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RESEARCH PAPER

Neogene–Quaternary in Tandilia, South America: litho- bio-magnetostratigraphy

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Abstract This paper aims to contribute to the stratigraphic and geochronological knowledge of the Neogene–Quaternary of the geologic province of Tandilia by doing lithostratigraphic, paleomagnetic and paleontological analyses. Four lithostratigraphic units have been recognized. The oldest (Late Miocene) constitutes a unit composed of colluvium deposits; it lays in erosional unconformity over the Neoproterozoic rocks. This unconformity is related to important events in the Andes during the Middle-Late Miocene. Over the oldest colluvial sediments, and placed in erosional unconformity, there are sediments assigned to the Barker Formation which are essentially fluvial deposits with a development of several paleosols. Owing to the fossil remains, this unit is assigned to the Montehermosan-Chapadmalalan Stage/Age, whereas the paleomagnetic record would correspond to C3A, Gilbert and Gauss chrons. So, the age is narrowed to the timespan 7.1–3.1 Ma (Late Miocene–Early Pliocene). The Vela Formation lays in erosional unconformity over the Barker Formation. It also has fluvial origin, while the youngest unit (Las Ánimas Formation) corresponds to loess. Both units provide normal polarity and were assigned to Brunhes chron (<0.78 Ma). The Vela Formation presents fossil remains from Bonaerian-Lujanian Stage/Age and belongs to the Middle Pleistocene. The hiatus between the Barker and Vela Formations seems to be considerable: it represents at least 2.6 million years. The reason for the lack of sedimentary records is still a matter of discussion. The deposition of Las Animas Formation seems to span the last 40,000 years. However, this could be linked to a major entrance of wind-carried sediments during dry periods, including the Last Glacial Maximum. The hiatus between the Vela and Las Ánimas Formations may have been over 100,000 years.

Keywords Late Cenozoic · Loess · Argentina · Hiatus · Tandil

RESUMEN El objetivo del presente trabajo es contribuir al conocimiento estratigráfico y geocronológico del Neógeno-Cuaternario de la provincia geológica de Tandilia por medio de análisis litoestratigráficos, paleomagnéticos y paleontológicos. Se han reconocido cuatro unidades litoestratigráficas. La más antigua (Mioceno tardío) está compuesta por depósitos coluviales y se encuentra en discordancia erosiva sobre las rocas neoproterozoicas. El origen de esta discordancia se relaciona con importantes eventos en los Andes durante el Mioceno medio-tardío. Sobre los mencionados sedimentos coluviales, mediante una discordancia erosiva, yacen los sedimentos asignados a la Formación Barker. Son esencialmente fluviales, con

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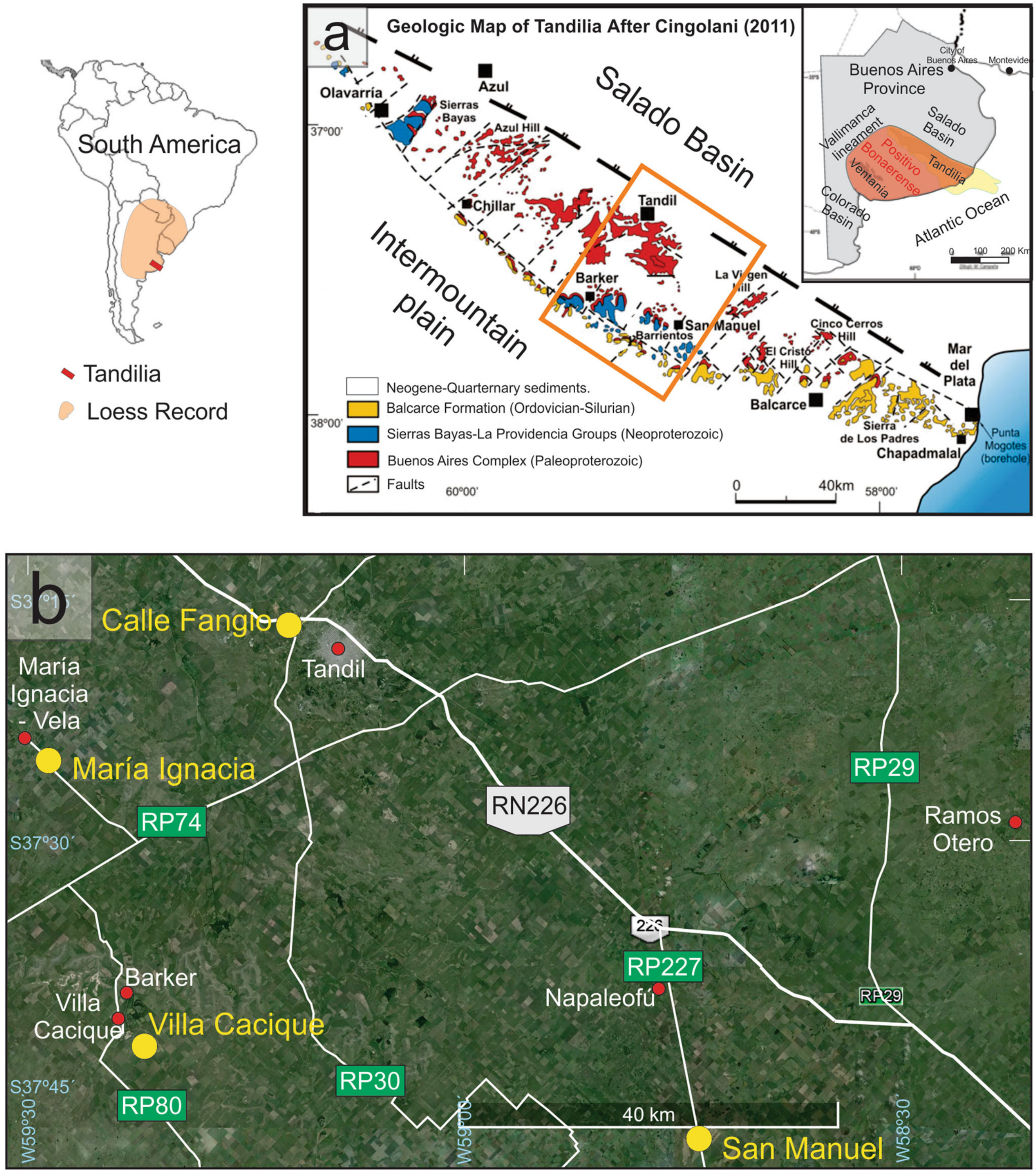

Fig. 1 Location of the study area. **a** Geologic map of geologic province of Tandilia (after Cingolani 2011); above (left), map of Buenos Aires province showing the Positivo Bonaerense morphostructural zone location and its limits. **b** Detailed map showing the location of the stratigraphic sections in yellow

desarrollo de varios paleosuelos. Debido a los restos fósiles, esta unidad es asignada a la Edad/Piso Montehermosense-Chapadmalalense, mientras que el registro paleomagnético correspondería a los crones C3A, Gilbert y Gauss. Por lo tanto, la edad de la unidad se encuentra en el lapso 7.1–3.1 Ma (Mioceno tardío–Plioceno temprano). La Formación Vela se apoya mediante discordancia erosiva sobre la Formación Barker. También tiene origen fluvial,

mientras que la unidad más joven (Formación Las Ánimas) corresponde a loess. Ambas unidades proporcionan polaridad normal y se asignan al Cron Brunhes (<0.78 Ma). La Formación Vela presenta restos fósiles de Edad/Piso Bonaerense-Lujanense y se asigna al Pleistoceno medio. El hiato entre las formaciones de Barker y Vela parece ser considerable: representa al menos 2.6 millones de años. La razón de la falta de registro sedimentario entre ambas unidades es aun motivo de discusión. La depositación de la Formación Las Animas parece abarcar los últimos 40,000 años. Sin embargo, esto podría estar relacionado con un ingreso principal de sedimentos transportados por el viento durante los períodos secos, incluido el último máximo glacial. El hiato entre las formaciones Vela y Las Ánimas puede involucrar más de 100,000 años.

PALABRAS CLAVE Cenozoico tardío · Loess · Argentina · Hiatus · Tandil

1 Introduction

Late Cenozoic deposits in the highlands of Buenos Aires province received less attention than those in the plains. This work is done in order to improve and integrate the knowledge of the Neogene–Quaternary deposits of the mountain ranges area of the geologic province of Tandilia (Fig. 1a). The sedimentary sequences were studied by applying stratigraphic, sedimentological, magnetostratigraphic and paleontological techniques, in four representative sections (Fig. 1b). These deposits partially cover the mountain ranges and are part of the so-called Pampean loess of South America (Zárate 2003). These loessic sediments include mainly minerals such as plagioclase, volcanic lithoclasts, volcanic glass, quartz, potassium feldspars, titanomagnetites, ilmenite, pyroxenes and amphiboles (Teruggi et al. 1973; Rabassa 1973; Zárate and Blasi 1991, 1993), which reveal a clear orogenic influence of Cordillera de los Andes. It is considered that the transportation from the piedmont of the Andes took place in many steps, involving fluvial, aeolian and mass movement processes. Volcanic glass from Plinian eruptions was carried by the wind from the Andean volcanic arc to the study area. There was also local contribution from areas of higher elevation, mainly for the coarser fraction (Rabassa 1973). The main purpose of this work is to contribute to the stratigraphic knowledge of the geologic province of Tandilia and a better understanding of the Negeone-Quaternary sedimentary dynamics of South America.

The Tandilia and Ventania mountain ranges and the plain between them constitute what is referred to as the Positivo Bonaerense morphostructural zone (Bonaerian High), which limits with the Vallimanca lineament to the northwest, the Salado tectonic basin to the north and the Colorado tectonic basin to the south (Fig. 1a).

Table 1 Stratigraphic scheme of the Late Cenozoic in the Sierras de Tandil according Rabassa (1973)

Lithostratigraphic units	
Watersheds	*Fluvial areas*
Las Ánimas Fm	Alluvium
	Tandileufú Fm
Vela Fm	
Barker Fm	

Neogene–Quaternary sediments in Tandilia partially cover Precambrian and Early Paleozoic rocks. These include the igneous–metamorphic basement of Paleoproterozoic age (Buenos Aires Complex), Neoproterozoic deposits of a shallow continental shelf of carbonate and siliciclastic composition (Sierras Bayas Group) and Early Paleozoic shallow marine ortho-quartzites (Balcarce Formation). Shown in the geologic map the distribution of the rocks mentioned above (Fig. 1). A review of the pre-Cenozoic geological background of the geologic province of Tandilia was performed by Cingolani (2011).

The first work related to Cenozoic stratigraphy of the geologic province of Tandilia was done by Tapia (1937) using boreholes located in the Balcarce valleys (Fig. 1a). The author indicated that the sedimentary cover would reach a thickness of 165 m, decreasing towards the slope of the hills. The base of the sequence corresponds to a conglomerate with a clayey matrix, above which Tapia (1937) described as pelites and sandstone assigned to the Pliocene, although he did not reject the possibility of a younger age (Pleistocene). A calcareous level exists on the top of these deposits. Above that and in erosional unconformity is an aeolian unit denominated "Médano Invasor" which was assigned to Late Pleistocene based on fossil contents.

The first lithostratigraphic Late Cenozoic scheme for this region was made by Rabassa (1971, 1973) in Sierras de Tandil (Table 1). He described the Barker, Vela and Las Ánimas Formations in the interfluvial areas, and in the fluvial areas, alluvial Holocene deposits that lie over the Tandileufú Formation (fluvial). These in turn, lie in erosional unconformity over Vela Formation.

The Barker Formation was described as compact, reddish-brown siltstone, with pedogenesis. Rabassa (1973) indicated also that it may be aeolian. Later, Gómez Samus (2016) would recognize sedimentary structures of fluvial origin. The age is still uncertain and there are no published fossil findings or radiometric dating to date. Rabassa (1971, 1973) assigned it unconvincingly to Pliocene–Lower Pleistocene. Later, Gómez Samus and Bidegain

(2014) obtained in the María Ignacia village (near Tandil city) reversed magnetic polarity directions that were assigned to Late Gilbert Chron (3.6–4.2 Ma).

The Vela Formation lays in erosional unconformity over the Barker Formation, it presents a variable granulometry and its color is light brown. Rabassa (1973) considered an aeolian genesis, but with important channeled hydric signals. Gómez Samus and Bidegain (2014) and Gómez Samus (2016) indicated that the sediments would have been deposited mainly in a fluvial environment. Towards its top, it is developed a topographic surface corresponding to a regionally extensive calcareous crust; these calcium carbonate deposits may also been affecting older units (Rabassa 1973; Gómez Samus 2016). Rabassa (1973) assigned the Vela Formation to the Middle Pleistocene. In agreement with this Gómez Samus and Bidegain (2014) indicated that this unit was deposited during the Brunhes Chron (< 0.78 Ma). Gómez Samus (2016), based on correlations with outcrops present in Cliffs of the Atlantic coast, suggested that it would correspond to mainly Stage/Age Bonaerian (450–130 Ka. sensu Cione et al. 2007) which is similar to the interpretation of Fidalgo and Gentile (1995). They indicated that fluvial deposits in the Cliff to the south of Mar del Plata corresponded to the youngest Allomember of the Punta San Andrés Alloformation, interpreted as a braided, non-confined fluvial system (Beilinson and Raigemborn 2013), which could be correlated with Vela Formation in Tandilia. In erosional unconformity over the calcareous regional crust lie the sediments of the Las Ánimas Formation (aeolian sandy silt), assigned to the Late Pleistocene-Holocene (Rabassa 1971, 1973). The sediments of the Tandileufú Formation have a fluvial origin and would have deposited at the same time as the Las Ánimas Formation (Rabassa 1971, 1973).

Other stratigraphic proposals for Late Cenozoic deposits of Tandilia were done by Teruggi et al. (1973), Fidalgo et al. (1986), Martínez (2001), Zárate and Mehl (2010) and Poiré et al. (2005, 2013, 2014, 2016).

The sequence described by Teruggi et al. (1973) in Sierras de Balcarce was correlated to the Rabassa (1971) scheme. It involves seven levels over the crystalline basement. Levels 1 and 2 are colluvium-fluvial deposits with paleosols and were correlated to the Barker Formation. Nonetheless, Gómez Samus (2016) and Gómez Samus et al. (2016a, 2017) indicated that both levels were younger than Barker. The third level, mainly fluvial with high amount of $CaCO_3$ (Tandil Paleosurface), was correlated to the Vela Formation. Level 4, which is dominated by loess, was correlated to the Las Ánimas Formation. The rest of the above mentioned levels are more recent materials. In Sierras de Balcarce a stratigraphic scheme was proposed for colluvium deposits (Martínez 2001), that included three lithostratigraphic units of matrix-supported orthoconglomerates, which were tentatively correlated with those units of the scheme of Rabassa (1973), although he did not exclude the possibility of older ages for the lower unit.

The scheme proposed by Fidalgo et al. (1986) corresponds to the Tapalqué creek basin (Olavarría) and it, along with other schemes by the same author, is the most widely used for applied geological and hydrogeological studies in Tandilia (see Silva Busso and Amato 2012 and Giaconi et al. 2014). The authors used terms defined for the northeast of Buenos Aires province (Fidalgo et al. 1973). They indicated that the Pampeano Formation presents plenty of carbonates at its top and assigned it to the Upper Pliocene–Middle Pleistocene. Overlaying this unit described the Lujan Formation (fluvial and swamp environments with paleosols), and La Postrera Formation (loess), both units from Late Pleistocene to Holocene. The aforementioned authors did not indicate correlations to previous schemes.

Zárate and Mehl (2010) worked in the Azul creek basin and described four lithostratigraphic units which they correlated with, among others, those of the Rabassa (1973) and Fidalgo et al. (1986) schemes. The oldest unit (lithostratigraphic unit 1), clayey silt, compact, intense red, poorly stratified, was correlated to the Barker Formation and was assigned to the Pliocene. The following unit (lithostratigraphic unit 2), brown silt with a thick calcareous crust, was correlated to the Vela and Pampeano Formations. The youngest unit (lithostratigraphic unit 3), corresponds to a loess mantle and was correlated to the Las Ánimas and La Postrera Formations. Finally, Zárate and Mehl (2010) mentioned a unit with fluvial characteristics (lithostratigraphic unit A), which was correlated to Tandileufú and Luján Formations.

In different conference papers, Poiré et al. (2005, 2013, 2014, 2016) proposed a stratigraphic scheme for Late Cenozoic deposits in Sierras Bayas (Olavarría), without making any correlation to other schemes. It includes four units (from the base to the top La Alcancía, El Polvorín, La Esperanza and El Búho). The oldest one is clast and matrix supported conglomerates, with whitish calcareous crusts. The following unit includes conglomerate, sand and mud, with few calcareous concretions, which were interpreted as fluvial and flood plain deposits. For this unit, De los Reyes et al. (2013), Zurita et al. (2014) and Zamorano et al. (2015) indicated the presence of vertebrates from Chapalmalalan Stage/Age (5.3–3.3 Ma; sensu Verzi and Montalvo, 2008) and Gómez Samus et al. (2014) registered normal magnetic polarity in the mid-basal section which they tentatively attributed to Gauss Chron (3.6–2.6 Ma). This scheme continues with conglomerates followed by loessic facies strongly calcretized, with fossil content from the Bonaeriane-Lujanian Stage/Age (450–11

Ka. sensu Cione et al. 2007). Finally, the youngest unit corresponds to sandy loess, brown, massive, attributed to the Lujanian Stage/Age (130–11 Ka. sensu Cione et al. 2007).

2 Methodology

The field work comprises the sedimentological description of four stratigraphic sections (Figs. 1b, 2), including characteristics such as thickness, type of contact, granulometry variations, structure, fossil content and pedogenic features. The criterion followed to select the sections was to sample the best representative profiles. Some schematic panels (sketches) in order to consider the lateral variations as the sedimentary columns for lithostratigraphic control were also represented (Figs. 3, 4, 5, 6). Besides, the different environments and the paleontological remains were taken into consideration in order to improve the knowledge of the study area. A detailed description of the fossil content was made with the purpose of biostratigraphic interpretations. The timespan indicated for Stages/Ages and biozones are based on the work of Cione and Tonni (2005), Cione et al. (2007), Verzi and Montalvo (2008) and Tomassini et al. (2013). The paleomagnetism analysis was done for stratigraphic and chronologic interest, for which 233 samples were collected in ten paleomagnetic profiles (PP1–PP10) whose location and relation to the lithologic units is shown in the panels (Figs. 3, 4, 5, 6). Four paleomagnetic profiles correspond to the Villa Cacique section (PP1–PP4), one to the María Ignacia section (PP5), three to the Calle Fangio section (PP6–PP8) and two to the San Manuel section (PP9–PP10). Paleomagnetic sampling was performed using the method described in Bidegain (1991), Bidegain et al. (2005, 2012), Bidegain and Rico (2012), Rico and Bidegain (2013), Gómez Samus and Bidegain (2014), Gómez Samus et al. (2016a, 2017), among others, which has given excellent results in the magnetostratigraphic studies of the Pampean sediments. The vertical distance of the site of sampling varied between 5 and 20 cm. The samples were analyzed with a magnetometer minispin Molspin Ltd. and an alternating field demagnetizer of the same brand. The demagnetization started at low fields of 2.5 mT, and reached peak fields of between 80 and 100 mT, in at least eleven steps (2.5–5–7.5–10–15–20–25–30–40–60–80 mT). The data thus obtained was processed with the SUPERIAPD2000 software and analyzed by stereographic projections, demagnetization curves and by the end point diagrams. The characteristic remanent magnetization (ChRM) and maximum angular deviation (MAD) were estimated for all the samples by using the Kirschvink method. The information generated by the paleomagnetic analysis, including mass normalized magnetic intensity (J°), magnetic declination (D) and magnetic inclination (I), was represented related to the lithostratigraphic units of the profiles. It was possible to identify normal, reverse and anomalous (namely, declinations that are roughly opposite to what they should be for the measured inclinations) polarity zones, that were related to the lithostratigraphic analysis and fossil content and the stratigraphic descriptions, also allowed the assignment of polarity changes to the geomagnetic reversal time scale of Gradstein et al. (2012).

3 Analysis of the results

3.1 Lithostratigraphy and sedimentology

Sediments showed loessoid characteristics, corresponding to primary loess and reworked loess, mainly by fluvial activity (Figs. 3, 4, 5, 6). Four lithostratigraphic units were identified in the Villa Cacique stratigraphic section, while only three in the other localities. So it was possible to establish a correlation between them, based on lithological properties (Figs. 3, 4, 5, 6) and stratigraphic arrangement (Fig. 7). Additionally, most of the units can be assigned to the Rabassa (1973) lithostratigraphic scheme (Table 1), which will be followed in this work. In all of them, there is a clear recognition of the Barker, Vela and Las Ánimas Formations. At the base of the Villa Cacique section a unit was identified which was not described in the scheme of Rabassa (1973), which we to refer as "unnamed unit". These lithostratigraphic units are indicated by different colors in the panels and columns (Figs. 3, 4, 5, 6) and in Fig. 7. Their main characteristics are described below and are summarized in the Table 2.

"Unnamed Unit" Corresponds to a matrix-supported conglomerate (fanglomerate) (Fig 8a) which lies in erosional unconformity over the Loma Negra Formation (Neoproterozoic). Maximum thickness observed is close to 2 meters, with a lateral extension that exceeds 300 m. Its clasts correspond to limestone and subordinately quartzite blocks from the Precambrian sedimentites. The matrix is clayey, reddish (hue 7.5 to 5 YR), with vertic features (Fig. 8b) that show evidence of smectite presence, and root imprints. The lower half of the unit has abundant $CaCO_3$, is massive and hard, and it contains concretions of a considerable size (up to two meters in diameter). This unit is interpreted as a mass movement deposit mixed with loessic material, affected by pedogenesis.

Barker Formation This unit lies in erosive unconformity over the "unnamed unit" in the Villa Cacique section, while in other profiles the base of Barker Formation was not reached. This unit is partially lithified and consists of silts with variable amounts of sand and clay; some levels

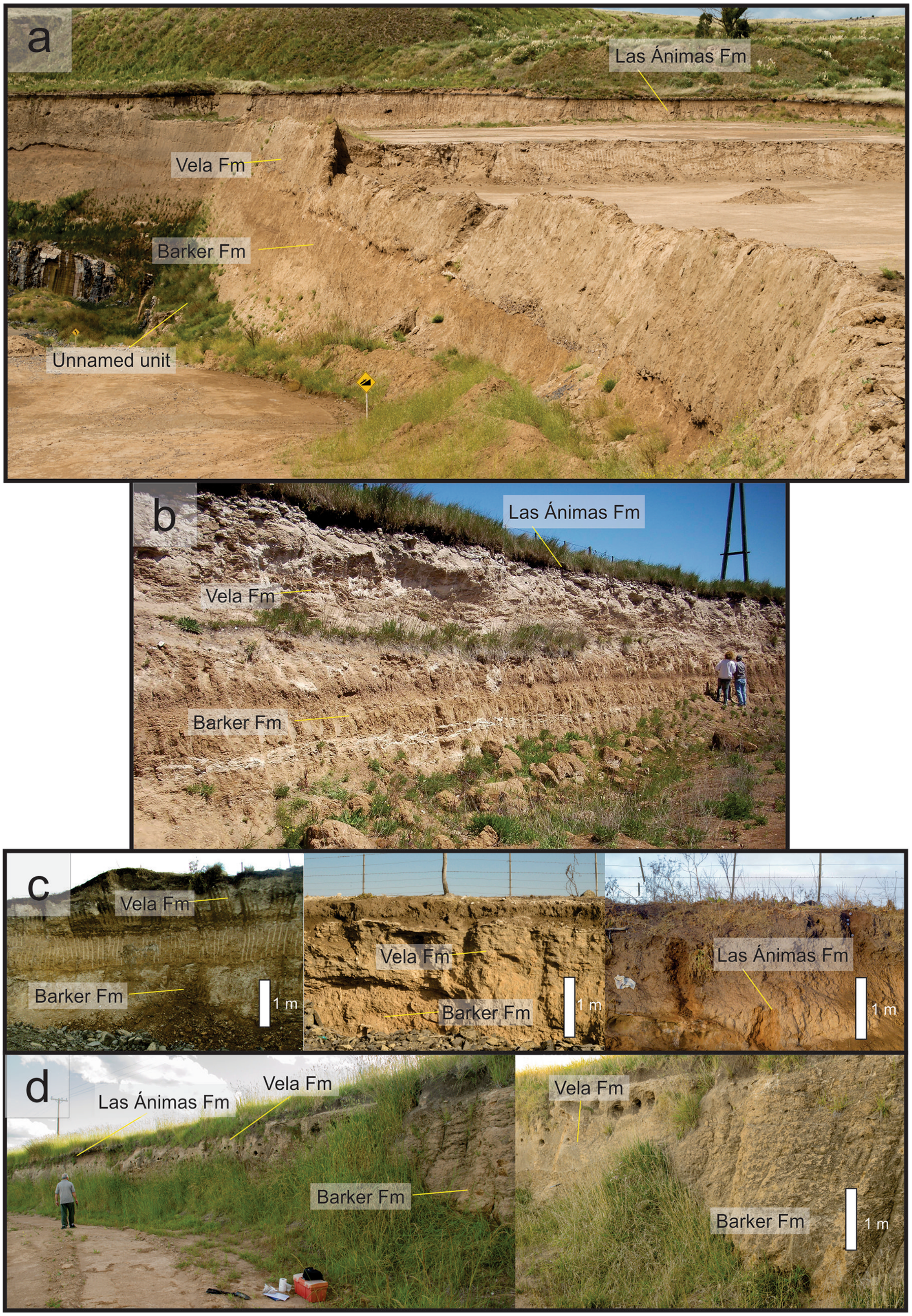

Fig. 2 Stratigraphic sections. **a** Villa Cacique; **b** María Ignacia; **c** Calle Fangio; **d** San Manuel

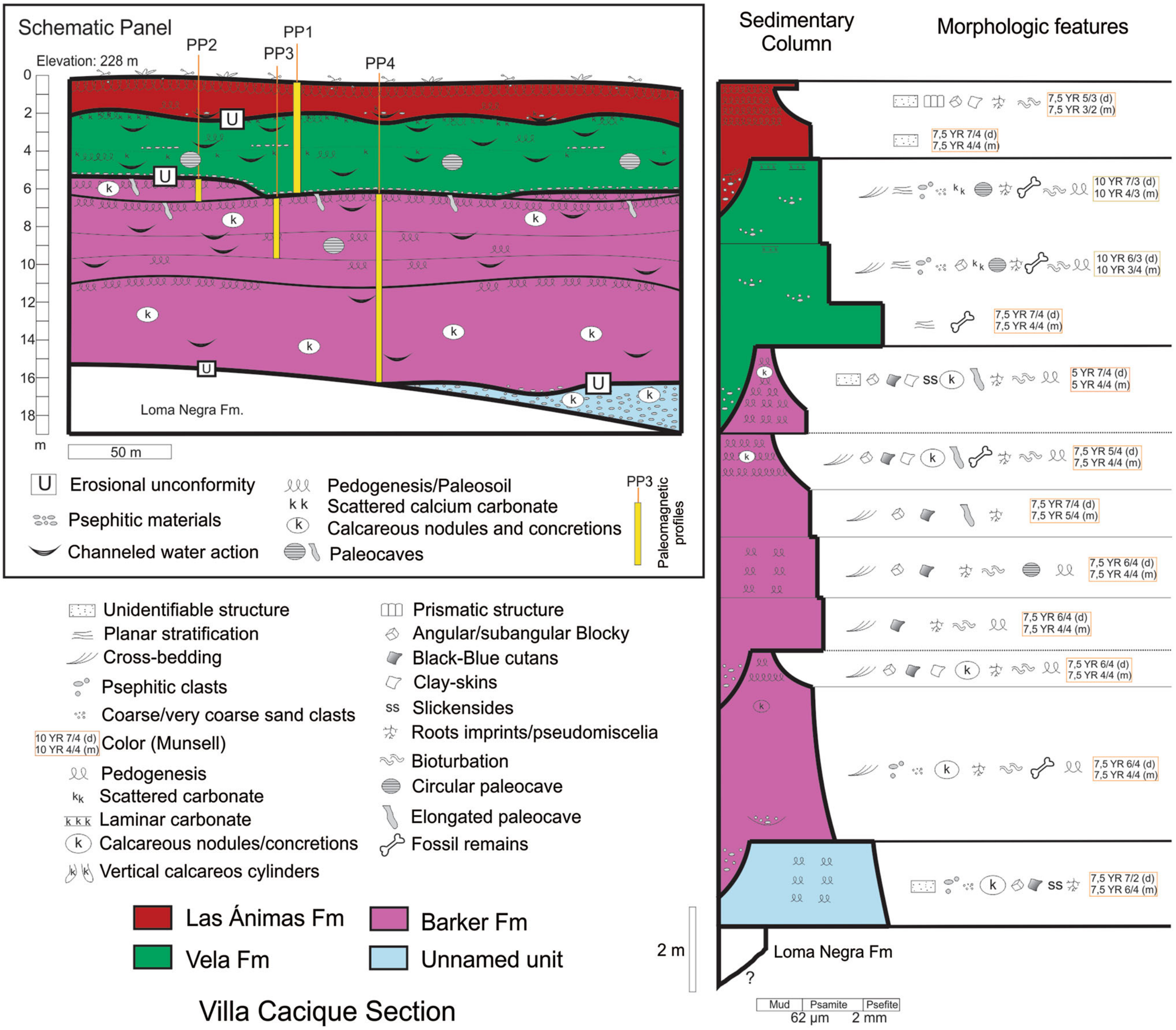

Fig. 3 Schematic stratigraphic sequence and sedimentary column of the Villa Cacique section

have psephitic accumulations, corresponding to Precambrian rock fragments and reworked siltstones, such as those seen in the base of this unit in the Villa Cacique profile (Fig. 9a). The sediments of Barker Formation are brownish-red (hue 7.5 YR) showing diffuse sedimentary structures, generally with crossbedding (Fig. 9b) and parallel stratification, which are indicative of fluvial environments. In the María Ignacia section there is a massive silt level at the top of the profile, probably linked to an aeolian environment. Pedogenic features are common in the entire unit, with several conspicuous paleosols levels. Generally, they show prismatic structure and sub-angular blocks, with clayey and manganese coatings (Fig. 9c), where also identified rhizoconcretions and calcareous concretions of great diameter (Fig. 9d). Elongated paleocaves (krotovinas) were observed in paleosols of the Villa Cacique section (Fig. 3), there were abundant elongated paleocaves with a diagonal shape (Fig. 9e) and containing the observed fossil remains shown in Fig. 10, which will be described below.

Vela Formation: Generally lies in erosional unconformity over the Barker Formation, although it may also be found over older units, even over the crystalline basement. It corresponds to silty sands, with conspicuous crossbedding (Fig. 11a) and subordinated parallel lamination; it contains important psephitic accumulations, most of them in lenses (Fig. 11b); which are more abundant on its base (Fig. 11c). It shows high carbonate content, mainly concentrated at the top, where it constitutes a duricrust of regional extension (Fig.11e), linked to the named Tandil

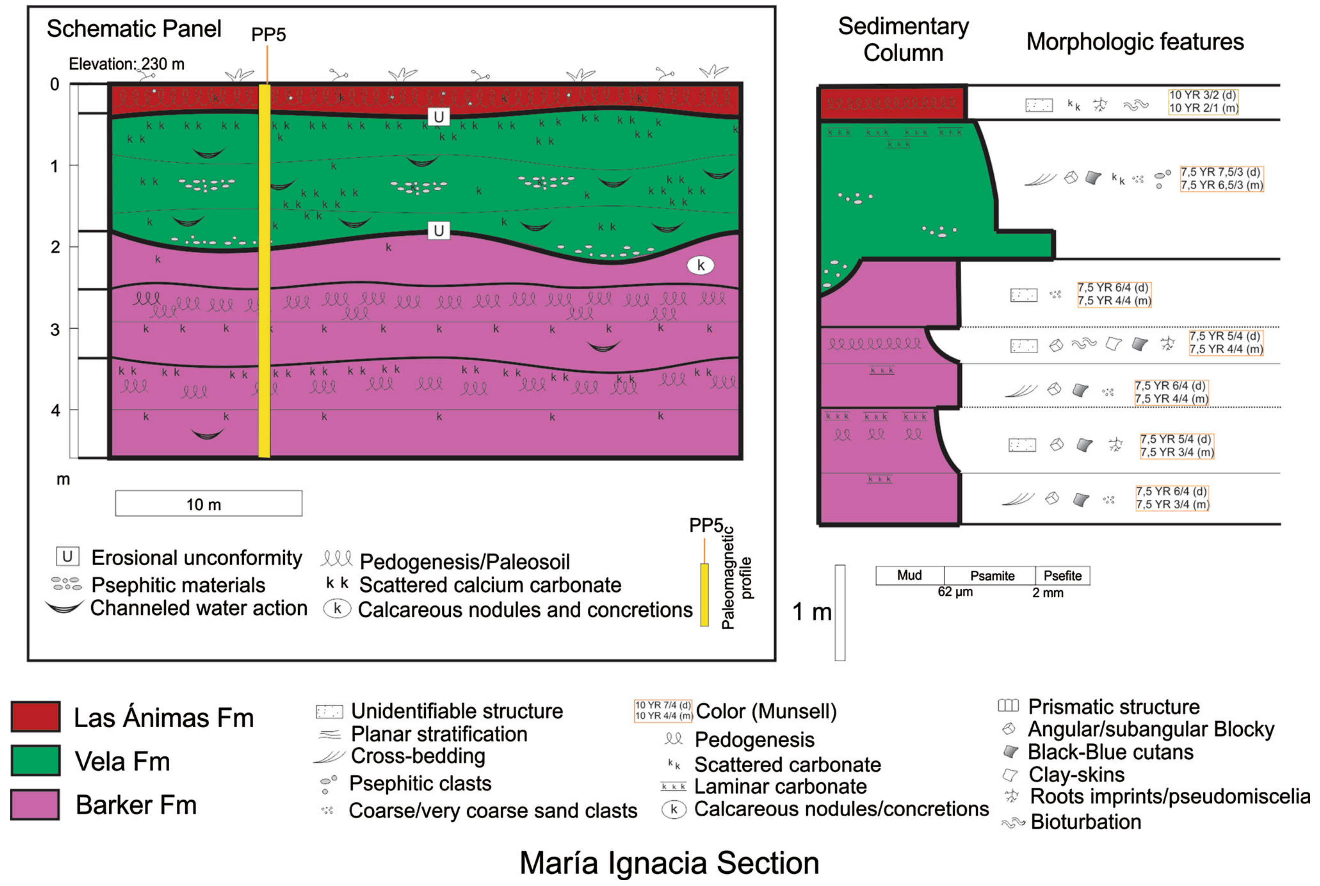

Fig. 4 Schematic stratigraphic sequence and sedimentary column of the of the María Ignacia section

paleosurface (Teruggi et al. 1973). Also, observed were circular paleocaves of large diameter (Fig. 11d), containing fragmented fossil remains and fossil traces of the genus *Taenidium*. The deposits that form this unit are of fluvial origin and of higher energy than those of the Barker Formation.

Las Ánimas Formation: It is an aeolian (loess) unit laying in erosional unconformity (or paraconcordance) over older units. It includes well-sorted sandy silts without recognizable primary structure (Fig. 12). Paleochannels are well represented at the base. This unit constitutes the parental material for most of the soils of the region (see Gomez Samus et al. 2016b). Soils thicknesses are in the order of centimeters, and in places, the loess is completely pedogenized.

3.2 Paleontological records and biostratigraphy

The fossil content found in the top of the Barker Formation was classified as *Lagostomus* (*Lagostomopsis*) sp. and *Actenomys priscus* (Table 3).

Regarding *Lagostomus* (*Lagostomopsis*) sp., at least one dozen species from this subgenus were recognized by many authors for the Neogene in the Pampean Plain. For Cione and Tonni (1995) and Nasiff et al. (2013), this taxon has an extended biochron, from Chasicoan Stage/Age to Chapadmalalan Stage/Age (~ 8 to 3.27 Ma, Late Miocene to Early Pliocene). The high amounts of species and the lack of comparison between them have made it hard to determine the species from largely fragmented material. As a first approach to the systematics of this subgenus, Rasia and Candela (2013) redescribe *L.* (*L.*) *incisus* (Ameghino 1888). This species is characterized by the presence of an anteroposteriorly much more compressed and more obliquely implanted lower dentary series that in *Lagostomus maximus*. This morphology is found in the fossils analyzed here. These features are similar to those in the species *L.* (*L.*) *laminosus* (Ameghino 1891; see Nasif et al. 2013).

Actenomys is of great importance for the biostratigraphy of the Neogene and Pleistocene. Not only *Actenomys*, but also *Eucelophorus*, correspond to the Neogene, but they both show different ecomorphologies (Reig and Quintana 1992; Fernández et al. 2000). Fossils of *Actenomys* were often found in marine cliffs in Buenos Aires province (De Santis and Moreira 2000; Elissamburu et al. 2011), particularly for the Montehermosan and Chapadmalalan

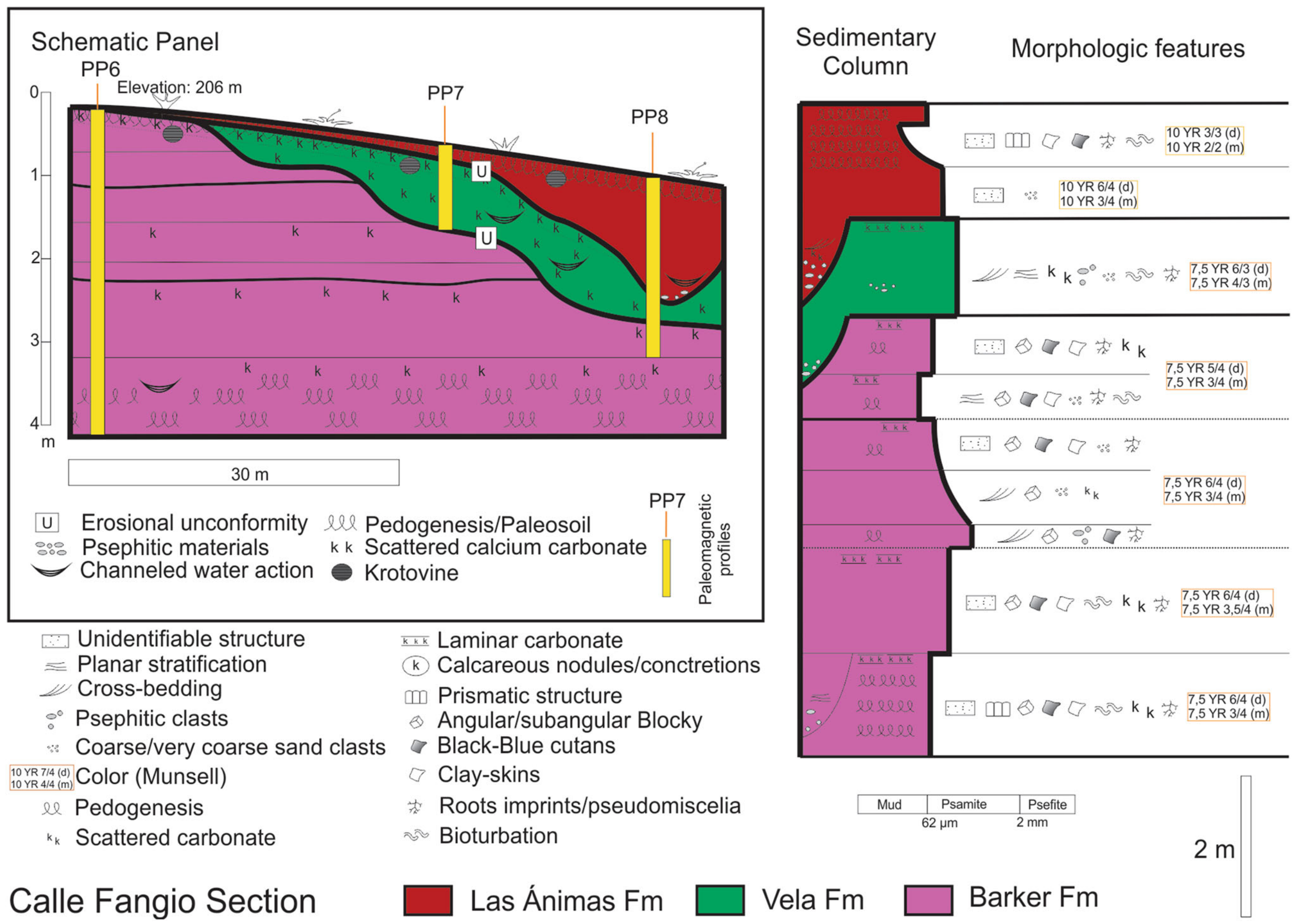

Fig. 5 Schematic stratigraphic sequence and sedimentary column of the Calle Fangio section

Stages/Ages (Early Pliocene). *Actenomys priscus* is the only species recognized for this genus; it is characterized for a slender mandible, with a prominent retromolar fossa, diatema anteroposteriorly large, maseteric crest is not prominent and originates at the level of m2–m3, lower incisors stylized and proodont, and not reduced m3 (De Santis and Moreira 2000; Verzi 2002).

Both taxa (*Lagostomus* (*Lagostomopsis*) sp and *Actenomys priscus*) were mentioned by Deschamps (2005) in the south of Buenos Aires province, for Saldungaray and La Toma Formations. Based on the fauna found in these units, the author stablished the *Actenomys priscus-Plohophorus cuneiformis* Biozone, and mentioned that *A. priscus* is abundant, and that this biozone can be correlated to the *Trigodon gaudry* Biozone, defined in the Farola Monte Hermoso locality (Cione and Tonni 1999). Deschamps (2005) assigned the *Actenomys priscus–Plohophorus cuneiformis* Biozone to the Early Montehermosan Stage/Age. Afterwards, Tomassini et al. (2013) established the *Eumisops laeviplicatus* Biozone to Montehermosan Stage/Age and indicated that *Actenomys priscus* was found in all of Monte Hermoso Formation facies and that it is abundant. On the other hand, *Lagostomus* (*Lagostomopsis*) *incisus* is identified for the Monte Hermoso Formation facies that involves from the oldest to the youngest age. In this way it is possible to say that this taxon is also Montehermosan Stage/Age even though it is not as abundant as *A. priscus*. Meanwhile, Tomassini et al. (2013) assigned the *Eumysops laeviplicatus* Biozone to 5.28–4.5/5.0 Ma and correlated it to the *A. priscus–Plohophorus cuneiformis* Biozone.

It has to be emphasized that in the Vela Formation were observed many fragments of fossil remains, which were more difficult to assign to any. These remains seem to comprise *Hoplophorini indet* osteoderms, and the distal half of a fused metatarsal of Camelidae indeterminate, possibly from the genus *Lama*, and assigned to the Bonarian–Lujanian Stage/Age.

3.3 Paleomagnetism and magnetostratigraphy

The Barker, Vela and Las Ánimas Formations were analyzed for paleomagnetism in all stratigraphic profiles. It was impossible to sample the "unnamed unit".

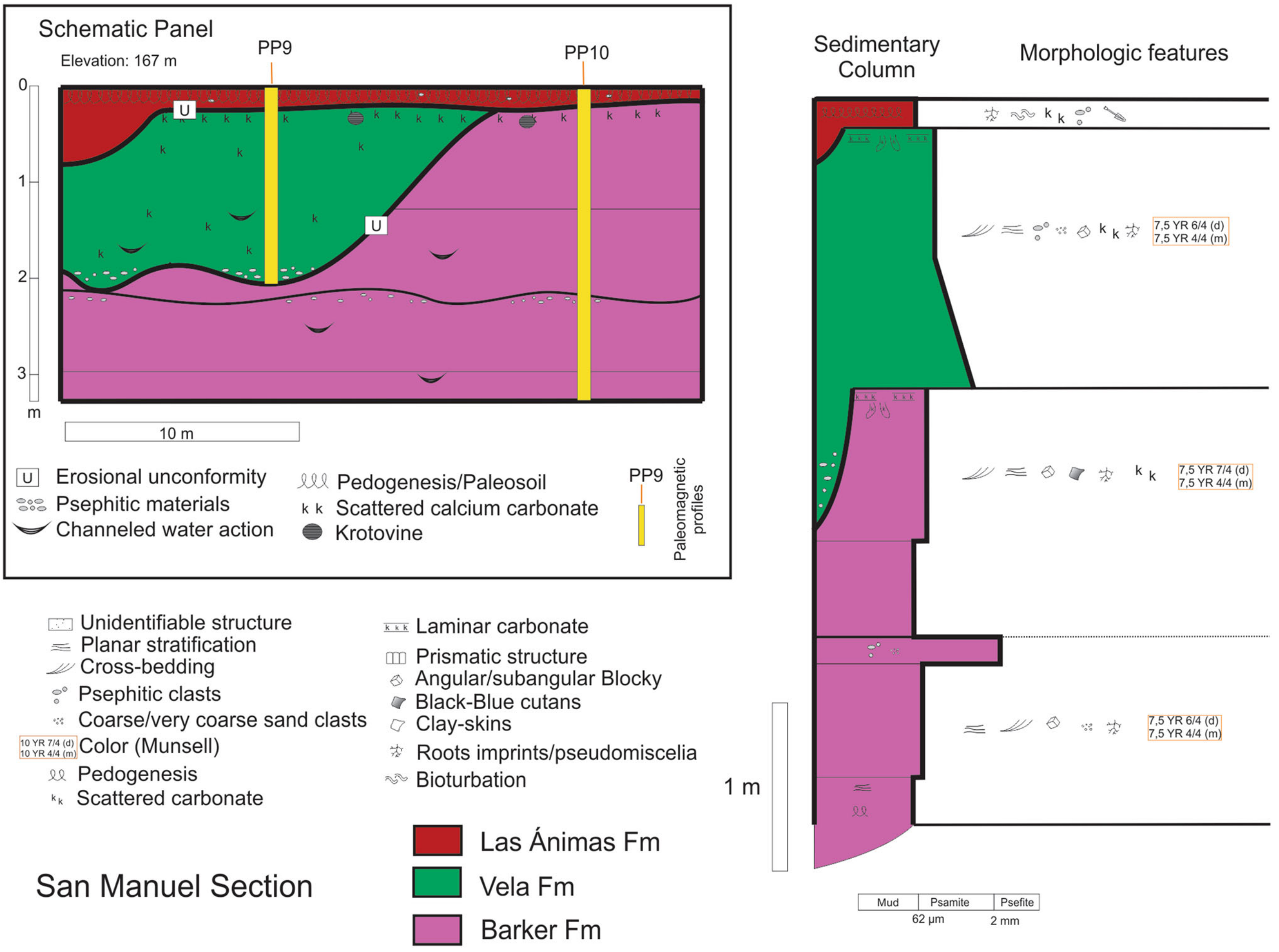

Fig. 6 Schematic stratigraphic sequence and sedimentary column of the San Manuel section

Magnetic intensity mass normalized (J°) oscillated between 1.4 and 683 × 10^{-6} Am^2/kg (Figs. 13, 14, 15, 16).

Characteristic Remanent Magnetism (ChRM) directions were determined after erasing viscous components from peak field which varied from 2.5 to 10 mT. Afterwards, the samples were demagnetized with decreasing of intensity, generally towards the origin of the orthogonal systems; typical behavior for titanomagnetites-bearing sediments. The decay of some samples did not completely reach the origin, but the straight-line fits were very close to it (Fig. 17). Latter is indicative of the presence of an antiferromagnetic phase, like hematite. The values of the maximum angular deviation (MAD) were below 15°. ChRM directions determined normal, reverse and anomalous magnetic polarity zones. The mean $\alpha95$ values of all magnetic polarity zones were 9.6°, always lower than 30°.

Based on the paleomagnetism, lithostratigraphy and biostratigraphy, it was possible to establish a magnetostratigraphic correlation scheme (Fig. 18). For the sediments of the Las Ánimas and Vela Formations, only normal polarity directions were determined (Figs. 13, 14, 15, 16, 18), which were firmly attributed to the Brunhes Chron (< 0.78 Ma). The Barker Formation sediments recorded reverse, normal and anomalous polarities. The fossil remains described in the reverse polarity zone at the top of the Barker Formation (Figs. 13, 18) are useful markers for the establishment of a reliable magnetostratigraphic sequence in the region. The minimum age for the fossils is considered to be 3.2 Ma. Therefore, the reversely magnetized deposits in which the fossils were found, could not be younger than the Mammoth Sub-Chron (3.3–3.2 Ma) and can therefore be confidently assigned to the Gauss Chron. Consequently, the upper normal polarity level corresponds to Middle Gauss (older than 3.1 Ma) and the normal polarity zone located below the fossiliferous level to Early Gauss (3.2–2.6 Ma). Following with this interpretation, the magnetozones of the base would correspond to the Gilbert Chron (6.0–3.6 Ma) and probably to the C3A Chron (7.1–6.0 Ma). Based on the thickness of the magnetozones and the nature of the sediments (Fig. 18),

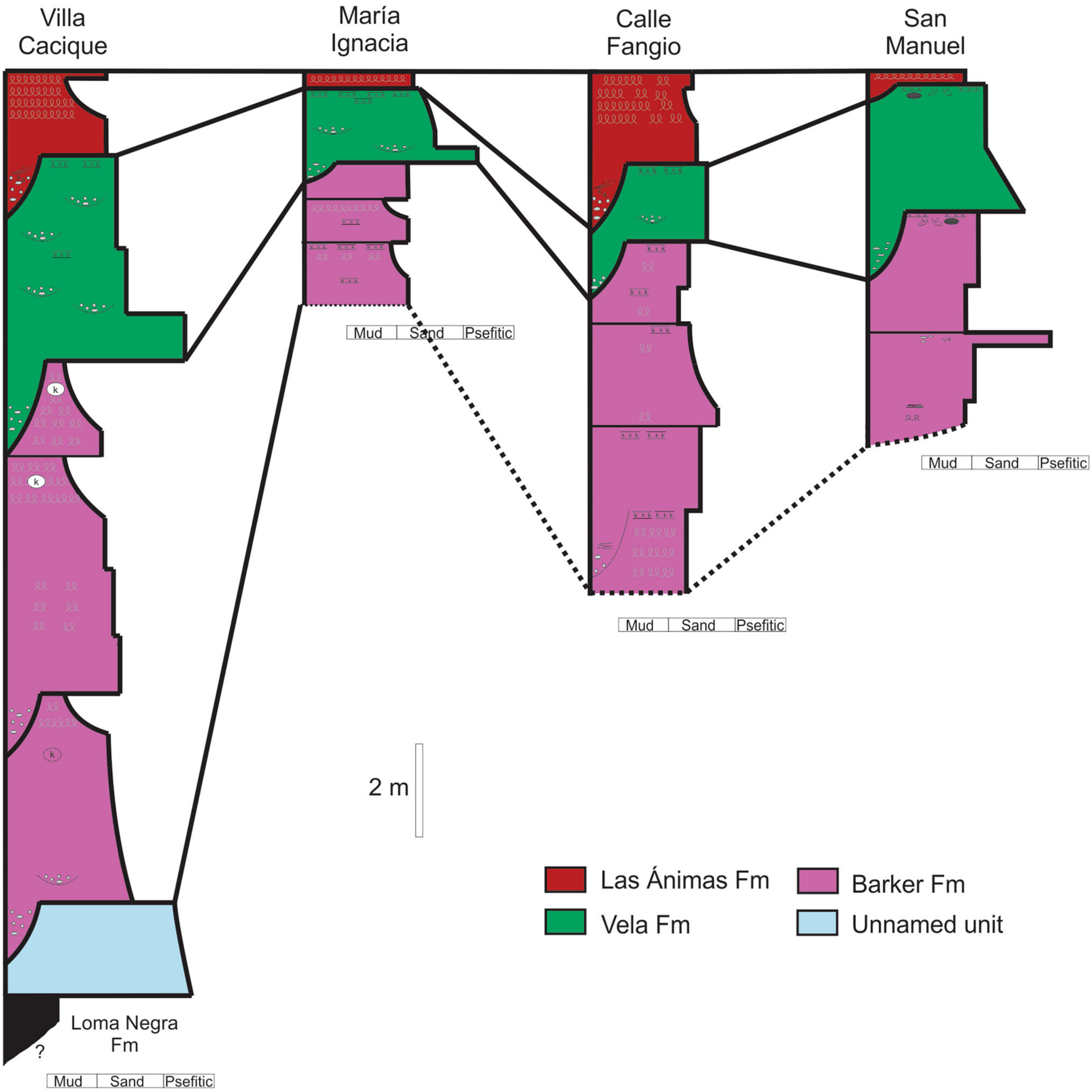

Fig. 7 Litoestratigraphic correlation scheme

the rate of deposition increases to the top of the Barker Formation, in Villa Cacique.

As we have previously expressed the fossils could correspond to *Eumysops laeviplicatus–Plohophorus cuneiformis biozone* (5.3–4.5/5.0 Ma), then the age of the Barker Formation may be somewhat older. Based on the aforementioned data, deposition of the Barker Formation may have started before C3A Chron and terminated during the Gilbert Chron (Fig. 18).

In all the other stratigraphic profiles, the Barker Formation reveals reversed, anomalous and normal polarity that cannot be assigned precisely to the geomagnetic reversal time scale. However, given the considerable thickness of the reversed zones, this could correspond to the Gilbert Chron, even though other possibilities cannot be discounted.

The presence of some anomalous polarity zones has also been reported in previous paleomagnetic studies carried out

Table 2 Description and sedimentary environments of the lithostratigraphic units of the Neogene–Quaternary of the Sierras de Tandil, Stage/Ages, magnetic polarities and chrons and proposed ages

Lithostratigraphic unit	Description	Sedimentary environment	Stage/age	Magnetic polarity	Magnetic chron	Age		
Las Ánimas Fm	Sandy silt, well-sorted, without recognizable primary structure. Brown color	Aeolian (loess)	Lujanian–Platan?	Normal	Brunhes	Quaternary	Late Pleistocene–Holocene	< 40 Ka
Vela Fm	Silty sands and conglomerates with cross and paralell stratitication. Lightbrown color. Abundant $CaCO_3$ that towards the top is grouped in horizontal layers (Tandil Paleosurfase)	Fluvial	Bonaerian				Middle Pleistocene	450–130 Ka
Barker Fm	Coarse silt and fine sand. Reddish brown color. Present conglomerate levels and paleosols development. Difuse cross-bedding and paralell stratification; scarse levels structureless	Fluvial; eventually aeolian	Montehermosan–Chapadmalalan	Reverse–Normal–Anomalous	C3A?–Gilbert–Gauss?	Neogene	Late Miocene–Early Pliocene	7.1–3.1 Ma
Unnamed unit	Matrix-supported conglomerate; clast-supported towards the base. The matrix is silty clay, loessoid, redish, with vertic features; pedogenetic evidences	Colluvial	–	–			Late Miocene	< 12 Ma

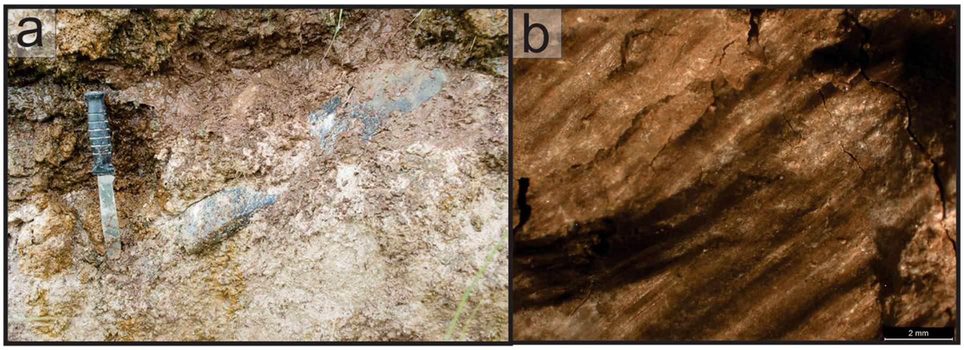

Fig. 8 The "unnamed unit". **a** Clast of micritic limestone in clay matrix; **b** slickensides in matrix

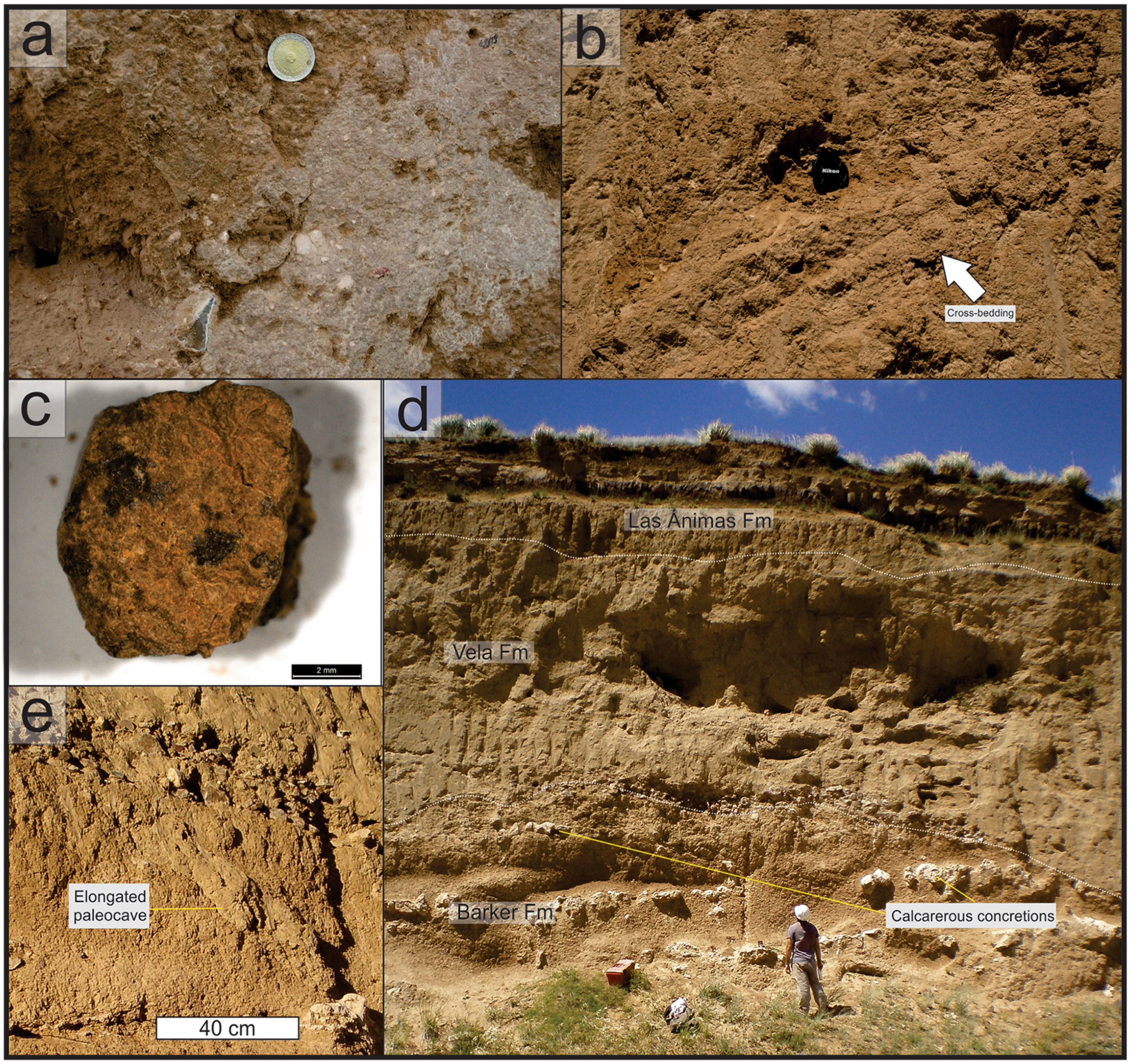

Fig. 9 Barker Formation. **a** Matrix supported conglomerate; **b** cross-bedding; **c** subangular blocky of the paleosol; **d** Loma Negra quarry (Villa Cacique), toward the base are indicated the carbonate concretions; **e** elongated paleocave

in loessic sediments from the Late Cenozoic (Nabel and Valencio 1981; Valencio and Orgeira 1983; Orgeira and Valencio 1984; Bobbio et al. 1986; Orgeira 1988, 1990; Bidegain, 1991; Nabel 1993; Bidegain et al. 2012; among others). Orgeira and Valencio (1984) suggest that anomalous directions are common in Pliocene sediments of Mar del Plata-Miramar cliffs. As a first approach to the knowledge of this phenomenon causes a summary of the explanations given until now is found in Gómez Samus (2016).

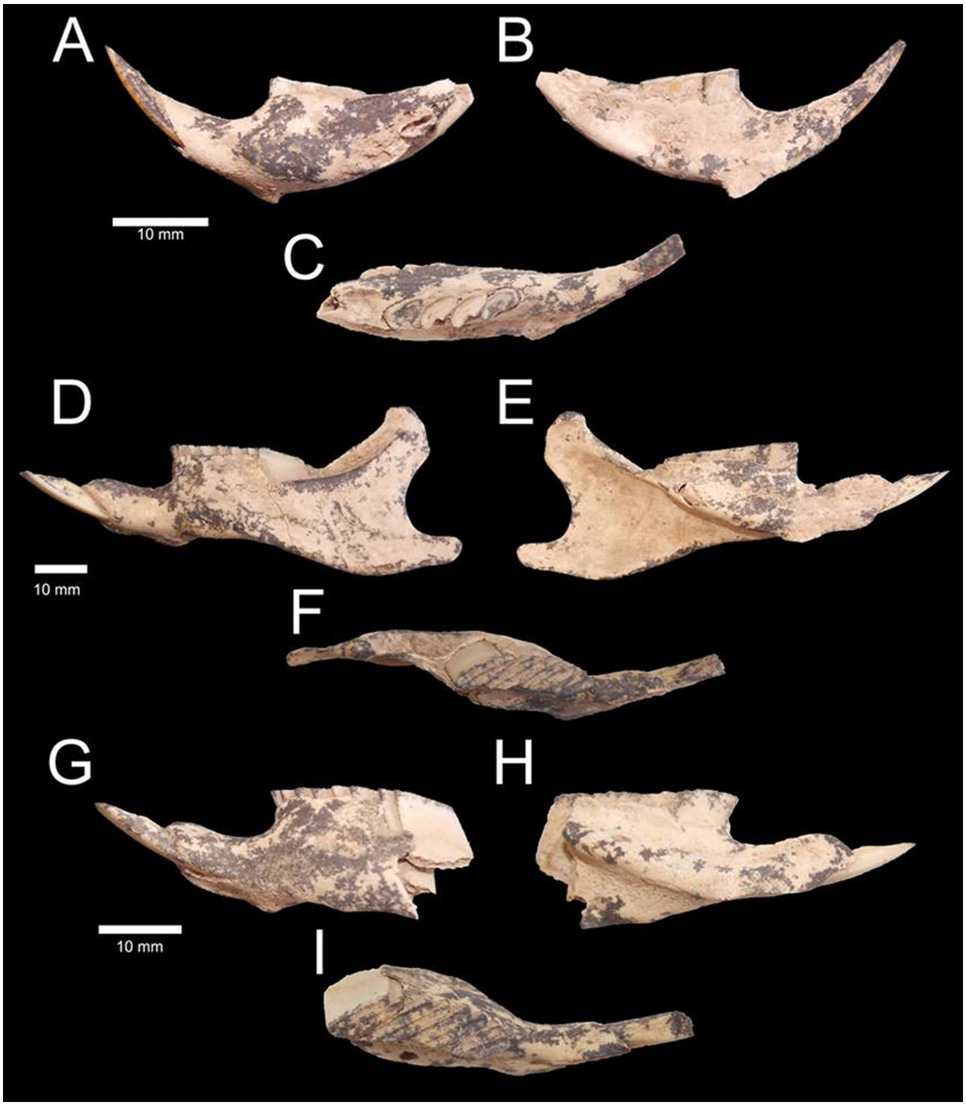

Fig. 10 Fossils of the Barker Formation. **a**–**c** Left hemimandible of *Actenomys priscus* in lateral (**a**), medial (**b**) and occlusal (**c**) views. **d**–**i** Two left hemimandibles corresponding to *Lagostomus* (*Lagostomopsis*) sp. In lateral (**d**, **g**), medial (**e**, **h**) and occlusal (**f**, **i**) views

4 Discussion

4.1 Ages and correlations with other sedimentary units

Based on geologic, paleomagnetic and paleontological characteristics it is possible to establish ages (Table 2) and relate the units with other stratigraphic schemes in Tandilia.

The "unnamed unit", despite the fact that it could not be sampled for paleomagnetism and that no fossil were found, was assigned to the Late Cenozoic cycle based on the matrix features, in particular its loessic character. This cycle of sedimentation started, according to Zárate (2005), around twelve million years ago. More precisely, and taking into account the stratigraphic correlations and the ages of overlying units, it is possible to limit its age to Late Miocene. Furthermore, it must be pointed out that in other localities of Tandilia, similar sediments are lying over Precambrian rocks, such as those described in Sierras de Balcarce (Tapia 1937; Martínez 2001) and Sierras Bayas (Poiré et al. 2013, 2014, 2016), indicating that this unit should be of considerable areal extension. Despite this, we decided not to establish a formal name for this new lithostratigraphic unit until a better definition of its regional expression and lateral extent is made.

The Barker Formation can be assigned to the Late Miocene–Early Pliocene based on its fossil content and the magnetic reversal records. However, if it is considered to belong to the Late Miocene–Early Pliocene Subcycle of Zárate (2005), must be younger than 7 Ma. This unit can be correlated with the deposits described by Poiré et al. (2005, 2013, 2016) in the locality of Sierras Bayas where also fossil fauna assigned to the Early Pliocene was found. The Barker Formation can also be correlated with the oldest unit of the Azul creek Basin (Zárate and Mehl 2010)

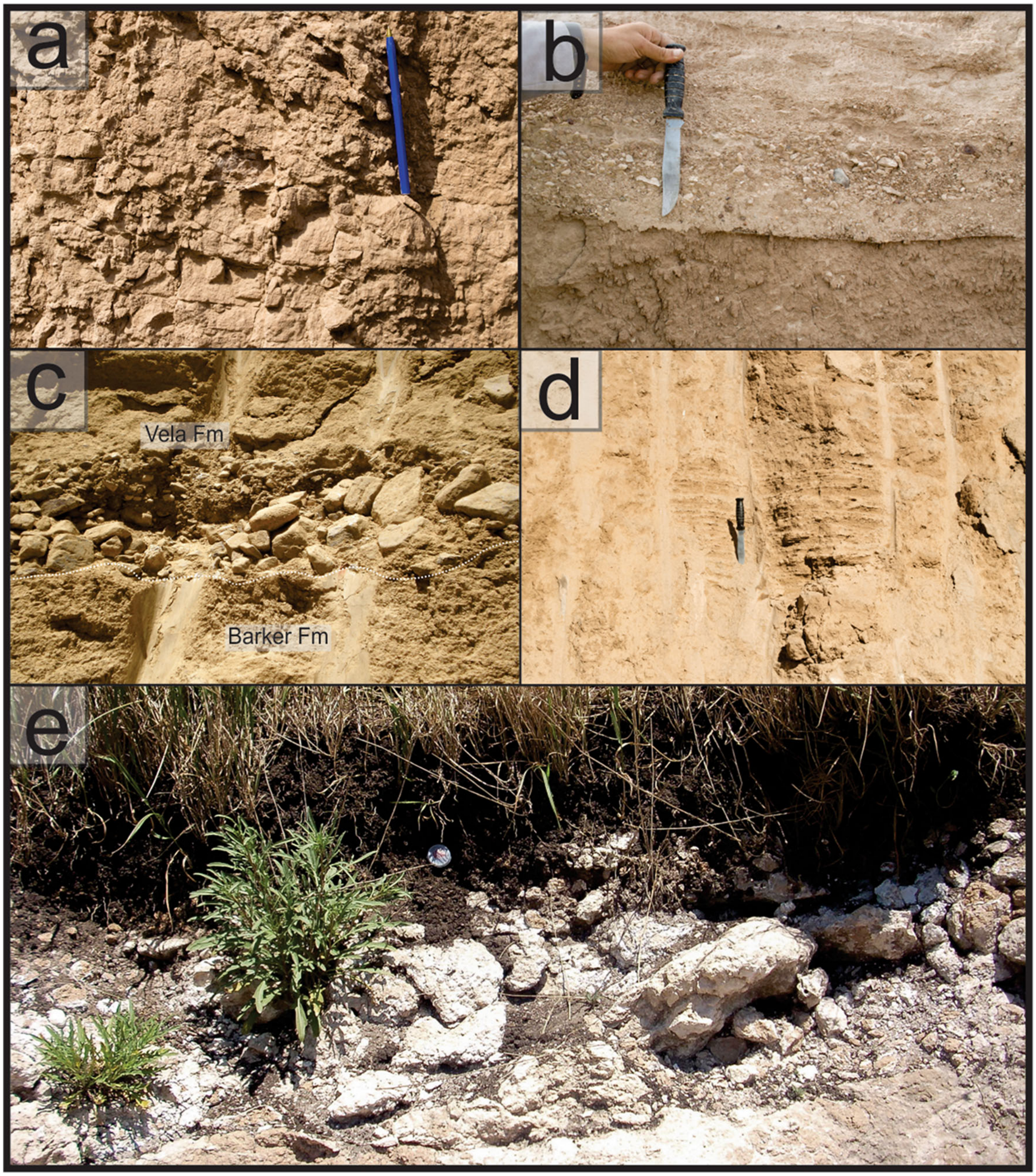

Fig. 11 Vela Formation. **a** Cross-bedding; **b** psephitic lenses; **c** basal conglomerate; **d** circular paleocave; **e** carbonate accumulation at the top (Tandil Paleosurface)

and with Pliocene sedimentary exposures of the cliff along the Atlantic coast (between Miramar and Mar del Plata) where Orgeira and Valencio (1984), Orgeira (1988, 1990) and Rico et al. (2014) recorded normal, reverse and anomalous polarities zones, which they assigned to Gauss and Gilbert Chrones. Barker Formation could also be correlated with the sediments bearing the Miocene–Pliocene boundary recently reported in the Quequén Salado River Basin (Beilinson et al. 2017).

The magnetic directions recorded in the sediments of the Vela Formation assigned it to the Brunhes Chron (< 0.781 Ma). Gómez Samus (2016) stated there is a calcareous crust (Tandil paleosurface) at the top of Vela Formation covering a huge area, reaching the Atlantic coast. This crust is covered by younger deposits assigned to the marine isotopic stage 5e (ca. 125 Ka) (Gómez Samus 2016). Therefore the Vela Formation was likely deposited during the Middle Pleistocene and given its fossil content would be younger than 450 Ka. The Vela Formation is

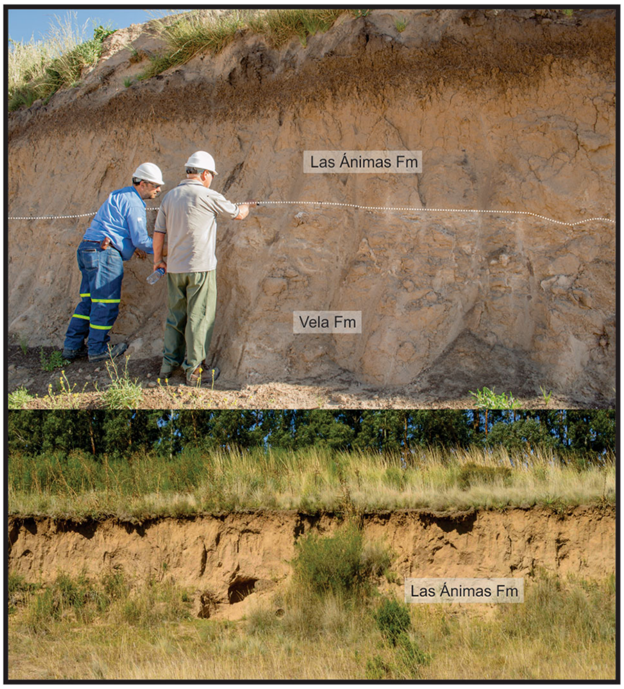

Fig. 12 Las Ánimas Formation

correlated to level 3 (Teruggi et al. 1973) and to LU2 (Gómez Samus et al. 2017) in the Sierras de Balcarce. Moreover it should be correlated to lithostratigraphic unit 2 of the Azul Creek Basin (Zárate and Mehl 2010) and to the La Esperanza unit in the Sierras Bayas (Poiré et al. 2013, 2014, 2016). Finally, it is worth mentioning that the Pampeano Formation of Fidalgo et al. (1986) would comprise not only the Barker but also the Vela Formations. This is an important point to highlight due to the widespread use in hydrogeology of his schemes in this region. In this sense, the sedimentary and lithologic differences make it possible to infer different hydraulic and hydrogeochemistry properties for both lithostratigraphic units. Experimental work evidenced these relationships based on hydrochemistry reactivity studies in loessic sediments and calcareous crusts from the Vela Formation in the region (Drietich et al. 2016; Vital et al. 2016).

The loess of Las Ánimas Formation was deposited during the Brunhes Chron. It is possible to correlate it to other aeolian deposits in Tandilia range, such as “Médano Invasor” (Tapia 1937), level 4 (Teruggi et al. 1973), La Postrera Formation (Fidalgo et al. 1986), lithostratigraphic unit 3 (Zárate and Mehl 2010) and the unit called El Búho (Poiré et al. 2013, 2014, 2016) in Olavarría. These deposits correspond to the Late Pleistocene–Holocene Subcycle (< 40 Ka) of Zárate (2005). It is inferred that most of the Las Ánimas sedimentary material would correspond to the Last Glacial Maximum (26–19 Ka; Clark et al. 2009), even though the presence of younger loess (Zárate and Blasi 1991) cannot be discounted.

4.2 Unconformities and hiatus

An aspect worth to mention in the sequences of Tandil is the presence of erosional unconformities, which evidence the gaps in the sedimentary record. To establish their origin it is necessary to describe specific studies which are not the main target of this paper. However, we were able make some observations and approaches to build some hypotheses.

The study area corresponds to a higher elevation zone, where the space for the accommodation of sediments is limited and the relatively high slopes favor fluvial erosion as well as coarse sediment deposition. It is worth mentioning that there are recent studies focused on explaining regional unconformities of the Late Cenozoic Cycle in the Pampeana Plain which introduce some concepts linked to neotectonics, in particular a perspective related to Andean dynamics (Folguera 2011; Folguera and Zárate 2011; Folguera et al. 2015). For instance, Folguera (2011) highlighted that, despite that the area corresponds to a passive

Table 3 Systematics of fossil remains of the Barker Formation

Assigned Material	Two left mandibles with the posterior end missing	Left mandibles with the posterior end missing
Order	Rodentia	
Suborder	Hystricognathi	
Infraorder	Caviomorpha	
Superfamily	Chinchilloidea	Octodontoidea
Family	Chinchillidae	Ctenomyidae
Subfamily	Lagostominae	–
Genus	*Lagostomus*	*Actenomys*
Subgenus	*Lagostomus* (*Lagostomopsis*)	–
Specie	–	*Actenomys priscus*

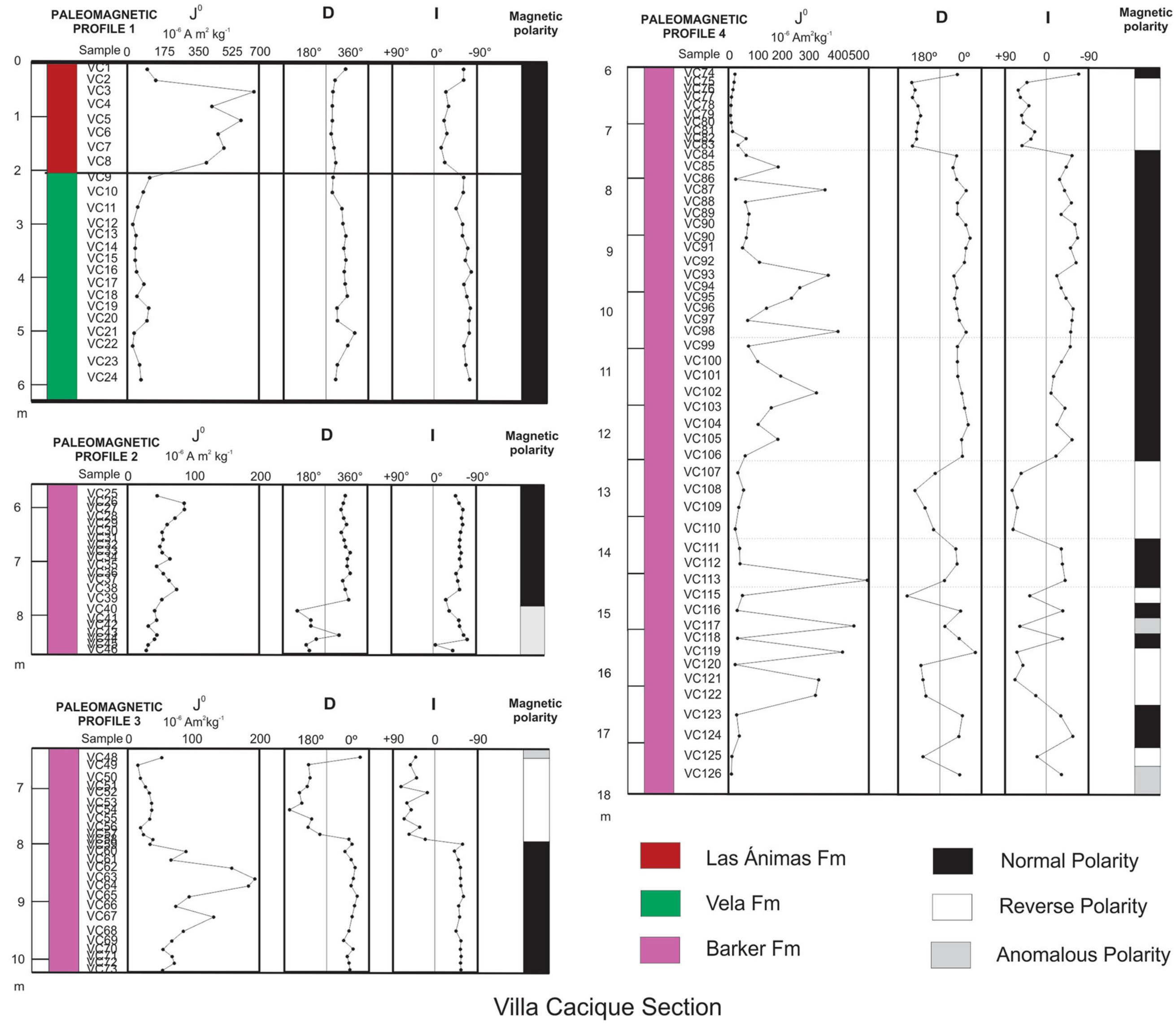

Fig. 13 Paleomagnetic profiles of the Villa Cacique Section

margin, there are record of seismicity in La Plata River (Benavídez Sosa 1998), that had their epicenters in the Punta del Este basin. In order to explain this phenomenon, Folguera (2011) considered, among others mechanisms, the influence of the so-called ridge-push forces, originated in the mid-oceanic-ridge area. Regarding neotectonic activity in Tandilia, it is worth mentioning a recent earthquake (November the 7th, 2016) which registered a magnitude of 4.0 on the Richter scale, with its epicenter close to Garré town Buenos Aires Province (Source: Instituto Nacional de Prevención Sísmica), which is a locality situated 200 km ENE of Olavarría city. Garré is located over Vallimanca lineament, which has a NE-SW direction and constitutes the occidental limit of the Positivo Bonaerense (see Fig. 1).

The oldest unconformity reported in this work separates the Cenozoic sedimentary cover from the Precambrian rocks. Demoulin et al. (2005) considered this erosional surface as the substrate of the Cenozoic cover in Tandilia, and they assigned it to Middle Miocene. The age indicated by the aforementioned authors matches important events in the Central Andes, such as the beginning of the so-called Pampean Flat Slab and the structuring of Malargüe fold and thrust (with the subsequent elevation of San Rafael Block) and Subandean System, estimated between 18 and 10 Ma (Allmendinger et al. 1990; Ramos et al. 2002; Ramos and Folguera 2005; Hernandez and Echeverría 2009; Folguera 2011; Folguera et al. 2015, among others). Following Demoulin et al. (2005), it is possible to link the

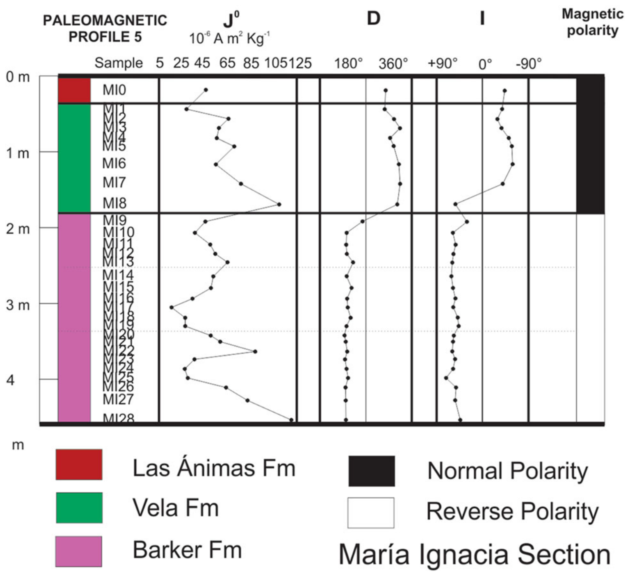

Fig. 14 Paleomagnetic profile of the María Ignacia Section

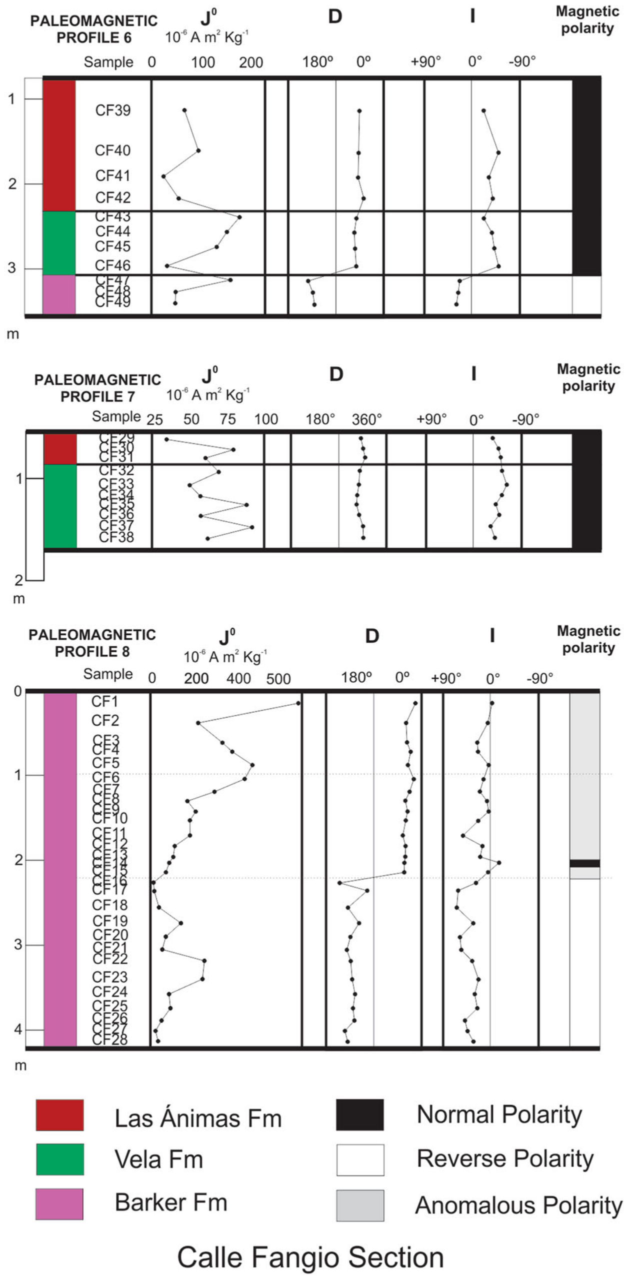

Fig. 15 Paleomagnetic profiles of the Calle Fangio Section

beginning of the Cenozoic sedimentation in Tandil to Andean tectonics.

The next unconformity, between the "unnamed unit" and the Barker Formation, would correspond to the Late Miocene. The sediments of the "unnamed unit" reveal strong pedogenic features (vertisolization, carbonatation), that indicate a period of geomorphic stability; with a posterior sedimentary reactivation, giving rise to the Barker Formation, which starts with fanglomerates at its base, followed by a fine-upward sequence. Folguera (2011) proposed a reactivation for the timespan of 6.8–5 Ma, which could correspond to the beginning of the Barker Formation deposition. This author indicated that the sedimentation continued for 4–3 Ma, when the Positivo Bonaerense would have uplifted, linked to ridge-push forces along old fracture zones, such as Vallimanca lineament and faults in tectonic basins of the Colorado and Salado. This would have ended with the sedimentation of foreland basins sequences. In agreement, we highlight the increase of depositional rates towards the top of the Barker Formation in Villa Cacique. It is also worth mentioning that the studied profiles (Calle Fangio and San Manuel sections) correspond mainly to hills, which are part of the drainage divide area. Towards the top of those hills, the Barker Formation is found at a few centimeters from the surface and constitutes an area that is not currently experiencing sedimentation. So it is possible that the Barker Formation was also deposited at lower elevations than the current ones. In Villa Cacique, the top of the unit corresponds to a highly developed argillic paleosol with large calcareous concretions, which suggest a long period of geomorphic stability. Erosional surfaces covered by fluvial deposits from Middle Pleistocene (Vela Formation) are found towards the hill sides (Calle Fangio and San Manuel profiles). These current landforms (hills), correspond to erosional remnant features, and reflect a clear topographic inversion.

The period of non-deposition between the Barker and Vela Formations is of at least 2.6 million years, including the Late Pliocene and Early Pleistocene. The erosion could be linked to a drop in the base level, even linked to possible tectonic causes. In this sense, it should be noted that in the

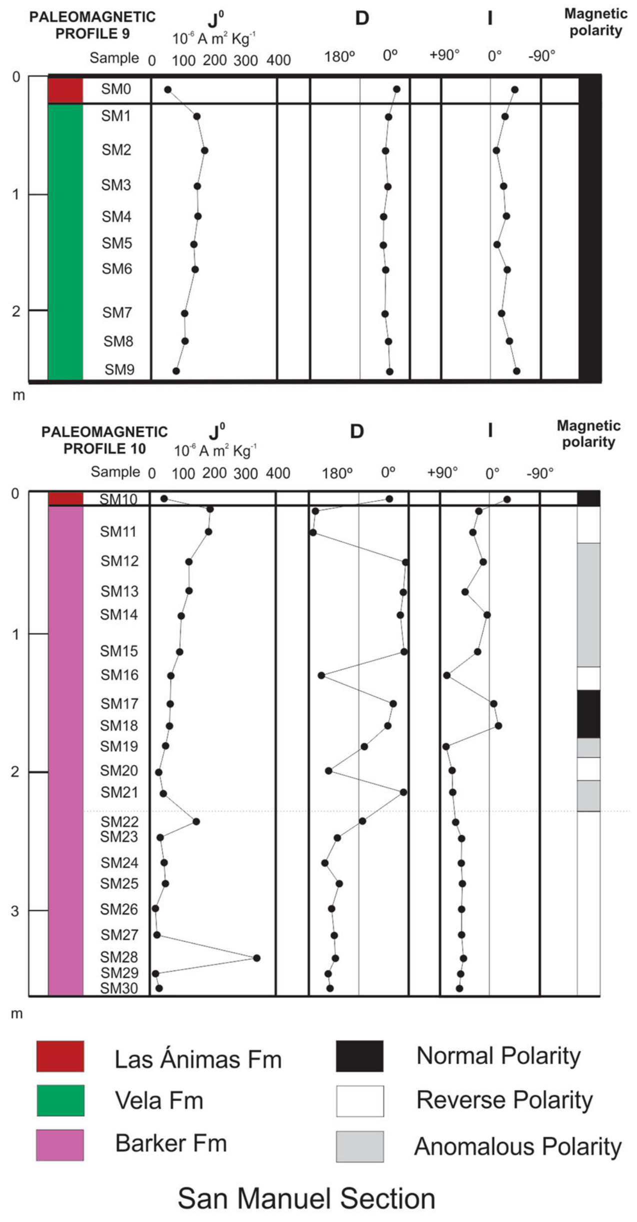

Fig. 16 Paleomagnetic profiles of the San Manuel Section

Balcarce area, Gómez Samus (2016) and Gómez Samus et al. (2016a, 2017) registered a lithostratigraphic unit with an intermediate age between the Barker and Vela Formations that was attributed to the Late Pliocene–Early Pleistocene. Thus, sedimentation should have been more or less continuous during this timespan. The erosion could be explained by fault system reactivation to the southeast of San Manuel (Fig. 1), which may have generated more accommodation for sedimentation in the Balcarce area. Furthermore, it is worth mentioning that Demoulin et al. (2005) records an old paleosurface (Early Cretaceous–Late Oligocene) that in Sierras de Balcarce was found 100 m below that in Sierras de Tandil, probably due to a relative drop of the Balcarce zone.

Finally, the fourth surface corresponds to the contact between the Tandil Paleosurface (which affects the Vela Formation and older units) and aeolian deposits (loess) from the Las Ánimas Formation and the timespan without sedimentary records (considered to be around 100,000 years). The Tandil Paleosurface represents a long period of stability during which it was partially covered by aeolian sediments in Late Pleistocene and Holocene, which in turn was linked to an increase in sediments availability and strong winds, in the dry seasons, mainly during the Last Glacial Maximum.

5 Summary and conclusions

- The deposition of the Neogene–Quaternary sediments in the Sierras de Tandil area began in the Late Miocene. The research carried out involved the four litostratigraphic units exposed from the base to the top: the “unnamed unit”, Barker, Vela and Las Ánimas Formations.
- The “unnamed unit” is considered younger than 12 Ma, and was deposited mainly during the Late Miocene. The Barker Formation may be attributed mainly to Gilbert Chron. The deposition of this unit began in the Late Miocene and continued during the Early Pliocene; being older than 3.1 Ma. The period of non-deposition, between the Barker and Vela Formations, is remarkably long of about 2.6 million years. Las Ánimas and Vela Formations showed normal polarities and are assigned to the Brunhes Chron (< 0.78 Ma). The Vela Formation was deposited during the Middle Pleistocene, and is considered to be younger than 450 Ka, while Las Ánimas Formation was deposited during the Late Pleistocene-Holocene and is considered younger than 40 Ka.

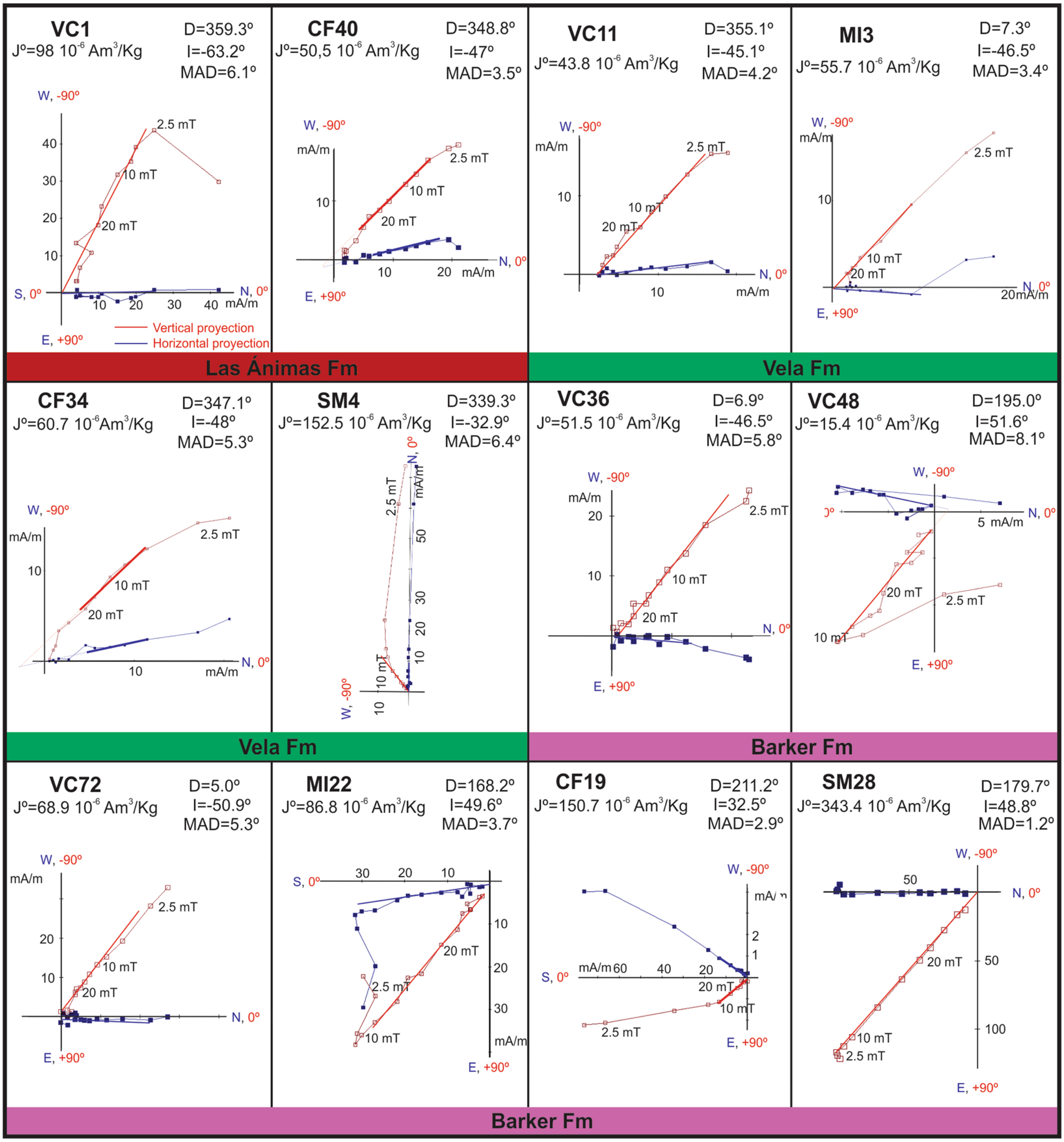

Fig. 17 Orthogonal projections and end points of paleomagnetic samples of Barker, Vela and Las Ánimas formations

– All the units are correlated with other ones in Tandilia, as for instance with localities of Balcarce and Sierras Bayas, showing their regional extension.

– The existence of unconformities are to be highlighted, due to the stratigraphic and timespan gaps they represent.

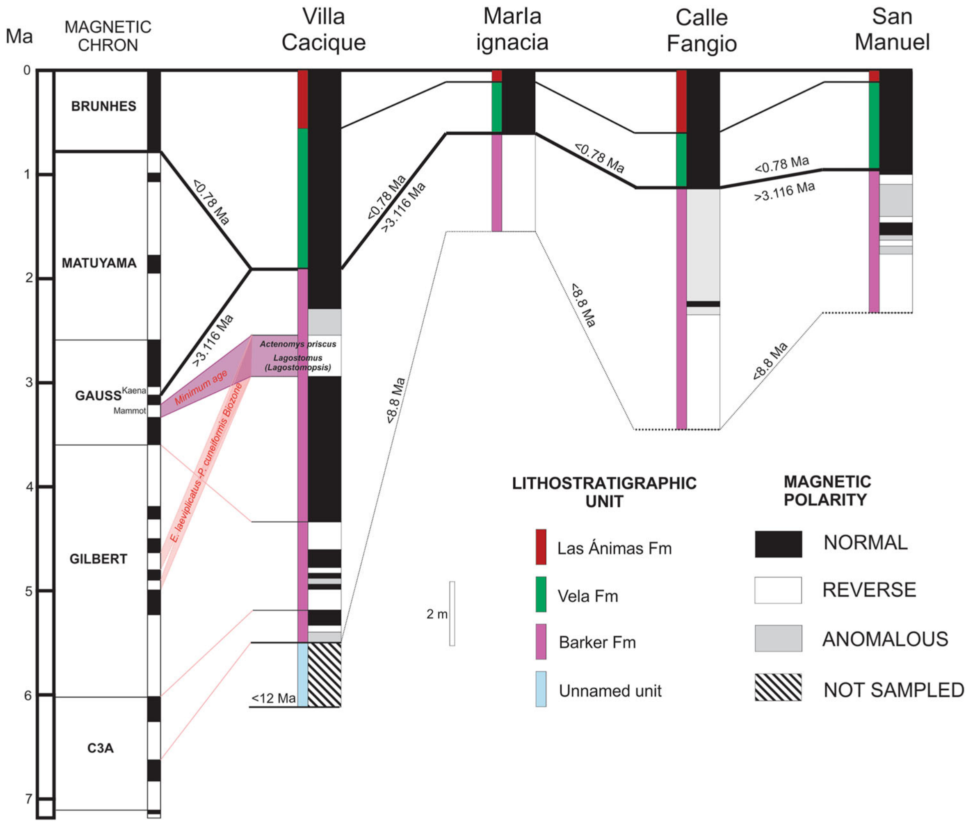

Fig. 18 Magnetostratigraphic correlation

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