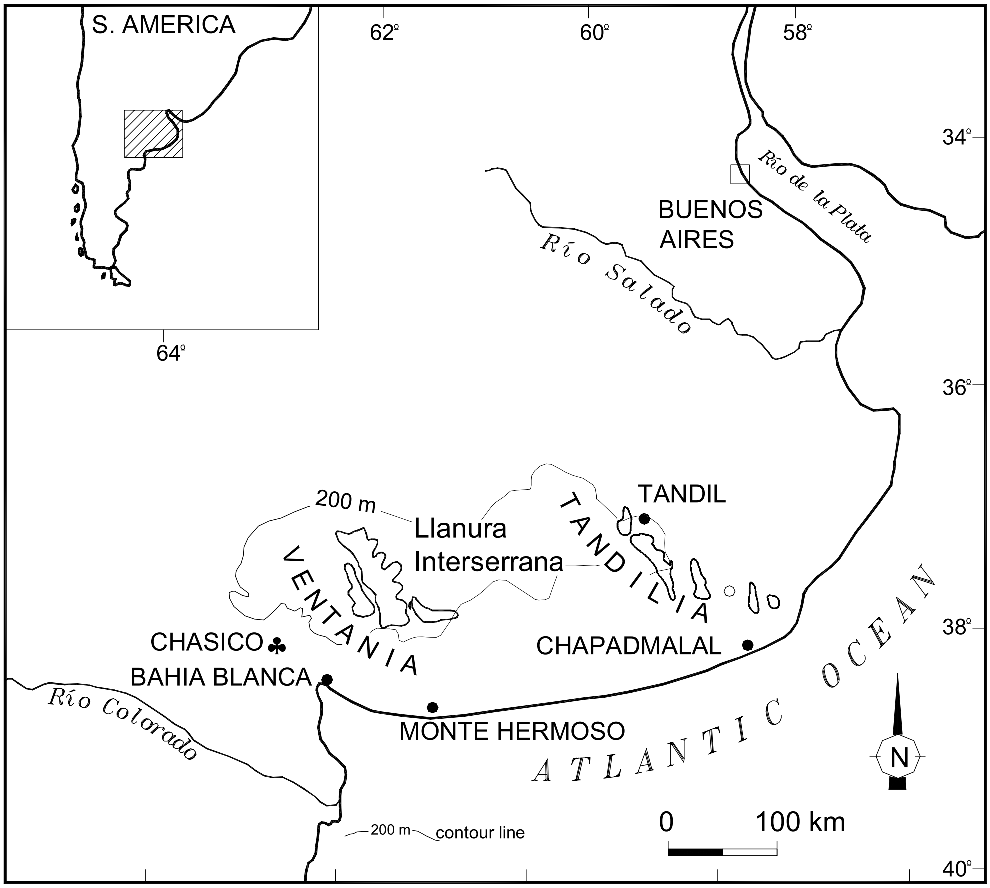

Fig. 1. Map of the southern Pampas showing location of Laguna Chasicó, Monte Hermoso, and Chapadmalal.

enable correlation of the stratigraphic sections. Grain-size and mineralogical analyses of selected samples were performed following standard procedures. The resulting lithofacies assemblage was analyzed and interpreted in terms of depositional environments. The study was supplemented by a regional survey in the area of Salinas Chicas and Laguna Chasicó.

Impact glasses were collected from sediments both at lower (believed to be a primary deposit) and higher sections and dated radiometrically using Ar^{40}/Ar^{39} techniques. Radiometric ($^{40}Ar/^{39}Ar$) age determinations used laser incremental heating methods and noble gas mass spectrometry, undertaken at the Berkeley Geochronology Center (see Renne et al., 1998), following the statistical program described by Sharp and Deino (1996). As described in greater detail in previous contributions dealing with the glasses (Schultz et al., 1998, 2004, 2006), glass samples were first gently crushed with a ceramic mortar and pestle and then hand picked for closer inspection. This procedure minimized any possible effects of alteration, xenocrysts, and vesicles. About 100–200 mg was selected under a petrographic microscope, after which final inspection yielded about 10–20 mg of material for incremental heating analysis.

Four sections totaling 9.36 m were acquired for paleomagnetic analyses, comprising lithofacies associations 1 and 2. After stepwise demagnetization up to 30 mT and measurement on a 2-G small-access cryogenic magnetometer, the reversal stratigraphy was compiled and compared with the magnetic polarity time scale (MPTS) of Schneider (1995). Without the radiometric date provided by the impact glass, the reversal patterns could not be identified uniquely.

3. Geological and geomorphological setting

The late Tertiary succession of the southern Pampean region comprises an extensive plateau capped by a thick calcrete crust, which in turn is covered by a thin apron of late Pleistocene–Holocene eolian deposits. The Chasicoan mammal-bearing deposits are exposed in a relatively very small area along the lower reach of Arroyo Chasicó, from which the majority of the fossil remains have been recovered since the early decades of the twentieth century, particularly the section between Estancia La Norma Alicia and Vivero Von Humboldt (Fig. 2). Other sites surrounding Laguna de Chasicó, Salinas Chicas, and Laguna El Salitral provided limited numbers of fossil specimens (Fidalgo et al., 1978, 1987; Bondesio et al., 1980).

Other Chasicoan-bearing deposits have been reported in the Sierras Pampeanas of San Luis and mountain valley areas of Catamarca and San Juan in northwestern Argentina (Bondesio et al., 1980). Recently, a Chasicoan age

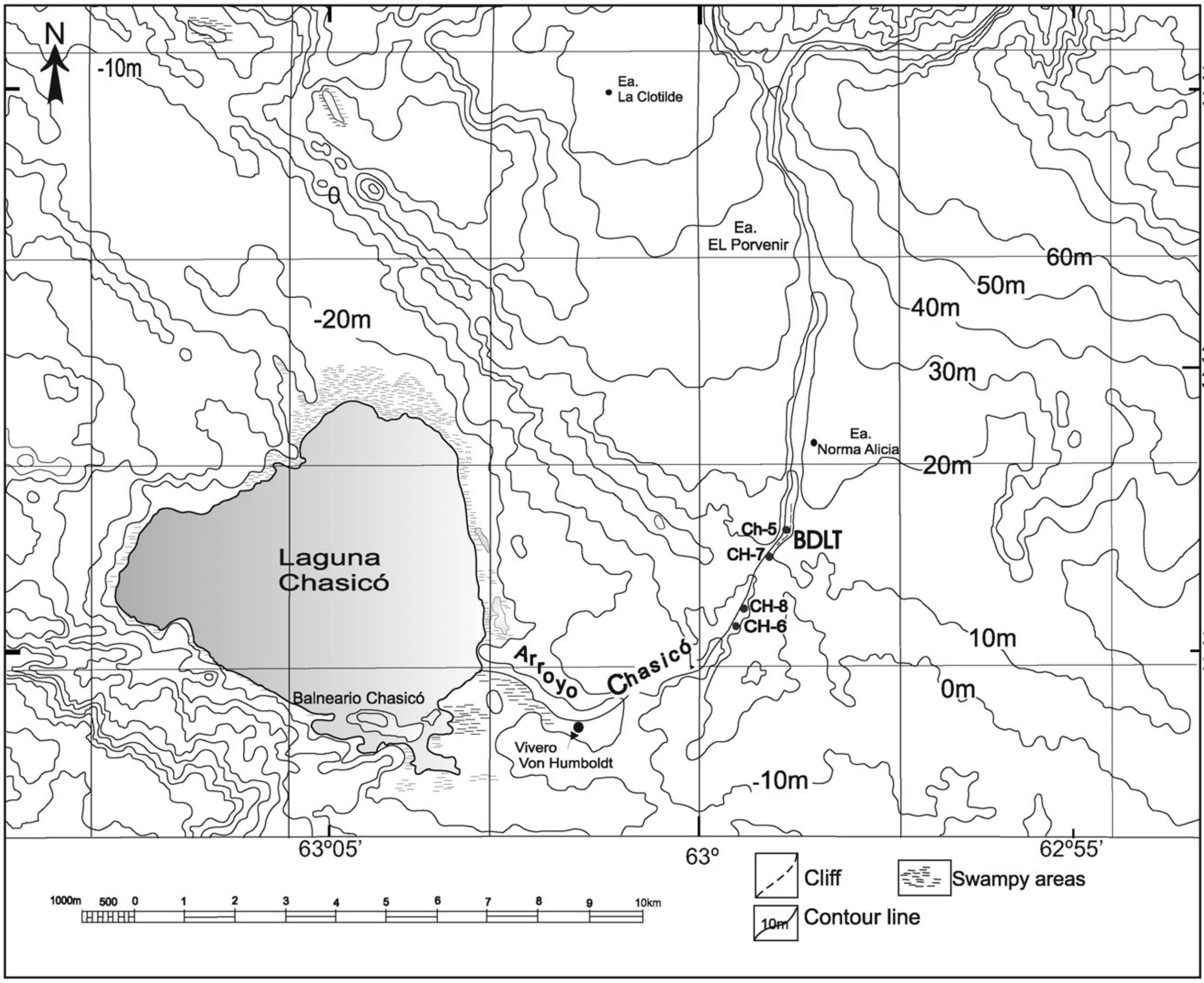

Fig. 2. Topographic map of the lower reach of Arroyo Chasicó and Laguna Chasicó showing location of sections CH5, CH6, CH7, and CH8.

was attributed to sediments exposed along two very small roadcuts situated in the western margin of the southern Pampean plain (Verzi, 1999).

The study area is near the boundary of a NW-SE elongated topographic depression. Faults with NW-SE, E-W, and NE-SW trends (Bonorino et al., 1987) cross the region within the major tectonic setting of the Colorado sedimentary basin (Juan et al., 1996). Altitudes of −20 and −40 m below sea level are recorded at the margins of Laguna Chasicó and Salinas Chicas, respectively. In this region, the late Tertiary plateau gradually descends from the foothills of Ventania range to the Chasicó depression (Figs. 1 and 2).

4. Stratigraphy

Most papers published on the Chasicoan deposits have focused primarily on the recovered faunal record. Such studies provide only general comments on the lithological characteristics and stratigraphy of the exposed succession. Since the first contributions, several researchers have reported the transitional biostratigraphic character of these exposures, including taxa of both Rio Frias-Collon Curá (Friasian) and the Huayquerian and Montehermosan (Kraglievich, 1960).

Pascual (1961) was the first to group the Chasicoan mammal-bearing deposits formally into a lithostratigraphic unit, the Arroyo Chasicó Formation (ACF). The lower and upper stratigraphic boundaries of ACF are poorly defined, and the lower contact is not exposed to direct observation. A succession of 160 m thick continental deposits, overlaying Miocene marine deposits (Barranca Final Formation), are reported from a drilling core (Laguna Chasicó 1) at Vivero Von Humboldt, 6 km downstream from BDLT (Fig. 2). These sediments have been included in the ACF (Zambrano, 1980). The upper stratigraphic boundary of the ACF is exposed but poorly documented. The unit has been interpreted as overlain by Huayquerian-bearing deposits recording the biozone of *Macrochorobates scalabrinii* (Tonni et al., 1998), which is proposed as the biostratigraphic base of the lower Huayquerian stage (Cione et al., 2000). This faunal assemblage reportedly comes from "sandy and conglomerate sediments" of unspecified stratigraphical and geographical location (Tonni et al., 1998).

In the late 1970s, Fidalgo et al. (1978) performed a regional survey in the Chasicó area and attempted to characterize the ACF lithologically, with some textural and mineralogical information. This information, together with the fossil remains recovered, was used to subdivide the ACF into the lower Vivero Member (VM) and the upper Las Barrancas Member (LBM) (Bondesio et al., 1980). Since then, this subdivision has been widely used and accepted in the paleontology community; hence collected fossil remains in this stratigraphic setting are typically placed in the context of these members (e.g., Cione et al., 2000).

The VM was characterized as a 2–3 m thick, massive, dominantly silty deposit cropping out along the stream channel and the lowermost part of the river cliffs on both sides of the lower reach of Arroyo Chasicó, where its type section was defined (Fidalgo et al., 1978). Following these authors, its lower contact is not exposed and grades upward into the LBM. Biostratigraphically, a "pansantacrucian" fossil assemblage is recorded in the VM (Bondesio et al., 1980; Fidalgo et al., 1987).

The LBM was characterized by a higher sand content than the underlying VM, with a maximum exposed thickness of 30–40 m. It was mapped over a more extensive area with exposures surrounding Salinas Chicas and Laguna Chasicó and along the upper part of the cliffs of the lower reach of Chasicó Creek (Fidalgo et al., 1978, 1987). Glassy fragments of impact glass (escorias) up to 10 cm in diameter are mentioned. The rounded shape of some fragments is reported, leading the authors to suggest some sort of transport (Fidalgo et al., 1978). Following Bondesio et al. (1980) and Fidalgo et al. (1987), the fossil record of the LBM is dominantly composed of "pan-araucanian" specimens representing a transitional assemblage between those of the VM and the Huayquerian assemblages.

The outcrops of the ACF along the lower reach of Arroyo Chasicó are discontinuously exposed within the 8–10 m high cliffs on both sides of the creek. Quaternary fluvial and eolian deposits unconformably cover the unit.

The BDLT site is the most continuous exposure, extending nearly 400 m along the creek with an average thickness of 10 m. The remaining sections consist of 20–50 m long discontinuous exposures separated by areas covered by younger sediments and dense vegetation. The ACF is also exposed across a 50–80 m wide exhumed surface, extending to either side of the present stream, as a result of fluvial erosion. This surface, gently sloping downstream, is usually masked by a salty coating.

About 1500 m downstream from BDLT, narrow channels incise the ACF surface, resulting in 2–3 m thick exposures along their walls. In this sector, the outcrops of the ACF are cut by vertical fractures, some widened by fluvial erosion.

The sedimentary succession is a fining-upward sequence. The basal lithofacies association 1 (Table 2, Fig. 3) is dominantly composed of lithofacies Sp. It crops out extensively across the fluvially eroded surface where sections CH6, CH7, and CH8 are located, but its lower stratigraphic boundary is not exposed (Fig. 3). At BDLT, Sp comprises the lowermost 1.5 m of section CH5. The maximum thickness of this lithofacies measured 2.9 m at section CH8. It is composed of light brown, very fine, remarkably homogeneous sandstones. Lenticular sets exhibit very well-defined planar cross-bedding of low to medium angle inclination; thickness of foresets ranges from 2 to 5 cm. Abundant fragments of disarticulated fossil remains scattered throughout the sedimentary matrix were recovered during the stratigraphic survey.

Three paleosols (P1, P2, and P3) are present in this lithofacies association, all characterized by finer textures and darker color than their parent materials, with abrupt upper boundaries and transitional lower boundaries. P1 is laterally continuous for nearly 1 km with its best exposures between sections CH6 and CH8. It consists of a 50–70 cm thick, silty, and very fine sandstone layer of tabular geometry exhibiting bioturbation features and weak aggregation. Carbonate nodules and carbonate accumulations form a distinct horizon 50 cm below the P1 surface. P2 is less continuous laterally than the other two paleosols, having been almost completely removed at some places by fluvial erosion (scoured surfaces), and it shows a weaker degree of development. P3 is a mudstone layer that can be traced laterally for nearly 2 km. It exhibits a distinct structure consisting of subangular, fine, blocky aggregates; invertebrate bioturbation features; very common rootlets; and numerous vugs of irregular shape.

Table 2
ACF lithofacies and paleoenvironmental interpretation

Lithofacies Association	Code	Lithofacies	Sedimentary structure	Interpretation
3	Fh	Mudstone	Horizontal stratification	Swampy environment, floodplain
	Fm	Mudstone	Massive	
	FSh	Sandy siltstones	Horizontally bedded	Crevasses?
	P	Clayey siltstone to mudstone	Pedogenic structure	Paleosols
2	FSm	Sandy siltstone	Massive	Overbank deposits, floodplain
	FSp	Sandy siltstone	Coarse cross bedding	Marginal channel
	P4, P5	Siltstone to mudstone	Pedogenic structure	Paleosols
1	Sp	Very fine sandstones	Planar cross bedding	Channel bars
	P1, P2, and P3	Silty sandstone to mudstone	Pedogenic structure	Paleosols

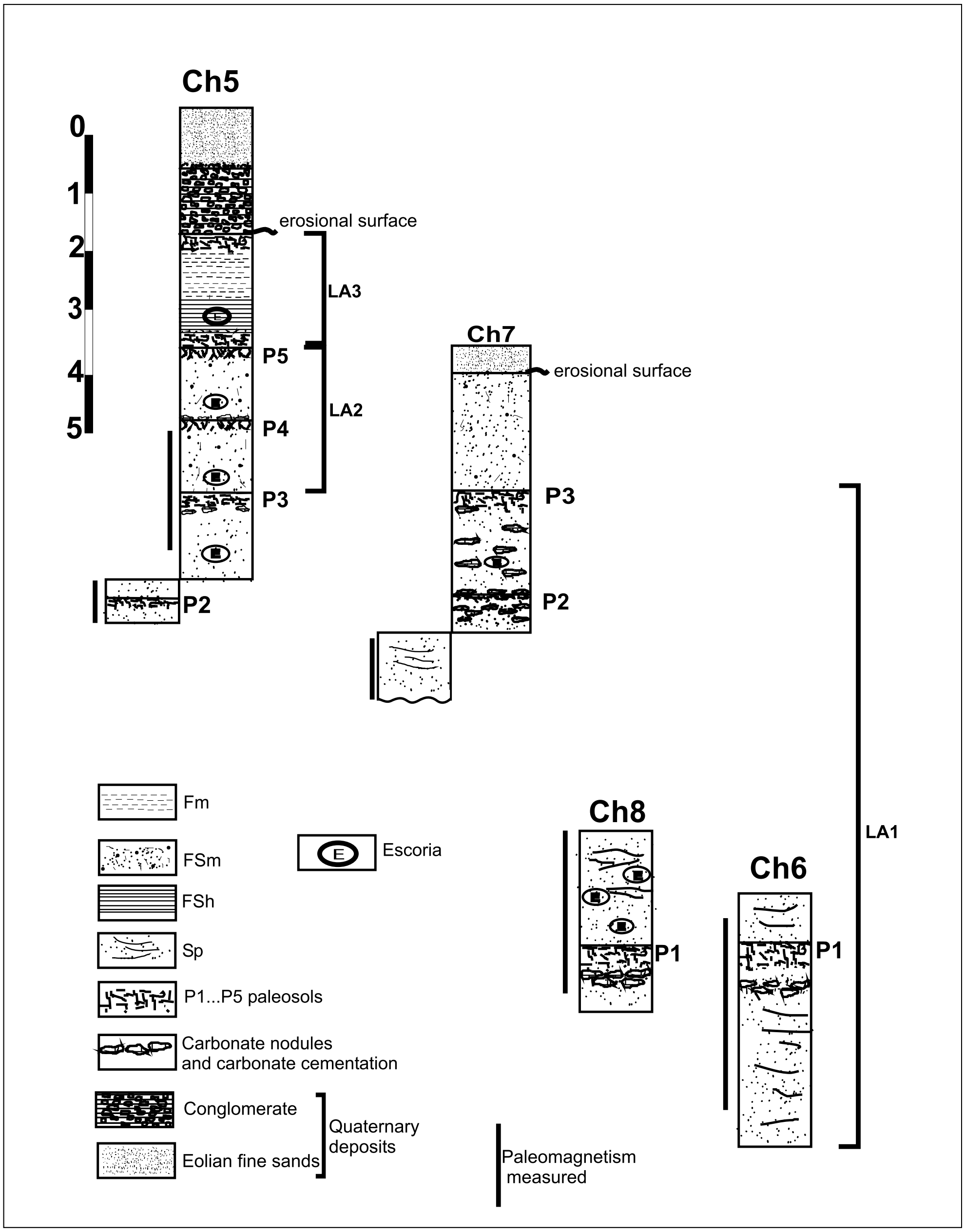

Fig. 3. Stratigraphic logs of sections CH5, CH6, CH7, and CH8 along Arroyo Chasicó.

Many escorias and tierras cocidas also have been recovered from the middle and upper parts of lithofacies Sp, stratigraphically above P1. No escorias were found below the P1 surface. The greatest concentrations and biggest specimens (40 cm in diameter) of escorias were recovered from the middle part of lithofacies Sp. Clusters of large escorias in lithofacies Sp can achieve collective dimensions exceeding 5 m. The preservation state and interrelationships (split but pieces that fit together) indicate that these escorias represent a primary deposit, emplaced with minimal reworking or transport from its original location.

Lithofacies association 2 is well exposed along the cliffs of BDLT site, as shown in section CH5 (Fig. 3), with an average thickness of 5–6 m. The lower boundary is transitional to lithofacies Sp and unconformably overlain by lithofacies association 3. The dominant lithofacies is a light brownish, friable, and sandy siltstone of massive appearance (FSm), including a lowermost section of massive silty fine sandstones (SFm) that grades downward to the very fine sandstones of lithofacies Sp. Coarse, generally poorly defined, cross-bedded sandy siltstones (FSp) are associated with shallow and wide scour surfaces. Intraclasts of siltstones and very fine sandstones, as well as rounded and subrounded to subangular escoria fragments, are common throughout the sedimentary matrix. Escoria fragments occasionally form lag-gravel concentrations along scoured surfaces with clast sizes ranging between 1–2 mm and 7–8 cm.

Two paleosols (P4, P5) with different lateral continuity are included in lithofacies association 2. As previous paleosols, both exhibit finer textures and darker colors than their parent material. P4, which crops out in the middle of the BDLT site, consists of a silty layer partially eroded by scoured surfaces. P5, the uppermost paleosol of lithofacies association 2, consists of a mudstone layer showing irregular blocky aggregation; common clayey cutans were found in thin sections.

Carbonate accumulations are very abundant in lithofacies association 2, including highly resistant, nodule-like features and irregularly shaped cemented sediments. These carbonate accumulations tend to show a pattern of subhorizontal concentrations extending laterally for several meters along paleosol surfaces or sedimentary contacts and forming layers 30–50 cm from the paleosol surfaces. A 15 cm thick calcrete crust consisting of massive, platy accumulations is developed on top of P5. Gypsum is also found as tiny crystals or cementing the sediment matrix. A few medium-sized burrowing structures (30 cm in diameter) have been found.

Lithofacies association 3 forms the uppermost part of ACF and is unconformably overlain by a Quaternary fluvial conglomerate (Bajada de los Toros Conglomerate, Fidalgo et al., 1978, 1987). It is exposed in the upper section of BDLT with an average thickness of 1.8 m. The lower contact of this association is an abrupt subhorizontal surface marked by the upper surface of a calcrete layer capping lithofacies FSm. Upstream of section CH5, it fills depressions deeply carved into lithofacies FSm; at some points, these depressions reach the uppermost part of lithofacies Sp. This association is dominantly composed of a reddish-brown to greenish mudstone displaying well-defined, fine horizontal stratification (Fh). Sedimentary particles larger than 0.05 mm compose less than 15% of the lithofacies. In local depressions, it consists of basal, sandy siltstones horizontally bedded (FSh) grading upward to mudstones (Fm). Disarticulated fossil remains are very frequent, whereas escorias (usually heavily weathered) are reduced to a few rounded to subrounded fragments.

Paleosols identified in lithofacies association 3 are laterally discontinuous. Their morphological properties include fine textures (clayey siltstones layers) of yellowish and greenish colors with medium to fine, blocky to irregular prismatic structure. Fe-mottles are common, but carbonate accumulations are much less abundant than in the other two lithofacies associations, usually restricted to rhizoconcretions or scattered carbonate nodules.

The lithofacies associations exhibit a similar petrological composition consisting of volcaniclastic material (primary and reworked pyroclastics). Grains of both basaltic and andesitic rocks represent the most abundant particles, with percentages of about 40%. Oligoclase-andesite plagioclases (mainly zoned) comprise around 25%, with 15–20% of the volcanic glass including up to 8–10% of weathered volcanic shards. The light mineral suite also includes (in order of relative abundance) K-feldspar (10%), quartz (up to 5%), sedimentary rock fragments (1–2%), and mixed pyroclastic fragments. Heavy minerals represent only 2–3% of the mineral assemblages and include hornblende, augite, biotite, and opaques, in order of decreasing abundance. Minor heavy minerals include muscovite, clorite, hypersthene, epidote, allophone, and zircon. In general, the mineral grains are weathered with partial alteration to sericite or carbonate replacement. Pumice volcanic glass shards are frequently devitrified into aphanitic microcrystalline aggregates or display dissolution features. Nevertheless, the bulk sediments exhibit relatively little total alteration based on the Chemical Index of Alteration (Schultz et al., 2004), following Taylor and Mc Lennan (1985).

5. Discussion

5.1. Lithofacies and paleoenvironmental reconstruction

The lithofacial associations described herein indicate that the sedimentary succession recorded by the ACF was a result of episodic sedimentation in a fluvial environment of a mixed-load stream under progressively decreasing energy. Lithofacies association 1 is interpreted as channel-bar deposits consisting of three main episodes of aggradation separated by intervals of stability on a fluvial basin when P1, P2, and P3 developed. Hypothetically, these channel-bar deposits might have been generated by a sandy braided to meandering system, according to lithofacies characteristics, but more information is needed to test this hypothesis. The stratigraphic setting of the lowermost, largest, and best-preserved escorias indicates that the impact event occurred during the second sedimentation episode of channel-bar deposits, some time after the soil-forming interval of P1.

The second episode of sedimentation was followed by a new interval of stability when paleosol P2 developed. Reactivation of sedimentation gave way to the third sedimentation episode and accumulated sediments that gradually fine upward and indicate a transition from a channel environment to marginal channel and/or floodplain environment, as recorded by the overlying lithofacies association 2. A third interval of relative stability followed when paleosol P3 formed.

Subsequently, aggradation continued with two new episodes of sedimentation represented by the deposition of lithofacies Fm (lithofacies association 2), separated by paleosol P4. According to their general lithological features, these deposits probably accumulated by relatively high-density flows in a marginal channel and/or floodplain environment. Fluvial erosion preceded the aggradational events and excavated broad, shallow scours on the paleosol surfaces, thereby reworking and redepositing paleosol fragments and escorias. The second episode of siltstones sedimentation was followed by the formation of P5.

The localized depressions at the basal contact of lithofacies association 3, formed after the development of P5, are interpreted as the result of a fluvial episode of erosion that excavated relatively deep and narrow channels in lithofacies Fm. These depressions were filled by the mudstones composing lithofacies Fh in generally low-energy conditions of sedimentation in a swampy environment. The morphology displayed by paleosols in these settings indicates dominant hydromorphic conditions with soil formation in seasonal stagnant waters. These general conditions may explain the occurrence of heavily weathered fragments of escoria in this section.

The mineralogical composition of the deposits indicate that the fluvial system, which deposited the Chasicoan mammal-bearing deposits, drained an area dominated by volcanic and pyroclastic rocks, such as the westward region by the Andean foothills. There, extensive outcrops of andesitic and basaltic units were generated by Andean volcanism during the Cenozoic (Ramos, 1999a).

5.2. Radiometric ages and paleomagnetism

The detailed approach and results for the radiometric ages of the glasses are given in Schultz et al. (2004). Both samples yield similar results. Glass from reworked sediments higher in section CH5 at BDLT (but within the ACF) contains evidence for increased weathering, based on its appearance and low radiogenic yield. It yields a date of 9.3 ± 0.3 Ma. Better preserved glass from lower in section yields an age with higher accuracy of 9.23 ± 0.09 Ma, now accepted as the age of an impact somewhere near Laguna Chasicó that was responsible for the escorias. These results differ from a previously reported date with greater uncertainties of 10 Ma from the same exposure (Schultz et al., 1999), which was based on analyses in another laboratory. The new age is superior because of the better analytical techniques, as described, the quality and quantity of the analyzed materials, and the higher resolution of the extraneous argon. The selected escoria glasses yield an incremental heating spectrum with initial release of non-atmospheric, extraneous ^{40}Ar in the first step, followed by three additional steps. This approach results in a weighted average plateau age of 9.21 ± 0.08 Ma (see Schultz et al., 2006 for details including the release spectrum).

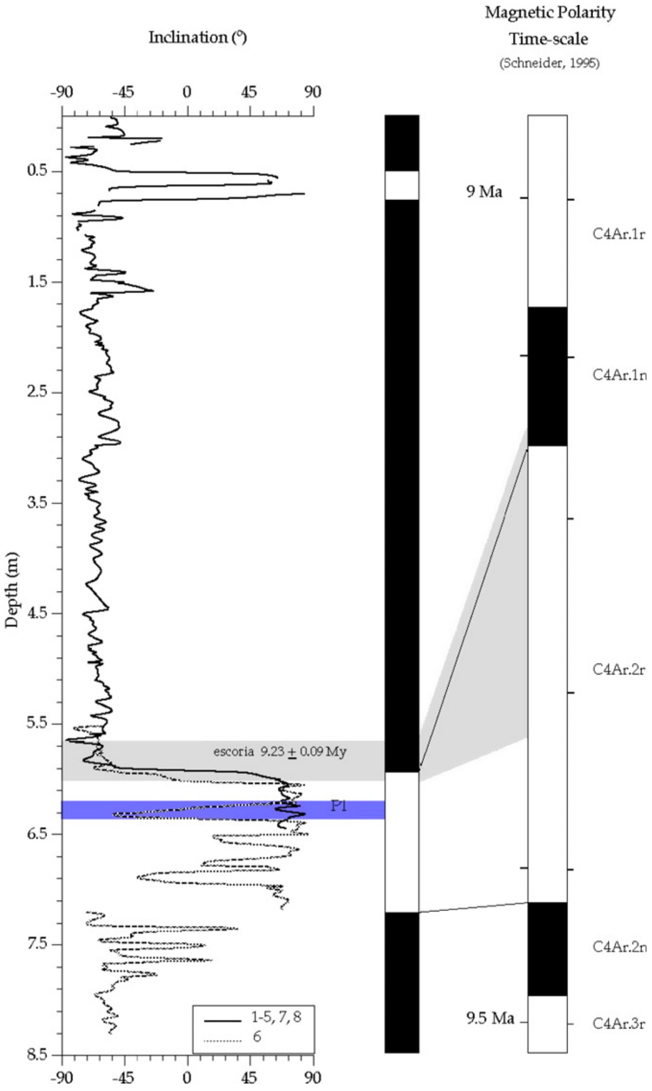

Fig. 4. Inclination data from ACF compared with the magnetic polarity time-scale (MPTS) of Schneider (1995). The dark line represents composite data for sections 1–5, 7, and 8. The shaded line is from section 6 and is tied to the other record based on the reversal boundary and paleosol P1. The escoria age provides a means to link the ACF reversal stratigraphy to the MPTS, confining the age of the section between 9.07–9.49 Ma.

The dated glass provides a benchmark for constraining the magnetic reversal stratigraphy for the ACF shown in Fig. 4. The lowest occurrence of the largest and best-preserved masses of impact glass is considered the date of the sediments. The glasses were found near the reversal boundary at 5.9 m. Considering the 9.23 ± 0.09 Ma age of these glasses, that polarity change would have to be the C4Ar.1n/C4Ar.2r boundary (9.15 Ma) from the MPTS of Schneider (1995). The lowermost reversal boundary at approximately 7.2 m is assumed to be the C4Ar.2r/C4Ar.2n boundary (9.43 Ma) (Schneider, 1995). The base of the unit is entirely within a normal polarity zone, interpreted as the C4Ar.2n chron, and therefore must be no older than 9.49 Ma, the age of the C4Ar.2n/C4Ar.3r boundary (Schneider, 1995). The upper unit (0–5.7 m) is almost entirely within a normal polarity zone and interpreted as the C4Ar.1n chron; it must be no younger than 9.07 Ma because the upper boundary is not encountered (Schneider, 1995). The brief reversed interval between 0.5–0.8 m is not considered a chron of its own but instead thought to be a brief excursion of the Earth's magnetic field recorded during a period of rapid sedimentation. As stated previously, this interval is massive and characteristic of high-density flows, which would allow deposition of the uppermost 5.5 m in as little as 0.08 Ma (given a sedimentation rate of 7.5 cm/kyr). Such sedimentation rates would be more than sufficient to record changes in the Earth's magnetic field on the order of geomagnetic excursions lasting 10^3 years (King and Peck, 2001). With the escoria age to constrain the magnetic reversal, the entire 9.4 m section clearly represents no more than 0.42 Myr. The relative size of the normal and reversed polarity zone suggests significant changes in sedimentation/erosion between lithofacies associations 2 and 1.

5.3. Lithostratigraphic and biostratigraphic implications

Fidalgo et al. (1987) note that the VM is exposed at the lowermost part of the cliff at BDLT, as well as along the present channel of the lower reach of Arroyo Chasicó. An exception was the area downstream from BDLT, where the LBM was identified on the basis of recovered fossil remains. In this area, narrow channels incise through the sediments sampled in sections CH7 and CH8. The lateral and vertical arrangement of the lithofacies differentiated herein indicates that progressively older stratigraphic levels are exposed downstream along the fluvial channel of Arroyo Chasicó. Section CH8, consisting of outcrops of lithofacies association 1, records the stratigraphically lowest beds, followed by sections CH6 and CH7, both of which document progressively younger beds deposited in a channel bar environment. Section CH5 at BDLT records the youngest stratigraphic beds of the succession, represented by lithofacies associations 2 and 3. The lithofacies arrangement contradicts previous results by Fidalgo et al. (1978) and Bondesio et al. (1980).

In summary, previous interpretations of the biostratigraphy involve significant inconsistencies in light of this revised stratigraphy, because the VM, bearing the biozone of *Chasicotherium rothii* (Cione et al., 2000; Cione and Tonni, 2005), would include lithofacies associations 2 and 3, whereas the LBM, bearing the biozone of *Chasicotatus ameghinoi* (Cione et al., 2000; Cione and Tonni, 2005), may encompass lithofacies associations 1–3.

5.4. Chronology of Chasicoan SALMA

From a geotectonic perspective, the Chasicoan sedimentary units were traditionally considered the lowest part of a continental silty sequence deposited between the pre- and main phase of the third tectonic movement of the Andean orogeny in the Pampean region (Reig, 1957 in Pascual, 1961). Pascual et al. (1996) place the Chasicoan together with the older Friasian in the Protoaraucanian subcycle, which environmentally represents the development of widespread and varied plains (''edad de las planicies australes'') with an age estimated between 11 and 3 Ma (Pascual et al., 1996: 291).

The beginning of Chasicoan sedimentation was placed after the general withdrawal of the mid-Miocene transgression (Pascual et al., 1996). According to Ramos (1999b), the transgression extended across most of eastern South America, covering the Pampas, Chaco region, and Patagonia up to the Andean foothill and reaching areas near the central and northern Andes of Argentina. The regional regression that followed was thought to be synchronous with the 10.5 Ma global sea level fall cited by Haq et al. (1987) (see Verzi, 1999; Pascual et al., 1996).

An approximate duration of 1 Ma from 9 to 10(?) Ma was provisionally assigned to the Chasicoan SALMA (Flynn and Swisher, 1995) on the basis of the magnetostratigraphy of similar exposures in northwestern Argentina. Tonni et al. (1998) proposed that the ACF was deposited during the earliest part of the late Miocene (Tortonian). The Chasicoan ''stage'' is presently placed approximately between <9 Ma (*ca* 8.7 Ma) and 10 Ma (see general chronostratigraphic chart by Cione et al., 2000 and Cione and Tonni, 2005).

On the basis of the new radiometric ages benchmarked by the lower (primary) escoria layer, the second episode of sedimentation recorded by lithofacies Sp must have occurred around 9.23 Ma. Because the lower boundary of the ACF is not exposed, and considering the 160 m thick deposits of similar lithology reported from the drill core, the beginning of sedimentation must be much older, probably exceeding 10 Ma. Hence, the previous interpretation by Pascual et al. (1996) that the Chasicoan sedimentation followed the withdrawal of the mid-Miocene seas is supported here. Although uppermost lithofacies association 3 is younger than 9.02 Ma, the total duration of sedimentation remains unconstrained and could have extended to 8.7 Ma.

6. Conclusions

Lithostratigraphically, the lithofacies identified does not support the current differentiation of the Arroyo Chasicó Formation into two members. Stratigraphic correlations performed following the lateral continuity of the paleosols clearly indicate instead that fluvial erosion of the present Arroyo Chasicó exposed older layers downstream from the BDLT site, not younger ones, as concluded by Bondesio et al. (1980). Because the identification of the two members occurred primarily due to their paleontological content, they represent biostratigraphic entities, not lithostratigraphic units. These results create serious questions for the stratigraphic provenance of fossil remains collected during the past 25 years. Collections that refer to either LBM or VM cannot be properly interpreted, because their lithological identification and lateral continuity are insufficiently defined. Moreover, the absence of detailed references to the precise stratigraphic setting of the fossil remains collected by different teams requires that the late Miocene biostratigraphy be reassessed. In addition, the significance, identification, and boundaries of recently proposed local biozones (Tonni et al., 1998; Cione et al., 2000; Cione and Tonni, 2005) should be reexamined carefully. New fossil collections within the context of the stratigraphic analysis presented herein will shed light on the biostratigraphy and paleobiological changes of the late Miocene. The new radiometric dating of impact glasses and paleomagnetic reversals also establishes, for the first time, independent age constraints that will enable the placement of the revised biostratigraphy into a global, environmental context.

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