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The La Tinta pole revisited: Paleomagnetism of the Neoproterozoic Sierras Bayas Group (Argentina) and its implications for Gondwana and Rodinia

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ABSTRACT

The Late Ediacaran to Cambrian Sierras Bayas Group (Villa Mónica, Cerro Largo, Olavarría and Loma Negra Formations) and the Cerro Negro Formation, exposed along the Tandilia system in the province of Buenos Aires (Argentina) were revisited and studied paleomagnetically. Our results supersede those of Valencio et al. (1980) for the La Tinta Formation (old stratigraphic name of these units). Three hundred and twenty-eight samples were collected from forty-four sites in gently folded to subhorizontal strata distributed along the whole stratigraphic succession. Detailed paleomagnetic study comprised systematic stepwise demagnetization by both AF and thermal methods, the latter being generally the most effective in isolating the characteristic remanence. Different magnetic components were defined from different units of the succession. Besides a recent, probably viscous, secondary component (component A), the most widespread magnetic remanence (component B) is a dual-polarity post-tectonic secondary remanence. This component, carried by both hematite and magnetite, corresponds to that originally determined by Valencio et al. (1980) and previously interpreted as primary. This component found in all carbonatic rocks of Villa Mónica and Loma Negra Formations as well as in several claystones and siltstones of the Olavarría Formation do not pass conglomerate and regional tilt tests. The mean in situ direction of component B is Dec: 359.8°, Inc: −63.3°, *n*: 85 samples, *k*: 24, α95: 3.2° and yields a paleomagnetic pole virtually identical to the previous one of Valencio and colleagues. It also matches those recently determined from secondary magnetizations in carbonatic and clastic Ediacaran units exposed in Uruguay.The pole positions suggest a Late Permian–Triassic age as the more likely for the acquisition of component B and reveal the presence of a widespread remagnetization event that affected very large areas of the Rio de la Plata craton. Despite this widespread event, some clastic units (claystones, marls) apparently escaped remagnetization. A pre-tectonic, dual polarity, mean remanence (Dec: 28.7°, Inc: 56.1°, *n*: 17 samples, *k*: 15, α95: 9.5°) was isolated from the latest Ediacaran–Early Cambrian Cerro Negro Formation (component C). In addition, the Ediacaran Olavarria Formation recorded another apparently ancient remanence, although no field test is available. Its direction (component D) is at Dec: 350.9°, Inc: 47.3°, *n*: 13 samples, *k*: 37, α95: 7.0°. Siltstones and claystones of the Ediacaran Cerro Largo Formation were carriers of a characteristic remanence (component E) that shows a better directional grouping after bedding correction, although the field test is not statistically significant, and yield a mean corrected direction at: Dec: 73.7°, Inc: −36.6°, *n*: 11 samples, *k*: 15, α95: 12.1°. Finally, a purple horizon of marls on top of the Villa Mónica Formation associated with weathering processes before deposition of the Colombo diamictite, was carrier of a characteristic remanence that attained a better grouping after bedding correction, but again with no statistical significance. This direction (component F) was at Dec: 43.4°, Inc: −36.3°, *n*: 7 samples, *k*: 45, α95: 9.1°. Components C–F are interpreted as ancient magnetizations associated either to post-depositional or early to late diagenesis. Mean geomagnetic poles computed from these components fall on the apparent polar wander path for the Rio de la Plata craton from around 600 to 520 Ma, in a correct stratigraphic order and with ages consistent with the most likely ages (or slightly younger) of the different sampled units. These results confirm the already proposed Ediacaran to Cambrian APWP for the Rio de la Plata craton, indicating that it remained at intermediate to low latitudes during most of the

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Ediacaran. Comparison with coeval paleomagnetic poles from other cratons indicate that by 575 Ma the Rio de la Plata and Congo-Sao Francisco cratons were likely a single plate. It also strongly argues against the generally accepted model that the Rio de la Plata craton was part of the conjugate margin of Eastern Laurentia during the final stages of Rodinia break-up at around 580 Ma.

1. Introduction

The Late Proterozoic is a fascinating period of Earth history that witnessed the break-up and dispersal of a supercontinent called Rodinia (Hoffman, 1991; McMenamin and McMenamin, 1990), followed by the assembly of a new supercontinent by the end of that era, Gondwana (e.g. Rogers and Santosh, 2004). In those few hundred million years dramatic global paleogeographic changes took place that might have contributed to the accelerated biotic evolution (Kirschvink and Raub, 2003 and references therein) as well as major climatic events, such as the hypothetical global glaciations (e.g. Hoffman et al., 1998). In order to reconstruct the Earth history at those times and understand these processes, precise paleogeographic reconstructions throughout the Late Proterozoic are essential.

Due to the lack of preserved ocean floor anomalies and hot spot tracks and the paucity of the biogeographic records, paleogeographic reconstructions for the Late Proterozoic rely heavily on paleomagnetic data. Paradoxically, Proterozoic paleomagnetic data are scarce and generally of lower reliability than Phanerozoic data. Furthermore, the geographic entities that are basically used for Phanerozoic reconstructions (i.e. present day major continents) are no longer valid in most cases and many individual cratons must be considered independently, producing in this way a significant increase in the number of paleomagnetic poles needed for reliable global paleoreconstructions. Considering the relatively smaller exposures of Proterozoic rocks and a complex geologic history affecting them, it is no surprise that progress in the Neoproterozoic paleogeography, however significant in the last decades, is slow.

The Rio de la Plata craton (RP, Fig. 1) is one of the crustal blocks with Archean and/or Paleoproterozoic basement, that was part of Western Gondwana (Dalla Salda et al., 1988; Cingolani and Dalla Salda, 2000). Its paleogeographic evolution and relationships to neighbouring blocks during Gondwana assembly are controversial and very poorly known (for a recent review of geologic evidence see Cordani et al., 2000; Rapela et al., 2007, 2011; Bossi and Cingolani, 2009). Its disputed relations with the Kalahari, Congo-Sao Francisco, Amazonia and Pampia blocks (e.g. Rapalini, 2005) make RP a likely key player in unraveling the processes that led to the formation of the Gondwana supercontinent and its Neoproterozoic relations with Laurentia (e.g. McCausland et al., 2007, 2011).

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 and Pisarevsky, 2005; Li et al., 2008), no conclusive geologic evidence supports 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. Kröner and Cordani (2003) have suggested that both RP and Congo-São Francisco cratons never took part in Rodinia. Rapela et al. (2007) have also suggested that RP had no connection with Mid-Proterozoic (Grenvillian) orogens during the Neoproterozoic.

The available paleomagnetic data from RP for the Neoproterozoic have been recently discussed by Tohver et al. (2006) and Rapalini and Sanchez Bettucci (2008). From these reviews it is evident that the paleogeographic evolution of RP is very poorly known. In particular, there is no paleomagnetic constraint for the paleoposition of RP prior to 600 Ma. A preliminary apparent polar wander path for the interval 600–500 Ma has been recently proposed (Sánchez Bettucci and Rapalini, 2002; Rapalini, 2006; Rapalini and Sanchez Bettucci, 2008). The latter authors have suggested that the old La Tinta Formation pole (Valencio et al., 1980), used for many years in paleogeographic reconstructions of RP for the mid-Neoproterozoic (ca. 750 Ma) is not valid because it may correspond to a Permo-Triassic or Paleogene remagnetization. However, Rapalini (2006) published conclusive evidence of primary magnetizations from a section of Neoproterozoic claystones exposed in the same Tandilia System of central Argentina, few tens of kilometers away from the main outcrops studied by Valencio and colleagues.

Considering the importance that a well-defined apparent polar wander path (APWP) for RP may have in Neoproterozoic global paleogeographic reconstructions and in defining possible connections between Laurentia and Western Gondwana blocks, a new systematic paleomagnetic study was carried out in different localities and different units of the Neoproterozoic Sierras Bayas Group and the latest Ediacaran to Cambrian Cerro Negro Formation. These units correspond to those originally studied by Valencio et al. (1980) and labelled as La Tinta Formation (e.g. Cingolani and Bonhommé, 1982). In that study no consideration was taken for the different stratigraphic units that compose now the Sierras Bayas Group, no field test was performed to ascertain the primary or secondary nature of the remanence and the characteristic remanence was obtained through old fashioned blanket demagnetization. As such, our new study can be considered as revisiting the La Tinta Formation.

By investigating a much larger collection than the original study, and using up to date paleomagnetic methodologies we confirmed that most rocks from the Sierras Bayas Group are affected by a much younger remagnetization event, as already suggested by Rapalini and Sanchez Bettucci (2008). However, few sites, mainly on red to purple claystones and marls, apparently escaped this regional remagnetization and provided four new mean virtual geomagnetic poles that assist in defining the APWP for RP in the interval 600–500 Ma. The significance of the refined APWP for RP in terms of paleogeography and tectonic evolution is analyzed.

2. Geology and stratigraphy of the sampled units

The Tandilia System is a 350 km long, northwest–southeast oriented orographic belt, located in the Buenos Aires province of Argentina (Fig. 1). It represents the southernmost exposures of basement rocks that unambiguously belong to the Rio de la Plata craton. It comprises an igneous-metamorphic basement covered by a succession of Neoproterozoic to Lower Paleozoic sedimentary rocks. The basement rocks are mainly granitoids, orthogneisses and migmatites of 2.26–2.07 Ga (Hartmann et al., 2002; Pankhurst et al., 2003), intruded by undeformed basic dykes (Cingolani, 2011).

The Neoproterozoic to Eo-Paleozoic cover comprises up to 500 m of clastic and carbonatic unmetamorphosed sedimentary rocks. The succession is subdivided into the Neoproterozoic Sierras Bayas Group, the Ediacaran–Cambrian Cerro Negro Formation and the Ordovician to Silurian Balcarce Formation. The Sierras Bayas Group (Fig. 2) is composed of the Villa Mónica Formation,

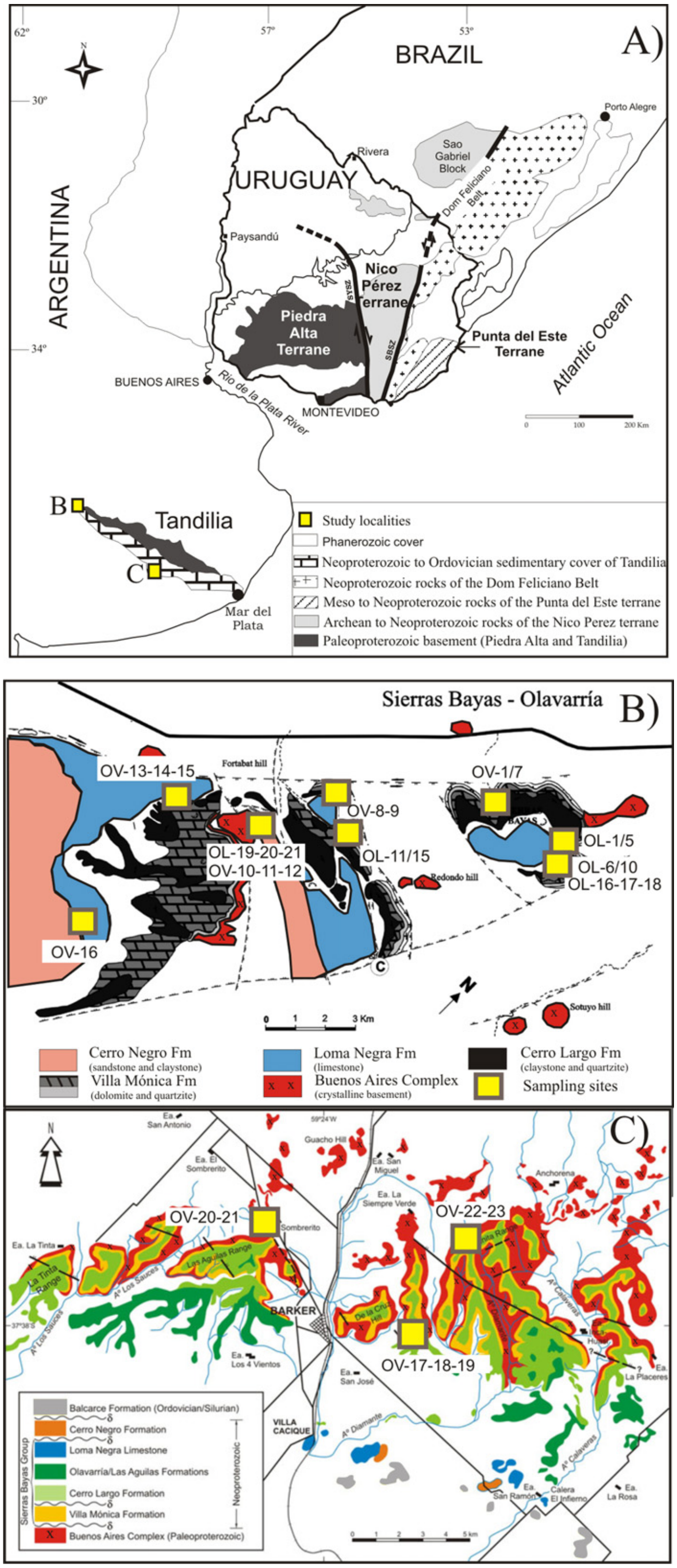


Fig. 1. (A) Main morphotectonic units of the Rio de la Plata craton and location of the sampling localities near Olavarria and Barker along the Tandilia system. (B) Schematic geologic map of the Olavarria locality and distribution of sampling sites. (C) Schematic geologic map of the Barker locality and distribution of sampling sites. Part B modified from Gómez Peral et al. (2007). Part C modified from Cingolani (2011).

The Colombo Diamictite, the Cerro Largo Formation, the Olavarría Formation and the Loma Negra Formation (Poiré and Gaucher, 2009). The Villa Mónica Formation is the older sedimentary unit of the region. It is around 52 m thick and it is made up of two sedimentary facies associations, (a) quartz–arenites and arkosic sandstones at the base and (b) dolostone including shallow marine stromatolites dolostone and shales at the top. The age of the Villa Mónica Formation is not accurately defined. Its rich stromatolite assemblages led Poire (1993) to suggest a Tonian–Cryogenian age (c. 850 Ma). Rb–Sr geochronology of illitic shales within the dolostones yielded an age of 793 ± 32 Ma (Cingolani and Bonhomme, 1988). Detrital zircon geochronology on three samples (Rapela et al., 2007; Gaucher et al., 2008; Cingolani, 2011) from different localities show an unimodal population of Palaeoproterozoic age, clearly indicating provenance from the underlying Buenos Aires Complex. Gómez Peral et al. (2007) provided evidence of a significantly higher diagenetic degree of alteration in the Villa Mónica Formation with respect to the overlying units, which was interpreted in favour of a significant hiatus between them. Comparison of isotopic curves ($^{87}Sr/^{86}Sr$ and $\delta^{13}C_{carb}$) for the dolostones of this unit with global reference ones points to 720–750 as a likely age for these carbonates.

The top of this unit is characterised by red to purple marls that suggest a period of exposure and weathering of the succession. On top of these red marls lie the diamictites and shales of the recently defined Colombo Formation, which is composed of around 8 m of whiteish, massive mudstones and claystones bearing exotic clasts up to 2.5 m in diameter. Convolute structures, chert breccias and fine orthoconglomerate also occur (Poiré and Gaucher, 2009).

The succession continues upward with the 40-m-thick clastic sedimentary rocks of the Cerro Largo Formation which represents a second marine transgression (Poire, 1993; Poiré and Gaucher, 2009). It consists of finely bedded, varicolored, glauconitic sandstones, hetherolithic facies and cross-bedded quartz–arenites. Microfossils found in top levels of this unit point to a Late Ediacaran age. According to provenance geochronological studies (Gaucher et al., 2008), the sandstones (Fig. 2) are characterised by a dominant Palaeoproterozoic detrital zircon population, with subordinate Archean to lowermost Paleoproterozoic and Mesoproterozoic ages.

The Cerro Largo Formation passes transitionally into siltstones and claystones of the Olavarría Formation (Andreis et al., 1996) with a maximum thickness of 37 m. Paleoenvironmental interpretations suggest shallow-marine deposits in a transgressive system tract. Rb–Sr ages on illitic shales point to a Neoproterozoic age (Bonhomme and Cingolani, 1980). Particularly, in the Barker area, the middle part of the unit comprises red claystones with high iron content (32–70% Fe_2O_3) up to 9 m in thickness, which could be correlated with other late Neoproterozoic iron deposits in SW Brazil and Uruguay (Gaucher, 2000; Gaucher et al., 2003, 2004).

A second carbonatic interval is represented by the youngest formation of the Sierras Bayas Group. The 40–45 m thick Loma Negra Formation is composed almost exclusively of reddish and black micritic limestones, deposited by suspension fall-out in open marine ramp and lagoonal environments. In these limestones, several diagenetic processes were recognised by Gómez Peral et al. (2007) and after chemostratigraphical studies the Loma Negra Formation fits in global $^{87}Sr/^{86}Sr$ and $\delta^{13}C_{carb}$ trends for the latest Ediacaran (Zimmermann et al., 2011). Recent finding of Cloudina sp. in this formation (Gaucher et al., 2005) is consistent with this estimate and suggests a maximum depositional age around 550 Ma (Condon et al., 2005).

A highly irregular karst surface separates the limestones of the Loma Negra Formation from the clastic sediments of the Cerro Negro Formation. This is a 100–400 m thick unit characterised by reddish and greenish, brown olive claystones and heterolithic

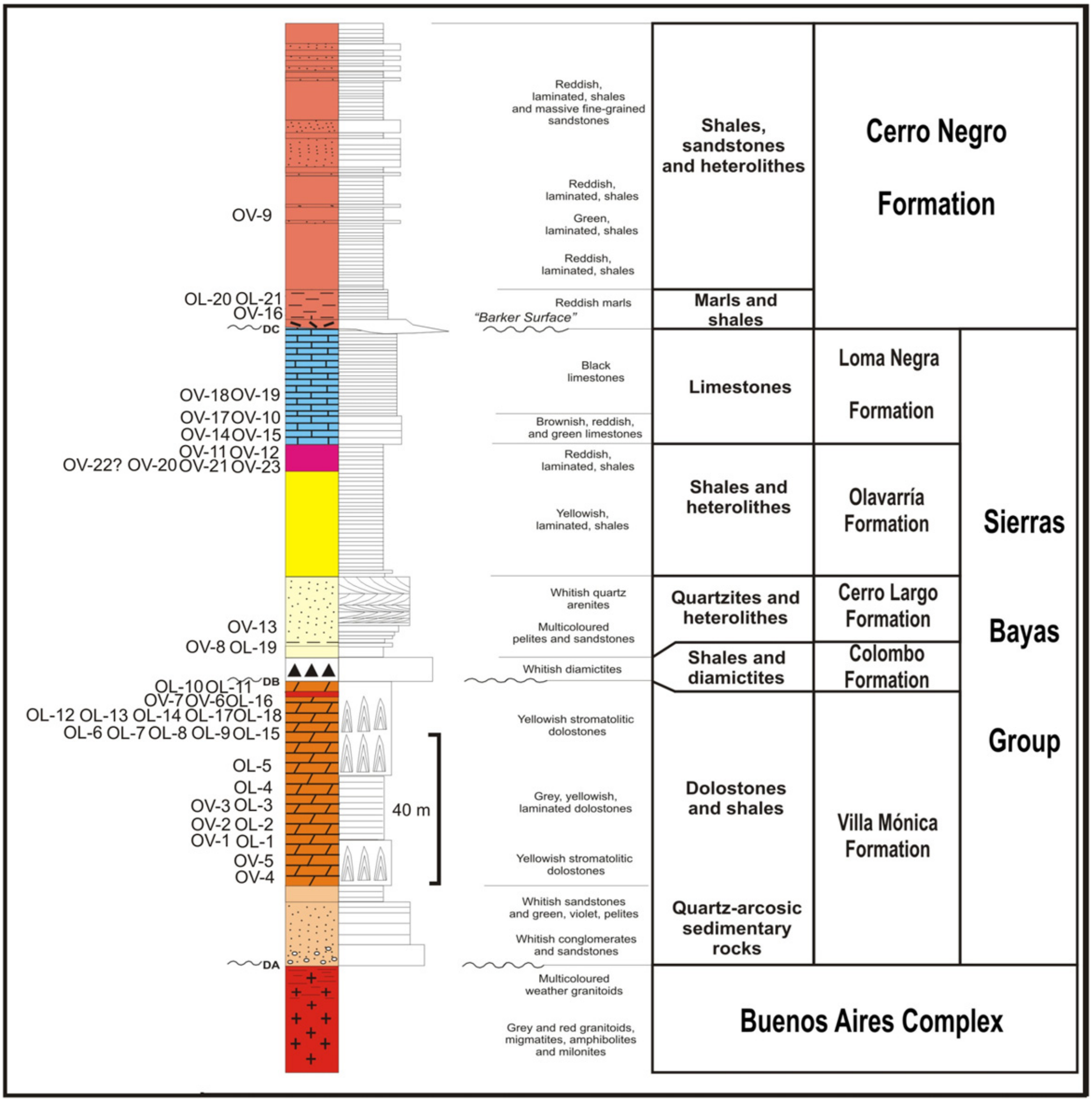


Fig. 2. Stratigraphic column of the Sierras Bayas Group and Cerro Negro Formation and stratigraphic position of the sampling sites.

fine-grained sandstone and claystone interbeds, mainly formed in upper to lower intertidal flats. The lower part of the Cerro Negro Formation consists of reddish residual clayish deposits, micritic limestones and marls, and breccias with a phosphatic level (Leanza and Hugo, 1987; Barrio et al., 1991). The upper contact with the Balcarce Formation is not exposed and completely unknown. The basal karst surface has been correlated on a regional scale with South Africa, Namibia, Uruguay and the Paraguay Belt in Brazil (Poiré and Gaucher, 2009; Poiré, 2008) and related to a marine regression that exposed the Loma Negra shelf. Poiré et al. (2007) proposed the name of "Barker Surface" to identify this regional discontinuity in the SW margin of Gondwana. If this correlation is valid would suggest that initiation of deposition of the Cerro Negro sediments took place at around 545 Ma. Faunal content is restricted to typical acritarchs of latest Ediacaran times with no reported findings of Cambrian micro- or macrofossils (Gaucher and Poiré, 2009). This suggests that this unit was probably deposited during the Ediacaran–Cambrian transition.

In general, the Tandilia Neoproterozoic sedimentary rocks show no signs of internal deformation and were slightly tilted or remained flat-lying (Iñiguez et al., 1989). Dip of strata never exceeds 35°. However, some deformation was described by González Bonorino (1954), including two systems of open folds with subhorizontal axes trending NW–SE and NE–SW, respectively as described by Massabie and Nestiero (2005). These authors interpreted that both systems interfere being likely part of a single deformational event. This folding, which also affected the Cerro Negro Formation, must have taken place probably in Cambrian or Early Ordovician times since the uppermost Late Ordovician to Silurian Balcarce Formation is not affected by any tectonic disturbance.

3. Paleomagnetic study and results

Our study was carried out in two main localities, the Olavarría and Barker areas. Figs. 1 and 2 illustrate the location and stratigraphic positions of sampled localities and sites. Three hundred and twenty-eight samples from 44 sites were collected in the Cryogenian to Ediacaran Villa Mónica Fm., the Ediacaran Cerro Largo, Olavarría and Loma Negra Formations and the Ediacaran–Cambrian Cerro Negro Formation. Sampling was carried out in limestone, dolostone, red claystone and marls in the localities of Olavarria and Barker. It was done in two field trips, and samples were collected with a gasoline-powered portable drill. Standard one-inch diameter cores (5–9 cm long) were oriented with both magnetic and sun compasses whenever possible. No systematic discrepancies were found between both types of measurements. Cores were sliced into 2.2 cm long specimens. Paleomagnetic measurementes and demagnetizations were carried out at the Laboratorio de Paleomagnetismo Daniel A. Valencio from IGEBA (University of Buenos Aires) and in the Paleomagnetic Lab of University of São Paulo. Measurements were done in 2G (DC squids) cryogenic magnetometers. Demagnetization was performed with a static 3 axis degausser attached to the cryogenic magnetometer and an ASC two-chamber paleomagnetic furnace, with an internal field <10 nT. In São Paulo both the cryogenic magnetometer and the paleomagnetic furnace are housed into a shielded room with internal field <1000 nT.

Two to ten pilot specimens per site were submitted to stepwise alternating magnetic fields and thermal demagnetizations (e.g. Butler, 1992). Assessment of magnetic behaviour of pilot specimens allowed the best stepwise demagnetization procedure to be determined for the remaining specimens at each site. Typical demagnetization sequences were: 3, 6, 9, 12, 15, 20, 25, 30, 40, 50, 60, 70, 85, 100, 115, 130 and 145 mT or 60, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 585, 615, 640, 660 and 680 °C. In most sites thermal demagnetization proved to be a better demagnetization technique, and therefore was more widely used in the whole collection of samples than the AF method. During thermal treatment, bulk susceptibility was controlled to identify possible chemical or mineralogical changes due to experimental heating. Magnetic components were identified individually and computed by means of principal component analysis (PCA, Kirschvink, 1980). Magnetic components were defined with at least three steps (generally five or more) and MAD $\leq 15^\circ$ (over 75% of components were defined with MAD $< 10^\circ$). Besides a small proportion of samples that showed unstable magnetic behaviour when submitted to stepwise demagnetization and from which no magnetic component could be isolated, most samples were carrier of at least one magnetic component. The overall collection presented different magnetic components which in most cases are closely related to the lithologic type and/or stratigraphic position of the sampled unit. The main magnetic characteristics are described below.

3.1. Component A

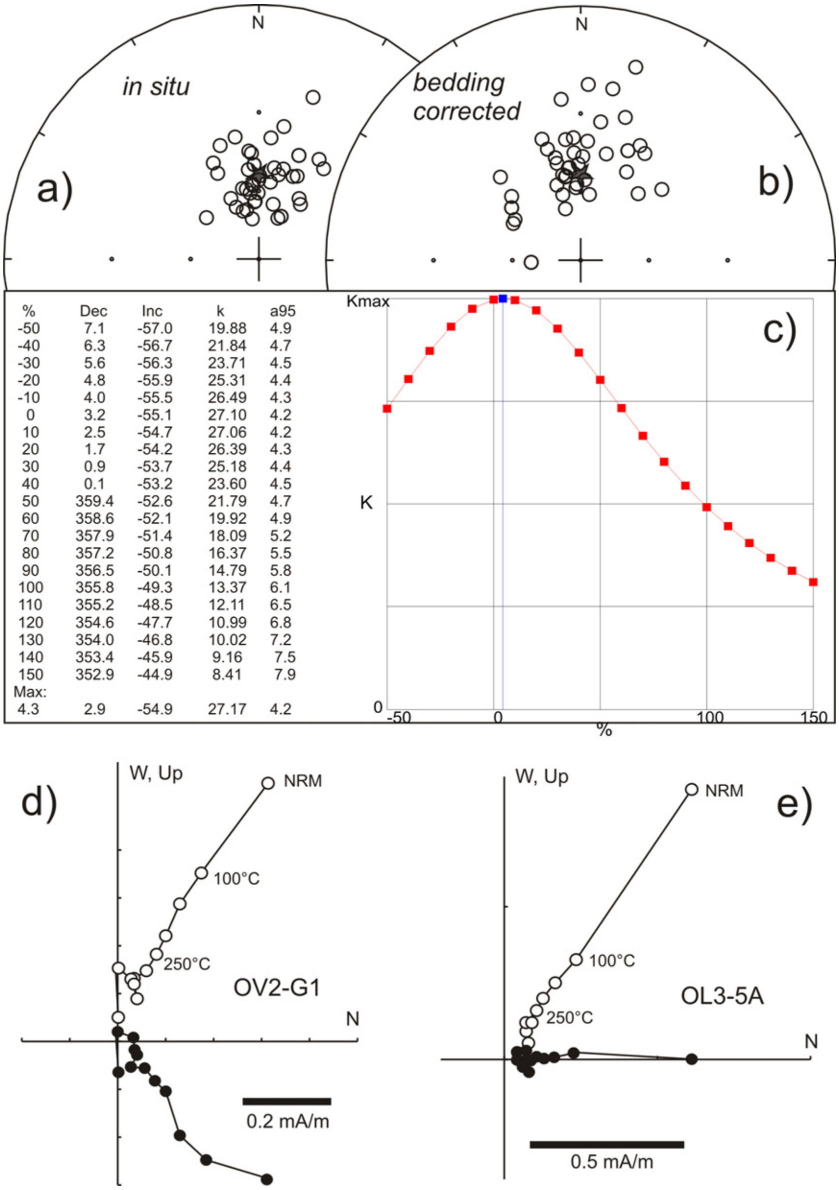
A low-temperature, low coercivity magnetization was isolated in forty-four samples, mainly, but not exclusively, from the Villa Mónica Formation. Unblocking temperatures were generally ≤350 °C and maximum destructive fields were in most cases under 20 mT. All directions were of negative inclinations (normal polarities, Fig. 3a) and its in situ mean is: Dec: 3.2°, Inc: −55.1°; $n = 44$ (samples), $\alpha95 = 5.4^\circ$, $k = 27$. After bedding correction, the mean direction is Dec: 355.9°, Inc: −49.3° with $\alpha95 = 6.1^\circ$, $k = 13$ (for details on bedding correction values see Table 3 in the appendix). Performance of the direction–correction fold test (Enkin, 2003) yields a negative fold-test optimum untilting at 4.7 ± 23.1% indicating a post-tectonic remanence. Stepwise untilting of remanence directions (Fig. 3c) indicates maximum likelihood of remanence being acquired at 4.3% of untilting which is statistically undistinguishable from 0%. Negative result of the tilt test, low unblocking temperatures and coercivities, exclusive normal polarity and consistency of the in situ mean direction with the expected geomagnetic dipole direction for the study region (Dec: 0°, Inc: −56.5°) strongly suggest that component A is a recently acquired (<780 ky) viscous magnetization.

3.2. Component B

A high unblocking temperature, high coercivity, dual polarity magnetic component (Fig. 4) was found in a large number of sampling sites. This component is the most characteristic for most lithologies of the Sierras Bayas Group. It was found in most dolostones (sites OL-1-2-3-4-5-14-15-17-18, OV-1-2-3-4-5) and marls (sites OL-6-7-8-9-11-12-13-16, OV-6-7) of the Villa Mónica Formation. It is also present in most samples of limestones of the Loma Negra Formation (OV-10-15-17-18-19) and in the claystones and siltstones of the Olavarría Formation in the locality of Barker (OV-20-21-22-23). It is apparently absent in the samples collected from the Cerro Largo (claystones) and Cerro Negro (marls and siltstones) Formations. In the marls, claystones and siltstones this component was usually carried by hematite as suggested by unblocking temperatures ≥640 °C (Fig. 4a and b). In the dolostones and limestones, identification of magnetic carriers is more complex as the demagnetization behaviour was more variable. In many cases (Fig. 4c and d) magnetite is the apparent magnetic carrier as suggested by unblocking temperatures close to 580–590 °C and low to moderate coercivities. However, in several other samples the presence of goethite is indicated by sudden loss of 30–70% of natural remanence at 100–150 °C. Pyrrhotite cannot be ruled out as a minor magnetic carrier in some samples with a significant drop in the remanence intensity between 300 and 350 °C. Rock magnetic studies are presented in the following section.

Distribution of "in situ" sample characteristic remanence directions (Fig. 5a) shows a dual polarity magnetic component with an average direction at: Dec. 359.8°, Inc: −63.3°, n: 85 samples, k: 24, α95: 3.2°. Grouping of directions after bedding correction is significantly worse (Dec: 356.8°, Inc: −58.0°, k: 15, α95: 4.1°). As in the previous case, a statistical stepwise tilt-test was performed (Enkin, 2003) that indicates maximum likelihood of acquisition of remanence "in situ" (−9.3 ± 18.9% of bedding correction). Stepwise untilting show maximum k at −6.9% unfolding, statistically undistinguishable from the in situ direction (Fig. 5c). This clearly suggests a post-tectonic, and therefore secondary, origin for the most widespread magnetic component observed in the Sierras Bayas Group. This is also indicated by a negative result of a conglomerate test performed on the black limestones of the Loma Negra Formation, sampled at the Loma Negra quarry in Barker (37°41′S, 59°21′W). Eleven clasts of an intraformational breccia composed of black limestone fragments immersed in a matrix of quartzose sandstone were sampled (Fig. 6A). Thermal and AF demagnetization permitted isolation of a characteristic component, probably due to magnetite. All samples were collected from a single 3 m^3 block extracted from the quarry front, since direct sampling of the rock in situ was not allowed. Although the geographic orientation of the sampled rock and, therefore, of the magnetic component is unknown, a test can be performed on whether the remanence has been randomly oriented during deposition of the conglomerate or has been acquired afterwards, being consistent in all clasts. Fig. 6B shows how consistent the characteristic remanent directions obtained from the clasts of the Loma Negra breccia are. This is further evidence of the secondary origin of the remanence carried by most stratigraphic units of the Sierras Bayas Group.

A reversal test (McFadden and McElhinny, 1990) yielded a negative result for component B. The "in situ" means of normal and reverse directions (Fig. 3a) show an angular deviation of 17.3°, very much higher than the critical angle of 5.7°. Despite this, 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. Cause for failure of the reversal test is assigned to the probable presence of an undetected minor contamination with a superimposed secondary component (component A?). It is interesting that Rapalini and Sanchez Bettucci (2008) found similar results in the remagnetised limestones of the Ediacaran Cerro Victoria Formation.



%	Dec	Inc	k	a95
-50	7.1	-57.0	19.88	4.9
-40	6.3	-56.7	21.84	4.7
-30	5.6	-56.3	23.71	4.5
-20	4.8	-55.9	25.31	4.4
-10	4.0	-55.5	26.49	4.3
0	3.2	-55.1	27.10	4.2
10	2.5	-54.7	27.06	4.2
20	1.7	-54.2	26.39	4.3
30	0.9	-53.7	25.18	4.4
40	0.1	-53.2	23.60	4.5
50	359.4	-52.6	21.79	4.7
60	358.6	-52.1	19.92	4.9
70	357.9	-51.4	18.09	5.2
80	357.2	-50.8	16.37	5.5
90	356.5	-50.1	14.79	5.8
100	355.8	-49.3	13.37	6.1
110	355.2	-48.5	12.11	6.5
120	354.6	-47.7	10.99	6.8
130	354.0	-46.8	10.02	7.2
140	353.4	-45.9	9.16	7.5
150	352.9	-44.9	8.41	7.9
Max:				
4.3	2.9	-54.9	27.17	4.2

Fig. 3. Sample remanence directions of component A in situ (a) and after bedding correction (b). Schmidt projection. Open (closed) circles represent directions pointing up (down). (c) Statistical parameter *k* vs percentage of unfolding plot. Note that maximum *k* is attained at approximately in situ (4% of unfolding). (d) Example of demagnetization behaviour plotted in a Zijderveld (1967) diagram for a sample carrying low unblocking temperature component A; (e) idem d. W: west, N: North Open (solid) symbols mean projection onto the vertical (horizontal) plane.

Pole position of this remagnetization is virtually identical to that of component B of the Sierras Bayas Group (see Section 5).

Considering the possibility that component A contamination may be affecting the whole mean direction of component B, directions with negative inclination (B1) were considered separately from those with positive inclinations (B2). As shown in Fig. 5d and e and Table 1, both carry a post-tectonic remanence. Paleomagnetic poles computed separately from B1 and B2 are also presented in Table 1. B1 pole falls very close to the present day geographic pole, supporting a suspicion of incomplete removal of a recent overprint in that group of directions.

As discussed below, component B corresponds to the one observed by Valencio et al. (1980) on the basis of which the La Tinta Fm. paleomagnetic pole was computed. These results clearly indicate that such paleomagnetic pole is invalid for Neoproterozoic paleogeographic reconstructions, in agreement with the conclusions of Rapalini and Sanchez Bettucci (2008) from similar results obtained in Neoproterozoic sedimentary rocks exposed in Uruguay.

3.3. *Component C (Cerro Negro Formation)*

A different component was isolated at sites OL-20, OL-21, OV-9 and OV-22. They all correspond to red to purple fine sandstones to pelites. The first three sites are located in the Olavarria area and undoubtedly belong to the Ediacaran–Cambrian Cerro Negro Fm. The latter is located in the Barker area and its stratigraphic position is not clearly determined. According to our paleomagnetic results it likely corresponds to the Cerro Negro Formation as well. This magnetic component was carried by hematite as defined by very high unblocking temperatures. Fig. 7 illustrates the magnetic behaviour of these samples. Component B is observed as a lower temperature component (unblocking temperature <650 °C) in sample OV22-F1, while a different component with a discrete unblocking temperature higher than 650 °C corresponds to the characteristic magnetization (component C). In all except one sample component C is of positive inclination (corresponding to reverse polarity, Fig. 8). Mean remanence direction in situ for

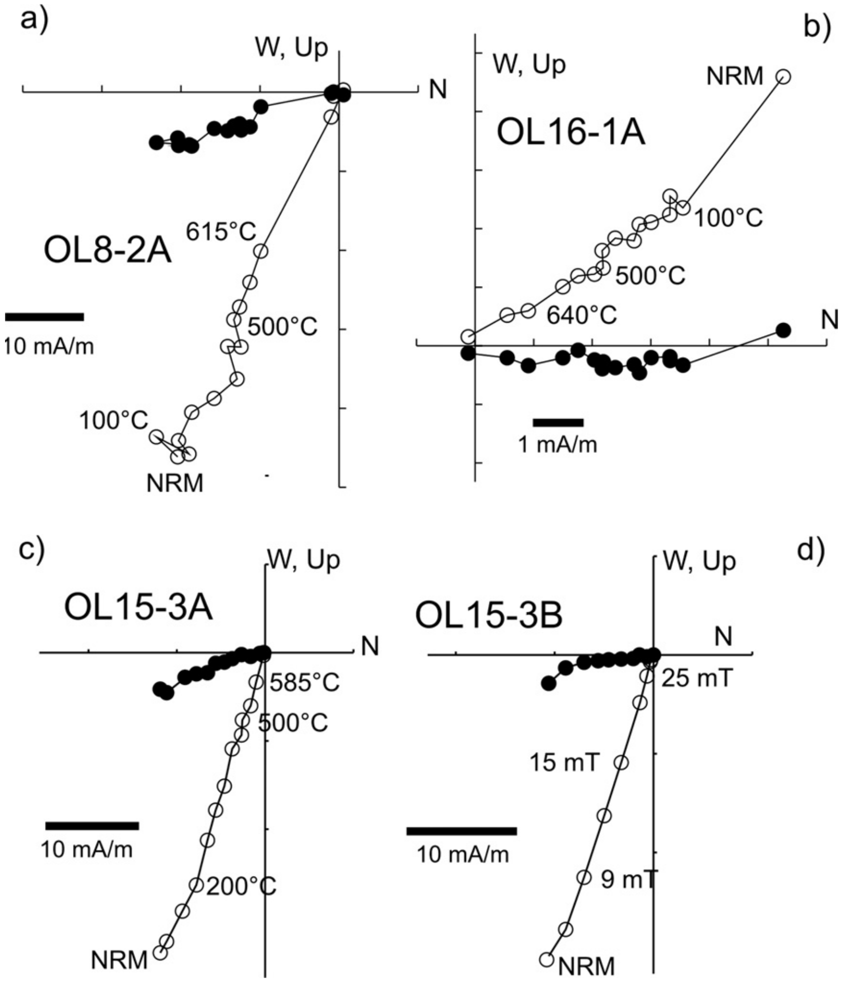


Fig. 4. Examples of demagnetization behaviour to thermal (a)–(c) and AF (d) cleaning of samples carrying widespread component B. References as in Fig. 3.

this magnetic component is Dec: 15.6°, Inc 49.7° (*k*: 11, α95: 11.1°, *n*: 17). A significant improvement of the statistical parameters is attained after bedding correction (Dec: 28.7°, Inc: 56.1°, *k*: 15, α95: 9.5°) suggesting a pre-tectonic magnetization. This is confirmed by the direction–correction fold test of Enkin (2003) which yields a positive result (optimum value of bedding correction 74 ± 55%). Stepwise untilting yields maximum *k* at 75.1% of unfolding. Although this value could suggest an early syntectonic magnetization, the partially corrected mean direction and its statistical parameters are undistinguishable from that at full bedding correction. Considering component C as the primary magnetization of the Cerro Negro Formation, a Cambrian age for its paleomagnetic pole is expected.

3.4. Component D (Olavarría Formation)

Thirteen samples from two sites on the upper levels of the Olavarría Fm. (OV11, OV12) exposed in the Olavarria area were carrier of a north to north-west directed magnetic component (D) with moderate positive inclination. They were defined at temperatures suggestive of hematite (>630 °C, Fig. 9). Demagnetization could not proceed successfully over 650 °C due to viscous behaviours. In situ mean remanence direction (Dec: 350.9°, Inc: 47.3°, *n*: 13, *k*: 37, α95: 7.0°, Fig. 10a) shows virtually no modification after bedding correction (Dec: 349.3°, Inc: 49.9°, Fig. 10b) with the same statistical parameters since the very small tectonic tilting of the sampled rocks are identical at both sites. Therefore,

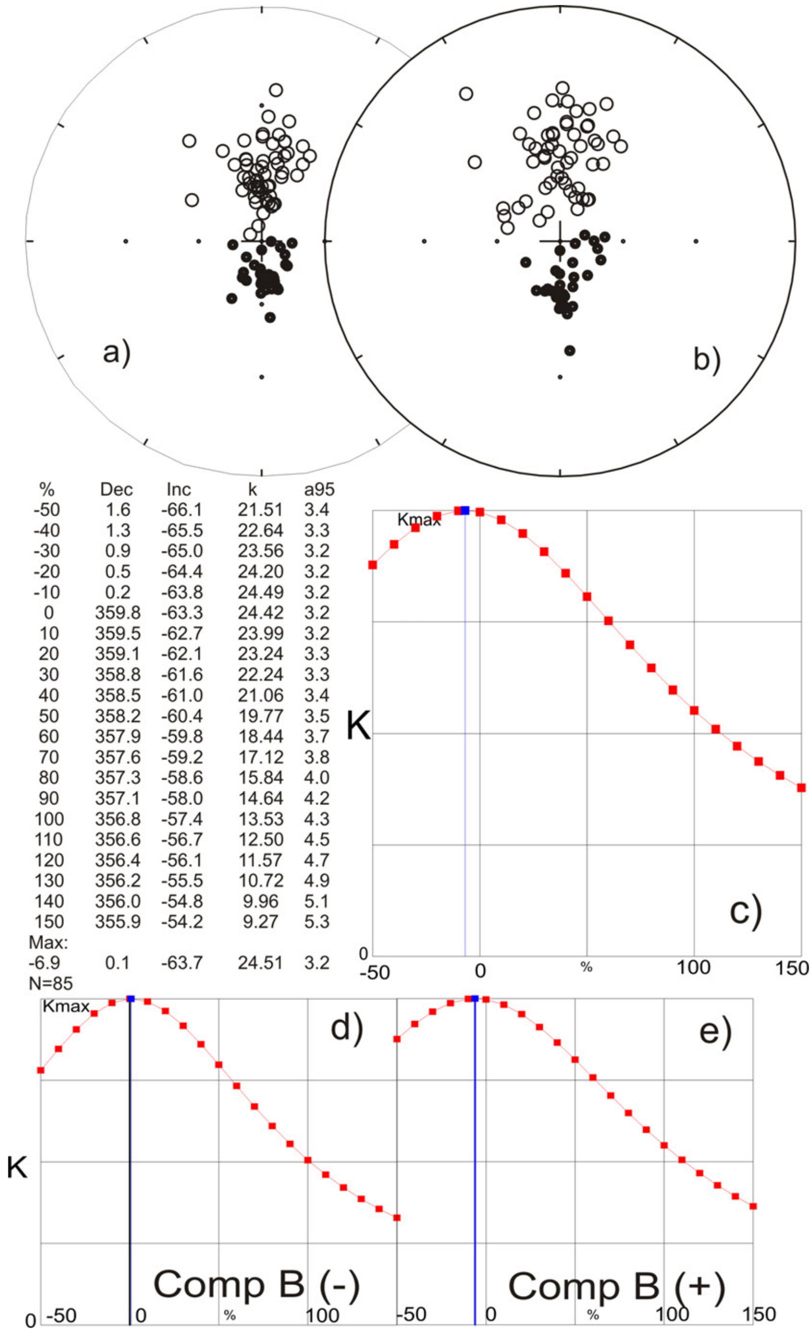
Table 1
Mean remanence directions for the different magnetic components determined in this study.

Magnetic component	Geologic unit	*n*	Dec (°)	Inc (°)	α95 (°)	*k*	Dec[a] (°)	Inc[a] (°)	α95[a] (°)	*k*[a]
A	Villa Mónica F. and others	44	**3.2**	**−55.1**	**5.4**	**27**	355.9	−49.3	6.1	13
B	Villa Mónica, Olavarría and Loma Negra Fs.	85	**359.8**	**−63.3**	**3.2**	**24**	356.8	−58.0	4.1	15
B1	Villa Mónica, Olavarría and Loma Negra Fs.	55	**1.4**	**−57.2**	**3.8**	**27**	358.8	−49.9	5.4	14
B2	Villa Mónica, Olavarría and Loma Negra Fs.	30	**174.2**	**74.3**	**3.7**	**52**	170.3	70.5	4.9	29
C	Cerro Negro F.	17	15.6	49.7	11.1	11	**28.7**	**56.1**	**9.5**	**15**
D	Olavarría F.	13	350.9	47.3	7.0	37	**349.3**	**49.9**	**7.0**	**37**
E	Cerro Largo F.	11	83.7	−41.9	13.4	13	**73.7**	**−36.6**	**12.1**	**15**
F	Villa Mónica F.[b]	7	42.1	−46.1	10.0	37	**43.4**	**−36.3**	**9.1**	**45**

n: number of samples used to compute the mean. Dec, Inc: magnetic declination and inclination, α95 and *k* Fisherian statistical parameters. B1 and B2 corresponds to means of directions of component B with negative and positive inclinations, respectively.

[a] Directions after bedding correction. In bold directions used to compute paleomagnetic poles.

[b] Component determined from marls at the top levels of the Villa Mónica Formation and associated to weathering process previous to deposition of the Colombo Diamictite.



%	Dec	Inc	k	a95
-50	1.6	-66.1	21.51	3.4
-40	1.3	-65.5	22.64	3.3
-30	0.9	-65.0	23.56	3.2
-20	0.5	-64.4	24.20	3.2
-10	0.2	-63.8	24.49	3.2
0	359.8	-63.3	24.42	3.2
10	359.5	-62.7	23.99	3.2
20	359.1	-62.1	23.24	3.3
30	358.8	-61.6	22.24	3.3
40	358.5	-61.0	21.06	3.4
50	358.2	-60.4	19.77	3.5
60	357.9	-59.8	18.44	3.7
70	357.6	-59.2	17.12	3.8
80	357.3	-58.6	15.84	4.0
90	357.1	-58.0	14.64	4.2
100	356.8	-57.4	13.53	4.3
110	356.6	-56.7	12.50	4.5
120	356.4	-56.1	11.57	4.7
130	356.2	-55.5	10.72	4.9
140	356.0	-54.8	9.96	5.1
150	355.9	-54.2	9.27	5.3
Max:				
-6.9	0.1	-63.7	24.51	3.2
N=85				

Fig. 5. Sample remanence directions of component B in situ (a) and after bedding correction (b). Schmidt projection. Open (full) circles represent directions pointing up (down). (c) Statistical parameter *k* vs percentage of unfolding plot. Note that maximum *k* is attained at approximately in situ (−7% of unfolding). (d) idem (c) for directions with negative inclinations. (e) idem (c) for directions with positive inclinations.

corresponding pole positions for the in situ and tilt corrected mean remanence directions are virtually identical.

3.5. *Component E (Cerro Largo Formation)*

Eleven samples from three sites (OV-8, OV-13 and OL-19) on the Cerro Largo Formation were carrier of an East directed magnetic component with negative and shallow to moderate inclinations. The three sites are located in the Olavarria region and correspond to purple claystones. Fig. 11 illustrates the magnetic behaviour of these samples. In some cases (e.g. sample OV13-B1) a large remanence contribution was erased at 100–150 °C, suggesting the presence of goethite. A high temperature component (unblocking temperatures between 600 and 685 °C) was isolated and defined as component E. In situ mean direction of this component is Dec: 83.7°, Inc: −41.9° (*n*: 11, *k*: 13, α95: 13.4°, Fig. 12a). After bedding correction statistical parameters improve and the bedding corrected direction is Dec: 73.7°, Inc: −36.6° (*n*: 11, *k*:15, α95: 12.1°, Fig. 12b). Performance of the direction–correction tilt test of Enkin yields an statistically undetermined result (optimum correction 118 ± 153%). Stepwise untilting shows higher *k* at 118% of bedding correction which is not distinguishable from 100% ultilting. Despite statistical uncertainty best clustering of directions at about full untilting, and lack of resemblance to younger paleomangetic directions in the study area, suggest that a pre-tectonic magnetization is more likely. A paleomagnetic pole was computed from the bedding corrected mean remanence direction.

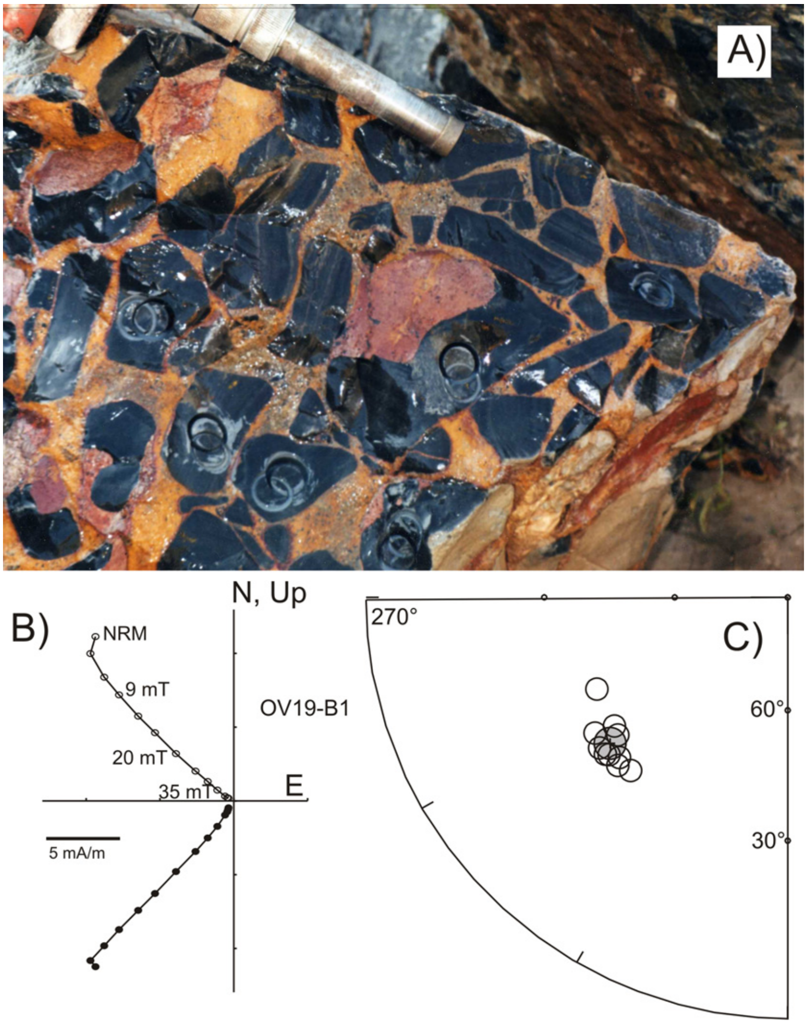


Fig. 6. (A) Photograph of the sampled carbonatic breccia of the Loma Negra Formation to perform a conglomerate test. Rock sampled belonged to a loose, unoriented block in a quarry. Some of the drilled clasts are seen in the picture. The drilling bit is shown as a scale. (B) Typical magnetic behaviour of the sampled limestone clasts submitted to stepwise demagnetization. Note the univectorial decay of the remanence. (C) Sample characteristic remanence direction from the clasts of the carbonatic breccia. Grey circle indicates the mean. Note the very tight grouping of directions indicative of a negative conglomerate test for component B.

3.6. *Component F (top levels of Villa Mónica Fm – Colombo Diamictite)*

Sites OL10 and OL11 correspond to purple to violet marls that constitute the top levels of the Villa Mónica Formation and are immediately overlain by the Colombo Diamictite. Seven samples from these sites were carrier of a high temperature component (unblocking temperature > 650 °C, Fig. 13a) directed towards the NE with intermediate negative inclinations. In situ mean remanence direction is Dec: 42.1°, Inc: −46.1° (*n*: 7, *k*: 37, α95: 10.0°). After bedding correction, the statistical parameters improve, however application of the direction–correction tilt test of Enkin (2003) yields an undetermined result with optimum value obtained at 99% (±147%) of bedding correction. Small number of samples and angles of bedding correction are the likely causes for this result. Stepwise untilting (Fig. 13d) yields maximum *k* at 97% of correction, virtually identical to 100%. Despite the inconclusive statistical test, best grouping of directions after full bedding correction is

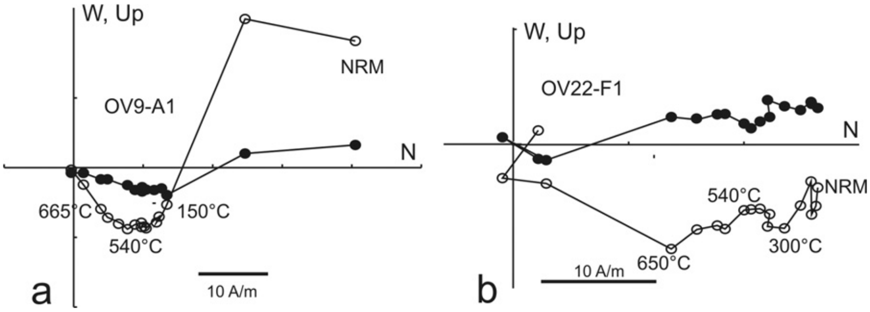
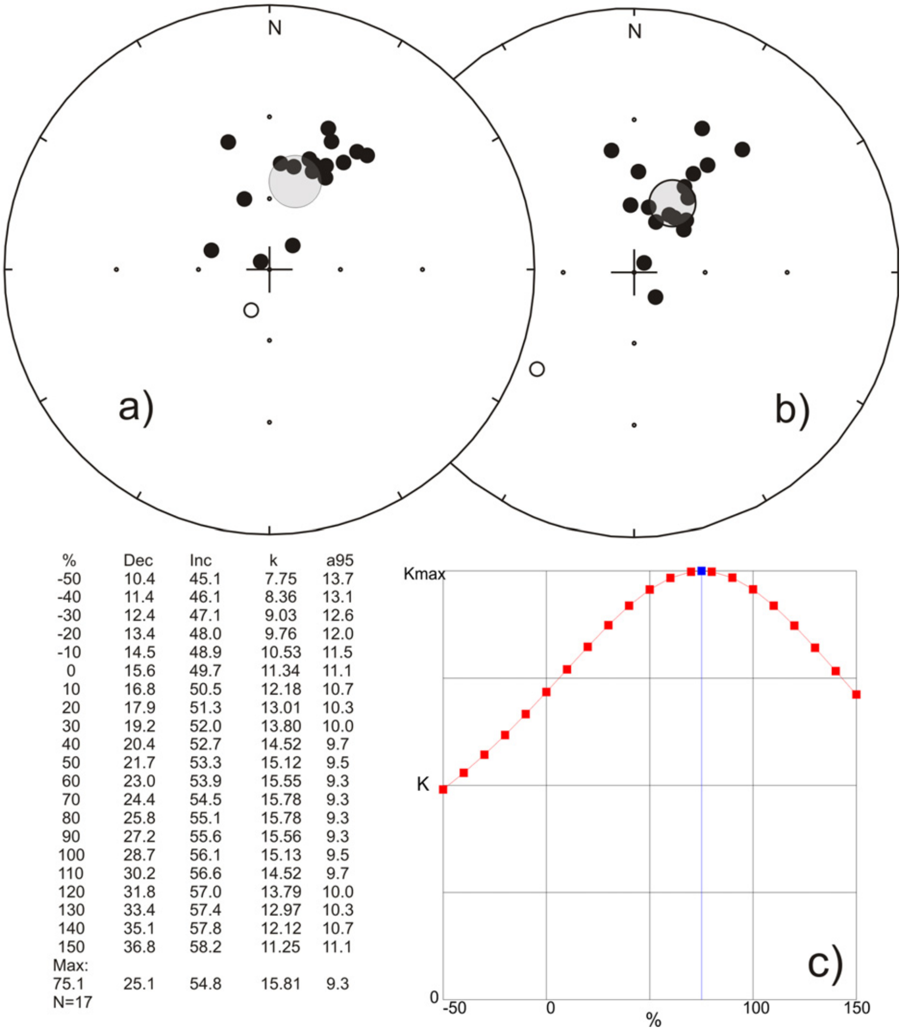


Fig. 7. Two examples of demagnetization behaviour of samples carrying component C (Cerro Negro Formation) submitted to thermal cleaning. Note the presence of two magnetic components. Component C is isolated at very high temperatures (over 600 °C). References as in Fig. 3.



%	Dec	Inc	k	a95
-50	10.4	45.1	7.75	13.7
-40	11.4	46.1	8.36	13.1
-30	12.4	47.1	9.03	12.6
-20	13.4	48.0	9.76	12.0
-10	14.5	48.9	10.53	11.5
0	15.6	49.7	11.34	11.1
10	16.8	50.5	12.18	10.7
20	17.9	51.3	13.01	10.3
30	19.2	52.0	13.80	10.0
40	20.4	52.7	14.52	9.7
50	21.7	53.3	15.12	9.5
60	23.0	53.9	15.55	9.3
70	24.4	54.5	15.78	9.3
80	25.8	55.1	15.78	9.3
90	27.2	55.6	15.56	9.3
100	28.7	56.1	15.13	9.5
110	30.2	56.6	14.52	9.7
120	31.8	57.0	13.79	10.0
130	33.4	57.4	12.97	10.3
140	35.1	57.8	12.12	10.7
150	36.8	58.2	11.25	11.1
Max:				
75.1	25.1	54.8	15.81	9.3
N=17				

Fig. 8. Sample remanence directions of component C in situ (a) and after bedding correction (b). Schmidt projection. Open (full) circles represent directions pointing up (down). (c) Statistical parameter *k* vs percentage of unfolding plot. Note that maximum *K* is attained at approximately 75% of unfolding.

interpreted as a pretectonic remanence being more likely. The bedding corrected direction is Dec: 43.4°, Inc: −36.3° (*n*: 7, *k*: 45, α95: 9.1°). A paleomagnetic pole was computed on the basis of it.

4. Rock magnetism

In order to better characterise the minerals carrying the remanence, some rock magnetic studies were performed on representative samples of the whole collection. Isothermal remanent magnetization acquisition curves were carried out on 30 samples from different sites (Fig. 14). Most samples show the presence of at least two magnetic fractions, a low-coercivity one (ferrimagnetic phase) attaining saturation at about 150 mT could be observed at different proportions in all samples. A high-coercivity fraction (antiferromagnetic phase) was also observed in most samples with no saturation up to 2 T. Different proportions of

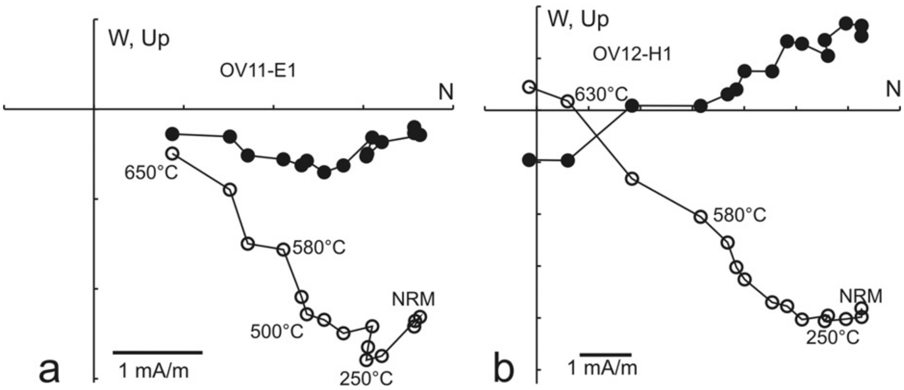


Fig. 9. Two examples of demagnetization behaviour of samples carrying component D (Olavarría Formation) submitted to thermal cleaning. References as in Fig. 3.

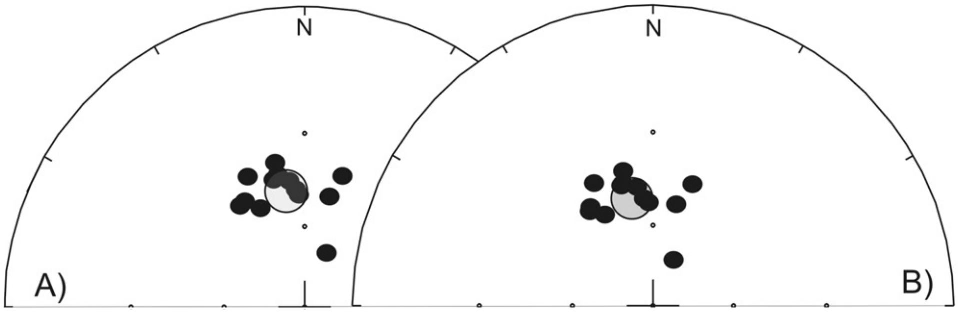


Fig. 10. Sample remanence directions of component D in situ (a) and after bedding correction (b). Schmidt projection. Full circles represent directions pointing down. Grey circle represents error elipsse sorrounding the sample mean direction. Note that the remanence directions are virtually unaffected by the structural correction.

both phases are clearly seen in samples carrying component B (Fig. 14a) which has been demonstrated as a secondary magnetization and suggesting a complex remagnetization process. Siltstones and marls carrying an apparent primary magnetization (components C, D and F) show a more homogeneous IRM acquisition curves (Fig. 14b), with a dominant ferrimagnetic phase and a subordinate antiferromagnetic one.

Low and high temperature thermomagnetic curves (χ vs T) were obtained for selected samples of the whole collection in order to better characterise the magnetic carriers. Curves were produced with a MFK1-A kappabridge (AGICO SA) complemented with apparatus CS-2 and CS-L. Low temperature runs were done between around −185 °C and room temperature, and high temperature curves span from room temperature up to 700 °C. Bulk susceptibility was also measured during cooling back to room temperature. Heating was carried out in an inert atmosphere produced by continuous pumping of argon in the heating chamber. Fig. 15 shows some of these curves. The high T curves show irreversible paths in all cases, indicating generation of ferromagnetic s.l. minerals due to experimental heating. In most cases magnetite is produced, as indicated by the well-defined Curie temperature in the cooling part of the curve. Samples OV-2 and OV-23 also show apparent formation of hematite, while maghemite is apparently created in the heating-cooling cycle of sample OV12. Heating curves of samples carrying component B show a much larger increase of bulk susceptibility than those carrying other components. In opposition to that, cooling curves suggest comparable amounts of neoformed minerals in both set of samples. Important formation of new magnetic minerals during heating may pose some suspicion on the adequacy of thermal demagnetization for isolating the magnetic components. However, as described and illustrated above (Figs. 5, 7, 9, 11 and 13), most thermally demagnetised samples showed no evidence of magnetic viscosity or instability over 400–500 °C, and linear trends towards the origin of coordinates in the demagnetization diagrams developed well over 600 °C. Furthermore, bulk susceptibility measurements of samples after each demagnetization step showed that this parameter was kept within a range of plus–minus 25% of the original value after 580 °C in over 80% of the cases and within 50% up to 640 °C, suggesting that crushed material used for the thermomagnetic curves is likely more prone to chemical alteration during experimental heating than rock specimens.

The low temperature curves show approximately neutral (OV-2), negative (OV6, OV12, OL11) and positive (OV23) slopes of K vs T. In all cases the curves suggests that ferromagnetic s.l. contributions are dominant with respect to the paramagnetic signal (from 75% to 100%). No evidence of Verwey or Morin transitions is observed.

5. Discussion and interpretation

The widespread post-tectonic magnetic component B is by far the most characteristic remanence found in the Sierras Bayas Group. This was mainly isolated in calcareous units (i.e. limestone and dolostone), particularly in the Villa Mónica and Loma Negra Fms. However, some marls and claystones were also carriers of this secondary remanence. Comparison with the original results of Valencio et al. (1980) indicates that the remanence isolated by these authors corresponds to this component. Its clear secondary origin confirms that the old results of the La Tinta Formation cannot be used for Precambrian paleogeographic considerations, as already suggested by Rapalini and Sanchez Bettucci (2008). These authors found significant evidence of a widespread remagnetization in different Neoproterozoic sedimentary units of Uruguay with very similar paleopole position that was interpreted as a probable Late Permian or Early Tertiary remagnetization. Fig. 16 illustrates

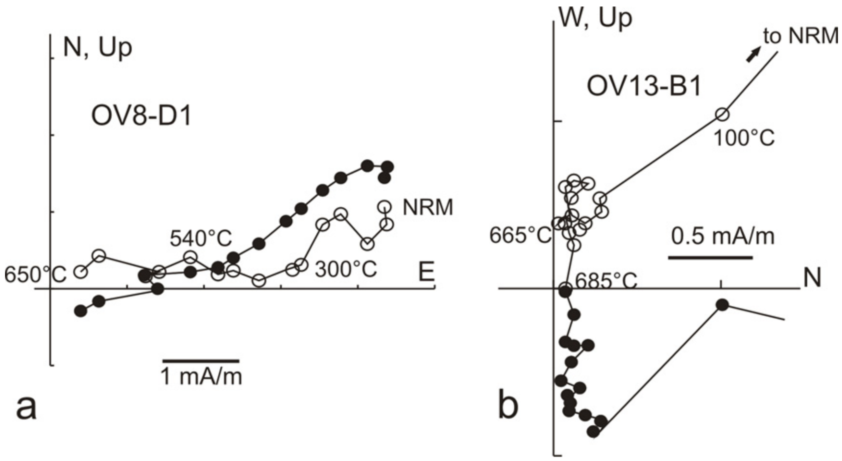
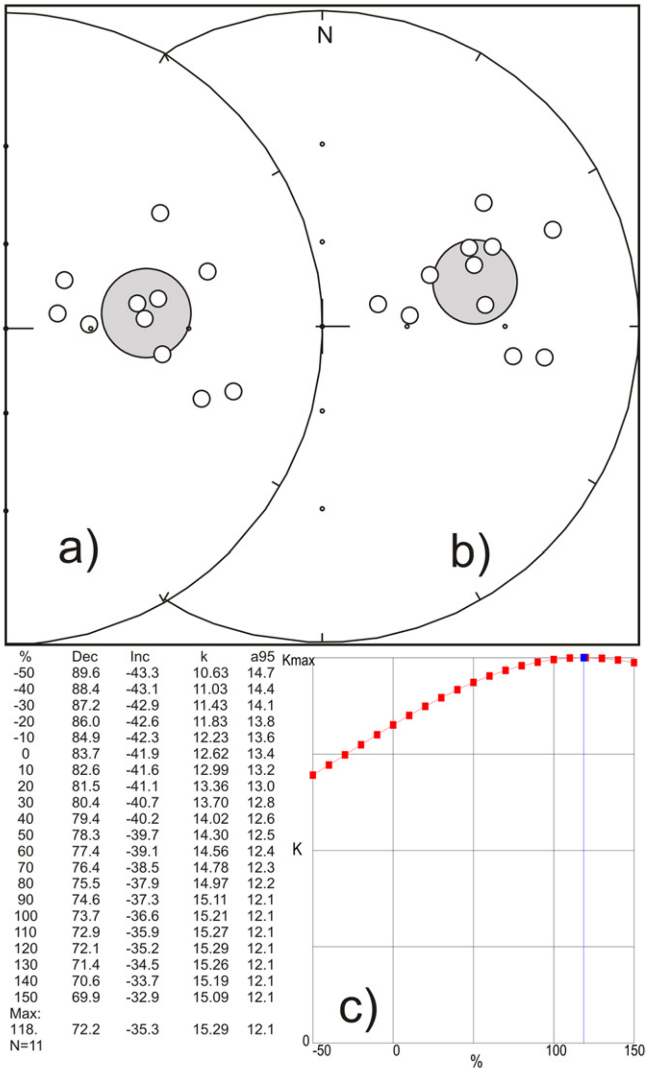


Fig. 11. Two examples of demagnetization behaviour of samples carrying component E (Cerro Largo Formation) submitted to thermal cleaning. References as in Fig. 3.



%	Dec	Inc	k	a95
-50	89.6	-43.3	10.63	14.7
-40	88.4	-43.1	11.03	14.4
-30	87.2	-42.9	11.43	14.1
-20	86.0	-42.6	11.83	13.8
-10	84.9	-42.3	12.23	13.6
0	83.7	-41.9	12.62	13.4
10	82.6	-41.6	12.99	13.2
20	81.5	-41.1	13.36	13.0
30	80.4	-40.7	13.70	12.8
40	79.4	-40.2	14.02	12.6
50	78.3	-39.7	14.30	12.5
60	77.4	-39.1	14.56	12.4
70	76.4	-38.5	14.78	12.3
80	75.5	-37.9	14.97	12.2
90	74.6	-37.3	15.11	12.1
100	73.7	-36.6	15.21	12.1
110	72.9	-35.9	15.27	12.1
120	72.1	-35.2	15.29	12.1
130	71.4	-34.5	15.26	12.1
140	70.6	-33.7	15.19	12.1
150	69.9	-32.9	15.09	12.1
Max:				
118.	72.2	-35.3	15.29	12.1
N=11				

Fig. 12. Sample remanence directions of component E (Cerro Largo Fm.) in situ (a) and after bedding correction (b). Schmidt projection. Open circles represent directions pointing up. Grey circle represents error elipsse sorrounding the sample mean direction. (c) Statistical parameter *k* vs percentage of unfolding plot. Note that maximum *k* is attained at approximately 118% of unfolding.

the paleomagnetic poles obtained from component B of the Sierras Bayas Group and the remagnetised poles of the Cerro Victoria, Yerbal and Rocha Formations in Uruguay. The old La Tinta pole from Valencio et al. (1980) is also depicted. The similar pole positions strongly suggest coetaneous remagnetization of all these sedimentary units. Although the Cerro Victoria and Sierras Bayas units are dominated by calcareous beds, the Yerbal and Rocha Formations are composed of red to brownish fine-grained sandstone and siltstones, indicating that remagnetization also affected some clastic units as well.

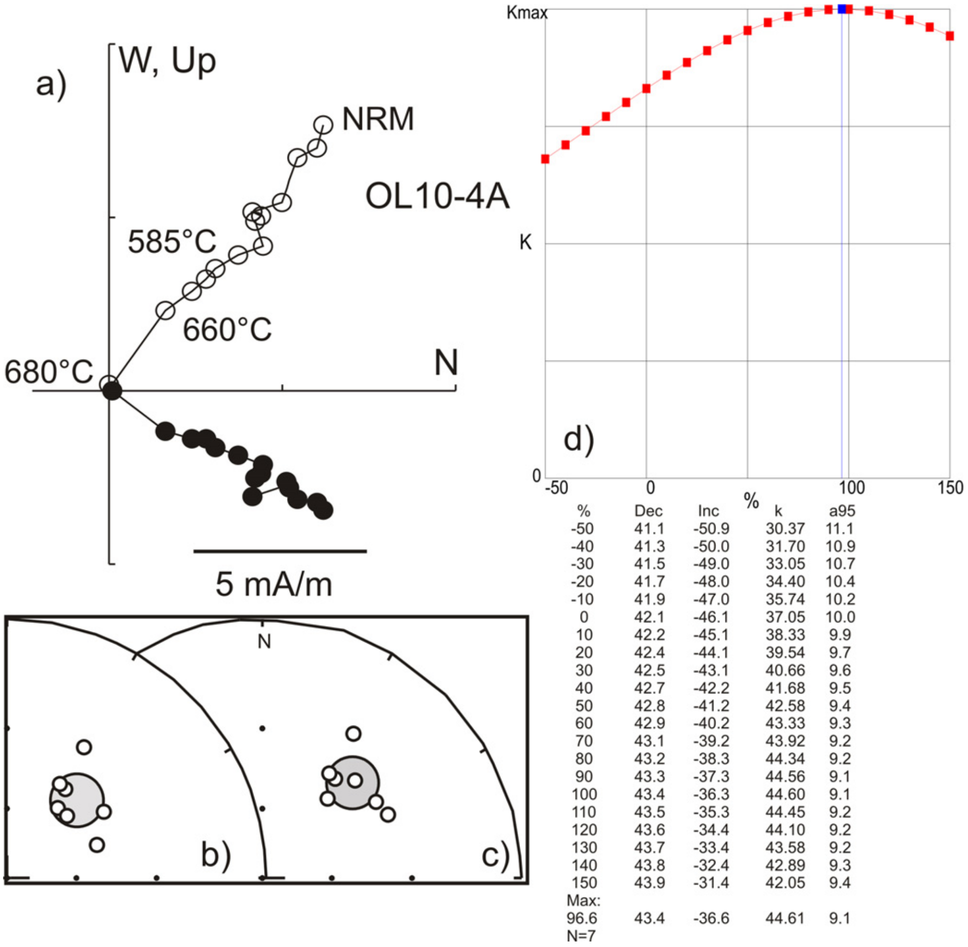
Rapalini and Sanchez Bettucci (2008) discussed with some depth different alternatives for the source of the Late Permian or Early Tertiary remagnetizing event. They concluded that the most likely causes are: (i) remagnetizing fluids expelled from an orogen migrating into the foreland (e.g. Oliver, 1986), in this case associated to the Permian San Rafaelic orogenesis (see for instance Rapalini and Tarling, 1993; Font et al., in press), including deformation along the Sierra de la Ventana fold belt, due to possible collision of Patagonia (see for instance Ramos, 2008); or (ii) regional geothermal anomalies and subsequent hydrothermal processes associated to the very large Choiyoi magmatic province (Llambías et al., 2003; Kleiman and Japas, 2009) of Late Permian–Early Triassic age. It was more difficult for these authors to find a suitable regional geologic event that could explain such remagnetization during the latest Cretaceous–early Tertiary.

All paleomagnetic poles obtained in this study are presented in Table 2. Component C (Cerro Negro Fm), component D (Olavarría Fm), component E (Cerro Largo Fm) and component F (Colombo Diamictite) belong to red claystones and siltstones or marls and undoubtedly correspond to magnetic components acquired at different times since their positions are widely different. Unfortunately, the number of samples from which these paleomagnetic poles have been computed is low (particularly components E and F). Component C statistically passed a tilt test suggesting a primary origin for the remanence. Results of the tilt test for components E and F are not statistically significant, although stepwise untilting yields better clustering at around 100% correction, which suggest (but does not prove) a primary remanence. Component D has no tilt test, but its position before and after untilting is virtually identical. In all cases the pole positions do not coincide with post-Cambrian reference pole positions for South America and Gondwana, suggesting they correspond to ancient, and possibly primary magnetizations. This is consistent with the finding of unremagnetised red claystones of Ediacaran age in the Sierra de los Barrientos (Rapalini, 2006), 35 km to the SE of the Barker sampling locality of this study. Our new results confirm that some lithologies (mainly red claystones and siltstones) have escaped the regional remagnetization and encourage new paleomagnetic studies in different areas of the Tandilia system on these lithologic types.

Fig. 17 depicts the positions of poles SBc, SBd, SBe and SBf, corresponding to the already mentioned components, together with other Ediacaran to Cambrian poles for the Rio de la Plata craton and other Gondwana blocks, all rotated into African coordinates according to the tight Gondwana reconstruction of Trindade et al. (2006). The obtained paleomagnetic poles are broadly consistent with the apparent polar wander track proposed for the Rio de la Plata craton by Sánchez Bettucci and Rapalini (2002) and Rapalini (2006). Furthermore, the poles follow a relative position along the path in accordance with the respective stratigraphic position of the corresponding units. This coherence provides additional confidence on the validity of the results.

SBc falls on the late Early Cambrian section of the Gondwana APWP, suggesting an age of magnetization for the Cerro Negro Fm between 520 and 510 Ma. This is consistent with the traditional Cambrian age assigned to this unit (e.g. Gómez Peral et al., 2007; Gaucher et al., 2005), but somewhat younger than recent considerations that place the Cerro Negro Fm. at the Ediacaran–Cambrian transition due to lack of Cambrian fossils (Gaucher and Poiré, 2009). SBd corresponds to the Olavarria Fm. Its position on the APWP suggests a magnetization age around 540–530 Ma, i.e. early Early Cambrian. An earliest Cambrian age for deposition of the Olavarria Fm. is not consistent with the updated stratigraphic knowledge of the Sierras Bayas Group, since the Olavarria Fm. is overlain by the limestones of the Loma Negra Fm. that carry fossils of *Cloudina* sp. indicative of latest Ediacaran (Gaucher et al., 2005). However, since no tilt test was available for this unit, we have no certainty on the nature of magnetization, and an Early Cambrian remagnetization or late diagenetic magnetization, several million years younger than deposition, are both possible.

SBe falls in a position between the paleomagnetic poles of the Los Barrientos (Rapalini, 2006) and Sierra de Animas 2 (Sánchez Bettucci and Rapalini, 2002) on one side, and the Campo Alegre (D'Agrella Filho and Pacca, 1988) and the Playa Hermosa VGP (Sánchez Bettucci and Rapalini, 2002) on the other. The Sierra de las Animas magmatic complex has been recently dated more accurately by Oyhantçabal et al. (2007) who provided a radiometric age



%	Dec	Inc	k	a95
-50	41.1	-50.9	30.37	11.1
-40	41.3	-50.0	31.70	10.9
-30	41.5	-49.0	33.05	10.7
-20	41.7	-48.0	34.40	10.4
-10	41.9	-47.0	35.74	10.2
0	42.1	-46.1	37.05	10.0
10	42.2	-45.1	38.33	9.9
20	42.4	-44.1	39.54	9.7
30	42.5	-43.1	40.66	9.6
40	42.7	-42.2	41.68	9.5
50	42.8	-41.2	42.58	9.4
60	42.9	-40.2	43.33	9.3
70	43.1	-39.2	43.92	9.2
80	43.2	-38.3	44.34	9.2
90	43.3	-37.3	44.56	9.1
100	43.4	-36.3	44.60	9.1
110	43.5	-35.3	44.45	9.2
120	43.6	-34.4	44.10	9.2
130	43.7	-33.4	43.58	9.2
140	43.8	-32.4	42.89	9.3
150	43.9	-31.4	42.05	9.4
Max:				
96.6	43.4	-36.6	44.61	9.1
N=7				

Fig. 13. (a) One example of demagnetization behaviour of samples carrying component F (top levels of Villa Mónica Fm.), submitted to thermal cleaning. (b) in situ sample remanence direction of component F. (c) Idem (b) after bedding correction. (d) Statistical parameter *k* vs percentage of unfolding plot. Note that maximum *k* is attained at approximately 97% of unfolding.

of 579 ± 2 Ma (Ar–Ar in hornblende). The Los Barrientos pole is no precisely dated and was originally assigned an age of ca. 550 Ma. That succession was originally interpreted as representative of the Cerro Negro Formation. Our new results suggest that it most likely corresponds to the Cerro Largo Formation. A recent geophysical survey in the area is consistent with this interpretation (Gil, 2012).

On the other hand, the Campo Alegre volcanics have been dated by U–Pb as 595 ± 5 Ma (Citroni et al., 1999). This constrains the age of magnetization for SBe as approximately 580–590 Ma. The virtual geomagnetic pole computed from the top levels of the Villa Mónica Formation and interpreted to represent the subaerial exposure previous to deposition of the Colombo Diamictite (SBf) falls

Table 2
Paleomagnetic and mean geomagnetic poles for the Rio de la Plata craton for the Ediacaran–Cambrian.

Geologic unit	PP	Lat	Long	A95 (dp/dm)	Age (Ma)	Age method	Reference
Cerro Victoria F. (remag)	CVc	28.8°	13.2°	11°/16°	500?	APWP	Rapalini and Sanchez Bettucci (2008)
Sierra de Animas 1	SA1	22.9°	8.7°	20°/27°	520	K/Ar	Sánchez Bettucci and Rapalini (2002)
Cerro Negro F.	SBc	17.9°	354.4°	10°/13°	520?	Strat. and APWP	This paper
Polanco F. (remag)	P	15.4°	359.3°	14°/17°	520?	APWP	Rapalini and Sanchez Bettucci (2008)
Olavarría F.	SBd	4.0°	322.8°	6°/9°	535?	APWP	This paper
Los Barrientos	LB	−47.0°	312.9°	11°/14°	570?	APWP	Rapalini (2006)
Sierra de Animas 2	SA2	−50.7°	311.1°	16°/21°	579	Ar/Ar (hornbl.)	Sánchez Bettucci and Rapalini (2002)
Cerro Largo F.	SBe	−66.9°	257.3°	8°/14°	580?	APWP	This paper
Villa Mónica F.	SBf	−76.2°	159.5°	6°/11°	590?	APWP	This paper
Playa Hermosa F.	PH	−74.1°	180.9°	9°/16°	590	U–Pb and Strat	Sánchez Bettucci and Rapalini (2002) and Lossada et al. (2011)
Campo Alegre F.	CA	−80.5°	68.5°	10°	595	U/Pb	D'Agrella Filho and Pacca (1988)

Age Method: argument used to compute more likely age for the paleomagnetic pole.

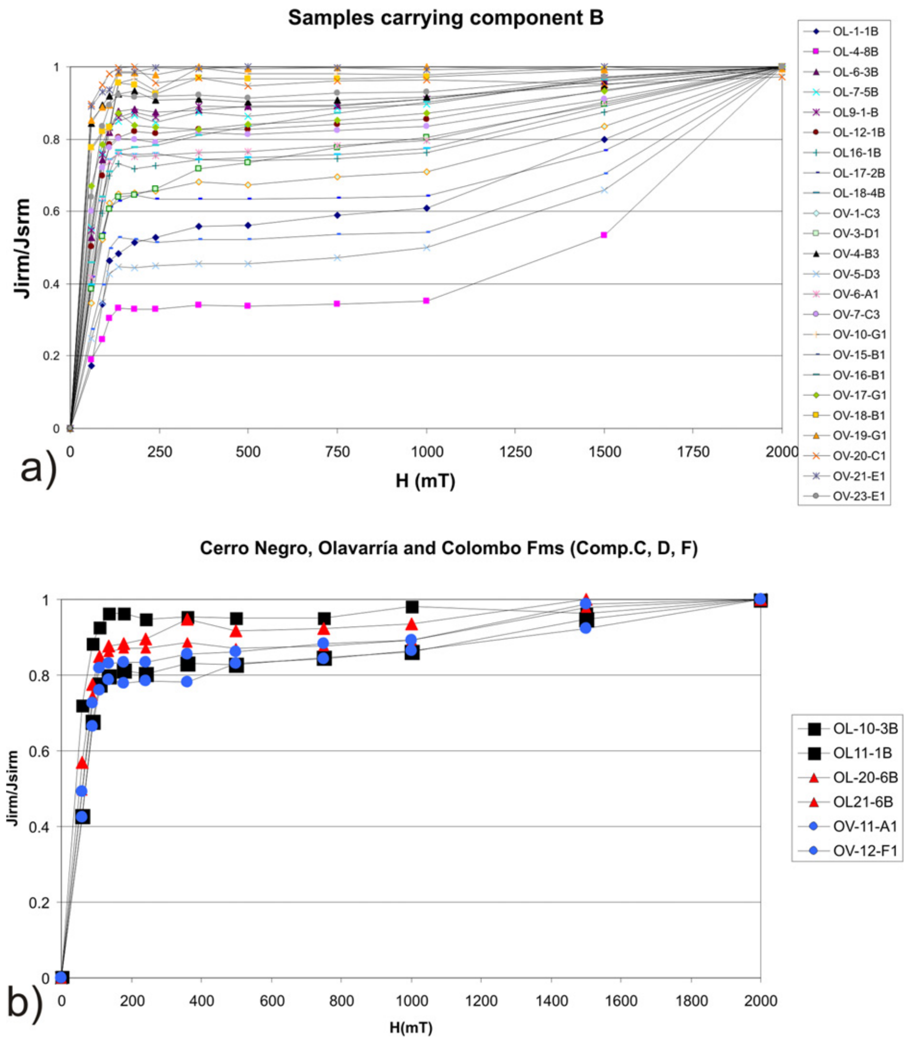


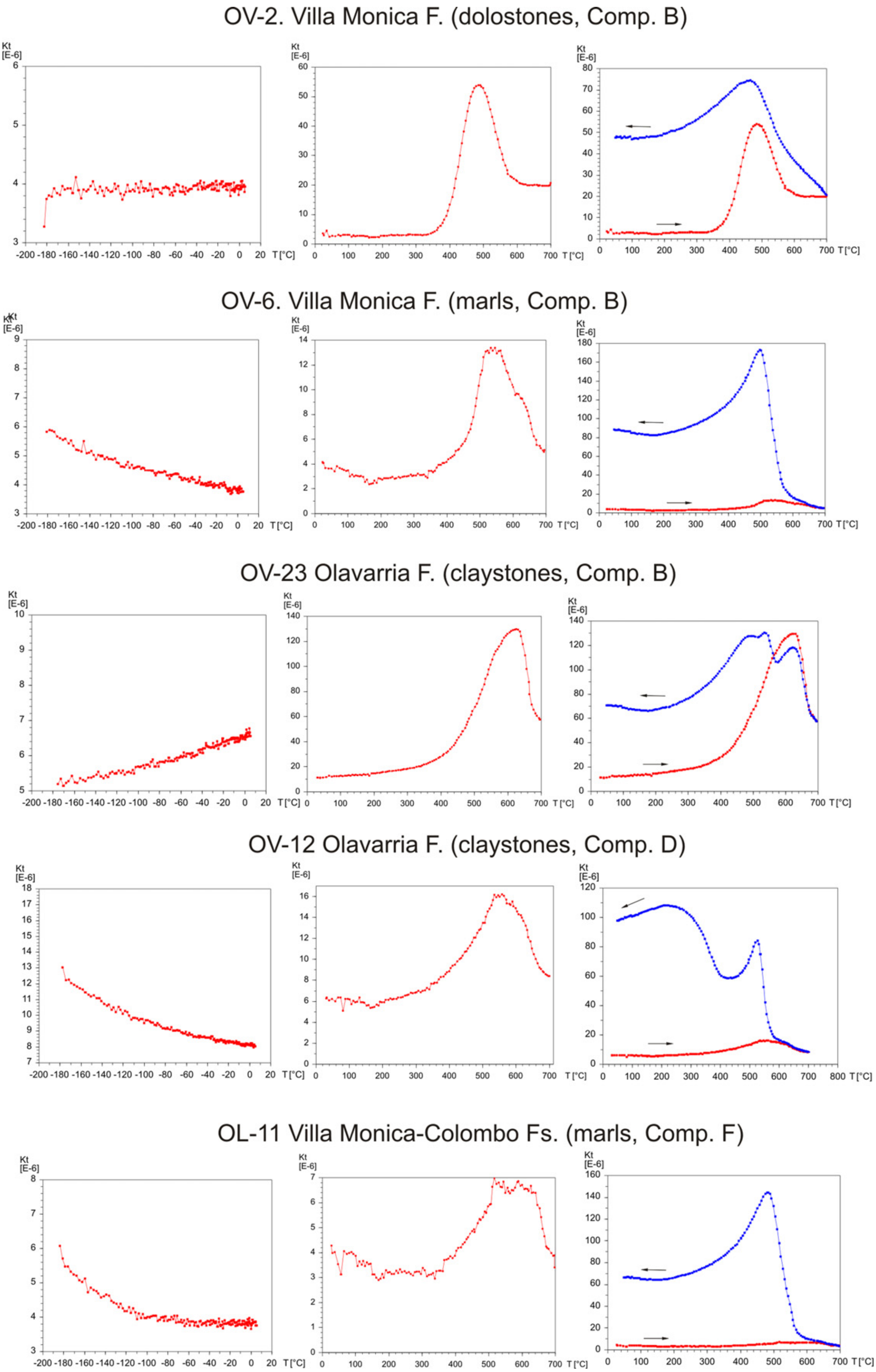
Fig. 14. Normalised acquisition curves of isothermal remanent magnetization for samples from the Villa Mónica, Loma Negra and Olavarría Fms. carrying component B. Applied field represented in linear scale. (b) Idem for samples of the Cerro Negro, Olavarría and top of the Villa Mónica Fm., carriers of component C, D and F, respectively. Note the presence of two magnetic phases (ferri and antiferromagnetic, respectively) in different proportions in most samples from all formations.

on a slightly older position in the Rio de la Plata path, coincident with the VGP from the Playa Hermosa Fm. and close to the Campo Alegre pole. The basal levels of the Playa Hermosa Fm. show evidence of glacial influenced environments (Pazos et al., 2008; Pecoits et al., 2008). A similar pole position for both VGPs suggest that the Colombo Diamictite and the Playa Hermosa basal levels are approximately coetaneous and open the question if the recently found and scarcely studied Colombo Fm. may be related to a glacial episode too.

Although independent information on the age of the studied succession is not precise, age constraints and coherence between pole position and relative and absolute stratigraphic ages point to a reliable apparent polar wander track for the Rio de la Plata craton between approximately 600 and 500 Ma. The oldest poles and VGPs correspond to the Campo Alegre, Playa Hermosa and Colombo Fms., at around 600–590 Ma. These are followed by the Cerro Largo pole (SBe) at 590–580 Ma, which is in turn followed by the Sierra de Animas 2 and Los Barrientos poles at 580–560 Ma. A long segment of the APWP joins the latter with the Olavarria Fm pole, a likely remagnetization at around 540 Ma. After the 530–525 Ma loop in the Gondwana path several Cambrian poles (SA1, CVc, P) from the Rio de la Plata craton are now joined by the 520–510 Ma Cerro Negro Fm. pole (SBc). As already mentioned, this interpretation implies a magnetizacion younger than the rock age for the Olavarria Fm. (SBd) and possibly also for the Cerro Negro Fm (SBc). This could be eventually avoided by in situ rotating the Rio de la Plata craton by some 30° ccw (implying a post-Early Cambrian cw tectonic rotation of the craton). This alternative cannot be completely rule out on the basis of the available data but it is considered less likely than the more conservative chosen here. This alternative would turn the consistency of the 550–510 Ma pole positions for different Gondwana cratons with those from the Rio de la Plata a mere coincidence, and would turn the older pole positions (LB, SA2) inconsistent with coeval poles from other Gondwana blocks.

5.1. Implications for Gondwana assembly

Despite disparities in quality and reliability of the above mentioned poles, as well as uncertainties in ages, we have now eleven paleomagnetic poles or mean virtual geomagnetic poles (Table 2) in a range of approximately 100 million years that permit reconstruction of the apparent polar wander track of the Rio de la Plata craton and comparison with coeval poles from other Gondwana blocks for the Ediacaran and Cambrian. Fig. 17 illustrates that since approximately 550 Ma the Rio de la Plata poles seem to merge with several



OV-2. Villa Monica F. (dolostones, Comp. B)

OV-6. Villa Monica F. (marls, Comp. B)

OV-23 Olavarria F. (claystones, Comp. B)

OV-12 Olavarria F. (claystones, Comp. D)

OL-11 Villa Monica-Colombo Fs. (marls, Comp. F)

Fig. 15. Representative low- and high-temperature thermomagnetic curves (χ vs *T*) for the study collection of samples. Different lithologies, units and components are represented. From left to right, the low temperature, high temperature and heating (red) plus cooling (blue) high temperature curves are respectively presented. Note that generation of significant quantities of magnetic minerals during heating is very frequent. Temperature is in °C. More references in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

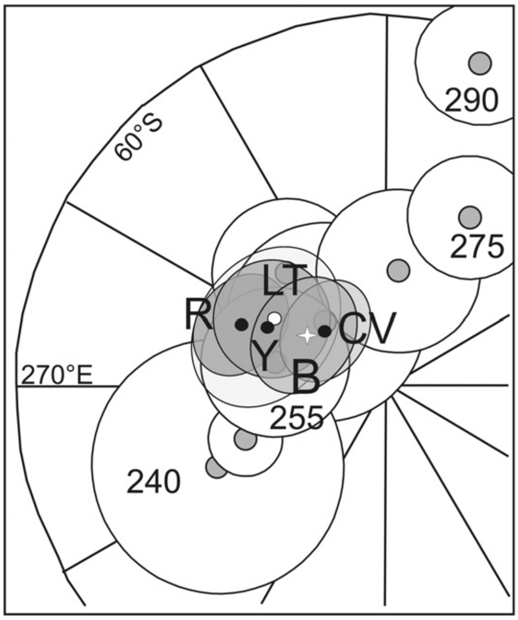


Fig. 16. Paleomagnetic pole position for component B of the Sierras Bayas Group (white star labelled B), and pole positions for La Tinta formation old pole (LT, Valencio et al., 1980, white circle) and recently published remagnetised poles for the Cerro Victoria (CV), Rocha (R) and Yerbal (Y) formations in Uruguay (Rapalini and Sanchez Bettucci, 2008, black circles). Grey ovals correspond to 95% confidence elipses around each pole. Late Paleozoic to Early Mesozoic South American reference paleomagnetic poles (Rapalini et al., 2006) are shown as grey circles. White circles correspond to their α95. Numbers indicate the most likely ages of the South American apparent polar wander path in Ma.

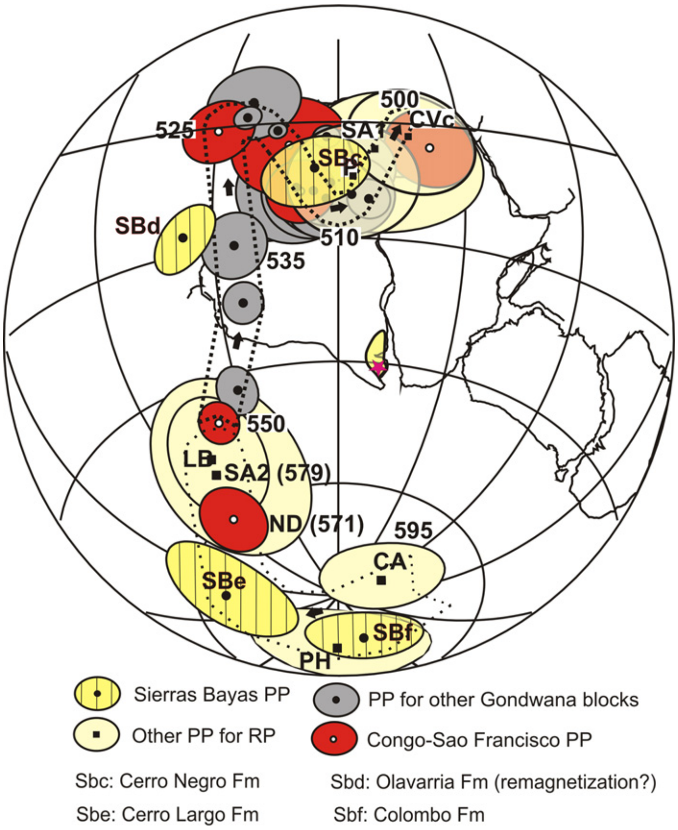


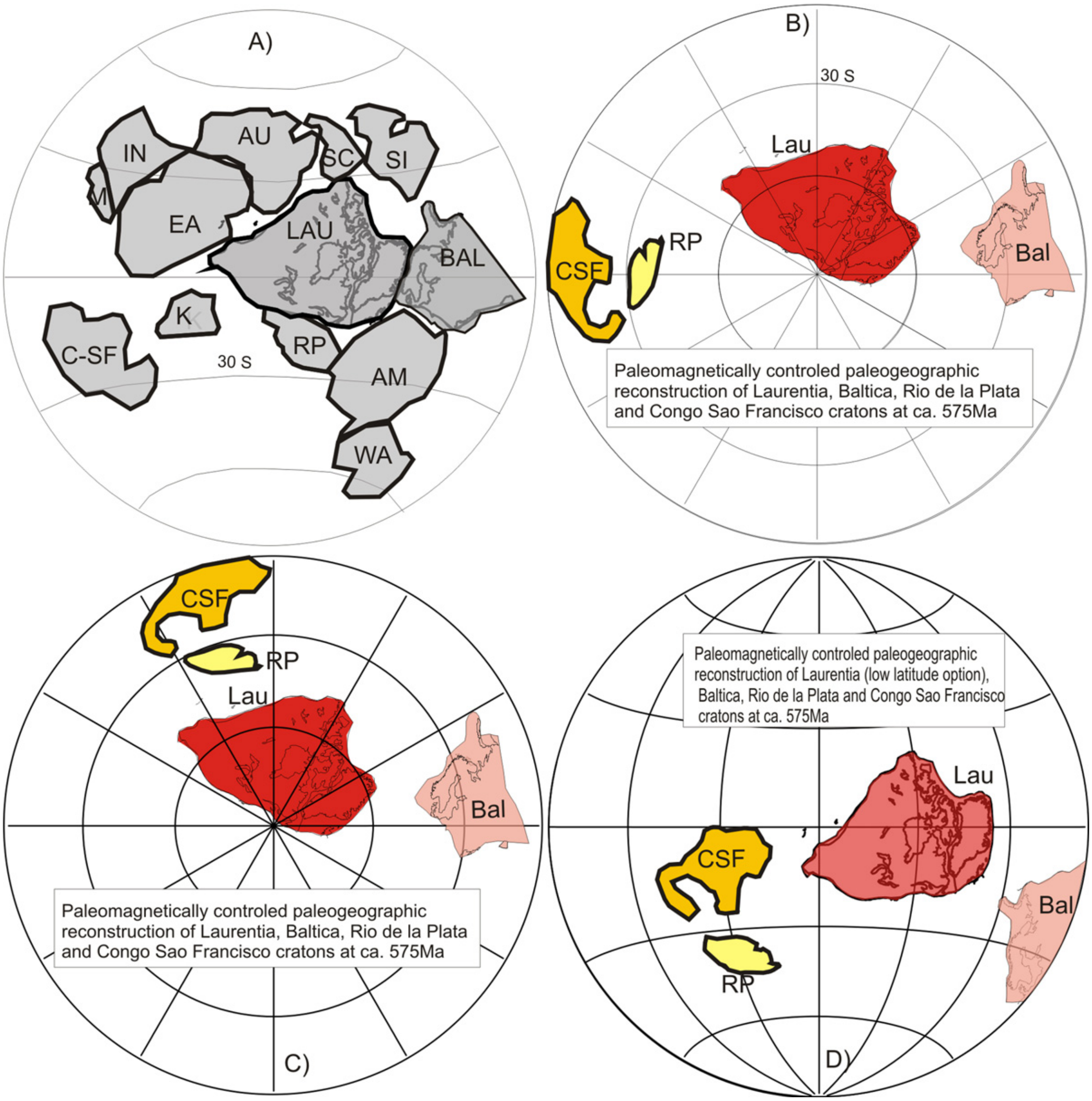
Fig. 17. Ediacaran to Cambrian paleomagnetic poles for the Rio de la Plata craton. Previously published poles are depicted in light yellow. Mean geomagnetic poles obtained from components C to F determined in this study are shown in dark yellow (SBc, SBd, SBe, SBf). Track of the apparent polar wander for this craton between 600 and 550 Ma is depicted as grey dotted lines. Poles for several Gondwana blocks (grey circles) and the apparent polar wander track defined by them between ca. 550 and 500 Ma (dark dashed lines) are also presented. Paleomagnetic poles from the Congo-Sao Francisco craton are shown in red. All poles are depicted in southern Africa coordinates following reconstruction of Reeves et al. (2004). Numbers between brackets indicate radimetric dating of specific poles, while numbers with no brackets the approximate age for the apparent polar wander path. More references in the text and Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Gondwana poles. Meert and Van der Voo (1996) were among the first to propose that a single APWP can be traced for all Gondwana blocks since approximately that age. This seems to be true for at least some large cratons of Gondwana (Congo-Sao Francisco, Arabia, Australia), but since several blocks have no paleomagnetic data of such age, a comprehensive test of this idea is not yet possible. Furthermore, several authors (Meert, 2003; Trindade et al., 2006; Tohver et al., 2006; Spagnuolo et al., 2012) have interpreted geologic and paleomagnetic evidence in terms of a very late (late Early to Middle Cambrian) final accretion of major cratonic blocks like Amazonia, Kalahari or East Antarctica to form Gondwana.

Moloto-Kenguemba et al. (2009) have recently published a paleomagnetic pole of about 571 Ma from the Nola dykes in the Congo craton. As shown in Fig. 17, this pole overlaps with the 579 Ma Sierra de las Animas 2 pole and the 550–590 Ma pole from Los Barrientos. This stongly suggests that both the Rio de la Plata and Congo-Sao Francisco cratons were already (or about to be) joined together by ca. 575 Ma. This is consistent with several geologic lines of evidence as reported by Campos Neto (2000) and Prave (1996) suggesting collision of both blocks by around 600 Ma.

5.2. Implications for Rodinia configuration and break-up

Kröner and Cordani (2003) have proposed that several African and South American blocks were never part of Rodinia. The Rio de la Plata craton is among those. This proposal is based, among other things, in the interpretation that important Neoproterozoic magmatic arcs on these blocks reflect the presence of large oceans between the core of Rodinia and the Congo-Sao Francisco, Kalahari and Rio de la Plata cratons. Furthermore, Rapela et al. (2007) have pointed out the dominant Paleoproterozoic basement units and the lack of exposed Mesoproterozoic rocks as fingerprints of the Rio de la Plata craton. The latter would be more easily explained if this craton did not take place in the late Mesoproterozoic Grenvillian orogeny, interpreted as the product of continental collisions during Rodinia assembly (Hoffman, 1991). In opposition to these recent opinions, it has been widely accepted in the paleomagnetic community, since the first models of Rodinia configuration were proposed, that RP was part of this supercontinent, being located with its (present-day) western margin against the eastern or southeastern (present-day) margin of Laurentia (North America). With minor changes, this position for the Rio de la Plata craton in Rodinia (Fig. 18A) has been kept by almost every researcher dealing with the paleogeographic reconstruction of this supercontinent (e.g. Dalziel, 1991, 1997; Weil et al., 1998; Meert and Torsvik, 2003; Li et al., 2008; but see alternative configuration in Hanson et al., 2004). Evans (2009) has recently proposed a radically different reconstruction of Rodinia, in which RP is close to the western margin of Laurentia. In both scenarios, a border of RP appears as the conjugate margin of a segment of Laurentia. Any paleomagnetic test of these models is severely hampered for RP by the lack of suitable exposed rocks (or exposed rocks at all!) of late Mesoproterozoic or Early Neoproterozoic ages, the lapse of time during which it is accepted that Rodinia existed (e.g. Meert and Torsvik, 2003). However, comparison of the available paleomagnetic data of RP and the Congo-Sao Francisco cratons



Paleomagnetically controled paleogeographic reconstruction of Laurentia, Baltica, Rio de la Plata and Congo Sao Francisco cratons at ca. 575Ma

Paleomagnetically controled paleogeographic reconstruction of Laurentia, Baltica, Rio de la Plata and Congo Sao Francisco cratons at ca. 575Ma

Paleomagnetically controled paleogeographic reconstruction of Laurentia (low latitude option), Baltica, Rio de la Plata and Congo Sao Francisco cratons at ca. 575Ma

Fig. 18. (a) Traditional reconstruction of Rodinia, with the Rio de la Plata craton attached to Eastern Laurentia (present-day coordinates, modified from Meert and Torsvik, 2003); (b) paleomagnetically controlled paleoreconstruction of Laurentia, Baltica, Rio de la Plata and Congo Sao Francisco cratons for ca. 575 Ma, considering the high latitude option for Laurentia. Laurentia has been positioned according to the Callander Complex paleomagnetic pole (577 ± 1 Ma, Symons and Chiasson, 1991), while Rio de la Plata and Congo-Sao Francisco are reconstructed using the Nola dykes pole (571 ± 6 Ma, Moloto-Kenguemba et al., 2009). Baltica is positioned according to Cawood and Pisarevsky (2006); (c) idem (b) but with Rio de la Plata and Congo Sao Francisco positioned close to the western margin (present-day coordinates) of Laurentia; (d) Paleomagnetically controlled paleoreconstruction of Laurentia, Baltica and Rio de la Plata-Congo Sao Francisco considering the low-latitude option for Laurentia. Laurentia has been positioned according to an interpolated pole between the Long Range dykes A pole (Murthy et al., 1992) and the Sept Iles Complex A (Tanczyk et al., 1987). Note that the position of the Rio de la Plata craton is incompatible with being the conjugate margin of Eastern Laurentia around 575 Ma during final break-up of Rodinia. More references in the text.

with those from Laurentia may shed some light on the likelihood of the proposed paleoreconstructions of Rodinia.

There is some basic agreement in the time constraints of Rodinia break-up. According to recent models (see Li et al., 2008 and references therein), Rodinia break-up occurred mainly in two well separated events. Break-up started as early as 750 Ma on the western side (present-day coordinates) of Laurentia, leading to the early separation of Greater India, followed by that of Australia, East Antarctica and South China. More than one hundred million years later break-up initiated on the eastern side, with beginning of separation of Amazonia and hypothetically also the Rio de la Plata craton at some time between 600 and 550 Ma. According to Cawood et al. (2001) the most likely time for drifting apart can be placed at around 570 Ma, followed by the later separation of smaller terranes from the same margin, like the Argentine Precordillera, at around 530 Ma.

Considering the APWP of the Rio de la Plata craton presented in Fig. 17, we can reconstruct roughly the paleolatitude and orientation of this block between around 600 and 500 Ma, which shows that RP was at intermediate to relatively low latitudes throughout the whole period, but that it underwent a major ccw rotation of nearly 180°. Since we now have paleomagnetic information for the Rio de la Plata, Congo-Sao Francisco and Laurentia for around 580–550 Ma, we can test whether this information is consistent or not with the classical paleogeographic reconstructions of Rodinia with RP as the conjugate margin of Eastern Laurentia. If so, APWP from both Laurentia and RP-Congo Sao Francisco must coincide within experimental errors when the cratons are repositioned into such configuration. However, as recently discussed by McCausland et al. (2011) comparison is not straightforward due to ambiguities in the interpretation of the database. In particular, it is well known that the Ediacaran paleomagnetic database of Laurentia has been a subject of debate for nearly two decades (Symons and Chiasson, 1991; Meert et al., 1994; Pisarevsky et al., 2001; McCausland et al., 2007, and many others). The main controversy arises from the presence of reliable paleomagnetic poles that suggest that Laurentia was at low paleolatitudes at around 615 Ma and since 560 Ma approximately, while in a brief period between 590 and 570 Ma it would have stayed at high, nearly polar, latitudes (McCausland et al., 2007, and references therein). Recent new paleomagnetic results from the Baie de Moutons syenite in Eastern Laurentia (McCausland et al., 2011) of ca. 585 Ma, have confirmed the presence of a high latitude component (A) with a second, unrelated, component (B) from slightly younger intrusions of the same complex yielding low paleolatitudes for Laurentia. Proposed explanations for this paradox have ranged from very fast plate tectonic displacements (Meert et al., 1994; McCausland et al., 2007), paleomagnetic artifacts due to unreliable data (Pisarevsky et al., 2001, 2008), very fast true polar wander (Evans, 2003; Kirschvink et al., 2005) or unusual geomagnetic geometries (Abrajevitch and Van der Voo, 2010). Anyway, all different positions can be reduced in paleogeographic terms into whether Laurentia experienced a short period between ca. 590 and 570 Ma in high latitudes or remained during the whole Ediacaran in low latitudes. This ambiguity is not present in the available database from the Rio de la Plata and Congo-Sao Francisco blocks.

The well-substantiated geologic evidence of rifting taking place along Eastern Laurentia at around 570 Ma (Cawood et al., 2001) indicates that separation of the conjugate block(s) that formed this part of Rodinia must have happened at approximately that time. Considering the classical reconstructions of Rodinia that place Rio de la Plata as one of such blocks, a simple test can be carried out on whether this is consistent with the available paleomagnetic evidence, since we now count with an acceptable data base from Rio de la Plata (plus Congo-Sao Francisco) and Laurentia for around 580–550 Ma. Furthermore, consistency of the classical Rodinia reconstruction (Fig. 18a) in either the "high latitude" or the "low latitude" option for Laurentia may serve as additional evidence in favour of one or the other model.

Fig. 18 illustrates the paleomagnetically controlled paleogeographic positions of Laurentia, Baltica, Rio de la Plata and Congo-Sao Francisco blocks for the middle Ediacaran (ca. 575 Ma). In Fig. 18b and c, the "high latitude" option for Laurentia has been adopted. Laurentia has been positioned according to the Callander Complex paleomagnetic pole (577 ± 1 Ma, Symons and Chiasson, 1991), while Rio de la Plata and Congo-Sao Francisco are reconstructed using the Nola dykes pole (571 ± 6 Ma, Moloto-Kenguemba et al., 2009). Baltica is positioned following the reconstructions of Cawood and Pisarevsky (2006). Fig. 18b shows a very wide ocean (over 3000 km) between Eastern Laurentia and western Rio de la Plata, which is incompatible with both being the conjugate margins of a rifting supercontinent at the same time. Considering the relative paleolongitudinal indetermination of comparing single paleomagnetic pole positions, Rio de la Plata and Congo-Sao Francisco have been rotated and placed near the western margin of Laurentia in an alternative reconstruction (Fig. 18c). This figure shows the western margin of Rio de la Plata facing that of Laurentia, somewhat in the mood of the "alternative" Rodinia of Evans (2009). However, rifting along the western margin of Laurentia during initial Rodinia break-up has been dated ca. 750 Ma (Li et al., 2008 and references therein), which turns a paleogeographic reconstruction 180 m.y. younger with little if any use in testing such configuration. This analysis shows that if the classical Rodinia configuration is valid, the paleomagnetic data of the Rio de la Plata and Congo-Sao Francisco craton argue against the "high latitude" option for Laurentia.

Fig. 18d presents a reconstruction in which Laurentia has been positioned according to the "low latitude" option, using an interpolated pole position between the Long Range dykes (615 Ma, Murthy et al., 1992) and the Skinner Cove volcanics (550 Ma, McCausland and Hodych, 1998) poles for 575 Ma. In this case the position of the western margin of the Rio de la Plata is facing in the wrong direction (south instead of north) to be the conjugate margin of Eastern Laurentia, which is clearly also incompatible with both the Laurentian and Rio de la Plata margins being at the beginning of a rifting and drifting process.

The available paleomagnetic data just discussed indirectly support tectonic models that portrayed the Rio de la Plata and Congo-Sao Francisco cratons as "non-Rodinian" blocks (Kröner and Cordani, 2003; Tohver et al., 2006). However, alternative interpretations such as a non-classic Rodinia configuration (like Evans, 2009), with Rio de la Plata positioned along other margins of Rodinia, or a classic-type reconstruction with a much older separation of the craton from Eastern Laurentia, merit further scrutiny. In the latter case, one of the blocks that rifted apart from the eastern margin of Rodinia at ca. 575 Ma (Cawood et al., 2001) might be the Pampia block (Ramos, 1988; Kraemer et al., 1995; Ramos et al., 2010), which later collided against the Rio de la Plata craton (Escayola et al., 2007) or Kalahari (Rapela et al., 2007).

6. Conclusions

A systematic paleomagnetic study was carried out on the Sierras Bayas Group and the Cerro Negro Formation of latest Precambian to Cambrian age, exposed in the Tandilia system in the province of Buenos Aires, central Argentina. A previous paleomagnetic study on these rocks, carried out three decades ago by Valencio et al. (1980), referred to this unit as the La Tinta Formation. Three hundred and twenty-eight samples from 44 sites were collected in the Cryogenian to Ediacaran Villa Mónica Fm., the Ediacaran Cerro Largo, Olavarría and Loma Negra Fms. and the Ediacaran–Cambrian Cerro Negro Fm. Sampling was carried out in limestone, dolostone, red claystone and marls in the localities of Olavarria and Barker. A predominant post-tectonic magnetization (component B) carried by both magnetite and hematite was isolated in most sites, particularly in carbonatic rocks. This component corresponds to that identified by Valencio et al. (1980) and interpreted as of primary origin, however its post-tectonic character and a negative conglomerate test indicate its secondary origin and suggest a Permian–Triassic age of magnetization. It is interpreted that these rocks have been remagnetised by a regional event that also affected Neoproterozoic clastic and carbonatic sediments in Uruguay and which may be related to the SanRafaelic remagnetization found along the Sierra de la Ventana and other areas of central and western Argentina (see recent review by Font et al., in press). A few sites from different units, only made up of red claystones, siltstones and marls showed the presence of older magnetic components which are likely primary in origin as some of them pass a tilt-test and yield four paleomagnetic pole positions ordered consistently along the APWP of the Rio de la Plata craton proposed for the interval 600–500 Ma (Rapalini, 2006; Rapalini and Sanchez Bettucci, 2008). Their respective positions in the path are consistent with their relative stratigraphic ages and the most likely absolute ages, being approximately constrained between ca. 590 and 510 Ma. The confirmed APWP for the Rio de la Plata craton indicates that this block was at intermediate to low paleolatitudes during the Ediacaran and that by around 575 Ma had already collided with the Congo-Sao Francisco craton or was very close to it. According to the paleomagnetic data of ca. 575 Ma it is highly unlikely that the Rio de la Plata craton was the crustal block that rifted apart from Eastern Laurentia during the final stages of Rodinia break-up. This holds true with both the high and low latitude options for Laurentia in the Ediacaran.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2012.09.007.

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