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Widespread remagnetization of late Proterozoic sedimentary units of Uruguay and the apparent polar wander path for the Rio de La Plata craton

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SUMMARY

A palaeomagnetic study was performed on three Neoproterozoic sedimentary successions exposed in central and eastern Uruguay in order to better constrain the palaeogeographic evolution of the Río de la Plata craton by the latest Proterozoic. These units comprise the latest Ediacaran to Early Cambrian calcareous Cerro Victoria Fm., exposed in the central Nico Pérez terrane, the late Ediacaran clastic Yerbal Fm. and the calcareous Polanco Fm., exposed in the Dom Feliciano belt, and the Ediacaran clastic Rocha Fm. exposed in the easternmost Punta del Este suspect terrane. The study showed that none of the units carry the original remanence and that they were affected by remagnetizations. The most widespread remagnetization is shown by the Cerro Victoria, Yerbal and Rocha Formations. A dual-polarity post-folding remanence, carried by hematite, was isolated in all these units. Mean directions from them are CV (Cerro Victoria): Dec: 179.1°, Inc: 59.0°, α95: 2.9°, $n = 79$ samples; Y (Yerbal): Dec: 182.4°, Inc: 61.9°, α 95: 4.5°, $n = 38$ samples; R (Rocha): Dec: 4.2°, Inc: −64.9°, α 95: 2.7°, $n = 42$ samples. Their corresponding pole positions are virtually identical (CV: 82.6°S, 309.3°E, A95: 3.9°; Y: 77.0°S, 298.4°E, A95: 5.9°; R: 76.6°S, 291.0°E, A95: 4.2°) suggesting the same magnetization age and process. Comparison with the South American path suggests the Late Permian–Early Triassic or the latest Cretaceous–Palaeogene as the most likely times for its acquisition. These poles are also identical to the pole of the Late Proterozoic La Tinta Fm., which is interpreted as affected by the same remagnetization, and therefore, invalid for palaeogeographic reconstructions. A different magnetic component, also dual polarity and post-folding, was defined at two sites of the Cerro Victoria Fm. and other two of the Polanco Fm., possibly carried by magnetite. The mean geomagnetic poles from both units (CVc: 4.2°N, 343.2°E, A95: 13.8° and P: 3.2°N, 325.8°E, A95: 15.2°) fall on the Middle Cambrian to Early Ordovician segment of the Gondwana APWP, suggesting that age for the remagnetization. This permits to establish the age of the tectonic event affecting the Neoproterozoic units of the Río de la Plata craton as Early Cambrian (*ca.* 525 Ma.). The available palaeomagnetic poles for this craton permit to constrain its palaeogeographic evolution only since approximately 600 Ma.

Key words: Palaeomagnetism applied to tectonics; Remagnetization; Cratons; South America.

INTRODUCTION

The Late Proterozoic is a fascinating and intriguing time in Earth's history. A dramatic change in global palaeogeography during that time was probably an essential ingredient in spectacular global events as the explosive diversification of life forms and hypothetical global glaciations (e.g. Knoll 1992; Hoffman *et al.* 1998). According to most accepted models, break-up of Rodinia supercontinent started by the beginning of the Late Proterozoic while formation of Gondwana probably took place by the end of that era (e.g. Hoffman 1991; Powell *et al.* 1993; Meert & Van der Voo 1997; Meert 2001). Despite a significant advancement in knowledge of the Earth history in the last two decades, a detailed global palaeogeographic evolution during the Neoproterozoic is still elusive. Several factors contribute to this deficit, but undoubtedly the lack of a sufficient number of reliable palaeomagnetic poles for the major tectonic blocks is a major source of uncertainty at this respect.

Figure 1. Schematic map of the Río de la Plata craton. Study areas are marked with squares. (1) Cerro Victoria Fm. in Nico Pérez terrane; (2) Yerbal and Polanco Formations in Dom Feliciano Belt; (3) Rocha Fm. in Punta del Este terrane (modified from Bossi & Navarro 1991; Bossi & Campal 1992; Preciozzi *et al.* 1993).

The Río de la Plata craton (RP) is a relatively small cratonic fragment of South America, but that may have played a key role during the assembly of Gondwana. In a Gondwana reconstruction, RP is surrounded by several tectonic pieces of great significance to unravel the global palaeogeographic evolution that led to the formation of this supercontinent. Among others, RP is bounded by the Achaean Kalahari, Congo—São Francisco, and Amazonia cratons as well as the Neoproterozoic (?) tectonic blocks of Pampia, Patagonia and Arequipa–Antofalla (e.g. Rapalini 2005).

The palaeogeographic evolution of RP in the Neoproterozoic is virtually unknown. Although, in many reconstructions of Rodinia, RP is placed attached to Amazonia, and therefore to Eastern Laurentia (e.g. Weil *et al.* 1998; Meert 2001; Collins & Pisarevsky 2005), no conclusive geological evidence is available for that reconstruction. Furthermore, several studies (e.g. Campos Neto 2000) have shown that in the Late Proterozoic RP was probably surrounded by several oceanic domains that were closed by the end of that era. Furthermore, Kröner & Cordani (2003) have suggested, based on geological evidence, that both, RP and Congo-São Francisco cratons never formed part of Rodinia. The available palaeomagnetic data from RP for the Neoproterozoic have been recently discussed by Thover *et al.* (2005). It is clear from this review that the palaeogeography of RP is almost unknown. In particular, there is no palaeomagnetic constraint for the palaeoposition of RP prior to 800 Ma, A preliminary apparent polar wander track for the interval 600–500 Ma has been recently determined (Sánchez Bettucci & Rapalini 2002; Rapalini 2006). For relatively older ages, the La Tinta Fm. pole (Valencio *et al.* 1980) is the only one that has been often used for a palaeogeographic reconstruction of RP in the mid-Neoproterozoic (*ca.* 750 Ma). However, as we discuss later, this pole is probably flawed.

Considering the importance that a well-defined apparent polar wander path (APWP) for RP may have in Neoproterozoic global palaeogeographic reconstructions, a systematic palaeomagnetic study was carried out in different Neoproterozoic sedimentary units exposed in Uruguay. Although none of them were found to carry the primary remanence, the results suggest that geologically significant remagnetizations affected all these units. This permits to shed new light on the interpretation of previous palaeomagnetic results for RP as well as to place some constraints on the main deformational event that affected marginal areas of the Río de la Plata craton during the final stages of Gondwana assembly (Brasiliano Orogeny).

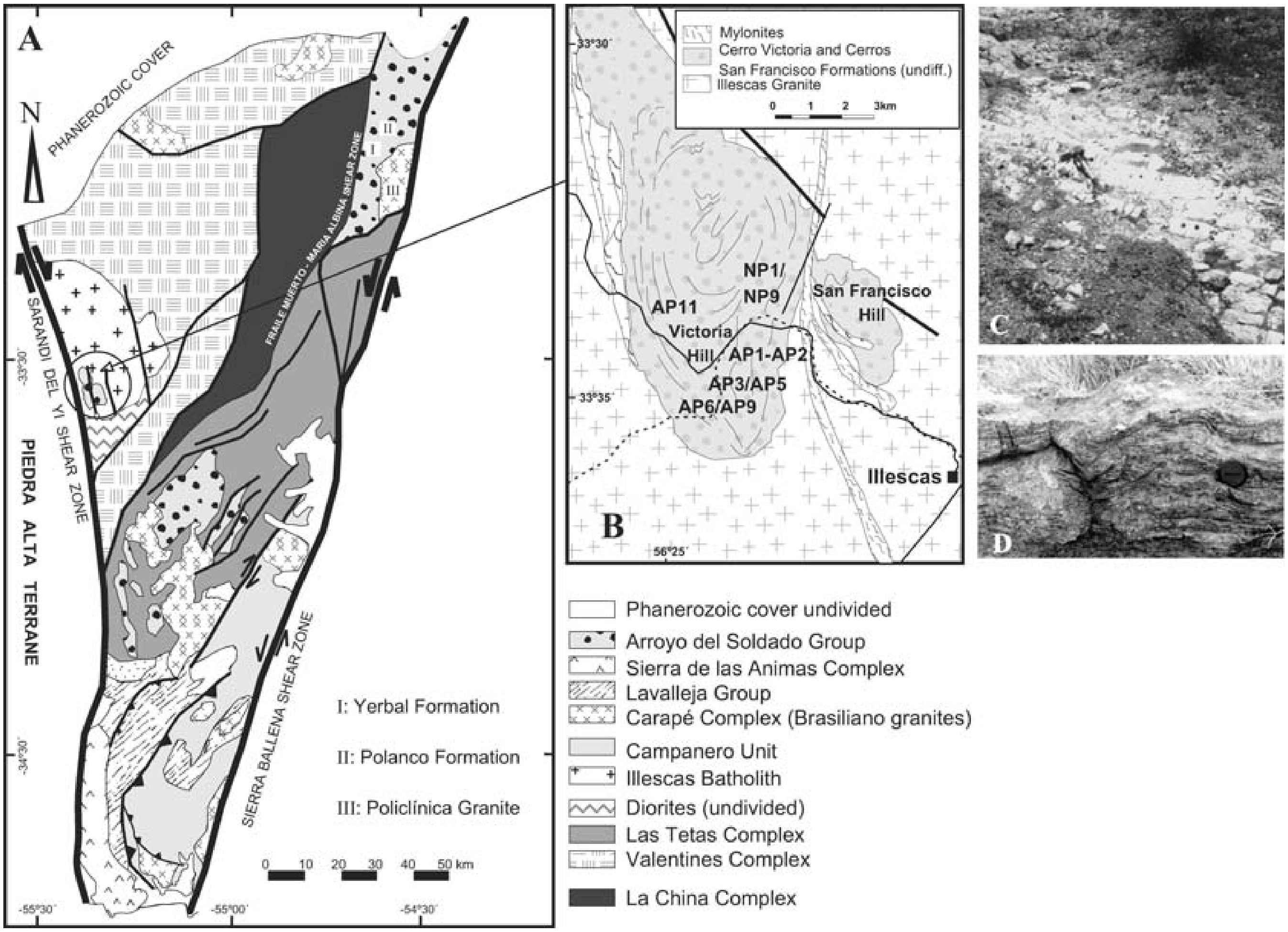

Figure 2. (A). Schematic geological map of the Nico Pérez terrane (modified from Mallman 2002), the Roman numbers corresponds to sampled outcrops of locality 2 (Fig. 1, I: Yerbal Formation, II: Polanco Formation and III: Policlínica Granite). (B) Inset map showing the distribution of the Cerro Victoria and Cerros San Francisco formations (modified from Montaña & Sprechmann 1993) and the location of sampling sites. (C) Oolitic limestones, sun compass as scale. (D) Levels of Cerro Victoria Formation with stromatolitic lamination cut by calcite veins and stylolites.

GEOLOGICAL BACKGROUND

RP extends from the southern province of Buenos Aires in Argentina up to the Rio Grande Do Sul and possibly the Santa Catarina states of SE Brasil. Most of Uruguay is included into this craton. For recent reviews on the geology of this area see papers by Basei *et al.* (2000), Cingolani & Dalla Salda (2000) and Rapela *et al.* (2007). This craton is characterized by gneisses, migmatites, amphibolites and granitic plutons of Early Proterozoic ages (*ca.* 2.5–2.0 Ma.). Important igneous activity also took place in Neoproterozoic times, but large areas of the craton remained unaffected (i.e. the Piedra Alta terrane, in western Uruguay and the Tandilia system in Argentina). Lack of Mesoproterozoic magmatism and deformation seems to be a significant characteristic of RP. The only area in which Mesoproterozoic geological activity has been documented is the Punta del Este terrane (PET, similar to the Cuchilla Dionisio terrane; Preciozzi *et al.* 1999), located on the eastern border of Uruguay and which has been recently interpreted as a fragment of the Kalahari craton in South America (Basei *et al.* 2005). During the Neoproterozoic several sedimentary successions, both calcareous and siliciclastic, developed along the whole RP, generally on top of the Palaeoproterozoic basement.

The Uruguayan geology can be divided into four major domains (Fig. 1), from west to east: (1) the Piedra Alta Terrane (*sensu* Preciozzi *et al.* 1991); (2) the Nico Pérez terrane (NPT, Bossi & Campal 1992), separated from the former by the Sarandí del Yí Shear Zone; (3) the Dom Feliciano belt (DFB, Fragoso Cesar 1980), mainly developed along the eastern margin of the former and (4) the PET (Preciozzi *et al.* 1999).

In this study, we present the palaeomagnetic results obtained from different sedimentary units of Neoproterozoic age that are exposed in the latest three domains. The Cerro Victoria Formation is located in the NPT, the Yerbal and Polanco Formations are better exposed in the DFB and the Rocha Group is part of the PET (1, 2 and 3, respectively in Fig. 1).

Nico Pérez terrane and Dom Feliciano belt

The Fraile Muerto-María Albina shear zone (Fig. 2) is a lineament proposed originally by Preciozzi *et al.* (1979) which separates the DFB from different units of the NPT. The NPT (Bossi & Campal 1992) is located between the Sarandí del Yí—Solís and Fraile Muerto—María Albina shear zones (Fig. 2) and it forms part of RP probably since Palaeoproterozoic times (Brito Neves &

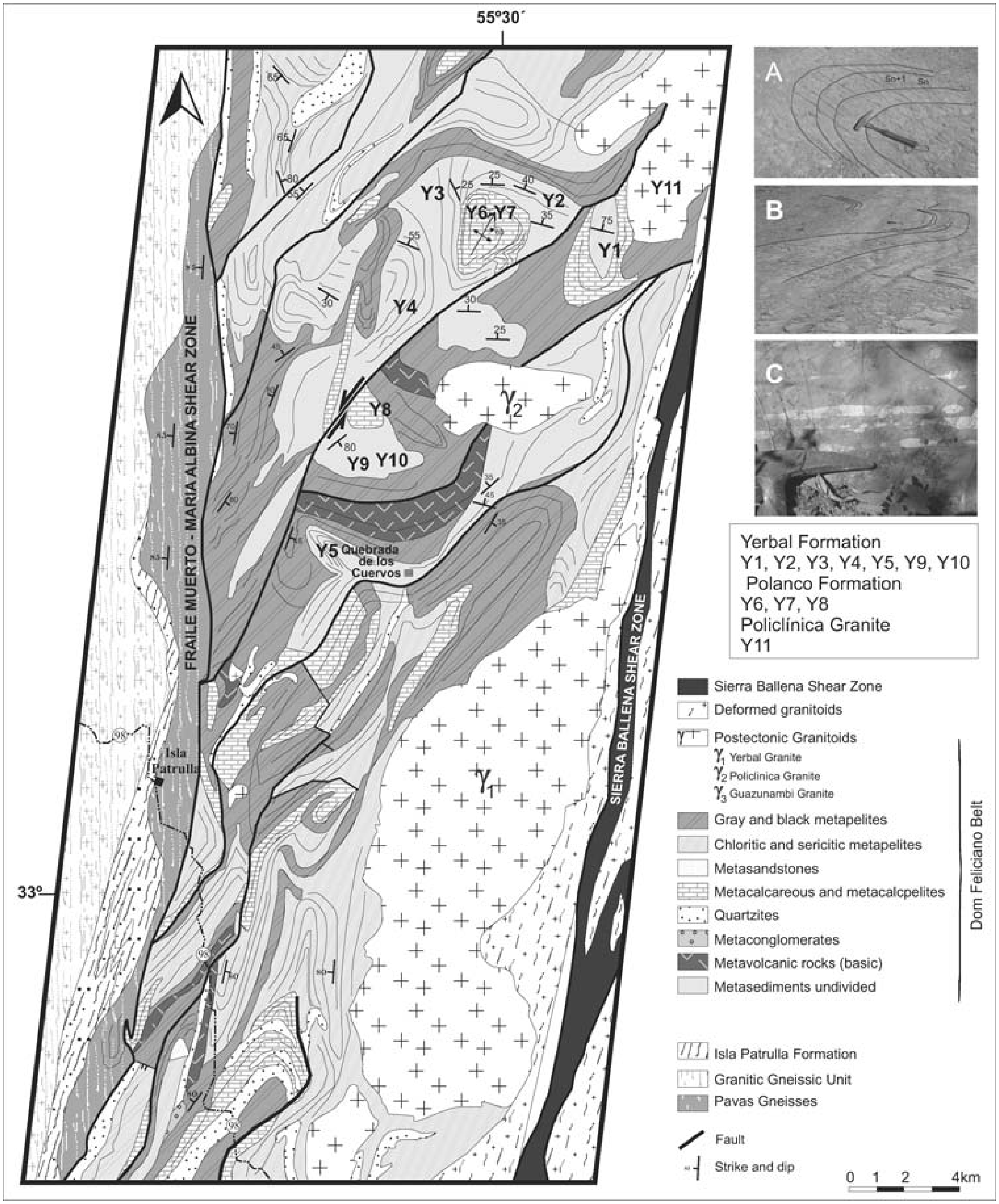

Figure 3. Geological map of Puntas del Yerbal and Isla Patrulla regions (locality 2, Fig. 1, modified from Preciozzi *et al.* 1989; Preciozzi & Pena 1989). (A) photo showing a similar fold with axial plane slaty cleavage. (B) Large fold with similar geometry, both in sericitic schist of Yerbal Formation, near Quebrada de los Cuervos locality. (C) Fish mouth type boudin (sensu Davis & Reynolds 1996). The presence of necks suggests that deformation occurred progressively. The length between the necks of boudins indicates the displacement.

Alkmim 1993). It is composed of a Neo-Achaean to Palaeoproterozoic metamorphic basement dominated by granulites, amphibolites, tonalites and marbles with a Neoproterozoic sedimentary cover.

The DFB (Fragoso Cesar 1980) extends along eastern Uruguay and southern Brazil. It is mainly composed by Neoproterozoic metavolcanic-sedimentary sequences in the west (the Porongos schist belt in Brazil and the Lavalleja Group in Uruguay) and medium- to high-K calc-alkaline granitoids in the east (the Pelotas and Aiguá batholiths and the Carapé Complex) with ages around 620–540 Ma (Sánchez Bettucci *et al.* 2001, 2003). The DFB has been interpreted as an active continental arc that evolved into a continent–continent collisional belt (Fernandes *et al.* 1992; Leite

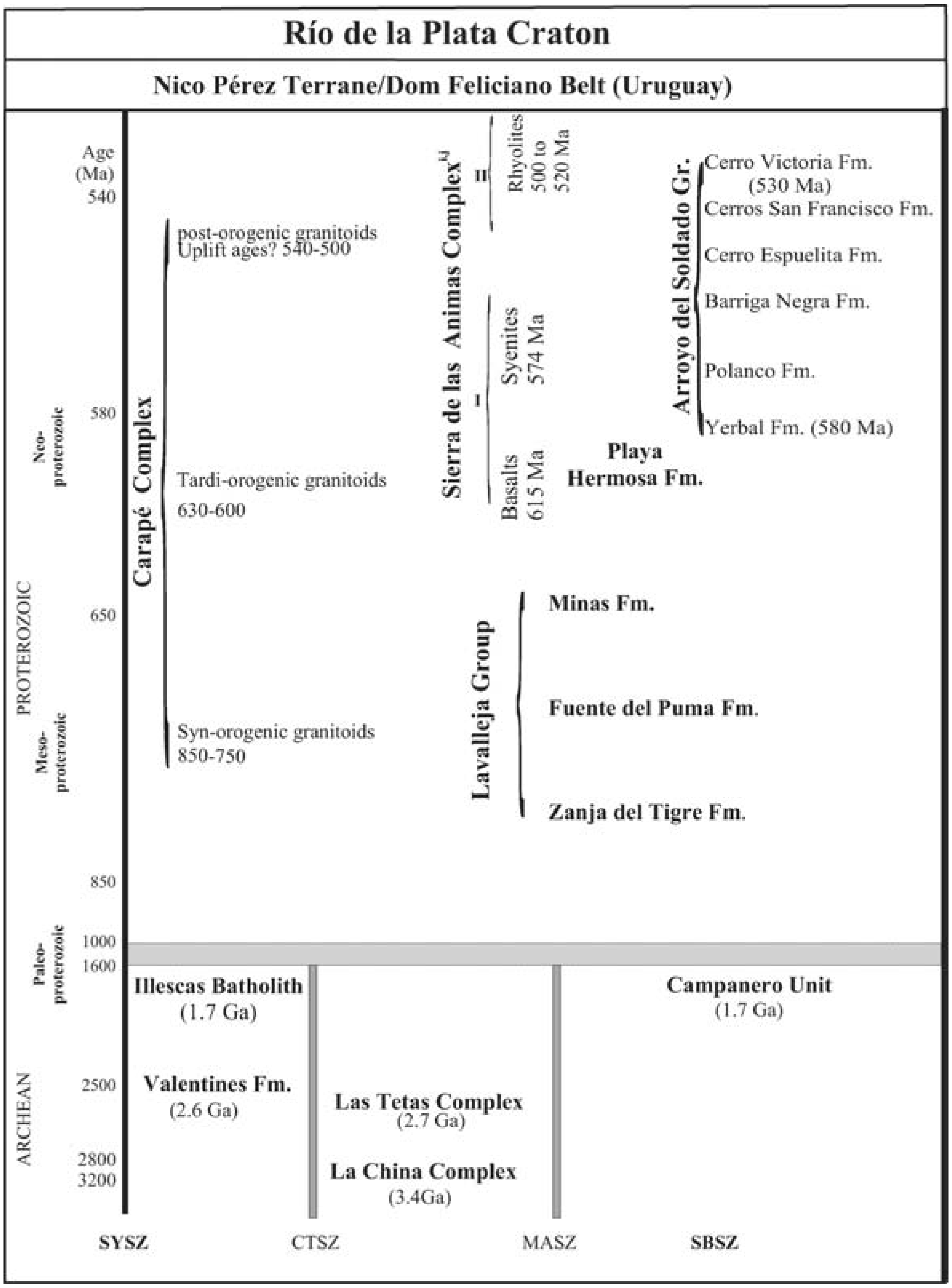

Figure 4. Stratigraphic chart of the Nico Pérez-Dom Feliciano region of the Río de la Plata craton.

et al. 2000; Sánchez Bettucci *et al.* 2003, and references therein). In Uruguay, the DFB can be interpreted as developed on the eastern border of the NPT.

In some areas the Lavalleja Group was redefined by Gaucher (2000) as the Arroyo del Soldado Group, stratigraphycally assigned to the 580–530 Ma time span (Gaucher *et al.* 2003, 2005) and correlated with the postglacial (post-580 Ma) units of the Corumbã Basin (Nogueira *et al.* 2003).

The composite stratigraphy of the Arroyo del Soldado Group has been interpreted as recording over 3000 m of a siliciclastic and calcareous sedimentary succession. However, this value (Gaucher 2000) is likely overestimated due to tectonic repetitions, the presence of refolded structures, and lack of cross-balanced sections that permit reliable palinpastic restoration. According to Gaucher *et al.* (2003), based on palynomorphs, skeletal fossils and chemostratigraphy, this succession was deposited between 580 and 530 Ma. The Arroyo del Soldado Group is constituted (sensu Gaucher 2000) by six formations, from base to top: Yerbal, Polanco, Barriga Negra, Cerro Espuelita, Cerros San Francisco and Cerro Victoria Formations. Three of them were sampled in our palaeomagnetic study (Yerbal, Polanco and Cerro Victoria Formations, Figs 2 and 3). The latter is better exposed in the NPT to the west of the DFB (Fig. 2). The stratigraphy of the Arroyo del Soldado Group is summarized in Fig. 4. Some details on the Yerbal, Polanco and Cerro Victoria formations are presented below.

The Yerbal Formation (Gaucher *et al.* 1998) is composed of 1500 m of siliciclastic deposits. Sandstones, which tend to dominate, are arkoses, subarkoses and quartz-arenites while banded pelites and siltstones also occur. Gaucher (2000) suggested that Arroyo del Soldado Group is not affected by metamorphism, and that the maximum

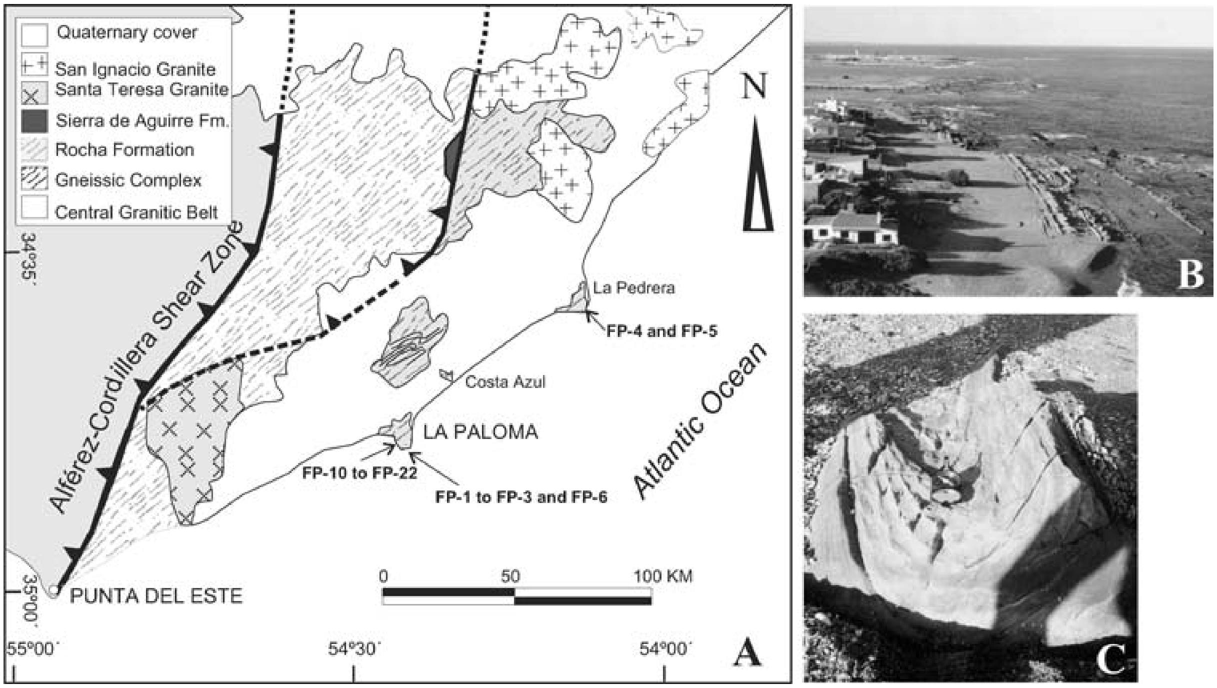

Figure 5. (A) Geological sketch of Punta del Este terrane (modified from Preciozzi *et al.* 1999). (B) Aerial view of the exposures of the Rocha Fm. in La Paloma. (C) An isoclinal fold of the Rocha Fm. in La Paloma outcrops.

temperature reached 200 °C. He has also described skeletal fossils (Gaucher 2000), consistent with that interpretation. Based on this literature, a palaeomagnetic sampling was carried out on this unit. However, regional geological reconnaissance, during and after palaeomagnetic sampling, and petrographic analysis revealed significant recrystallization and a low metamorphic degree reaching in some areas to tremolite schist with clinozoisite, calcite and tourmaline or sericite schist seldom with muscovite, quartz and biotite with lepidoblastic texture. Some levels of black phylites are also present. The metarkoses and metapsamites are intercalated with sericite schist. In Quebrada de los Cuervos (locality for palaeomagnetic sampling, Fig. 3) complex folding developed penetrative schistosity and bedding-parallel cleavage. Fold interference patterns have also been observed. Presence of crenulation cleavage confirms low to medium metamorphic degree as previously suggested by Vaz *et al.* (1985). Chlorite and white mica have grown parallel to the cleavage planes. Microtectonic features in quartz include undulate extinction, deformation bands and subgrain boundaries. This evidence suggests that local metamorphic effects due to nearby intrusions (Fig. 3) are not a likely explanation as suggested by Gaucher *et al.* (2003). Under these conditions preservation of skeletal fossils is at least problematic.

The Polanco Formation (Goñi & Hoffstetter 1964; Gaucher *et al.* 1996) is constituted by limestone and carbonatic rhythmites and conformably overlies the Yerbal Formation. Vaz *et al.* (1985, 1990) described the presence of calcareous breccias constituted by matrix of calcite, muscovite, quartz and siderite (?) with angular clasts of sericite schist (from Yerbal Fm.?). This unit is locally microfolded.

The Cerro Victoria Formation (Montaña & Sprechmann 1993; Gaucher *et al.* 1996) consists of micritic, stromatolitic and oolitic limestone (Fig. 2). This unit as well as the underlying Cerros San Francisco Formation is better exposed to the west of the DFB in the NPT. In this area, the older units of the Arroyo del Soldado Group are not exposed and in several spots the younger units are deposited on top of the Palaeoproterozoic Illescas batholith. Tectonic deformation is much less intense in this region and both formations are folded into an open syncline (Fig. 2). Stylolites (sutured type); containing clay minerals and ferric oxides are common.

Punta del Este terrane

Meso and Neoproterozoic rocks represent the basement of the recently defined PET (Preciozzi *et al.* 1999, 2003) in eastern Uruguay (Figs 1 and 5). The PET is separated from the DFB by the Alférez–Cordillera shear zone. The PET is composed by granitoids of diverse compositions, with variable degree of deformation. These include ophthalmic gneisses, granite-gneisses, migmatites and tonalitic granitoids formed around 1000 Ma (Preciozzi *et al.* 1999, 2003) with intercalated amphibolites, calc-silicate rocks and quartzites, comparable to the Namaqua-Natal Belt in South Africa. The extension of the PET is relatively reduced as it does not continue into the Brazilian territory and it has not been recognized in Argentina yet (see Rapela *et al.* 2007, for a recent speculation on this). It occurs exclusively in the eastern portion of Uruguay, between the localities of Punta del Este in the south and Velazquez in the north. Basei *et al.* (2001) suggested that the PET represents a fragment of the Kalahari craton that remained attached to South America after the opening of the South Atlantic. The age of collision of the Kalahari Craton with RP has been matter of debate with ages ranging from pre-600 Ma to Early Cambrian (e.g. Grunow *et al.* 1996; Prave 1996; Frimmel & Basei 2006). The ENE trending Alférez–Cordillera shear zone (Fig. 5) is interpreted as the suture of that collision (Basei *et al.* 2005). Others (e.g. Fragoso Cesar *et al.* 1987, among others), however, have suggested that the suture is located along the sinistral NE–SW Sierra Ballena shear zone (Figs 1 and 2). This is a mega-shear and has been correlated with the Purros shear zone of the Kaoko Belt of Namibia by Oyhantçabal *et al.* (2007).

A thick sequence of siliciclastic rocks affected by a very low metamorphic grade is recognized on top of the PET basement and it is named the Rocha Formation. This is exposed in the easternmost part of this terrane. Several relicts of a volcano-sedimentary deposit named the Sierra de Aguirre Formation (Masquelin & Tabó 1988; Fantin 2003) also overlie discontinuously the basement to the west. This latest unit has been dated as 578 Ma (Hartmann *et al.* 2002).

The Rocha formation (Sánchez Bettucci & Mezzano 1993, and references therein) is part of the sedimentary cover of the PET. It is mainly exposed along the coastline of SE Uruguay in a NE trending belt, 20–30 km wide and 120 km long. It has been characterized as a metasedimentary sequence (Sánchez Bettucci & Mezzano 1993 and references therein). It is composed of clastic sedimentary rocks, dominated by sandstone and siltstone with scarce conglomeratic levels. The metamorphic degree of these rocks grade from very low, in the SE to low in the NW. Primary sedimentary structures can be recognized in the less metamorphosed terms, such as hummocky, plane-parallel bedding, cross stratification, mud-draps and climbing ripples (Fragoso Cesar *et al.* 1987; Sánchez Bettucci & Mezzano 1993). Pazos & Sánchez Bettucci (1999) suggested a transitional fluvial to tidal plain environment for its deposition. At the La Paloma and La Pedrera localities (Fig. 5), where the palaeomagnetic sampling took place, the most conspicuous lithologies are massive green to red metapelites, sandstones and rhythmites. The sedimentary succession of the Rocha Fm. underwent polyphase folding with preferential NW plunge (50° to vertical) and eastward tectonic vergence. Tectonic slices of very schistose quartzite and granitoids are intercalated. The Rocha Fm. is in tectonic contact with Proterozoic migmatites of the Cerro Olivo Complex (Masquelin 2002) to the west.

This formation has been correlated with a similar one exposed along the Gariep Belt in South Africa (Basei *et al.* 2005). The Rocha Formation and the Oranjemund Group present strong similarities in lithology, metamorphic and deformational history and SHRIMP U-Pb ages on detrital zircons that suggest a similar source. A large amount of detrital zircons, in the Rocha Formation and the Oranjemund Group, display ages from 640 to 590 Ma indicating a maximum age of sedimentation of 590 Ma. Age of main deformation and metamorphism of the Rocha Fm. is constrained between the deposition (<590Ma) and the age of the poorly dated Santa Teresa Granite, exposed to the north of the outcrops of the Rocha Fm. and for which ages between 550 and 537 Ma have been published (Umpierre & Halpern 1971; Preciozzi *et al.* 1993).

PALAEOMAGNETIC RESULTS

Samples were always collected as cores of 2.54 cm in diameter (and 4–8 cm long) with a portable drill, during five field trips, and oriented through magnetic and sun compasses whenever weather permitted. All cores were sliced into standard 2.2 cm high specimens. Measurement of direction and intensity of the natural remanent magnetization was accomplished with a 2-G cryogenic DC Squids magnetometer. Demagnetization was performed with a static three axes degausser attached to the magnetometer and two ovens (ASC and Schonstedt). Measurement of bulk susceptibility was done with a Bartington MS-2 after each step of thermal cleaning to control possible chemical changes affecting the ferromagnetic fraction. Analysis of palaeomagnetic stability and determination of magnetic components were done independently for each specimen by principal component analysis (Kirschvink 1980) and means were obtained applying Fisherian statistics (Fisher 1953). The main work done at each locality and the experimental results are shown below.

Cerro Victoria Fm. (Nico Pérez terrane)

The Cerro Victoria Fm. consists in oolitic limestone that passes upward into stromatolitic limestone. Over 100 m of thickness have been described for this formation which would be the top unit of the Late Proterozoic Arroyo del Soldado Group (Fig. 4). According to some ichnofossils and stratigraphic constraints its more likely age is latest Ediacaran to earliest Cambrian. This unit is best exposed in the nucleus of the Arroyo de la Pedrera Syncline near the town of Illescas (33.5°S, 55.4°W). One hundred and thirty two oriented cores were collected with a portable drill from twenty sites distributed on both flanks of the syncline. Pilot samples were submitted to stepwise demagnetization techniques either by alternating field (in about 16 steps up to maximum demagnetizing fields of 140 mT) or thermal treatment (in about 13 stages up to 700 °C). In most cases thermal demagnetization proved more efficient to demagnetize the samples and isolate the magnetic components. Therefore, most remaining samples were submitted to stepwise thermal treatment up to 700 °C (in at least 10 steps).

Samples in most sites carried a characteristic remanence of unblocking temperatures well over 600 °C (Figs 6A–C) that was virtually unaffected by AF demagnetization. This behaviour indicates that hematite is the likely carrier of this magnetic component (B). Many sites also showed a superimposed magnetic component of low unblocking temperature (≤300 °C), of possible viscous or thermoviscous origin (Component A; Figs 6A and B). Two sites (NP-6, AP-1), however, presented a magnetic component (C) apparently carried by (Ti?) magnetite (Fig. 6D). All three components were found together only in one sample from site NP-6. At this sample Component A was isolated between 200 and 400 °C, Component C between 500 and 610 °C, and Component B between 610 and 700 °C. Sample and site mean directions and their statistical parameters are presented in Table 1 and Fig. 7. Component A could be determined consistently at six sites (Figs 7A and B). Significant worsening of the statistical parameters after bedding correction indicates that this component is post-tectonic, consistent with its low unblocking temperature and a possible recent origin. Application of Enkins DC test (Enkin 2003) on a site basis yields a negative test with optimum untilting at 18 ± 53 per cent, which indicates a post-tectonic magnetization. Exclusive normal polarity and a mean direction (Dec: 358.2°, Inc: −54.3°, *n*: 6 sites; α 95: 8.7°) undistinguishable from the present dipole field at the study locality corroborates this interpretation. The mean of the virtual geomagnetic poles (VGP) computed from each site direction is indistinguishable from the Earth spin axis (87.9°S, 31.2°E, A95: 11°, Table 1)

Component B is by far the most characteristic remanence of the Cerro Victoria Formation (Figs 7C–E and H). This component shows dual polarity, even within sites (NP-4, NP-7, NP-8, NP-9, AP-8 and AP-9). Polarity for computing the site mean direction was chosen according to the largest number of samples with one polarity. This suggests a long time for acquisition of remanence. Application of bedding correction produces a significant worsening of the statistics suggesting a post-tectonic acquisition of Component B (Table 1). Application of Enkins DC test (Fig. 7E) indicates a negative result with optimum untilting at −22 ± 38 per cent, confirming a post-tectonic nature for component B. A reversal test (McFadden & McElhinny 1990) was performed on the *in situ* site mean directions of this component. This yielded a positive result class 'C' (angle between normal and reverse populations = 7.4°, critical angle = 11.3°). Considering that dual polarities were recorded at several sites, a sample based computation of both mean direction and palaeomagnetic pole is probably more appropriate, as

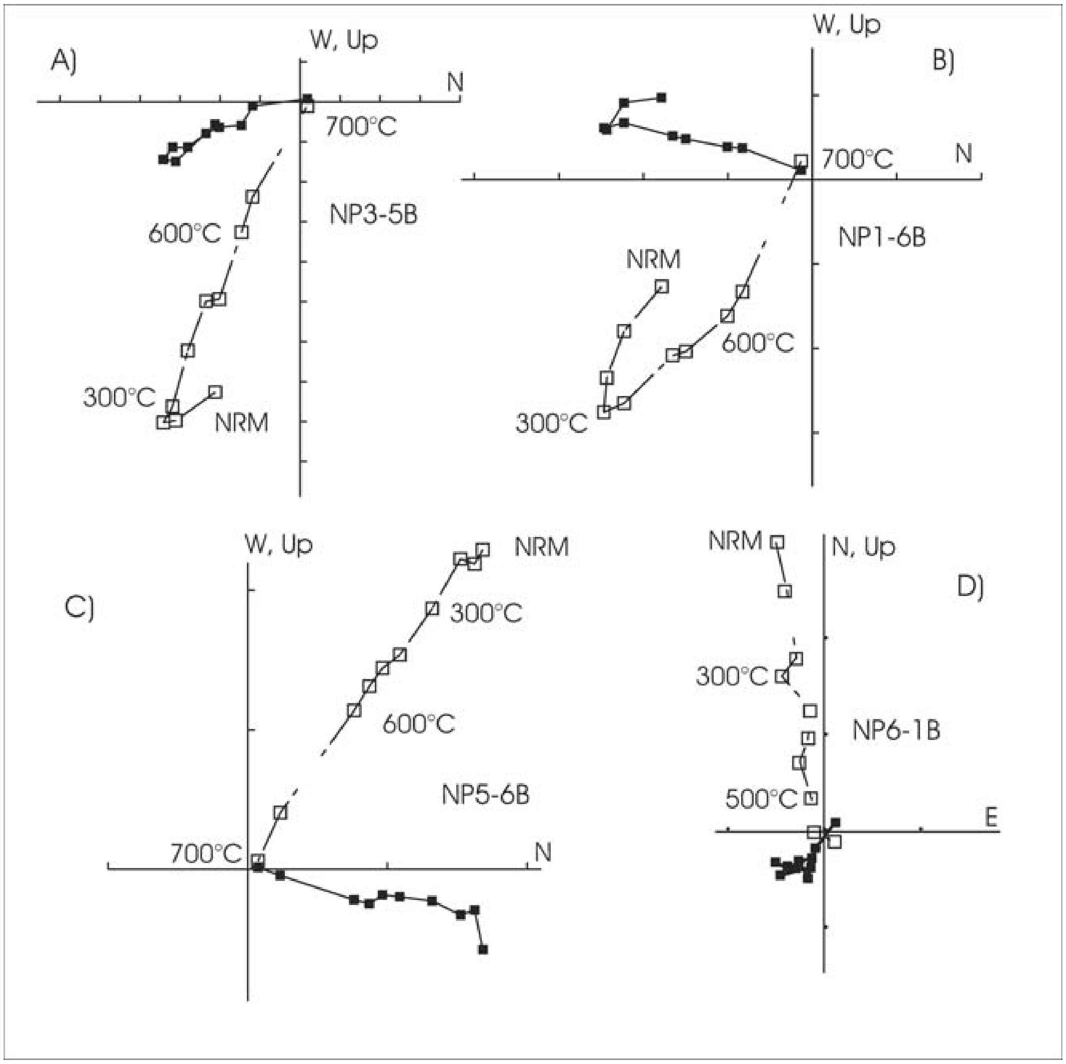

Figure 6. Representative demagnetization plots of samples from the Cerro Victoria Fm. (A–C) display samples carrying component (B) with unblocking temperatures over 650 °C. A low temperature component (A) is also present in cases (A) and (B). (D) corresponds to a sample carrying component (C) with unblocking temperatures around 500 °C. Open (solid) symbols correspond to vectorial projections on the vertical (horizontal) plane.

acquisition of magnetization by each sample may be considered an independent record of the Earth magnetic field. In this case, however, the reversal test is negative as the angle between the normal and reverse populations is 8.7° against a critical angle of 5.6° (Fig. 7H). Undetected minor contamination by components A or C could explain this failure. Very similar magnetic behaviour of 'normal' and 'reverse' samples and presence of both at the same sites strongly suggest that they correspond to the same magnetic component with opposite polarities. Table 1 shows mean directions computed both on site and sample basis, with nearly identical results. A VGP was computed from the '*in situ*' remanence direction of each sample. The average of them is the palaeomagnetic pole for component B of the Cerro Victoria Fm: 82.6°S, 309.3°, *n*: 79, A95: 3.9° (Table 1).

Component C, presumably carried by magnetite, was isolated only at two sites (Figs 7F and G). Within-site consistency was good for one site but poor for the other (Table 1). Both sites presented opposite polarities, a positive reversal test (McFadden & McElhinny 1990, angle between means = 17° versus critical angle = 23°) yields a statistically indeterminate result due to the large critical angle. After bedding correction, site means tend to diverge, with a negative reversal test in this case (95 per cent confidence, angle between means = 38° versus critical angle = 23°), suggesting a post-folding nature for this component too. In order to obtain a statistically meaningful mean, a sample basis was adopted to compute a mean VGP. Despite both polarities being recorded, the small number of samples and sites do not permit to consider this as a true palaeomagnetic pole. The mean VGP (CVc) falls at: 4.2°N, 343.2°E, A95: 13.8°.

Some rock magnetic properties were investigated by means of acquisition of isothermal remanence magnetization (IRM). Normalized curves for representative samples from all studied units are presented in Fig. 8. Samples from the Cerro Victoria formation are represented with solid symbols. Circles correspond to sites carrying component B, while triangles represent a site where component C was isolated. Lack of low-coercivity minerals and no saturation at 1T confirm hematite as the single magnetic carrier in samples carrying component B. However, the sample carrying component C shows a significantly different IRM acquisition curve. A sharp increase at low fields indicates the presence of a ferrimagnetic phase, consistent with magnetite as inferred from the demagnetization behaviours. Lack of saturation at 1 T confirms the presence of hematite as well.

Table 1. Palaeomagnetic results for the Cerro Victoria Fm.

					(°)	Bedding				(°)	VGP	
Comp	Site	*n* (N)	Dec (°)	Inc (°)	α 95/*k*	Strike (°)	Dip (°)	Dec∗ (°)	Inc∗ (°)	α 95/*k*	Lat (°)	Long (°)
A	NP-1	6	350.6	−57.7	15.5/*20*	156	15	10.0	−51.4	15.5/*20*	−81.0	359.4
	NP-2	8	344.9	−49.3	12.7/*20*	170	20	7.5	−47.1	12.7/*20*	−76.8	45.1
	NP-7	6	21.5	−46.3	16.5/*18*	166	8	27.5	−41.3	16.5/*18*	−70.6	202.7
	NP-10	6	4.6	−55.8	12.4/*30*	171	26	32.4	−43.3	12.4/*30*	−85.3	252.9
	AP-1	4	3.8	−54.2	11.1/*70*	15	45	326.3	−29.5	11.1/*70*	−86.6	237.0
	AP-9	3	339.4	−48.4	8.5/*209*	169	25	16.2	−53.2	8.5/*209*	−72.2	42.2
	Mean	(6)	358.2	−54.3	8.7/60			9.1	−46.7	15.5/*17*	−88.0	352.3
Mean VGPs : 87.9° S, 31.2° E, *N* = 6, A95: 11.6°, *k* : 34												
B	NP-1	6	199.8	63.6	6.2/*118*	156	15	214.8	51.8	6.2/*118*	−70.8	258.0
	NP-2	7	175.1	55.4	4.1/*213*	170	20	200.4	49.1	4.1/*213*	−85.3	2.1
	NP-3	6	159.4	66.0	8.5/*63*	168	20	200.2	61.6	8.5/*63*	−68.6	344.6
	NP-4	5	344.1	−58.5	12.7/*37*	178	25	23.9	−55.7	12.7/*37*	76.0	186.0
	NP-5	6	23.4	−57.4	8.5/*64*	161	25	40.9	−37.6	8.5/*64*	70.5	54.0
	NP-7	9	0.7	−55.3	5.5/*72*	166	8	11.1	−52.6	5.5/*72*	87.6	110.9
	NP-8	8	29.6	−60.5	10.5/*18*	168	16	44.4	−48.3	10.5/*18*	65.3	62.1
	NP-9	6	356.3	−68.4	12.9/*28*	167	16	33.9	−57.9	12.9/*28*	−71.7	311.9
	NP-10	7	167.0	59.4	5.7/*111*	171	26	205.2	52.1	5.7/*111*	−77.6	358.0
	NP-11	6	173.8	56.1	8.5/*64*	178	24	206.4	50.8	8.5/*64*	−84.0	1.0
	AP-3	4	156.9	43.1	13.2/*50*	47	42	151.4	2.8	13.2/*50*	−68.2	51.3
	AP-8	5	175.8	50.6	17.7/*20*	194	37	221.0	47.4	17.7/*20*	−85.8	64.9
	AP-9	4	358.6	−48.4	10.6/*76*	169	25	21.5	−39.1	10.6/*76*	85.7	288.0
	Mean	(13)	177.7	58.1	5.7/*53*			203.1	48.8	10.6/16	−84.4	323.0
	Mean	79	179.1	59.0	2.9/*31*			204.8	50.1	4.0/*17*	−80.8	278.7
Mean VGPs : 82.6° S, 309.3° E, *n* = 79, A95 : 3.9°, *k* : 18												
C	NP-6	9	235.4	−58.3	13.4/*16*	276	8	227.1	−52.6	13.4/*16*	1.2	344.4
	AP-1	4	40.3	43.5	24.3/*15*	15	45	62.1	15.5	24.3/*15*	19.8	343.0
	Mean	(2)	226.6	−51.1	–			236.3	−34.3	–	11.3	343.6
	Mean	13	229.6	−54.0	11.3/*15*			230.0	−42.7	14.7/*9*	7.6	343.9
Mean VGPs : 4.2° N, 343.2° E, *n* = 13, A95 : 13.8°, *k* : 10												

Note: Dec: magnetic declination, Inc. magnetic inclination, *n* (N): number of samples (sites), Dec∗ and Inc∗: declination and inclination after beding correction.

Yerbal and Polanco formations (Don Feliciano Belt)

The second palaeomagnetic study was carried out on the Yerbal and Polanco Formations and The Policlínica Granite, exposed in the DFB. A simplified geological map with location of sampling sites is shown in Fig. 3.

Ninety-five oriented cores were collected from eleven sites at this locality. Seven sites (Y1–Y5, Y9 and Y10; 64 samples) corresponded to the Yerbal Fm. Three sites (Y6–Y8; 23 samples) were located on the Polanco Fm., and a single site (Y11, eight samples) in the Policlínica Granite. This body intrudes the formerly mentioned sedimentary units and has been assigned to the Cambrian on the basis of correlation with other similar intrusives in nearby localities (Gaucher *et al.* 2005), although no radiometric dating has been reported yet. Positive palaeomagnetic results were obtained from six sites of the Yerbal Fm and two sites of the Polanco Fm. Sites Y8, Y9 and Y11, the latter on the granite, presented random directions of magnetization. Fig. 9 shows typical magnetic behaviours of samples from the Yerbal Fm. (Figs 9A–C) and the Polanco Fm (Fig. 9D). Samples from the Yerbal Fm. presented a characteristic magnetization carried by hematite as inferred from well-defined unblocking temperatures around 650–670 °C. Four out of six sites showed the presence of antipodal directions (see Figs 9A and B, from different samples of the same site). Only one site (Y-3) showed the presence of a low temperature component whose mean direction (Dec: 13.4°, Inc: −40.6°, α 95: 11.2°) is close to the present direction of the Earth magnetic field at the study locality. This suggests a possible viscous origin for this low temperature magnetization. On the other hand, both sites of the Polanco Fm. presented a characteristic component with unblocking temperatures around 500 °C suggestive of titanomagnetites. In this case a single sample from site Y-7 presented an opposite polarity while all others were directed towards the north with high to moderate positive inclinations (*in situ* coordinates). Fig. 10 presents the site mean directions of the Yerbal and Polanco formations, both *in situ* (Fig. 10A) and after bedding correction (Fig. 10B). In all cases individual sample directions were taken to the same hemisphere (in this case lower hemisphere). Visual inspection of Fig. 10 and Table 2 indicates that grouping of directions considerably worsen after bedding correction. Application of Enkins DC test (Enkin 2003) yields a negative result with optimal unfolding at 11 ± 16 per cent (Fig. 10C). Based on this a post-folding remanence is interpreted for the Yerbal Fm., and the '*in situ*' directions are used to compute the VGPs and the palaeomagnetic pole. Analysis of sample directions (Fig. 10D) from the Yerbal Fm. through the reversal test (McFadden & McElhinny 1990) indicates a positive test (class B). Since different polarities were recorded in most sites, it seems more correct in this case too to consider each sample direction as an independent measurement of the Earth Magnetic Field. A palaeomagnetic pole was computed by averaging the VGPs, yielding a pole position at 77.0°S, 298.4°E, *n*: 38, A95: 5.9°.

Rock magnetic properties of samples from the Yerbal Formation are illustrated by IRM acquisition curves in Fig. 8. Lack of significant low-coercivity phases and no saturation at 1 T indicates hematite as the likely only carrier of the remanence.

Characteristic remanence directions determined at sites Y-6 and Y-7 (Table 2, Figs 10A, B and E) for the Polanco Fm., also move

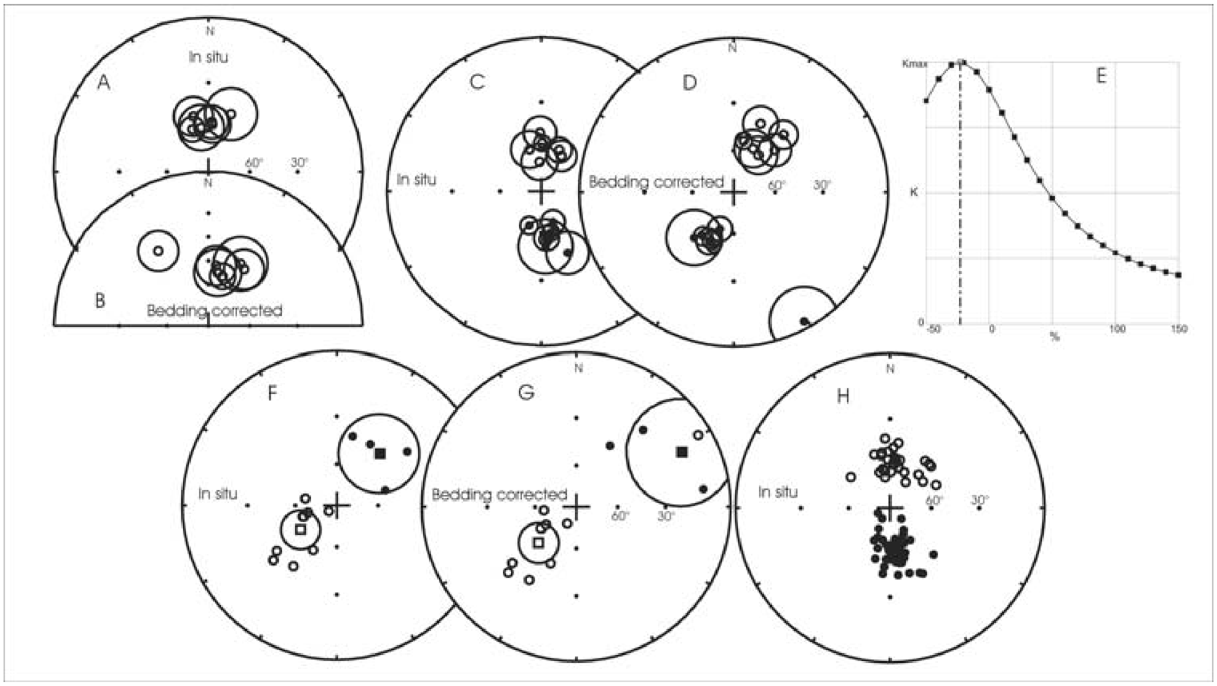

Figure 7. (A) Stereographic projection of *in situ* mean site directions of component (A) from Cerro Victoria Fm. Large circles indicate the 95 per cent confidence circles around the mean direction. (B) idem (A), after bedding correction. (C) Stereographic projection of *in situ* mean site directions of component (B) from Cerro Victoria Fm. (D) Idem (C) after bedding correction. (E) Statistical parameter *k* versus stepwise unfolding for the Cerro Victoria mean site directions of component (B). Dashed line indicates optimum unfolding. (F). Stereographic projection of *in situ* sample directions of component (C) from Cerro Victoria Fm. Mean site directions are represented by large squares with their corresponding 95 per cent confidence circles. (G) idem (E), after bedding correction. (H) *in situ* sample directions of component (B) from Cerro Victoria Fm. In all cases open (solid) symbols indicate projection on the upper (lower hemisphere). Mean site directions are also presented in Table 1. More references in the text.

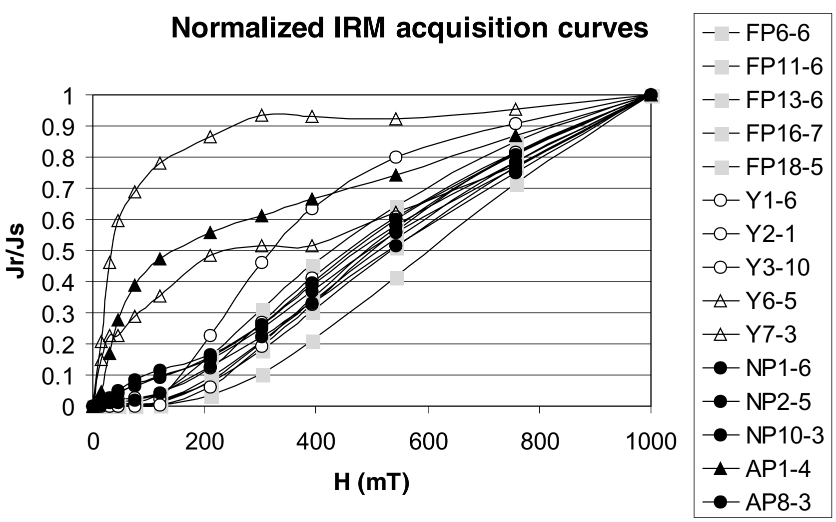

Figure 8. Normalized isothermal remanent magnetization (IRM) acquisition curves for representative samples from the Cerro Victoria Fm. (black symbols), Yerbal Fm (open circles), Polanco Fm. (open triangles) and Rocha Fm. (grey squares). The black triangle for the Cerro Victoria Fm. correspond to a sample carrying component C.

apart when bedding correction is applied. With only two sites, any statistical test is useless. However, qualitative analysis suggests a post-folding nature for this remanence too. Very different remanence directions (Fig. 10A) clearly show that timing of remanence acquisition by the Polanco Fm. significantly differs from that of the Yerbal Fm.

IRM acquisition curves for the Polanco Fm (open triangles, Fig. 8) show the presence of a ferrimagnetic phase with saturation around 250–300 mT, compatible with magnetite, plus the possible presence of hematite, as suggested by lack of saturation at 1T and high unblocking temperatures. Individual VGPs were computed from the *in situ* remanence direction of each sample (Fig. 10E). A mean of them is located at 3.2°N, 325.8°E (*n*: 12, A95: 15.2°). As in the case of Component C from the Cerro Victoria Fm. described before, the small number of samples and sites do not permit to consider this as a true palaeomagnetic pole.

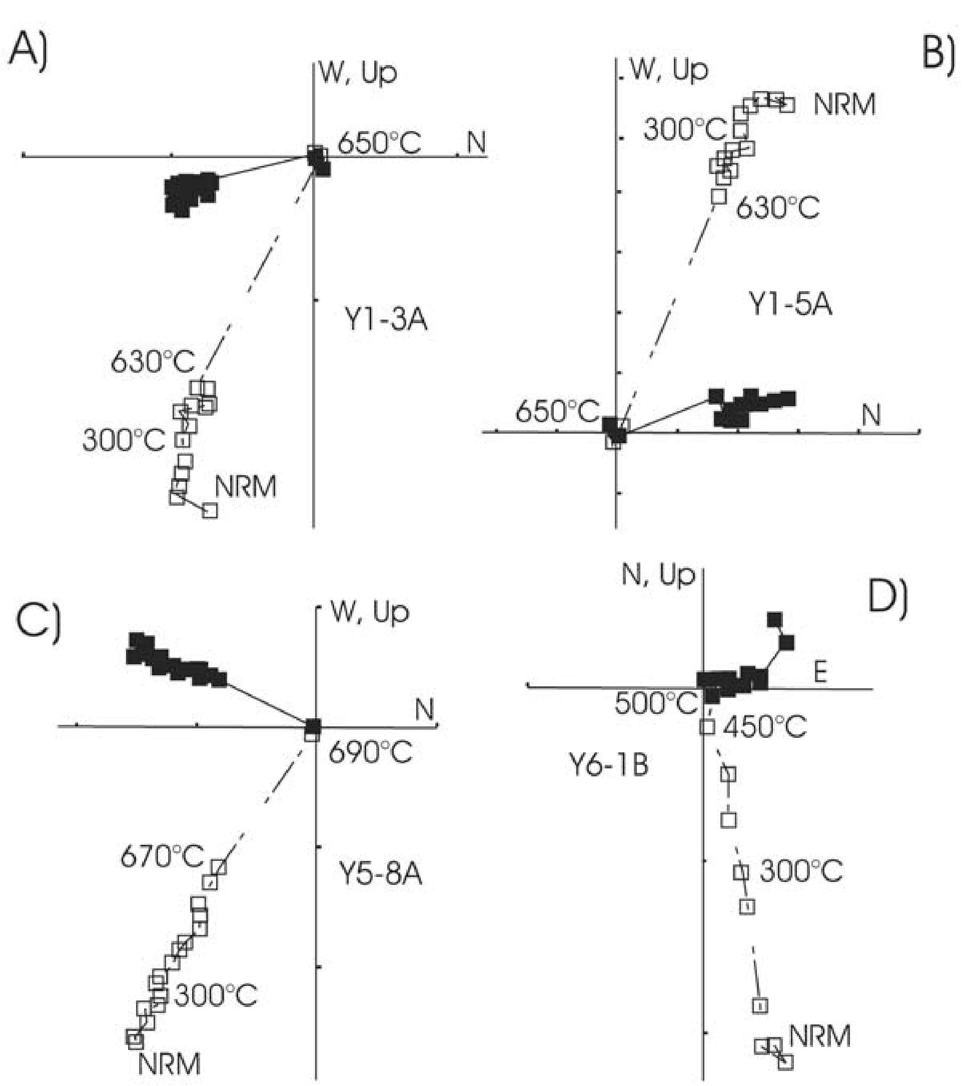

Figure 9. (A–C) Representative demagnetization plots of samples from the Yerbal Fm. Note the antipodal directions of the characteristic components of samples from the same site, represented in figures (A) and (B). Also note the high temperature unblocking remanence consistent with hematite as the magnetic carrier. (D) idem (A–C) for a representative sample of the Polanco Fm. Note the unblocking temperature around 500 °C. References as in Fig. 6. More references in the text.

Rocha Formation (Punta del Este terrane)

Palaeomagnetic cores were drilled at 19 sites on reddish siltstones and fine grain sandstones of the Rocha Fm. exposed along the Atlantic coast of SE Uruguay (Fig. 5) at two localities: La Paloma (17 sites, 126 samples) and La Pedrera (2 sites, 15 samples). Sites at La Paloma were distributed along 700 m of coast-line, where the folded sequence of the Rocha Fm. is superbly exposed (Fig. 5B). Although 6–10 samples were collected at each site, not all corresponded to the same stratigraphic level. In some instances double sites (e.g. 4 or 5 samples separated 0.5–1 m from the remaining) were defined. Fifty-nine samples from the whole collection were submitted to detailed stepwise demagnetization procedures (eight to AF cleaning, the remaining to thermal demagnetization). AF demagnetization proved inefficient to erase the natural remanent magnetization, with over 95 per cent of the original remanence remaining after application of 140 mT. Samples from one site at La Paloma (FP-22) and few samples from different sites showed unstable behaviour under thermal demagnetization. The remaining samples showed a very similar behaviour with a characteristic magnetic component with unblocking temperatures generally over 650 °C and antipodal directions, even within a site (Table 3, Fig. 11). High unblocking temperatures, unsuccessful AF cleaning and reddish colour of these sediments strongly suggest that hematite is the magnetic carrier. IRM acquisition curves (Fig. 8) confirm this interpretation showing lack of low-coercivity phases and no saturation at 1 T.

Sample characteristic directions are presented in Fig. 12 and Table 3, both before and after bedding correction. From Figs 12(A) and (B) it is clear that the remanence is post-folding. Enkin's DC test yields a negative result with an optimal untilting at -1 ± 4 per cent (Fig. 12C), confirming the post-tectonic nature of the remanence. Both groups of sample characteristic directions are antipodal as proved by a positive fold-test class B (McFadden & McElhinny 1990). A mean sample direction for the post-folding remanence of

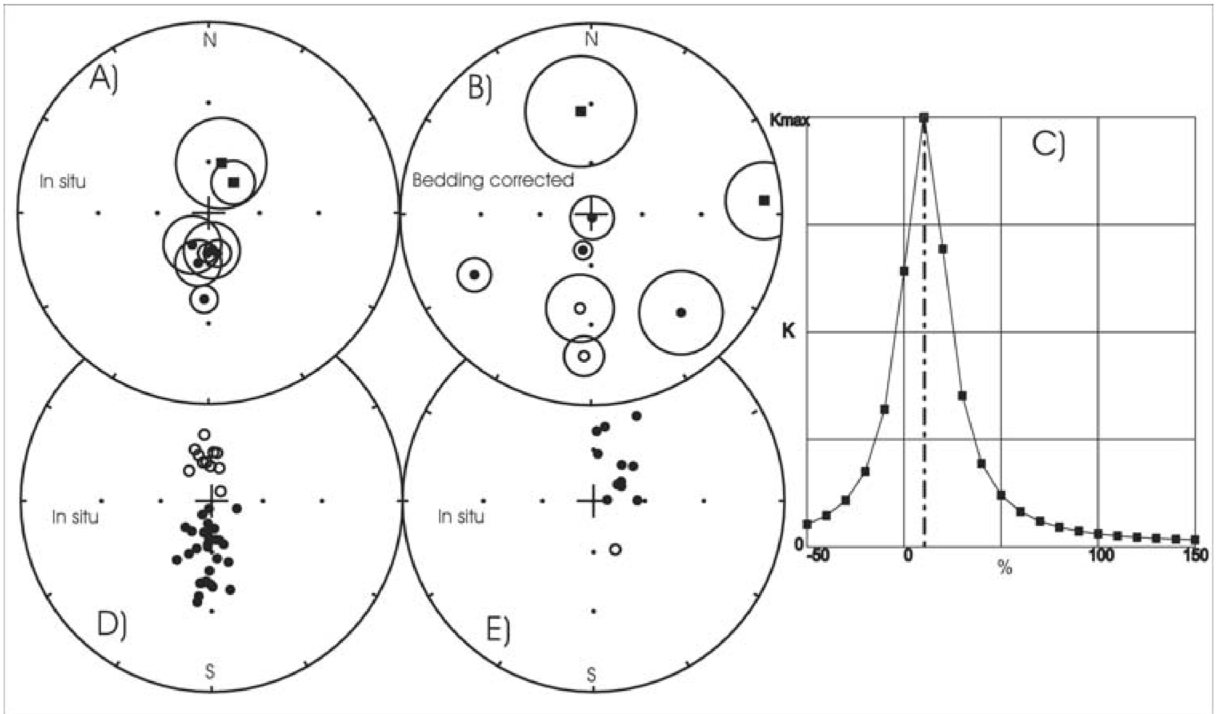

Figure 10. (A) Stereographic projection of *in situ* mean site remanence directions for the Yerbal (circles) and Polanco (squares) formations. (B) Idem (A), after bedding correction. (C) Statistical parameter *k* versus stepwise unfolding for the Yerbal Fm.. Dashed line indicates optimum unfolding. (D) *in situ* sample characteristic remanence directions for the Yerbal Fm. (E) Idem (D) for the Polanco Fm. References as in Fig. 7. See also Table 2.

Table 2. Idem Table 1 for the Yerbal and Polanco formations.

							Bedding					VGP	
Fm	Comp	Site	n (N)	Dec (°)	Inc (°)	(°) a95/*k*	Strike (°)	Dip (°)	Dec* (°)	Inc* (°)	(°) a95/*k*	Lat (°)	Long (°)
Yerbal	A	Y-3	5	13.4	−40.6	11.2/*48*	209	5	17.7	−41.8	11.2/*48*	−74.8	180.0
	B	Y-1	9	167.4	65.6	7.7/*45*	104	85	182.9	−16.8	7.7/*45*	−72.2	334.3
		Y-2	6	182.9	41.4	6.8/*98*	202	80	242.7	20.9	6.8/*98*	−80.6	142.0
		Y-3	8	181.6	66.3	5.3/*111*	209	5	192.7	68.2	5.3/*111*	−74.0	301.7
		Y-4	4	206.9	68.9	16.6/*32*	25	69	137.5	20.2	16.6/*32*	−62.4	268.9
		Y-5	7	191.7	60.1	12.9/*23*	284	28	162.6	87.8	12.9/*23*	−77.6	259.9
		Y-10	4	175.0	67.8	16.1/*34*	107	107	186.7	−37.3	16.1/*34*	−71.6	315.7
		Mean	(6)	184.0	62.2	9.9/*46*			187.1	27.8	60.1/*2*	−78.9	290.4
		Mean	38	182.4	61.9	4.5/*27*			190.9	32.0	18.1/*3*	−79.5	295.9
				Mean VGP: 77.0°S, 298.4°E, *n* = 38, A95: 5.9°, *k*: 16									
Polanco	B	Y-6	8	39.0	66.8	12.5/*21*	17	75	85.5	5.5	12.5/*21*	0.8	329.7
		Y-7	4	14.3	59.9	24.9/*15*	239	32	354.2	33.1	24.9/*15*	15.2	316.7
		Mean	(2)	25.1	63.9	[a]			44.9	26.5	[a]	–	–
		Mean	12	29.5	65.0	10.5/*18*			62.6	18.9	28.4/*3*	5.9	325.3
				Mean VGP: 3.2°N, 325.8°, *n* = 12, A95: 15.2°, *k*: 9.									

Full data is presented as Supplementary Material. [a]Values with no statistical significance. The right hand rule is applied for the bedding correction values. Mean values on a sample basis were used for computing the virtual geomagnetic poles for components B and C. Full data is presented as Supplementary Material.

the Rocha Fm. is Dec: 184.2°, Inc: 64.9°, $n = 42$ (samples), α 95: 2.7°. A palaeomagnetic pole was obtained by averaging the VGPs computed from each sample direction (Table 3). This pole (R) is located at 76.6°S, 291.0°E (*n*: 42, A95:4.2°).

DISCUSSION AND INTERPRETATION

Our study has shown that Ediacaran sedimentary successions exposed at three localities of central and eastern Uruguay present secondary magnetizations carried mainly by hematite. The main characteristic remanence isolated in all localities is post-folding and of dual polarity, even within sites, suggestive of a long acquisition time. The palaeomagnetic poles computed from component B of the Cerro Victoria Fm. and the characteristic remanence of the Yerbal and Rocha formations are illustrated in Fig. 13. It is evident that the three palaeomagnetic poles are almost identical, suggesting coeval acquisition of remanence. The three poles are presented in Fig. 13(A) together with a recent compilation of Late Palaeozoic to Early Triassic South American poles (Rapalini *et al.* 2006). All three poles coincide with latest Permian to Early Triassic palaeomagnetic poles for South America, suggesting a possible remanence acquisition age around 250 Ma. The dual polarities recorded in the

Table 3. Idem Table 1 for the Rocha Fm.

				(°)	Bedding				(°)	VGP	
Site	Sample	Dec (°)	Inc (°)	a95/*k*	Strike (°)	Dip (°)	Dec* (°)	Inc* (°)	a95/*k*	Lat (°)	Long (°)
FP-1	1-1	51	−73		45	106	19	−22		49.1	87.6
	1-4	11	−69		45	106	8	−14		70.6	105.4
FP-2	2-3	227	69		45	106	200	18		−52.5	258.8
	2-5	28	−68		45	106	14	−14		64.0	83.4
FP-3	3-2	19	−58		45	106	13	−4		74.3	56.0
	3-6	29	−61		45	106	17	−8		66.2	62.5
FP-4	4-3	164	69		176	97	236	0		−68.9	333.6
FP-5	5-2	180	59		176	97	235	−8		−84.9	305.8
	5-8	15	−61		176	97	58	15		76.2	72.3
FP-6	6-1	175	56		29	96	149	−23		−85.5	9.9
	6-4	166	60		29	96	143	−25		−77.3	2.4
	6-5	161	67		29	96	135	−23		−69.6	342.9
	6-7	149	65		29	96	133	−27		−63.8	358.4
FP-10	10-1	339	−64		209	63	96	−45		70.6	174.8
	10-4	17	−67		209	63	93	−29		70.5	91.2
FP-11	11-1	2	−72		29	117	318	34		67.7	122.9
	11-6	161	61		29	117	147	−46		−73.4	3.8
	11-7	172	64		29	117	146	−40		−77.4	332.3
FP-12	12-2	210	67		37	98	151	−10		−63.5	259.4
	12-3	204	66		37	98	151	−13		−67.6	260.6
FP-13	13-3	35	−63		28	109	326	14		61.6	66.5
	13-6	20	−70		28	109	319	21		66.2	95.9
	13-7	35	−70		28	109	318	16		58.9	84.9
FP-14	14-1	28	−66		30	109	325	18		65.2	77.7
	14-2	333	−58		30	109	324	45		68.1	197.4
	14-5	6	−56		30	109	336	29		84.8	58.3
	14-6	211	67		30	109	144	−17		−62.9	258.8
FP-15	15-2	187	64		30	101	145	−20		−77.8	282.1
	15-7	357	−54		30	101	334	28		87.5	218.8
FP-16	16-4	188	70		30	100	140	−17		−70.0	292.0
FP-17	17-1	177	64		31	98	144	−22		−78.8	316.6
	17-5	185	64		31	98	146	−18		−78.4	288.3
	17-6	190	65		31	98	145	−16		−75.6	277.4
FP-18	18-1	358	−63		29	100	324	23		80.1	134.1
FP-19	19-4	353	−62		33	84	324	12		79.9	156.2
	19-5	3	−65		33	84	325	7		77.5	116.3
	19-8	179	61		33	84	147	−10		−82.6	311.6
	19-9	349	−59		33	84	326	15		79.9	182.5
FP-20	20-7	0	−57		209	74	86	−29		87.1	125.8
	20-9	358	−64		209	74	94	−27		78.9	133.1
FP-21	21-2	325	−54		28	85	316	27		61.3	206.0
	21-5	22	−66		28	85	322	−2		68.8	82.4
	Mean	4.2	−64.9	2.7/65			335.3	3.9	13.7/4	−77.4	292.5
				Mean VGP: 76.6°S, 291.0°E, *n*: 42, A95: 4.2°, *k* : 29.							

In this case site means were not computed due to low number of samples per site.

study successions are consistent with a post-Kiaman age. Late Permian remagnetizations have been found frequently in southern South America, both along the Andes of Argentina (Rapalini & Tarling 1993; Rapalini *et al.* 2000; Rapalini & Astini 2005) and far from the continental margin (Rapalini 1998; Tomezzoli & Vilas 1999; Tomezzoli 2001). In all cases these remagnetizations have been associated to orogenic events. In our case all formations lie several hundred kilometres north of the orogenic front of the Ventana-Cape Fold Belts and were located in a tectonically stable area during the Late Palaeozoic. Therefore, if remagnetization caused by migrating fluids tectonically expelled from the orogen is invoked (Garven & Freeze 1984, Oliver 1986), a case like the Alleghenian remagnetization (Miller & Kent 1988; McCabe & Elmore 1989), that affected units located far away in the foreland, should be investigated in terms of magnetic mineral formation. On the other hand, a regional remagnetization associated to widespread magmatism is not likely. Although SW Argentina experienced the development of a huge magmatic episode during the Permo-Triassic ('the Choiyoi province', e.g. Llambías *et al.* 2003); the investigated localities are situated several hundred kilometres far from the nearest outcrops of the Choiyoi volcanics. On the other hand, the Late Permian to Triassic was a time of widespread continental climate in South America. Most sedimentary basins recorded gradual continentalization into arid climates during the Permian. Late Permian and Triassic red beds sequences are very common in different parts of South America, including Argentina and Uruguay (e.g. López Gamundi *et al.* 1994). Since the characteristic magnetization in the three units is carried by hematite, chemical precipitation associated to circulation of meteoric waters and variable levels of the water table in a highly oxidizing environment should be investigated as a possible mechanism.

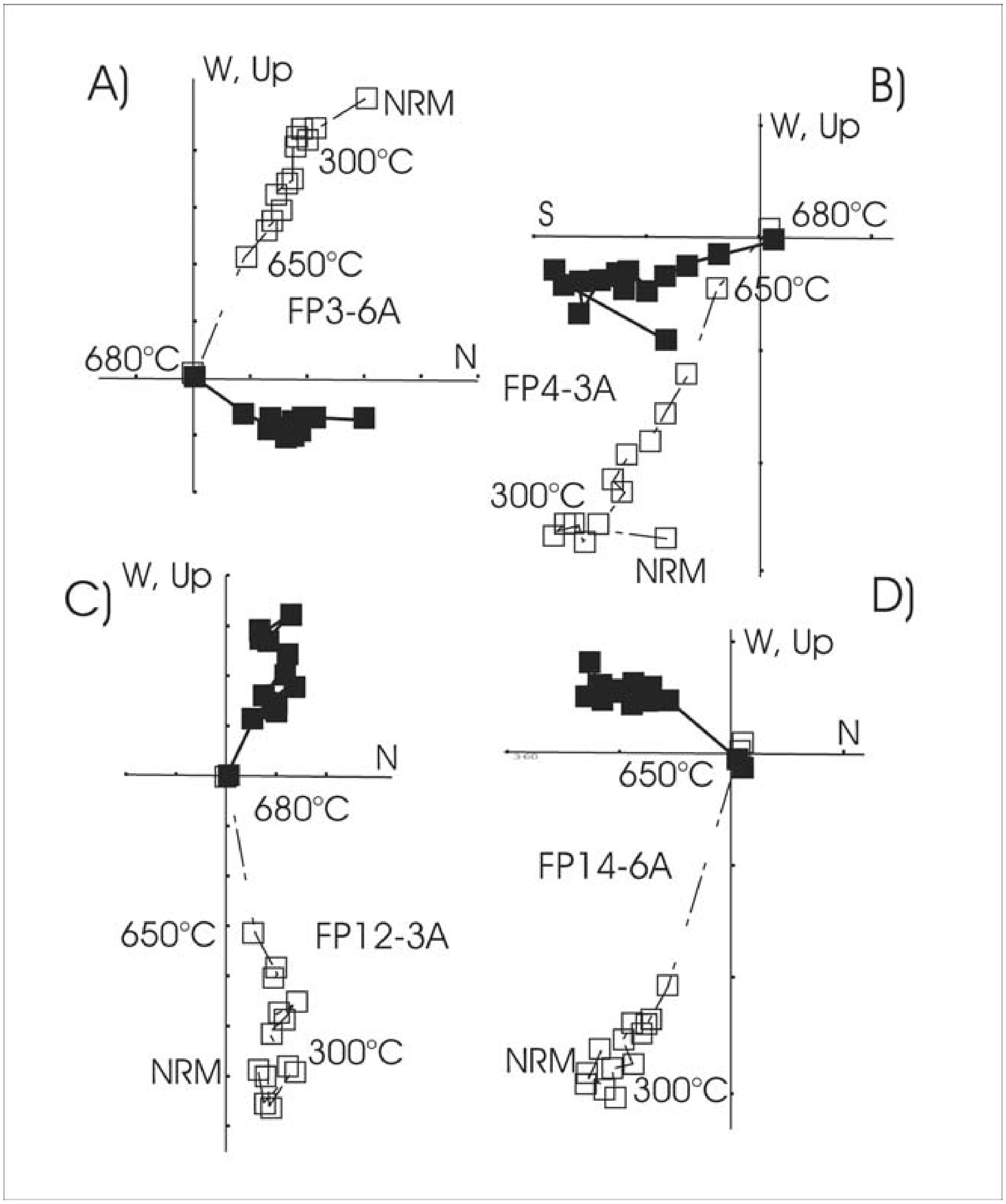

Figure 11. Representative demagnetization plots for the Rocha Fm. References as in Fig. 6.

Detailed mineralogical, diagenetic and rock magnetic studies are needed to better characterize possible processes that yielded the observed remagnetization (for an in-depth discussion of possible mechanisms of remagnetizations in sedimentary successions see Henry *et al.* 2004 and references therein). Although the latest Permian–Early Triassic age for this event looks as the more likely one, it is not the only possible interpretation. Fig. 13(B) shows the obtained palaeomagnetic poles in relation with the Mesozoic and Cenozoic South American mean poles as obtained by Somoza & Tomlinson (2002), Iglesia Llanos *et al.* (2003) and Vizán *et al.* (2004). The post-tectonic poles for the Cerro Victoria, Yerbal and Rocha formations partially overlap those corresponding to the middle Cretaceous (100 Ma), Late Cretaceous (75 Ma) and Palaeogene (50 Ma). A middle Cretaceous age for the remagnetization can be ruled out on the basis of the dual polarities found in the three successions, incompatible with the Cretaceous Normal Superchron that extended from about 118 Ma until 84 Ma. There is no reported tectonic or magmatic activity for the Late Cretaceous to Early Tertiary in Uruguay (Bossi & Navarro 1991; Bossi *et al.* 1998). This turns such age more unlikely for the widespread remagnetizing event found in the Neoproterozoic units. A latest Cretaceous increased pedogenic activity have been described for large areas of Uruguay (Ford & Gancio 1988; Bossi *et al.* 1998), interpreted as due to a humid subtropical climate. This climatic event produced a significant development of palaeosoils as well as diagenetic remobilization and deposition of iron oxides (as represented in the Asencio Formation), including a large production of hematitic concretions. Whether this climatic event could have caused the observed remagnetization carried by hematite is not certain. Although the widespread character of the remagnetization suggests this is not a very likely mechanism, it

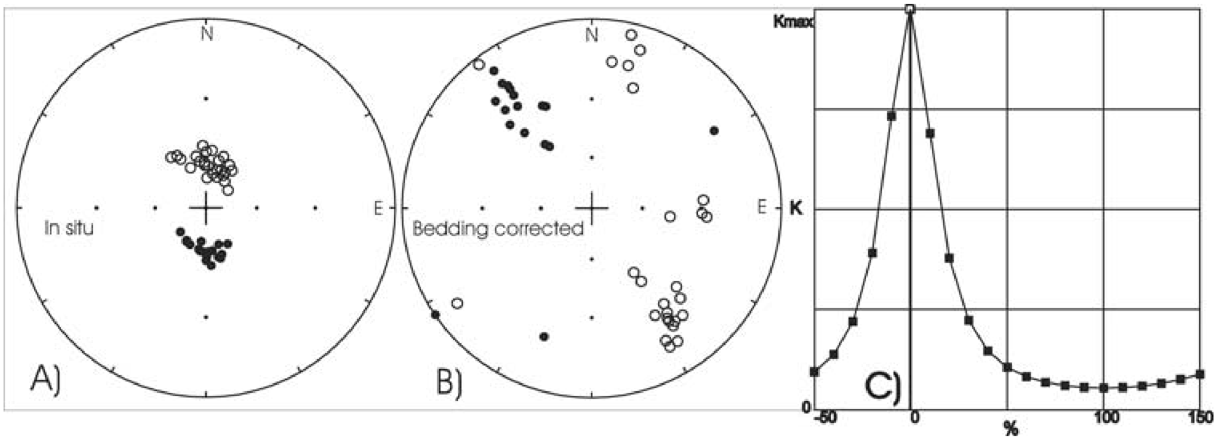

Figure 12. (A) Stereographic projection of *in situ* sample characteristic remanence direction of the Rocha Fm. (B) idem (A) after bedding correction. (C) Statistical parameter *k* versus stepwise unfolding. Dashed line indicates optimum unfolding. References as in Fig. 7. See also Table 3.

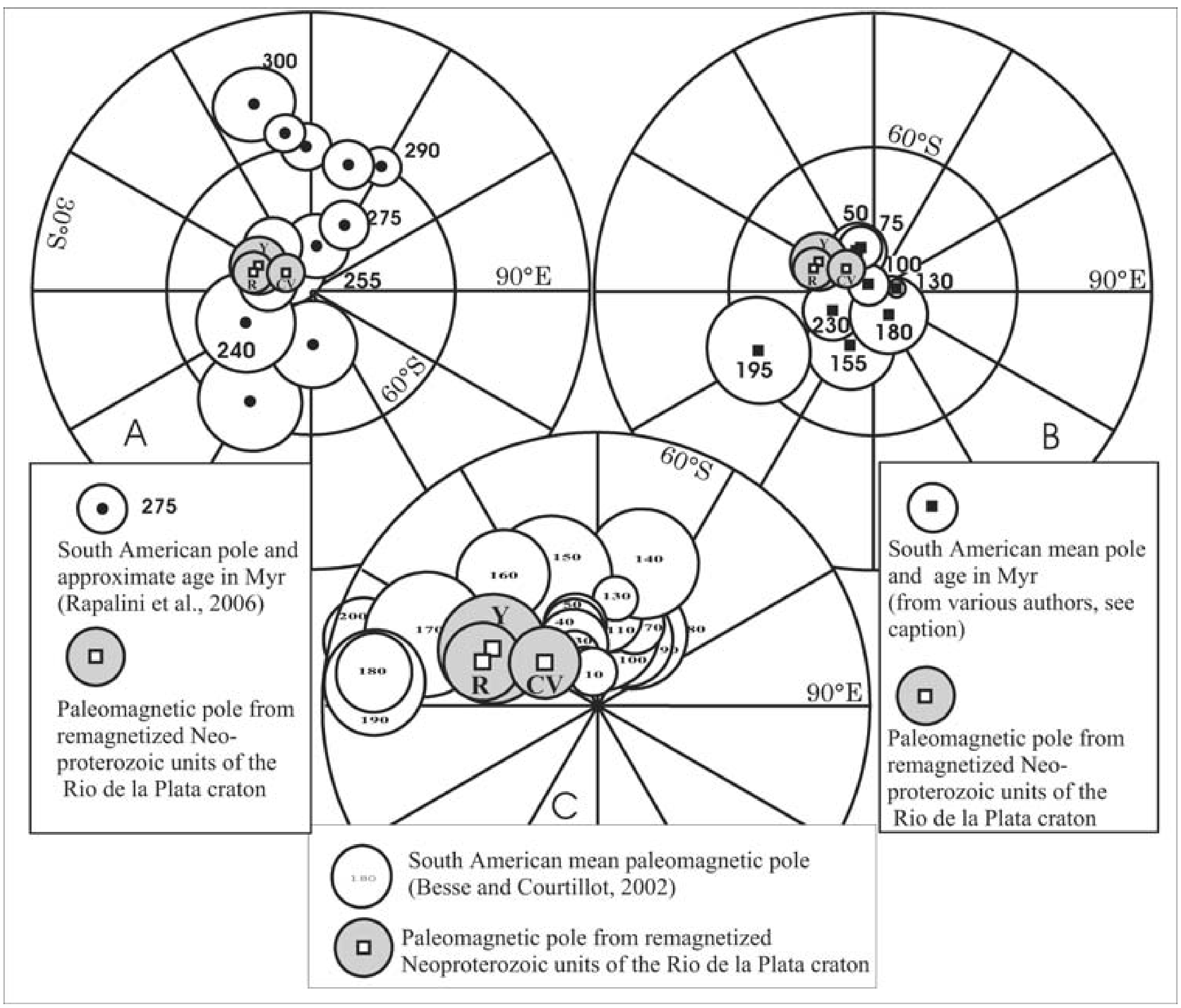

Figure 13. (A) Palaeomagnetic poles for the Cerro Victoria Fm. (component B, CV), Yerbal Fm. (Y) and Rocha Fm. (R) and its comparison with the apparent polar wander path of South America for the Permian to Early Triassic (Rapalini *et al.* 2006). Note the nearly identical pole positions for the three formations and its consistency with latest Permian South American poles. Numbers indicate approximate age in Myr of these poles. (B) Comparison of the same three poles with Meso-Cenozoic South American mean poles according to Somoza & Tomlinson (2002), Iglesia Llanos *et al.* (2003) and Vizán *et al.* (2004). CV, Y and R fall close to the Middle and Late Cretaceous and the Palaeogene mean poles. Circles around all poles correspond to their 95 per cent confidence circle. (C) Comparison of the same poles with the South American reference APWP of Besse & Courtillot (2002) for the last 200 Myr. Note that CV, Y and R tend to fall out of the path. Schmidt-type projection. Discussion in the text.

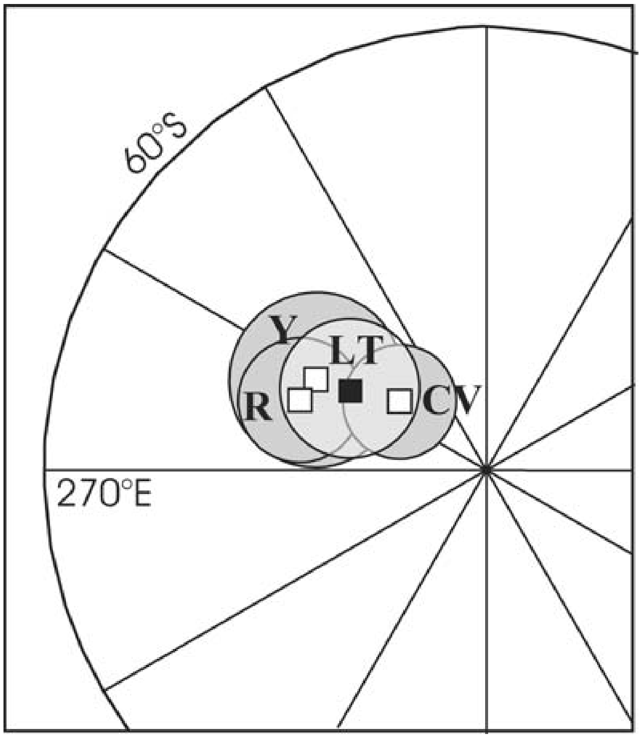

Figure 14. Comparison of the Cerro Victoria (CV), Yerbal (Y) and Rocha (R) formations poles (solid circles with white confidence ovals) with the La Tinta pole (LT, Valencio *et al.* 1980; white circle with grey confidence circle). Note the consistency of all 4 poles, strongly suggesting that LT is also remagnetized. Schmidt-type projection.

remains as the only possible way known to the authors for producing the remagnetization of the Neoproterozoic successions in the Late Cretaceous–Palaeogene.

Since no independent way to date the remagnetization is available, reference poles used for comparison are critical. Therefore, a different master path for South America (Besse & Courtillot 2002) has been used as well in order to define the most likely age of remagnetization. Fig. 13(C) shows no significant consistency of the palaeomagnetic poles for the Cerro Victoria, Yerbal and Rocha formations with the South American polar wander path since 200 Ma. There is only partial overlapping of the latter two poles with the Late Jurassic reference ones, while CV marginally overlaps a couple of Neogene poles. This suggests that a remagnetization event in the Permian–Triassic looks somewhat more likely.

No matter if the remagnetization occurred in the Late Permian–Early Triassic or during the Late Cretaceous–Palaeogene, its implications for the interpretation of the APWP of the Río de la Plata Craton are significant. Fig. 14 shows the remagnetized poles from Uruguay together with the La Tinta Fm. palaeomagnetic pole (LT) published by Valencio *et al.* (1980). The position of the four poles is virtually identical. The La Tinta Formation is an old-fashioned name for the Neoproterozoic Sierras Bayas Group (e.g. Iñiguez *et al.* 1989; Poiré 1993; Cingolani & Dalla Salda 2000). This is exposed in the province of Buenos Aires, Argentina, on top of the southernmost outcrops of the Río de la Plata craton basement. Although 'blanket demagnetization' was applied to a large proportion of the samples studied of the La Tinta formation, stepwise demagnetization of pilot samples showed very similar magnetic behaviour with a significant proportion of the natural remanence remaining after 600 °C. This suggests hematite as the likely carrier of the remanence. Dual polarity remanence was found in this formation, even within specimens from the same sample. Since the studied rocks were virtually subhorizontal, no tilt or fold test could be applied. Valencio *et al.* (1980) interpreted the dual polarity remanence as evidence of a primary magnetization and the La Tinta pole has been since widely used in Precambrian palaeogeographic considerations (e.g. Meert & Van der Voo 1997; Tohver *et al.* 2006). The identical pole position and very similar magnetic characteristics, including the dual-polarity magnetization, strongly suggest that the La Tinta formation pole corresponds to the same remagnetizing event that affected the Cerro Victoria, Yerbal and Rocha formations in Uruguay. In conclusion, LT should not be used any more for palaeogeographic or tectonic purposes. A detailed and systematic palaeomagnetic study of the different units that integrate the Sierras Bayas Group is underway (Rapalini *et al.* unpublished) to test if a primary remanence is present in any of these units. On the other hand, Rapalini (2006) has recently published palaeomagnetic results from Ediacaran red claystones exposed in the Sierra de los Barrientos (SE Buenos Aires province) with strong evidence of a primary magnetization in these sediments. The regional remagnetization shown by the La Tinta, Cerro Victoria, Yerbal and Rocha poles, did not affect, therefore, some areas or lithologies. This gives hope for further successful palaeomagnetic studies in Precambrian rocks of the region.

As discussed previously, two sites of the Cerro Victoria Fm. and other two of the Polanco Fm. were carriers of a post-folding remanence with a significantly different direction. Demagnetization behaviours and IRM acquisition curves suggested magnetite as the likely carrier of this remanence. Fig. 15 shows the position of the mean geomagnetic poles computed for the Cerro Victoria (Component C, CVc) and Polanco formations (P), in a Gondwana reconstruction (Reeves *et al.* 2004). These poles are plotted against the Gondwana path proposed by Trindade *et al.* (2006) for the Ediacaran–Cambrian times. According to these authors, large parts of Gondwana including RP, Congo-São Francisco, NE Africa, Arabia and most of Eastern Gondwana were already assembled by around 550 Ma. A very fast apparent polar wander is inferred from the path between *ca.* 550 and *ca.* 525 Ma. The sharp elbow at those times was interpreted by these authors as produced by the final amalgamation of Amazonia and NW Africa to Gondwana, as indicated by coincident poles from the Ntonya Ring structure (Briden *et al.* 1993) from NW Africa and the Araras 'B' pole (Trindade *et al.* 2003) from Amazonia with other Gondwana poles. The elbow at 525 Ma is followed by a significantly different path for the whole Gondwana until *ca.* 510 Ma, when a new important change in the path is observed until the pole is located in northernmost Africa for the latest Cambrian and the Early Ordovician. The positions of the mean geomagnetic poles for the Polanco and Cerro Victoria formations are consistent with the poorly dated SA1 (Sierra de Las Animas 1 pole of Sánchez Bettucci & Rapalini 2002). According to the Gondwana path shown in Fig. 15 a Late Cambrian to Early Ordovician age for the post-folding remagnetization of both units is inferred. Whether this is related to the magmatic activity expressed in the Sierra de Las Animas Complex, in southern Uruguay, or to uplift and cooling following the main deformational event that affected both units is yet to be established. It must be noted that remagnetizations of similar age have been found in the São Francisco and Amazonia cratons in South America (D'Agrella *et al.* 2000; Trindade *et al.* 2003). In any case, the obtained palaeomagnetic data suggest that deformation of the Arroyo del Soldado Group occurred prior to 510–500 Ma. Since bio- and chemostratigraphic data suggest that the Cerro Victoria limestones were deposited by the beginning of the Cambrian, this tectonic event probably occurred *ca.* 525 Ma, being also related to

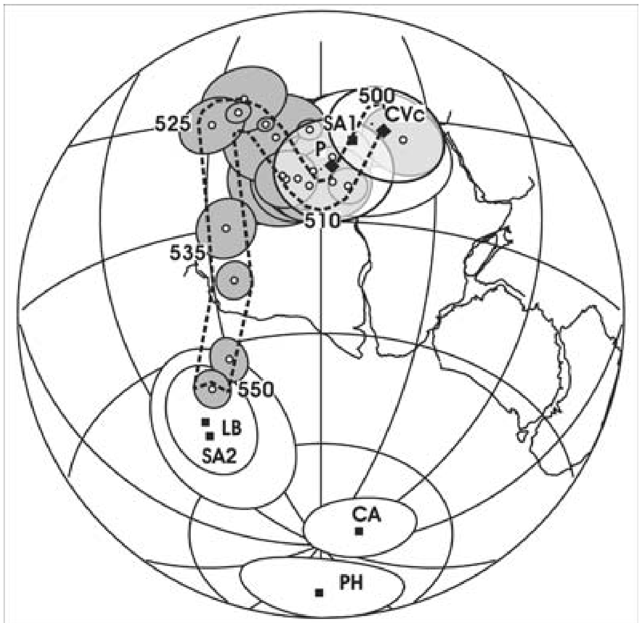

Figure 15. Ediacaran to Cambrian palaeomagnetic poles (white circles with their correspondent 95 per cent confidence circles in grey) and the apparent polar wander path (APWP) for Gondwana (modified from Trindade *et al.* 2006). Previous poles for The Rio de la Plata craton are represented as solid black squares with their 95 per cent confidence ovals in white. Mean geomagnetic poles obtained in this study are presented as larger black diamonds with their corresponding 95 per cent confidence ovals (semitransparent). CVc: Cerro Victoria component C; P: Polanco; SA1, SA2: Sierra de Las Animas 1 and 2 poles (Sánchez Bettucci & Rapalini 2002); LB: Los Barrientos pole (Rapalini 2006); PH: Playa Hermosa mean geomagnetic pole (Sánchez Bettucci & Rapalini 2002); CA: Campo Alegre (D'Agrella & Pacca 1988). Details on the poles for Gondwana in Trindade *et al.* (2006). Figures indicate approximate ages in Myr along the APWP.

the final stages of Gondwana assembly, and likely to docking of the Kalahari craton against the RP and Congo blocks.

Fig. 15 also shows the available palaeomagnetic poles for the Río de la Plata craton between *ca.* 600 and 500 Ma. (solid squares in Fig. 15). These poles define a very long path. Consistent poles for the late Cambrian–Early Ordovician and the late Ediacaran (*ca.* 550 Ma) with other Gondwana poles suggest that RP was already assembled to Congo-São Francisco, Arabia and probably Australia and India for that time. However, it should be noticed that the Pan de Azúcar syenite correspondent to SA2 (Sánchez Bettucci & Rapalini 2002) has been recently dated by Ar–Ar as 579 Ma (Oyhantçabal *et al.* 2007), suggesting a slightly older age for the pole than originally proposed by Sanchez Bettucci & Rapalini (2002). On the other hand, the consistent Los Barrientos pole (LB, Rapalini 2006) has no tight age constraints but permits a *ca.* 570 Ma age. The Campo Alegre lavas (595 Ma, CA, D'Agrella & Pacca 1988) and the Playa Hermosa mean geomagnetic pole (Sánchez Bettucci & Rapalini 2002) permit to tentatively trace back the APWP of RP until around 600 Ma. Considering that the La Tinta Fm. pole is no longer valid, there is no palaeomagnetic control on the palaeogeography of RP prior to *ca.* 600 Ma.

CONCLUSIONS

A palaeomagnetic study was performed on three Neoproterozoic sedimentary successions exposed in central and eastern Uruguay. These units comprise the latest Ediacaran to Early Cambrian calcareous Cerro Victoria Fm., exposed in the central NPT, the late Ediacaran clastic Yerbal Fm. and the calcareous Polanco Fm., exposed in the DFB and the Ediacaran clastic Rocha Fm. exposed in the Punta del Este suspect terrane. The study showed that none of the units carry the original remanence and that they have been affected by two remagnetizing events. The most widespread remagnetization is shown by the Cerro Victoria, Yerbal and Rocha formations, carried by hematite. This magnetization is post-folding and shows dual polarity, frequently at a single site. The pole positions obtained from them are virtually identical and their comparison with the South American path suggests the Late Permian–Early Triassic as the most likely interval for remanence acquisition. A less likely latest Cretaceous–Palaeogene or even Neogene age cannot be completely discarded. These poles are also identical to the pole of the Late Proterozoic La Tinta Fm. (Valencio *et al.* 1980), exposed in the Buenos Aires province of Argentina, which shows very similar magnetic characteristics and for which no field tests for the age of magnetization are available. This strongly suggests that the La Tinta pole is also a remagnetized one, and cannot be used for any tectonic or palaeogeographic purpose. A different magnetic component, also dual polarity and post-folding, was defined at two sites of the Cerro Victoria Fm. and other two of the Polanco Fm. In this case the magnetization is interpreted as probably carried by magnetite. The mean geomagnetic poles from both units fall on the Middle Cambrian to Early Ordovician segment of the Gondwana APWP, suggesting that age for the remagnetization. This also constrains the age of the last tectonic event that affected the Ediacaran–Cambrian Arroyo del Soldado Group as occurring more likely in the Early Cambrian (*ca.* 525 Ma). The available palaeomagnetic poles for RP permits to constrain its palaeogeographic evolution only since approximately 600 Ma.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

Appendix S1. The appendix contains full versions of Tables 1 and 2 (Word format).

This material is available as part of the online article from: http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-246X.2008.03771.x (this link will take you to article abstract).

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