Geologica Acta, Vol.8, Nº 4, December 2010, 373-397
DOI: 10.1344/105.000001578
Available online at www.geologica-acta.com

geologica acta

Paleomagnetism of the Carboniferous-Permian Patquía Formation, Paganzo basin, Argentina: implications for the apparent polar wander path for South America and Gondwana during the Late Palaeozoic

S.E. GEUNA [1] L.D. ESCOSTEGUY [2] C.O. LIMARINO [1]

[1] **Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires / CONICET**
Ciudad Universitaria Pab. 2, C1428EHA, Ciudad de Buenos Aires, Argentina. Geuna E-mail: geuna@gl.fcen.uba.ar. Phone number: 54-11-47883439

[2] **Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino**

ABSTRACT

The magnetic properties of the Carboniferous-Permian red beds of the Patquía Formation at Punta del Viento, Sierra de Umango and some previously reported localities, all in the Paganzo Basin (Argentina), have been studied. Whereas all sites are characterized by hematite as the main magnetic carrier and a reversed-polarity magnetic remanence, we found a pattern of variation in magnetic properties along the integrated column for Patquía Formation. The Lower Member (Late Carboniferous) showed higher intensity of natural and saturation isothermal remanent magnetisation (NRM and SIRM, respectively) than the Permian Upper Member. The fall in NRM intensity from the Lower to Upper Member of the Patquía Formation may be related to a change in quantity and/or grain-size of the hematite pigment, which may reflect the change in environmental and/or depositional setting. As for directional values of NRM, paleomagnetic poles reported for both sections are clearly different. The lower section provided a pole position coincident with Late Carboniferous poles for Gondwana, while the upper section poles are departed from the Early Permian position. We cannot decide whether the Upper Member pole is due to a primary magnetisation at 290 Ma or to a remagnetisation at ~260-270 Ma; even so, the obtained paleomagnetic pole is robust and indicates a rapid apparent polar wander in a ~30º counter clockwise rotation of the region, after deposition of the Late Carboniferous lower section, and in coincidence with the San Rafael Orogenic Phase.

KEYWORDS **Red beds. Paleomagnetism. Magnetic remanence. Apparent polar wander.**

INTRODUCTION

Continental red beds are of special significance in paleomagnetism, not only because they were the first sedimentary rocks to be studied in any detail (Turner, 1980) but also owing to red beds have demonstrated to be particularly suitable for paleomagnetic studies. Red beds share in common the red colour given by finely disseminated ferric oxides, usually in the form of haematite. They comprise a wide range of sedimentary facies mainly deposited in continental environments, though some examples of marine red beds have been also quoted (McBride, 1974; Franke and Paul, 1980; Limarino et al., 1987; Hu et al., 2005).

Haematite is usually the main carrier of magnetic remanence in red beds, and hence the age of the remanence is given by the time of haematite crystallization. Haematite in red beds may form by the oxidation of magnetite, the inversion of maghemite, or the dehydration of goethite, the latter formed by breakdown of hydrous clay minerals and ferromagnesian silicates (McBride, 1974; McPherson, 1980; Dunlop and Özdemir, 1997). All the reactions typically occur during burial in a sedimentary pile, through the diagenetic stage (early diagenesis, mesodiagenesis, telodiagenesis) in a process that strongly depends on basin conditions.

Continental red beds are extremely sensitive indicators of the nature and extent or red bed diagenesis. The paleomagnetic study shows that diagenesis must be a rate process in which the rate, including the rate of acquisition of magnetization, is determined by a) the original mineralogy of sediment, where immature sediments are susceptible to more extensive alteration and prolonged magnetization; b) the depositional conditions, finer grained sediments being less susceptible to alteration; c) the prevailing climate, warm arid climates being favourable for the long-continued alteration (Turner, 1980). The age of the magnetization in red beds is a direct result of the rate of acquisition of remanence, which is variable because it represents the sum of several discrete diagenetic processes.

The Paganzo Basin in western Argentina has been the site of deposition for Carboniferous-Permian red beds which provided several paleomagnetic poles, some of them controversial. Most of them were published before recent methodological advances in the paleomagnetic routine, and up till now no study has considered the characterization of the magnetic mineralogy of these red beds.

In this paper we present a preliminary study on a section in the Sierra de Umango in Paganzo Basin, where Carboniferous-Permian red beds can be compared with overlying red Cretaceous units. The comparison is extended to other localities studied before by Embleton (1970b), Valencio et al. (1977) and Sinito et al. (1979a). The magnetic properties were distinctive for the two members recognized in the Late Palaeozoic red beds: haematite is more abundant in the lower fluviatile facies than in the upper desert association, and both sections provided different paleomagnetic poles.

We compared the Paganzo basin paleomagnetic poles to the paleomagnetic record from other Gondwana plates during the Late Palaeozoic. We inferred the timing for remanence acquisition and analysed it in terms of diagenesis, haematite crystallisation and changes in the depositional setting.

GEOLOGICAL SETTING

The Paganzo basin covers an area of 140.000 km^2 where mainly continental sedimentation took place from the latest Early Carboniferous to the Late Permian (Limarino et al., 1996; Tedesco et al., 2010; Fig. 1). The sedimentary cover is thinner to the east, where it was deposited on Proterozoic igneous-metamorphic basement of the Sierras Pampeanas; in the western part, a narrow belt developed on more mobile areas, where thicker deposits lie upon metamorphic basement and Lower Palaeozoic sediments of the Precordillera (Azcuy et al., 1999). There is evidence of oblique convergence in the Late Palaeozoic subduction zone to the west (Mpodozis and Kay, 1992; Kay, 1993); strike-slip faults have controlled the development of the forearc basins (Fernández Seveso and Tankard, 1995). A N-S trending structural high, the Proto Precordillera, partially separated the Paganzo basin from its marine extensions to the west: the Río Blanco and Calingasta-Uspallata basins (Limarino et al., 1996; Fig. 1).

Terrigenous clastic fill of the Paganzo basin was originally subdivided into three "stages" referred to as Carboniferous, Permian and Triassic by Bodenbenber (1911). Azcuy and Morelli (1970) restricted the name Paganzo Group to the Carboniferous-Permian sections, separating

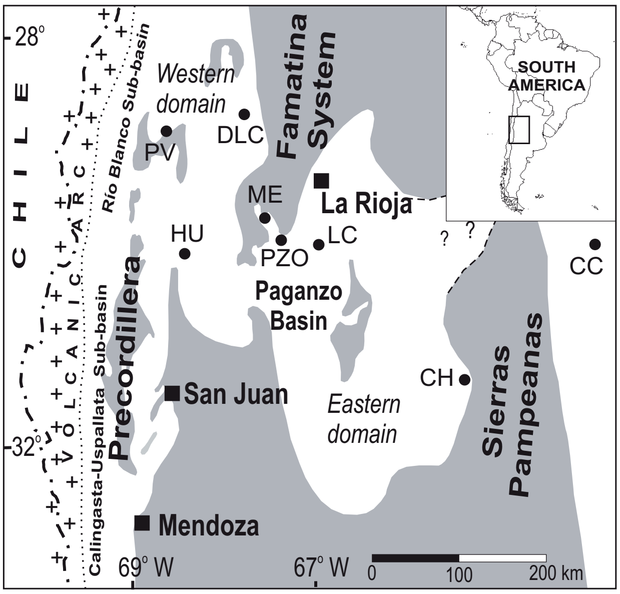

FIGURE 1 | **Sketch of Paganzo Basin, with localities referred in the text (modified from Azcuy et al., 1999). Locality codes as in table 3; PV is the location of the present study in Punta del Viento, Sierra de Umango.**

the Triassic sequence (usually referred to as the Upper Paganzo Section or “Paganzo III” in former paleomagnetic contributions) as an independent cycle. The Triassic extensional basins developed following a tectonic inversion marked by a major unconformity that truncates Permian sequences, identified with the Amanaica Orogenic Phase (Aceñolaza and Toselli, 1981; Limarino et al., 1988).

The infill of the Carboniferous-Permian basin comprises the Paganzo Group, consisting of three stratigraphic units: the Guandacol, Tupe and Patquía Fm. (Fig. 2). The first stage (Guandacol Fm.) began with deposition of diamictites or dropstone-bearing mudstones, followed by marine or deltaic dropstone-bearing sediments, deposited in the Proto Precordillera and in areas proximal to palaeotopographic highs. The Tupe Fm. represents Carboniferous aggradational and progradational filling dominated by fluvio-deltaic deposits, coal, and some black shales, interleaving to the west with shallow marine and deltaic deposits. The Patquía Fm. marks the final phase of basin fill and is characterised by stratigraphic onlap and a change from subaqueous to subaerial dominated sedimentation, comprising red beds deposited in ephemeral stream and playa-lake environments (Limarino et al., 2006).

The Patquía Fm. red beds lie unconformably on Tupe Fm., though the unconformity is noticeable only in marginal areas of the Paganzo basin, as it becomes a paraconformity basinward (Limarino et al., 2006). Fluvial sedimentation resulted in three major association of facies: 1) alluvial fans and proximal braided alluvial plains, 2) high-sinuosity river systems and 3) sand or gravelly channel belts encapsulated in floodplain deposits.

Braided or meandering fluvial deposits were progressively replaced by low-energy ephemeral river successions, and then by aeolian and lacustrine deposits (Limarino et al., 2006). Two different sections in the Patquía red beds have been distinguished based on the change from fluviatile to aeolian environments (Azcuy and Morelli, 1970). The transition from humid to semiarid conditions marked by this facial change in Patquía Fm. (López Gamundí et al., 1992) is accompanied by a change in the palaeocurrents patterns, from W-NW to SE, and in petrofacies, with higher supply of acidic volcanic lithic fragments, all of which can be interpreted as due to a change in regional dip lead by thermal doming and uplift in the Permotriassic magmatic arc to the west (Caselli and Limarino, 2002; Limarino et al., 2006). Silcretes formed in weathered tephra-rich paleosoils are found near the transition from the Lower to the Upper Member of the Patquía Formation (Limarino and Caselli, 1995), indicating that was a period of low depositional rate and a rising supply of volcanic material.

Simultaneous with deposition of red beds in the eastern basin, magmatic arc-related deposits are found in the western basin, linked with active subduction during the Late Palaeozoic. Convergence culminates in the San Rafael Orogenic Phase (SROP) during the Early Permian (Kleiman and Japas, 2009), whose effects in the western margin of Gondwana are reflected in a major erosion surface on which Choiyoi Magmatic Province (280-240 Ma) developed. Lower Choiyoi magmatism is calc-alkaline with typical continental-subduction signatures, coeval with transpression, followed by shoshonitic magmatism related to crustal thickening; it was followed by extension and ignimbrite “flare-up” (Upper Choiyoi), evidence of a change from transpressional to transtensional regimes during the Permian (Kleiman and Japas, 2009). The SROP might be responsible for the inversion observed in the eastern basins at the end of the Permian (~ Amanaica Phase, Aceñolaza and Toselli, 1981), as suggested by Azcuy et al. (1987).

Recent high-resolution U-Pb ages on tuffs allowed refining the timing of the different geological events in Paganzo basin (Gulbranson et al., 2008, 2010). An age of 319.6 ± 0.08 Ma places the Guandacol Fm. in the latest

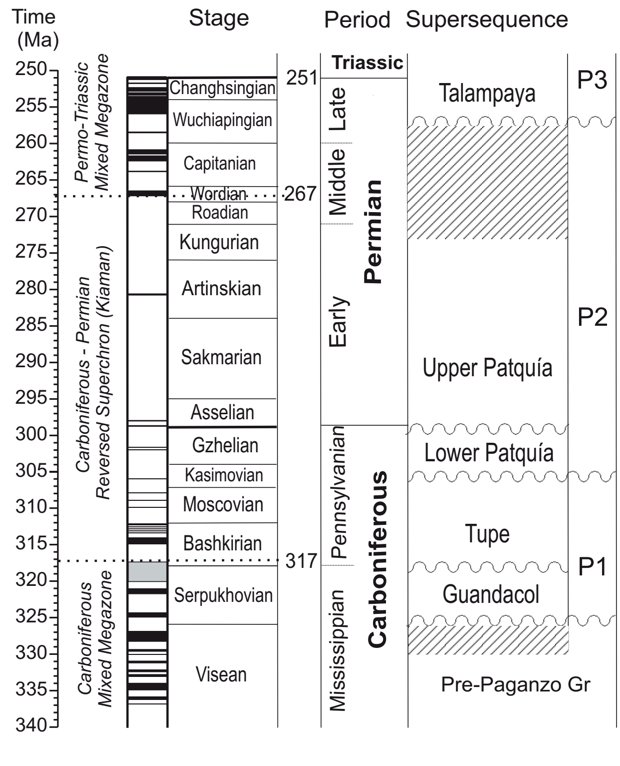

FIGURE 2 | **Stratigraphic framework for the Paganzo Group (from Gulbranson et al., 2008, 2010), referred to the Geomagnetic Polarity Time Scale (GPTS, Ogg and Smith, 2004); Carboniferous chronostratigraphy from Heckel and Clayton (2006). The column to the left is the magnetostratigraphy, white (black) indicating reversed (normal) polarity zones. The lithostratigraphic units recognized at present are accompanied to the right by the original denomination for Paganzo Group (Bodenbender, 1911; P1, P2 and P3 are Paganzo 1, 2, 3 respectively). GPTS generated with program TSCreator PRO (Ogg and Lugowski, 2008).**

Early Carboniferous, followed by Tupe Fm. in the Bashkirian (ages of 315.5 ± 0.07 and 312.8 ± 0.11). Patquía Fm., considered up to now as Permian in age, would have began its deposition as early as the Kasimovian, and continued well into the Permian (296.1 ± 0.08 Ma for the aeolian Upper Member; Gulbranson et al., 2008, 2010). The Patquía Fm. is truncated by the regional unconformity upon which red beds of Talampaya Fm. deposited; a volcanic ash near the base of Talampaya Fm. provided ages of 252.4 ± 0.07 Ma (Limarino, 2009), what places the unconformity in the top of Patquía Fm. in the Late Permian (Fig. 2).

Extensional basins developed during the Triassic and Cretaceous (Uliana et al., 1990). The Cainozoic Andean orogeny created the present relief, in some cases by inversion of major structures and the development of tilt-block foreland basins with Neogene fill (Ramos, 1999).

Paleomagnetism of Paganzo Basin

The infill of Paganzo Basin ends with Permian red beds which locally receive the names Patquía, La Colina or De la Cuesta Fm., hereinafter called Patquía Fm. (Fig. 2). The area was successively reactivated during Triassic, Cretaceous and Neogene times when continental deposits accumulated in local troughs. As a consequence, it is not infrequent to find continuous exposures of red beds with ages ranging from the Late Carboniferous-Permian to the Cainozoic. This makes a good scenario for comparison of magnetic properties in red beds of different ages and environments. A key point for comparison is magnetic polarity, as the Carboniferous-Permian section was deposited mainly during the Permo-Carboniferous Reversed Superchron (PCRS), a long interval of about 50 Ma, during which the geomagnetic field maintained nearly constant reverse polarity (Fig. 2). The lower limit of the PCRS is placed between 318 and 311 Ma (Opdyke et al., 2000; Buchan and Chandler, 1999), and the upper limit at about 267 Ma (Westphalian to early Late Permian; Menning, 1995).

Most of the Paganzo PCRS poles date from 30 years ago, and many are based on relatively sparse sampling, or derived from blanket cleaning experiments. However, several of the localities show well grouped NRMs with reversed polarity (e.g. Huaco and Los Colorados, Embleton, 1970a), and the remanence directions do not change during demagnetisation. A reappraisal of these poles was attempted recently by Geuna and Escosteguy (2004).

Many of the PCRS poles are departed from coeval poles and were suspicious of remagnetisation because they are concentrated around the geographic pole (Smith, 1999; McElhinny and McFadden, 2000; Tomezzoli, 2009). However, most of them are based on exclusively reverse polarity sequences, some of them of considerable thicknesses. The discrepancy among poles is especially striking in two cases that kept our attention and will serve to introduce the paleomagnetic problem in Paganzo basin: 1) Lower and Upper Los Colorados (Embleton, 1970b; Thompson, 1972), 2) Paganzo Village (Thompson, 1972; Valencio et al., 1977) vs. Las Mellizas Mine (Sinito et al., 1979a).

1) Los Colorados

Embleton (1970a) obtained 53 hand samples along a continuous homoclinal red bed section in Patquía Fm. He noted a change in the directions of magnetisation about halfway through the sequence, and for that reason calculated two different poles for the lower and upper strata. Thompson (1972) continued the sampling upwards, through the unconformity which separates Patquía Fm. from the overlying Talampaya (= Amaná) Formation (Permotriassic), and recalculated the Upper Los Colorados pole adding the new sites from the top of Patquía Fm.

Embleton (1970b) noted that, besides difference in the direction of magnetisation, the upper strata differ from the lower ones in having lower remanence intensity by one order of magnitude (3 vs. 40 mA/m). Careful examination of field notes lead us to conclude that the transition from “lower” to “upper strata” coincides with the change from the Lower to the Upper Member of the Patquía Fm., which is recorded in the Los Colorados section. The implications of this will be discussed later.

2) Paganzo Village and Las Mellizas Mine

These two sections belong to La Colina Formation and occur within the same district, although separated by 25 kilometres. Azcuy and Morelli (1970) correlated them because they are bounded by the same units (Carboniferous Lagares Formation at the base, and Permotriassic Amaná-Talampaya Formation above), and contain similar basaltic intercalations. The 5 meter-thick basaltic flows from both localities were used by Thompson and Mitchell (1972) to calculate a paleomagnetic pole. Radiometric K/Ar ages on the basalts were not the same (295 ± 5 Ma in Las Mellizas and 266 ± 5 Ma in Paganzo, Thompson and Mitchell, 1972), which was attributed by the authors to argon loss in Paganzo Village sample.

The 600 meter-thick sedimentary sequence from Paganzo Village was studied by Thompson (1972) and Valencio et al. (1977). The former used 35 samples of Patquía Fm., from both limbs of a steep anticline. They carried a pretectonic reversed characteristic magnetisation, determined after the elimination of a post-tectonic secondary component. Valencio et al. (1977) performed a more detailed and numerically larger collection of samples, but only in the eastern limb of the anticline. The sampling program concentrated mostly in the upper section of Patquía Fm., as the lower section (about 200 meters overlying the basaltic flow) is covered in this locality. They obtained more scattered final directions, probably due to incomplete elimination of secondary components, but the final result was essentially the same as obtained by Thompson (1972).

Sinito et al. (1979a) sampled the same sequence in Las Mellizas Mine, where the lower section, below and above the basaltic flow, is well exposed. They obtained an all-reversed characteristic magnetisation, but the pole position resulted different from the one from Paganzo Village. It was concluded that the two sequences were differing in age, supported by the rejuvenated K/Ar age obtained by Thompson and Mitchell (1972) for the interbedded basaltic flow in Paganzo Village.

As both sections represent the same lithostratigraphic unit at Formation level, Geuna and Escosteguy (2004) interpreted the difference between the poles from Paganzo Village and Las Mellizas Mine as produced by a rotation of the Paganzo Village section about a vertical axis. However, the careful examination of field notes shows that Las Mellizas Mine section was sampled in levels mostly underlying the basaltic flow, completely in the Lower Member of Patquía Fm. This brings us back to the original interpretation of Sinito et al. (1979a), as both poles differ in age. We address this question later.

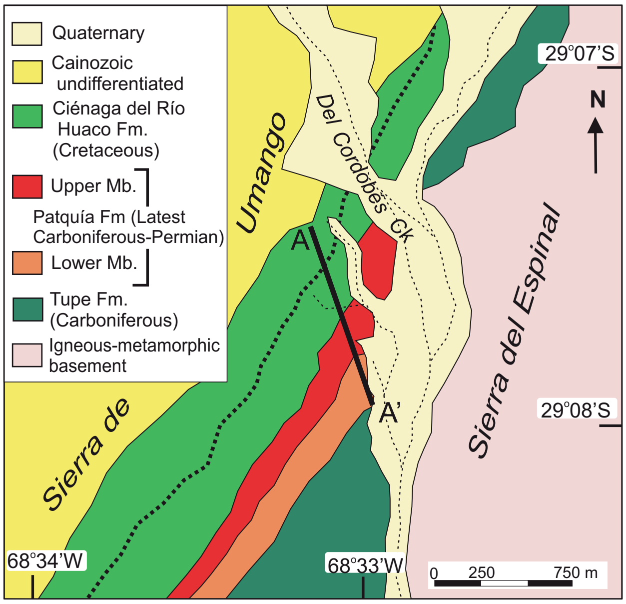

FIGURE 3 | **Geologic map of the Punta del Viento area (eastern flank of Sierra de Umango) after Fauqué et al. (2004). A-A' shows the trace of the sampled profile. The dotted line in Ciénaga del Río Huaco Fm. marks the possible location for the transition from the Upper Member of Patquía Fm. to Ciénaga del Río Huaco Fm. according to the paleomagnetic results.**

SAMPLING AND LABORATORY PROCEDURES

We chose a new locality in the eastern flank of the Sierra de Umango, La Rioja province, which contains a well exposed red-bed succession spanning from the Carboniferous (Patquía Fm.) through the Cretaceous (Ciénaga del Río Huaco Fm.) up to the Cainozoic (Vinchina Fm.) (Fauqué et al., 2004; Fig. 3). While the Cainozoic red beds are readily distinguishable by their orange colour, the limit between Permian and Cretaceous red beds was not able to be precisely established in the field; both units compose a 500 meters-thick sequence outcropping in Punta del Viento, containing the record of aeolian fields commencing about 100 meters above the base, and a basaltic flow 100 meters below the contact with Vinchina Fm. The aeolian fields were considered the highest possible level for the top of Lower Member of Patquía Fm., and the basaltic flow as the highest possible level for the base of Ciénaga del Río Huaco Fm. The 300 meters in between should contain the transition from Permian to Cretaceous section. Two block samples were taken from each of sixteen sites, distributed as follows: four sites (PV1-4) below the aeolian field (lowermost Patquía Fm.); six sites (PV5-10) from the zone containing the limit; and six sites (PV11-16) from the basalt and overlying Cretaceous red beds. Flat surfaces of the block samples were oriented using both Brunton and solar compasses whenever possible.

For paleomagnetic measurements, specimens of 2.5cm diameter and 2.2cm length were drilled. The demagnetisation procedures were completed alternatively at the Instituto Astronomico e Geofisico, Universidade de Sao Paulo (Brazil), or at the laboratory of the Rock Magnetism Group, CSIRO Exploration and Mining in North Ryde (Australia). Remanent magnetisation was measured using a three-axis 2G DC squid cryogenic magnetometer. Alternating field demagnetisation (AF) was carried out to a maximum of 110mT (peak) using a static 2G600 demagnetiser attached to the magnetometer. Step-wise thermal demagnetisation up to 680°C was performed using a two-chamber ASC, Schonstedt TSD-1 or the CSIRO programmable carousel furnace.

At least two specimens from each site were subjected to stepwise demagnetisation, to examine the coercivity and blocking temperature spectra of the natural remanent magnetisation (NRM). As a general procedure, AF demagnetisation was preceded by the application of heating to 150ºC, to eliminate the effects of modern goethite, whereas thermal demagnetisation was preceded by the application of low alternating fields (up to 10-20mT) to minimize the soft components carried by multidomain magnetite. Bulk magnetic susceptibility was measured after each thermal step in order to monitor possible magnetic mineral changes, by using a MS2W Bartington susceptometer or the CSIRO susceptibility bridge.

Isothermal remanent magnetisation (IRM) up to 2.3 T was applied to selected samples to identify the minerals carrying the magnetisation, by using an ASC IM-10-30 impulse magnetizer at the Universidad de Buenos Aires. IRM acquisition curves were examined by cumulative log-Gaussian (CLG, Robertson and France, 1994) functions using the software developed by Kruiver et al. (2001).

Magnetic behaviour of each specimen was analysed by visual inspection of Zijderveld plots, stereographic projections and intensity demagnetisation curves, to determine the characteristic remanence magnetisation (ChRM), by using principal component analysis (PCA, Kirschvink, 1980), with the software SuperIAPD.

A mean direction for each stratigraphic level was obtained by averaging magnetic components from specimens of each sedimentary bed (site). The single-stratigraphic-level directions within each section were averaged using standard Fisher (1953) statistics to obtain section-mean directions.

To make a comparison of magnetic properties from different localities, original data obtained from Paganzo Village (Valencio et al., 1977) and Mina Las Mellizas (Sinito et al., 1979a) were compiled in tables and graphs, including NRM intensities and ChRM directions at sample level. Also some representative samples were recovered from the repository of the INGEODAV, Universidad de Buenos Aires, to determine magnetic susceptibility and IRM acquisition curves.

Besides sites 1 to 4 of Punta del Viento, the Lower Member of Patquía Fm. is represented by 36 sites (62 samples; R1-48 and R93-106) in Las Mellizas Mine, collected by Sinito et al. (1979a). On the other hand the Upper Member is represented by 79 sites (159 samples, 6069-6228) used by Valencio et al. (1977) from Paganzo Village, and 5 levels (10 samples, R83-92) from Las Mellizas Mine.

In addition, we analysed samples from the overlying Amaná-Talampaya Fm. (Permotriassic), from Las Mellizas Mine (17 sites, 34 samples R49-R82) and Paganzo Village (10 sites, 21 samples, 6230-6250). The Cretaceous Ciénaga del Río Huaco Fm. was sampled only at Punta del Viento.

RESULTS

The results of the paleomagnetic and rock magnetic study on Punta del Viento samples will be shown at first, followed by a revision of the paleomagnetic study at sample level in Paganzo Village (Valencio et al., 1977) and Las Mellizas Mine (Sinito et al., 1979a). At last a comparison will be attempted.

Punta del Viento

A total of 53 specimens (about three per site) from Punta del Viento were treated by alternating magnetic fields (AF) or thermal demagnetisation to isolate the magnetisations of representative specimens from each site. AF demagnetisation proved effective only to remove a viscous remanence component carried by low-coercivity minerals (Fig. 4). Thermal demagnetisation was conducted in 100ºC increments from 200ºC to 400ºC, and then in 50ºC increments from 400ºC to 550ºC, followed by 10ºC steps up to 690ºC when remanence was completely unblocked (Fig. 4).

All the samples were characterised by a sharp decay of the intensity close to the Néel temperature of haematite (675ºC). This was variably preceded by a slow decrease at lower temperatures, most noticeable in sites PV5-16 (Fig. 4B, C), while sites PV1-4 showed characteristically blocky curves (Fig. 4A). Once viscous remanence was removed by AF lower than 15 mT or temperatures lower than 300ºC, thermal treatment showed the multivectorial nature of the remaining NRM, consisting of two components.

After 640ºC only one high-temperature component was removed; the second component isolated between 300 and 640ºC presumably represents a mixture of both intermediate- and high-temperature magnetisations being removed together (Fig. 4A). Angular difference between intermediate- and high-temperature components ranged from 0º (both components undistinguishable from each other) to 15º, with a mean difference of 10º. The mean values for the high-temperature component are given in Table 1.

Acquisition of IRM shows that saturation occurs at magnetic fields greater than 2 T indicating that haematite is the main magnetic mineral in these rocks (Fig. 5). Two-component models were best fitted to all IRM acquisition curves by applying the method of Kruiver et al. (2001). The lower coercivity phase is minor and was interpreted as magnetite, carrying the viscous component of the NRM; the higher coercivity phase shows remanence coercive force ranging from 300 to 630 mT, typical of haematite (Fig. 5, Table 2).

Only about 5 % of the SIRM was carried by magnetite in Patquía Fm. samples (Fig. 5, Table 2). This can be interpreted as a virtual absence of magnetite, as a very low fraction of this mineral would be enough to dominate the IRM due to its high saturation magnetisation. The only exception was sample 6088 taken from levels overlying an

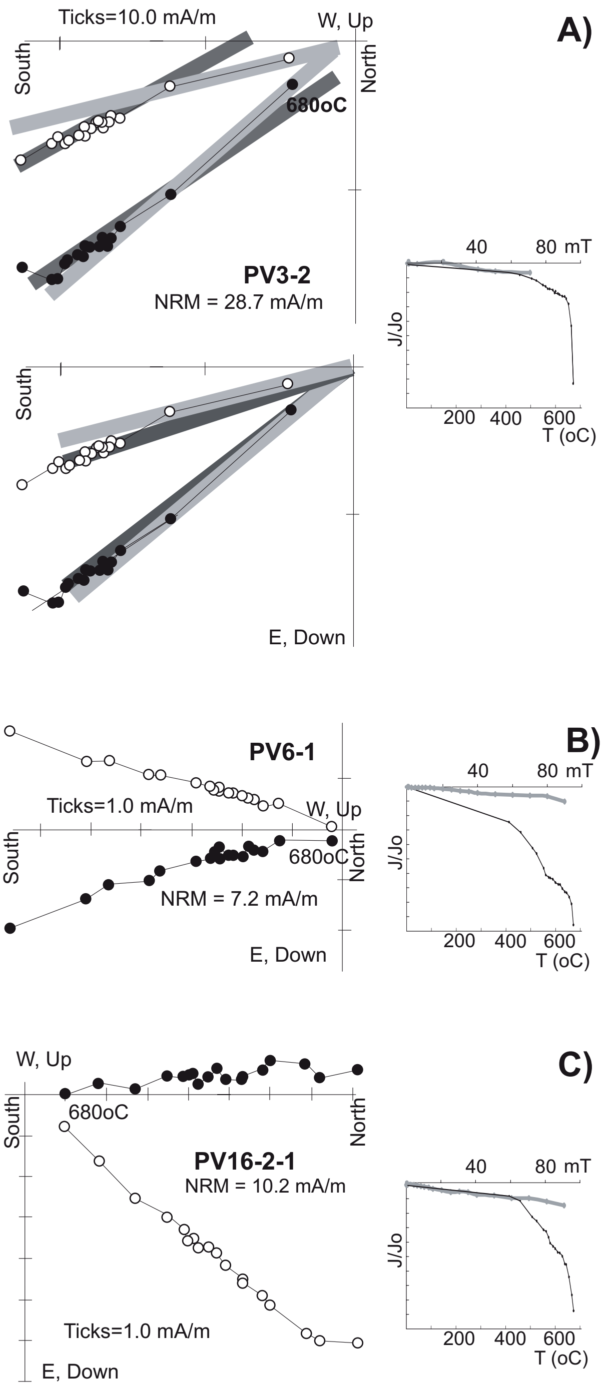

FIGURE 4 | **Examples of typical demagnetisation behaviour in the red beds from Punta del Viento area. Orthogonal projection (Zijderveld-type) diagram to the left, open (solid) symbols indicate projection onto the vertical (horizontal) plane. To the right, variation of NRM intensity along the demagnetisation. Thin black line, thermal demagnetisation (units in bottom axis). Thick grey line, AF demagnetisation of a companion sample (units in top axis). A) Lower Member of Patquía Fm., site 3. B) Intermediate sites interpreted as Upper Member of Patquía Fm., site 6. C) Ciénaga del Río Huaco Fm., site 16. Multicomponent behaviour was highlighted in A, where the two components carried by haematite (identified by two different gray shades) show an angular difference of about 10º. The same Zijderveld diagram is depicted below, where the dark gray line marks the direction of the component calculated from 450ºC blanket cleaning (a line joining 450ºC and the origin). The high-temperature component (light gray) differs from the blanket cleaning result by an angle of a few degrees (less than 5º).**

interleaved basaltic flow in Paganzo Village, with 39 % of SIRM carried by magnetite. Remarkably, a 15 to 40 % of the SIRM is carried by magnetite in samples from the overlying Permotriassic-Cretaceous red beds, which makes the absence of magnetite a distinctive characteristic of Patquía Fm. This indicates either that parental magnetite was completely haematitized in the older red beds or that it was absent in the supplied detritus.

When comparing the IRM curves from both members of Patquía Fm., the Lower Member shows the highest remanence coercive forces (Hcr ~ 600mT) and saturation isothermal remanent magnetisations (SIRM ~ 8 A/m). Samples from the Upper Member show lower SIRM (2-5 A/m), and eventually lower Hcr (~ 400mT). Values of Hcr between 100 and 1800mT (Dunlop, 1972) are typical for haematite in any of its variations, specularite of red pigment, as it is usual that both forms appear together in red beds.

Patquía Fm. red beds are mainly arkosic arenites with clastic texture showing planar to convex-concave contacts. They are composed by subrounded to subangular clasts of quartz, feldspars altered to carbonate or clay (illite and kaolinite), plagioclase and opaque minerals (Limarino et al., 1987). At least three classes of cement were identified: 1) haematite cement occurs as a thin coating around detrital grains, in rims of uneven thickness; 2) secondary quartz growth, occasionally including the iron coating, and 3) calcite fills the remaining intergranular pores, partially replaces the early formed cements and corrodes clasts. Types 1 and 2 were interpreted as formed during early diagenetic stages, in a shallow burial environment, while cement type 3 is supposed to have formed under mesodiagenetic conditions at greater burial depths (Limarino et al., 1987; Caselli et al., 1997).

Magnetic properties of fine-grained haematite are not readily interpretable, as microstructure and extrinsic influences seem to affect more those properties than just the magnetisation process parameters (Dankers, 1978; Turner, 1980; O'Reilly, 1984). However, experimental data on crushed material indicate largest SIRM for finest grain-size fractions of haematite, and an increase in Hcr with decreasing grain-size for grains smaller than 30μm (Dankers, 1978). Therefore changes in the IRM parameters from the Lower to Upper Mb of Patquía Fm. can be interpreted in terms of a decrease in the size of haematite pigment (lower crystallinity of iron-oxides?) or in the amount of specularite and pigment. The decrease in amount/size of haematite in facies related to the aeolian environment could be related either to the change in mineralogical composition of the parent material, or to a different rate of diagenesis reached by this material. Depleting in heavy minerals in aeolian sandstones would reduce the availability of iron-

TABLE 1 **Paleomagnetic data from Punta del Viento (La Rioja Province, lat. 29.1ºS, long. 68.6ºW).**

Site	N	*In situ*		Strike/Dip	Paleohorizontal		α_{95}	k
		Declination	Inclination		Declination	Inclination		
Patquía Fm, Lower Member (Late Carboniferous red beds)								
PV1	4	136.4	18.3	224/45	139.1	63.2	19.2	23.9
PV2	5	140.1	11.2	224/45	144.7	55.8	25.7	9.81
PV3	3	142	11.9	224/45	148.2	56.2	5.9	437.2
PV4	3	121.1	18.5	224/45	107.7	61.4	32.9	15.1
Mean	4/4	135	15.1				11.3	66.6
					136	60.1	11.3	66.6
					VGP: Lat= 52.5º S, Long= 350.9º E			
Patquía Fm, Upper Member? (Early Permian red beds)								
PV5	4	119.7	-17.3	210/91	119	73.7	39.1	6.5
PV6	4	157.9	-15.3	220/91	191.1	59	14.4	41.4
PV7	4	145.1	-27.2	214/90	159	56.1	18.5	25.5
PV8	3	155.9	-23.1	216/86	171.7	50.2	13	90.7
PV9	3	158.3	-2	213/80	196	52.9	11.4	117.2
Mean	5/5	147.7	-17.5				17.7	19.7
					173.5	60.4	15.4	25.6
					VGP: Lat= 76.7º S, Long= 313.0º E			
Ciénaga del Río Huaco Fm (Cretaceous red beds)								
PV10	3	351.7	4.3	214/60	5.5	-32.9	23.6	28.3
PV11	3	356.9	-15.4	221/65	37.4	-46.1	15.2	66.8
PV12	2	175.2	20	228/70	234.6	55.1	--	--
PV13	3	18	15.9	212/75	12.8	-8.8	38.3	11.4
PV14	3	334	20.6	223/81	347.7	-53.9	20	39.1
PV15	2	358.8	12.3	218/81	15.9	-35.2	--	--
PV16	4	355.4	37.9	218/81	348.1	-25.5	7.1	170.2
Mean	6/7	355.9	13				19	13.4
					7.9	-34.9	18.3	14.4
					VGP: Lat= 77.8º S, Long= 149.2º E			

N: number of specimens used in statistics; α_{95}: 95% confidence circle; k: Fisher (1953) precision parameter; VGP: virtual geomagnetic pole obtained from the mean direction of remanence.

bearing detrital grains and therefore the authigenic formation of haematite due to intrastratal alteration (Limarino et al., 1988).

The variation in IRM parameters correlates with a systematic difference in NRM (Table 2, Fig. 6), already noted by Embleton (1970b) in the Los Colorados section. NRM intensity for Lower and Upper Mb are usually above and below 10mA/m, respectively (Fig. 6); in addition, Upper Member samples show a tendency to the widening of the unblocking temperatures spectra (Fig. 4).

From the variation in magnetic properties along the profile, a division was established for Punta del Viento section, as follows:

1) Lower Member of the Patquía Fm. Sites PV1 to 4 showed NRM intensities ranging between 1 and 30mA/m. The NRM was composed of just one magnetic component, carried by haematite, with unblocking temperatures of 680ºC (Fig. 4), remanent coercive forces (Hcr) between 350 and 800mT, and saturation isothermal remanent magnetisation (SIRM) between 5 and 8 A/m (Fig. 5). Once the beds were restored to the palaeohorizontal, the ChRM showed positive inclination in all the four sites (Fig. 7).

2) Sites 5 to 9 overlying the onset of aeolian fields, were found to carry haematite with a positive inclination magnetic component, with a wider spectra of unblocking temperatures and a sharp decay at 680ºC (Fig. 4, 7). Coercive force is similar to sites in the Lower Member of Patquía Fm. (Fig. 5). However, NRM and SIRM intensities

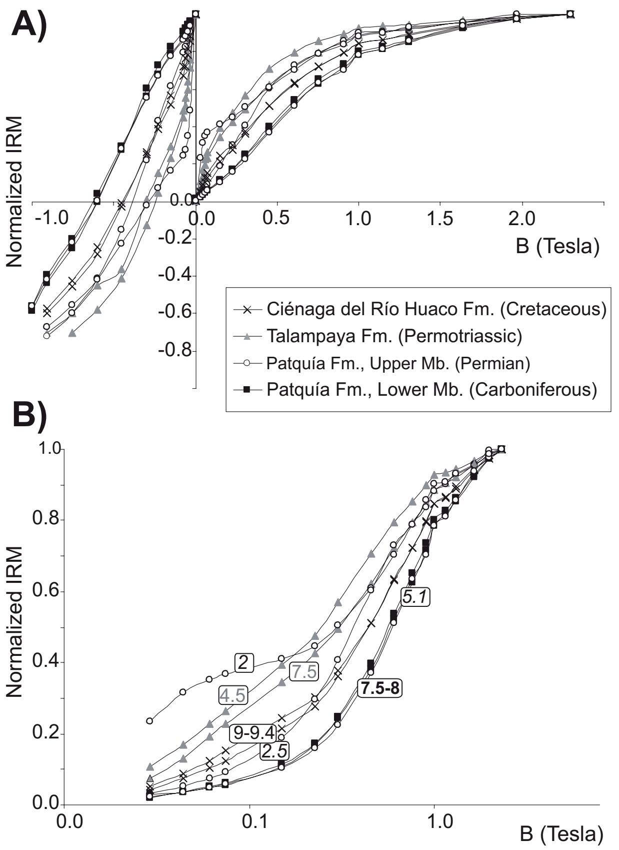

FIGURE 5 | **A) Acquisition of isothermal remanent magnetisation and back-field demagnetisation of SIRM for selected specimens, showing different combinations of magnetite and haematite as magnetic carriers. The intersection with the negative abscissa is the Hcr. B) The positive values in a in logarithmic scale; numbers into squares on curves are SIRM values in A/m for each sample (bold for Carboniferous, italics for Permian, gray colour for Permotriassic, and normal font for Cretaceous strata).**

were lower, ranging between 1 - 9mA/m and 2-3A/m respectively. We tentatively assign these 5 sites to the Upper Member of Patquía Fm. based on the all-reversed polarity.

3) Ciénaga del Río Huaco Fm. Sites 10-16 (including the basaltic flow at level 11) showed more variable NRM intensities ranging between 0.5 and 40 mA/m, with a mean of 8 mA/m. The NRM was composed of just one magnetic component, carried by haematite, with unblocking temperatures of 680ºC (Fig. 4), remanent coercive forces (Hcr) between 350 and 800mT, and SIRM of about 10 A/m (Fig. 5). The ChRM for six of the beds restored to the palaeohorizontal showed negative inclination (site 10 was the first to show normal polarity), with the remaining site giving a nearly antipodal direction (Fig. 7).

As for the direction of magnetic remanence, Patquía red beds show exclusively reverse magnetisation as expected, in contrast with double-polarity remanence obtained in the overlying Permotriassic-Cretaceous sequences (Fig. 6). However, there is a systematic difference between ChRMs of the Lower and Upper Member of Patquía Fm., in the same way as noted by Embleton (1970b) in Los Colorados. For the lower section in Punta del Viento, the mean direction after unfolding is Dec. 136.0º, Inc. +60.1º, α_{95} 14.5º, N = 4, while the upper section mean direction is Dec. 173.5º, Inc. +60.4º, α_{95} 14.1º, N = 5. Both populations are statistically different at 95% confidence level, separated by an angle of 18.5º (Fig. 7, Table 1). Qualified paleomagnetic poles cannot be obtained from these results as the number of samples is low. However, they will be useful as a guide to look for the pattern of change in bulk magnetic properties and remanence direction in other Paganzo localities.

The characteristic remanent magnetisation (ChRM) in Punta del Viento could be clearly separated only with a detailed thermal cleaning between 640 and 690ºC, which means that blanket cleaning at lower temperatures would not be *a priori* an adequate procedure for this kind of samples. Figure 4A illustrates the error of about 5º introduced in the direction of ChRM by ignoring the distinction of two intermediate- and high-temperature components. Two reasons for the error to be reduced to such a low value can be invoked: the low angular difference between intermediate- and high-temperature components (about 10º), and the unblocking spectra dominated by the higher temperature component. An error of 5º is in the range of the angular dispersion allowed to calculate the magnetic components; this means that ChRM determined by blanket cleaning at 450ºC cannot be distinguished from the high-temperature component for Punta del Viento samples (Fig. 7).

It is possible that samples from Paganzo Village (Valencio et al., 1977), and Las Mellizas Mine (Sinito et al., 1979a) had the same multicomponent behaviour. Hopefully also in these localities the influence of undetected intermediate-temperature components will not modify the final results. The similarity between NRM and blanket cleaned magnetisations is a good indication for this. The results obtained by applying the method of blanket cleaning at 450ºC in Paganzo Village and Las Mellizas Mine were revisited to clearly establish the correlation between changing magnetic properties and geological boundaries.

Paganzo Village

Patquía and Talampaya Fm. are folded together in an anticline in Paganzo Village; in the eastern limb both units are tilted about 50º to the southeast, and the change from Patquía to Talampaya Fm. is a disconformity marked by a basal conglomerate. As the limit between both sections did not result evident to Valencio et al. (1977), they preferred to place the limit between Permian Patquía and Permotriassic Talampaya Fm. based on the appearance of the first polarity change in samples 6203-6204 (about 475

TABLE 2 | **Summary of magnetic properties of red beds from the Paganzo basin.**

		NRM (mA/m)		Susceptibility (SI x10^{-5})		Isothermal remanent magnetisation (IRM)					
						Hcr	Magnetite fraction			IRM, haematite fraction	
						(mT)		SIRM$_{mt}$	B1/2$_{mt}$	SIRM$_{hm}$	B1/2$_{hm}$
Unit	Locality	Mean	Range	Mean	Range		%	(A/m)	(mT)	(A/m)	(mT)
K	Punta del Viento	8	2.5-16	16	5-40	445	13	1.3	33.5	9.2	560
Ptr	Paganzo Village	4.5	2-9	30	10-90	245	24	1.4	25	4.5	316
Ptr	Las Mellizas Mine	20	0.5-800	15	4-65	310	38	4.5	63	7.5	501
P?	Paganzo Village	5	1-20	16	5-80	290	39	1.3	25	2	631
P	Up Los Colorados*	3.5	1-10	6	2-16	390	7	0.2	25	2.5	398
P	Las Mellizas Mine	2	0.5-5	8	3-10	600	5	0.2	25	5.1	708
P?	Punta del Viento	5	2.5-8	7	3-10						
C	Las Mellizas Mine	11	1-120	11	2-25	605	5	0.4	25	8	631
C	Lw Los Colorados*	38	10-100								
C	Punta del Viento	20	11-25	10	8-12	630	4	0.3	25	7.5	708

IRM results obtained with IRM-CLG 1.0 (Kruiver et al., 2001). %: percentage of SIRM carried by magnetite fraction; SIRM: Saturation isothermal remanent magnetisation; B1/2: field value at which half of the NRM is reached; Hcr: Remanent coercive force.

Unit: K: Ciénaga del Río Huaco Fm. (Cretaceous); Ptr: Talampaya Fm. (Permotriassic); P: Patquía Fm., Upper Member (Permian); C: Patquía Fm., Lower Member (Carboniferous).

* NRM values after Embleton (1970b).

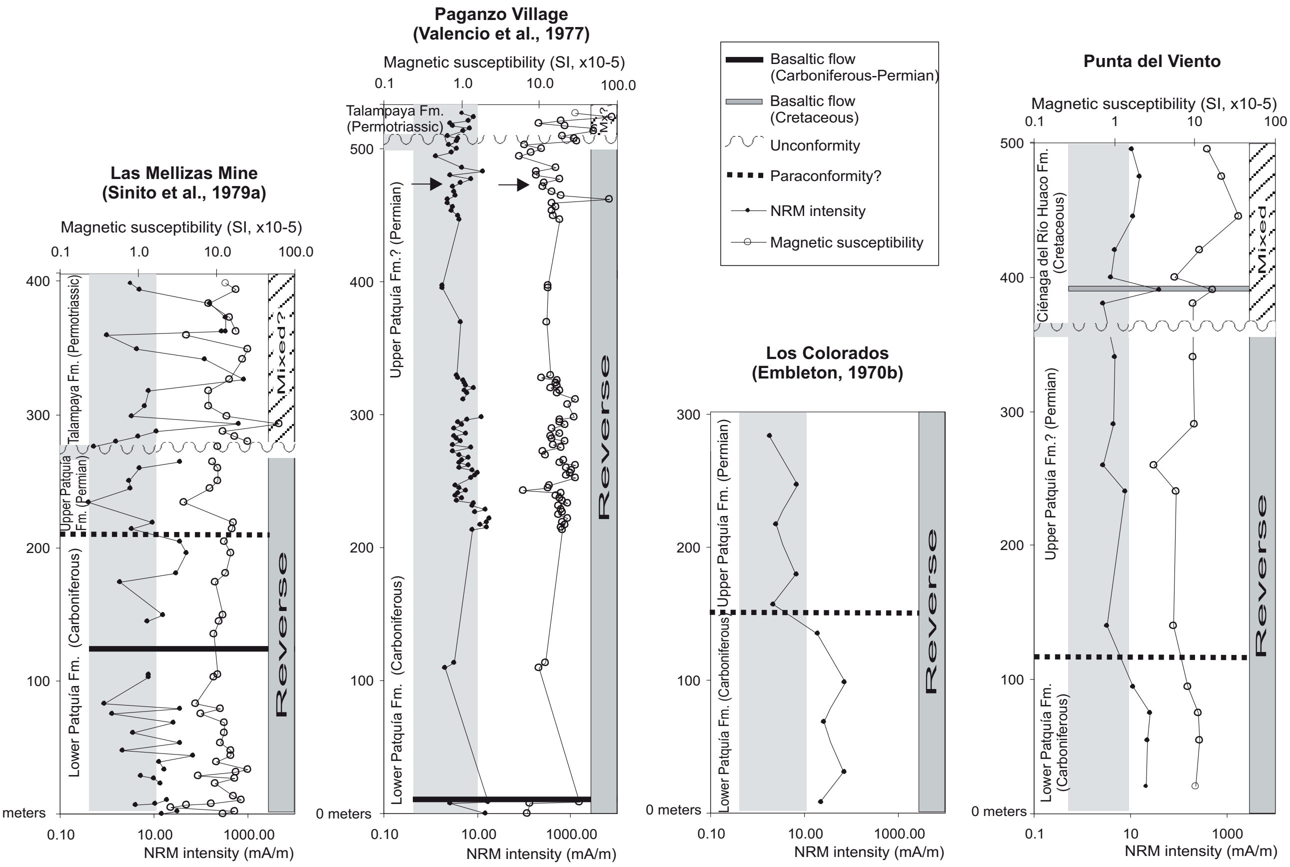

FIGURE 6 | **Curves of variation of natural remanent magnetization intensity and magnetic susceptibility along different sections in Patquía Fm. The column to the right indicates magnetic polarity (reversed or mixed). Arrows in the Paganzo Village section mark the level considered by Valencio et al. (1977) as the transition to the Permotriassic Talampaya Fm. NRM intensity values for Los Colorados section are an approximation based on mean values reported by Embleton (1970b).**

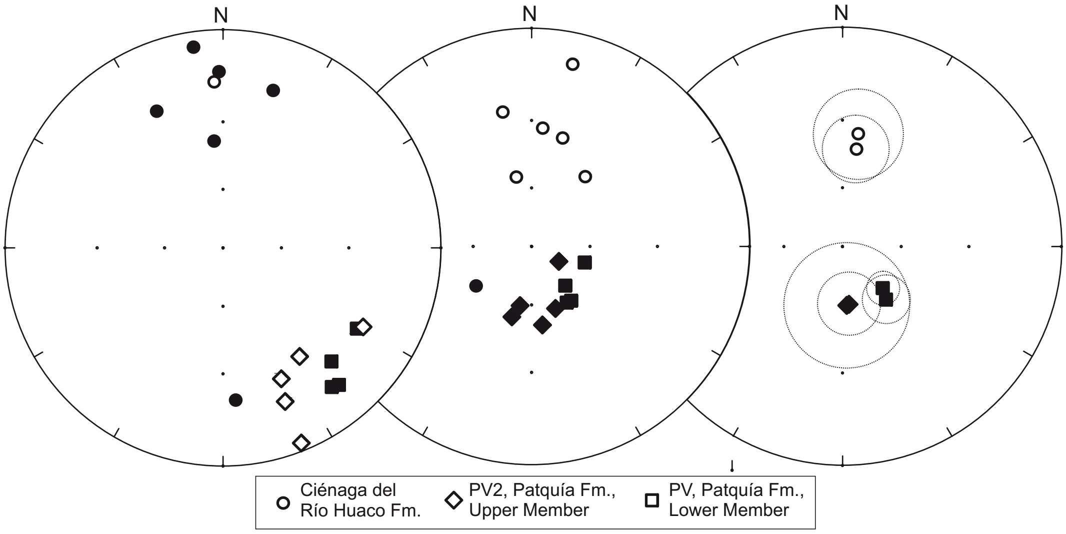

FIGURE 7 | **Site mean directions of the characteristic remanent magnetisation for units in Punta del Viento, before (left) and after (centre) structural correction to restore them to paleohorizontal. Different symbols are used for sites in Permian lower and upper sections (PV and PV2, respectively) and Cretaceous Ciénaga del Río Huaco Fm. The right panel shows the difference between results obtained from high-temperature components and 450ºC blanket cleaning for each of the three sampled sections. Full/empty symbol means positive/negative inclination. Wulf projection.**

stratigraphic meters above the basaltic flow), which they interpreted as the transition from the "Kiaman Magnetic Interval" (PCRS) to the Illawarra Zone of frequent polarity changes (Valencio et al., 1977).

Reverse polarity characterized all of the Patquía Fm. Samples above 6203-6204 became somewhat noisier, however the reversed polarity continues 30 more stratigraphic meters, up to samples 6237-6238, where clear polarity switching starts (see Valencio et al., 1977).

A revisit to Paganzo Village to compare field notes and outcrops allowed establishing that 25meters following the first reversal (28 reverse-polarity samples from 6205 to 6232) actually belong to Patquía Fm. The 6 meters-thick conglomerate marking the base of Talampaya Fm. was identified immediately under samples 6233-6234, 500meters above the basaltic flow (Fig. 6).

A careful study on magnetic properties of samples 6203-6204 is required to establish if the recorded normal polarity is actually due to a short reversal during the Permian. Notwithstanding it, paleomagnetic poles from Patquía and Talampaya Fm. in Paganzo Village need to be recalculated by moving the 28 reversed samples (6205-6232) from the latter to the former. This reduces the Talampaya results to a scattered population of 15 measured samples, characterized by intra-site inconsistency (Fig. 8A), perhaps due to an inadequate election of blanket cleaning; similar low quality results were reported by Sinito et al. (1979a) for Talampaya (formerly Amaná) Fm. in Las Mellizas Mine. No paleomagnetic pole can be calculated from this unit based on the analysed samples.

As for the Patquía Fm., we decided to recalculate the paleomagnetic pole based on site mean directions instead of samples. Seventy out of 79 sites showed good consistency between samples; three of them resulted in outliers directions (Fig. 8C). The final mean direction for the remaining 67 sites is Dec. 188.5º, Inc. 58.1º, $\alpha95$ 3.3º, k 28.1. The paleomagnetic pole is Lat. 77.9º S, Long. 260.1º, A95 4.3º, K 17.1. A representative paleomagnetic pole for this locality was obtained by combining these results with those provided by Thompson (1972) in both limbs of the anticline and from different samples (N=35, positive fold test). The combination was performed by using the McFadden and McElhinny (1995) method, and the results are shown in Table 3.

Las Mellizas Mine

Most of the section paleomagnetically sampled in Las Mellizas Mine belongs to the Lower Member of Patquía Fm. Ten samples were recovered from the Upper Member in the Corral Viejo section, but they showed very low intra- and inter- site consistency (Fig. 8B) and the magnetic directions were discarded. However, the NRM and SIRM properties of Corral Viejo were useful to compare with those from other localities.

The Talampaya Fm., unconformably lying on Patquía Fm., was also sampled by Sinito et al. (1979a) in Las Mellizas Mine. From the different bedding planes reported by the authors as used to perform the untilting of both units (strike and dip 52/13 for Talampaya Fm. and 1/18 for Patquía Fm.), a discordant relation between them can be deduced. Actually, both units show NE-SW strike and dip about 10-12º to southeast (Morelli, 1967); although Talampaya Fm. is indeed discordant on the top of Patquía Fm., the angle unconformity can only be detected regionally, because of the dissection of Patquía upper levels from one locality to another (Caselli, 1998; Caselli and Limarino, 2002). Locally both units dip equally, and the unconformity is marked by a basal conglomerate.

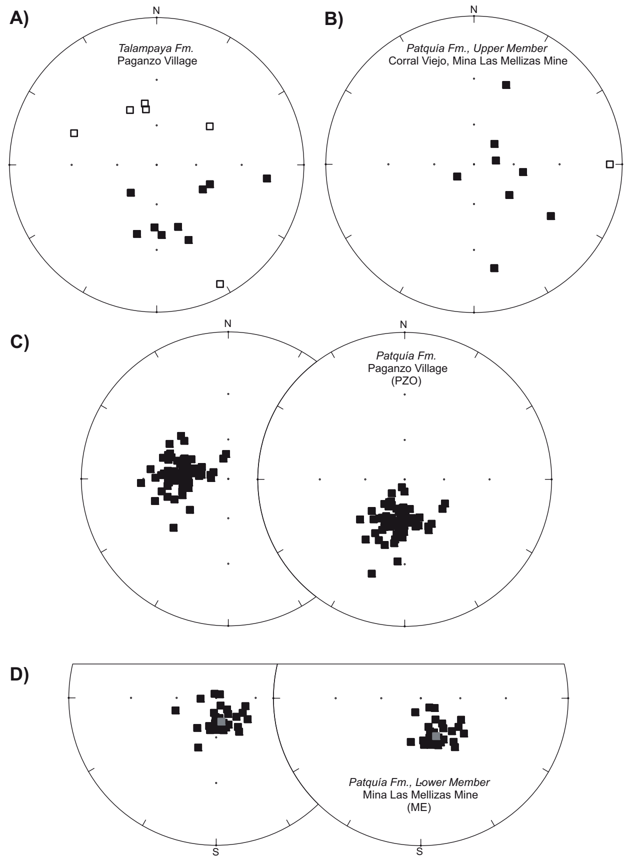

FIGURE 8 | **Directions of the characteristic remanent magnetisation for samples in Patquía and Talampaya (Amaná) Fm.; references as in figure 7, full/empty symbol means positive/negative inclination. A) Talampaya Fm. in Paganzo Village, obtained by Valencio et al. (1977) after structural correction to restore them to paleohorizontal. Once removed the sites actually belonging to the underlying Patquía Fm. from the original data, they are reduced to a scattered population. B) Upper Member of Patquía Fm., Corral Viejo section, Mina Las Mellizas Mine, obtained by Sinito et al. (1979a), after structural correction to restore them to paleohorizontal. C) Patquía Fm. in Paganzo Village obtained by Valencio et al. (1977), before (left) and after (right) structural correction to restore them to paleohorizontal (strike and dip 50/50). Data originally used by Valencio et al. (1977) at sample level were now averaged by site. D) Lower Member of Patquía Fm. in Las Mellizas Mine, obtained by Sinito et al. (1979a), before (left) and after (right) structural correction to restore them to paleohorizontal (strike and dip 53/13). Data originally used by Sinito et al. (1979a) at sample level were now averaged by site. Full/empty symbol means positive/negative inclination and the gray square is the mean direction for the basalt flow (Thompson and Mitchell, 1972).**

The untilting of Patquía Fm. around strike and dip 1/18 was therefore evaluated as incorrect. A new paleomagnetic pole was calculated based on site mean directions, and untilting by a bedding plane of 52/13, as reported for Talampaya Fm. Thirty-three out of 36 sites showed good consistency between samples and 3 of them resulted in outliers directions (Fig. 8D). The VGP obtained by Thompson and Mitchell (1972) from the basalt interbedded in the sequence agreed with VGPs from the red beds, and was computed as one additional site with unit weight. The final mean direction for the 31 sites is Dec. 155.8º, Inc. 60.3º, $\alpha95$ 3.9º, k 44.4. The paleomagnetic pole is Lat. 67.2º S, Long. 343.7º, A95 5.6º, K 22.6. This pole is in much better agreement with other coeval poles from South America (see Tables 3, 4).

DISCUSSION

The magnetisation isolated in different localities of Patquía Fm. red beds from Paganzo basin is shown in figure 9, *in situ* and referred to the palaeohorizontal. It is clear that magnetisation was acquired previously to the main deformation episode, which it is assumed to be the Andean Orogeny in Neogene times in this area. Unfortunately no other field test was able to be attempted for the remanence carried by the Permian red beds.

Figure 9 also shows that corrected mean directions define a streaked population. Two subpopulations can be distinguished, in close relation with the two members of Patquía Fm.

To analyse the meaning of the magnetic remanence and its noticed change, we have to recall that two magnetic components were determined in samples of Punta del Viento, both of them carried by haematite with different unblocking temperature spectra, and with directions departed by a small angle.

Turner (1980) identified three classes of magnetisation in red beds, reflecting progressive degrees of diagenetic alteration: Type A containing essentially a single component of magnetisation; Type B composite or multicomponent, acquired over a longer time interval, spanning at least one geomagnetic field reversal, and Type C due to a complete replacement of the original magnetisation due to the redistribution of pigmentary oxides long after deposition. The multicomponent character of Patquía Fm. remanence points to a Type B magnetisation, though it is clearly dominated by a high-temperature component that correlates well with geological transitions, and changes in magnetic mineralogy. This coincidence would be indicative of a primary remanence acquired early during diagenesis, but also

TABLE 3 | **Paleomagnetic (south) poles for Paganzo basin for the Late Paleozoic; poles recalculated in this work appear in italics. Punta del Viento poles are not included as they do not fulfill quality criteria to be considered as PPs, because of the low number of samples.**

Code	Age (Ma)	W	N	South American coordinates		African coordinates		Rock unit	FT	Pol.	Reference
				Lat S	Long E	Lat S	Long E				
CHL	251-274	250	21	-85.0	-64.0	-45.7	82.8	Río Chaschuil, Argentina	x	MX	GPMDB 166, 2723
CC	280-300	290	6	-79.3	290.6	-51.8	62.6	Cerro Colorado-Caminiaga, Argentina	F+	R	GPMDB 3618, 9158
DLC	280-300	290	6	-77.2	343.6	-41.5	65.9	De la Cuesta Fm., Famatina, Argentina	x	R	Spagnuolo et al. (2008)
CH	280-300	290	3	-85.2	358.6	-46.2	75.2	Chancaní Fm., Argentina	x	R	GPMDB 3618, 9157
LC2	280-300	290	27	-74.0	313.0	-45.8	56.3	La Colina Fm., Los Colorados Upper Beds, Argentina	x	R	GPMDB 166, 2721
PZO	280-300	290	102	-80.4	277.4	-53.9	65.1	La Colina Fm., Paganzo Village, Argentina	F+	R	Recalculated from Valencio et al. (1977), Thompson (1972)
LMP	280-300	290	53	-66.0	326.0	-37.8	50.5	Lowest Middle Paganzo	x	R	GPMDB 283, 3505
HU	300-315	310	9	-63.0	356.0	-27.5	60.2	La Colina Fm., Huaco anticline, Argentina	x	R	GPMDB 620, 3038
ME	300-315	310	31	-67.2	343.7	-33.8	57.8	La Colina Fm., Las Mellizas Mine, Argentina	x	R	Recalculated from Sinito et al. (1979a), Thompson and Mitchell (1972)
DSL	300-315 *a	310	8	-26.8	357.0	5.6	45	Del Salto Fm., Argentina	F+	R	Rapalini and Mena (2001)
LC	300-315	310	26	-59.5	357.5	-24	59.1	La Colina Fm., Los Colorados Lower Beds, Argentina	x	R	GPMDB 620, 3036
RB	300-320 *a	310	19	-75.0	291.5	-51.6	55.7	Río del Peñón & Punta del Agua Fm., Rincón Blanco, Argentina	F+	R	GPMDB 3618, 9156
MJ	304-312 *a	320	20	-47	210	-84.9	204.8	Majaditas Fm., Argentina	F+	MX	GPMDB 2320, 6044
BB	315-325 *c	320	25	-85.0	335.0	-47.5	73	Tupe Fm., Bum Bum Mine, Argentina	x	MX	GPMDB 166, 2720

* Results omitted from means as follows: a: Rotated block?, b: Poor statistical parameters, c: Discordant pole
W: Window age in Ma (as used in table 4)
FT Field tests: F: fold test, C: baked contact test, G: conglomerate test. +: positive, -: negative, ?: Indeterminate test
Pol.: Magnetic polarity, R: reverse, MX: mixed
Results taken from the Global Paleomagnetic Database (GPMDB) Ver. 4.6 (Feb 2005) following McElhinny and Lock (1996), with Reference number and Result number. Ages follow the timescale given in the GPMDB.

of a magnetisation acquired during a much later event of pigment redistribution, affecting discrete zones.

The geological meaning of the polar positions given by these units (Fig. 10) will be discussed by comparing them with paleomagnetic poles from South America and other plates forming Gondwana.

The Late Palaeozoic APWP for Gondwana

An apparent polar wander path (APWP) was constructed for Gondwana in the Late Palaeozoic, by using those paleomagnetic poles that have a Quality Index of $Q \geq 3$ following Van der Voo (1993). Poles from red beds in Paganzo basin (Fig. 10) were excluded, as they were used to calculate a separate APWP to compare with the Gondwana path. The selection made by McElhinny et al. (2003) was used as a starting point. As an additional constraint we decided not to use poles calculated from postectonic remagnetisations unless the age of the magnetisation was established by an independent method. Pre and syntectonic remagnetisations were not considered as well, given that no palaeohorizontal can be confidently established. Several poles coming from localities that were explicitly interpreted as rotated around vertical axes were also excluded, like Rincón Blanco Syncline (Geuna and Escosteguy, 2004), Del Salto Fm. (Rapalini and Mena, 2001), Majaditas Fm., Portezuelo del Cenizo Fm. (Rapalini et al., 1989), Choiyoi Gr (Rapalini et al., 1988) and Quebrada del Pimiento Fm. (Terrizzano et al., 2005). The following poles were discarded because of their poor statistical parameters, which might obey to multiple causes including undetected secondary components or problems with demagnetisation procedures: Itararé Subgroup, Piaui Fm., Rookwood Volcanics and Bulgonunna Volcanics (see Table 4 for references). Río Uruguay and Río Francia poles (Buggisch et al., 1993) were not included in the selection because sampling

TABLE 4 **Gondwana (south) paleomagnetic poles in NW Africa coordinates for the Late Paleozoic (370-250 Ma).**

Age (Ma)	N	Lat S	Long E	Rock unit	Field tests	Pol.	Reference
				Late Permian to Early Triassic (240-260)- 250 Ma			
240-260	35	-50.9	86.3	Komandodrifdam interval, Karoo basin, South Africa	G+	MX	De Kock and Kirschvink (2004)
250-260	11	-30.5	65.8	Gerringong Volcanics, Australia	x	R	GPMDB 995, 1852
242-256	6	-47.4	51.3	Mitú Gr., Bagua Grande, Perú	F+	MX	GPMDB 3524, 8959
250-260	10	-41.8	73.4	Independencia Gr., Paraguay	x	MX	Rapalini et al. (2006)
263 ± 5#	4	-45.6	56.1	Quebrada del Pimiento Fm., Argentina	x	MX	GPMDB 2648, 1205
263 ± 5# *a	7	-69.3	110.2	Quebrada del Pimiento Fm., Argentina	F+	MX	Terrizzano et al. (2005)
				Mid- to Late Permian (260-280)- 270 Ma			
256-266	4	-27.6	89.8	K3 beds, Songwe-Kiwira, Tanzania	x	R	GPMDB 324, 3448
267-276	10	-26.9	85.1	Permian Redbeds, Tanzania	F+	R	GPMDB 2736, 7104
275	24	-34.4	76.1	Tunas Fm., Argentina	F+	R	GPMDB 3293, 8459
230-270#*a	33	-58.3	288.5	Choiyoi Fm., Argentina	F+	R	GPMDB 2320, 6046
254 ± 10#	8	-39.8	64	Choique Mahuida Fm., Argentina	x	R	GPMDB 2649, 689
260-270#	16	-46.4	63.7	Tambillos Fm., Argentina	x	R	GPMDB 2475, 6376
275 ±	17	-69.6	249.1	Portezuelo del Cenizo Fm., Argentina	F+	R	GPMDB 2320, 6045
				Early Permian (280-300)- 290 Ma			
271-300	13	-29.1	57.8	Serie D´Abadla, upper unit, Algeria	x	R	GPMDB 1459, 685
271-300	11	-36	58	Djebel Tarhat Redbeds, Morocco	x	R	GPMDB 1080, 2037
271-300	45	-24	63.8	Chougrane Redbeds, Morocco	F+	R	GPMDB 723, 2279
271-300	12	-32.2	64.1	Taztot Trachyandesite, Morocco	x	R	GPMDB 723, 2280
271-300	11	-38.5	57.5	Serie D´Abadla, lower unit, Algeria	x	R	GPMDB 3275, 8422
271-307	4	-29	60	Chougrane Volcanics, Morocco	x	R	GPMDB 1859, 1618
276-307	7	-33.8	61.4	Lower Tiguentourine Fm., Algeria	x	R	GPMDB 2728, 7092
280 ± 2	8	-40.8	71.3	Jebel Nehoud ring complex, Sudan	x	R	GPMDB 3504, 8921
284-307	3	-38.7	56.8	Upper El Adeb Larache Fm., Algeria	x	R	GPMDB 2540, 6531
250-300 *b	9	-35	53.8	Rookwood Volcanics, Australia	x	R	GPMDB 3265, 8585
280-305	6	-29.9	66.7	Featherbed Volcanics, Australia	x	R	GPMDB 3266, 8412
283 ± 4	34	-33.7	68.6	Mt Leyshon Complex, Australia	C+	R	GPMDB 3531, 8966
287 ± 4	42	-39	65.4	Tuckers Igneous Complex, Australia	C+	R	GPMDB 3531, 8967
290-300	1	-25.3	59.9	Lower Marine Basalt, Australia	x	R	GPMDB 995, 1853
299 ± 6 *b	12	-31.2	70.9	Bulgonunna Volcanics, Australia	x	R	GPMDB 3330, 8531
260-280	60	-36.1	51.9	Floresta Fm., Sanfranciscana Basin, Brazil	x	R	Brandt et al. (2009)
280-295	9	-40.6	51.3	Copacabana Gr., Perú	F+	R	Rakotosolofo et al. (2006)
280-300#	10	-19.4	49.1	La Tabla Fm., Chile	x	R	GPMDB 1420, 597
				Late Carboniferous 2 (300-315)- 310 Ma			
300-315	6	-28.7	55.8	El Adeb Larache Fm., Edjeleh anticline, Algeria	F+	R	GPMDB 3484, 8867
307-312	10	-25.4	54.8	Lower El Adeb Larache Fm., Algeria	x	R	GPMDB 2540, 6529
307-326	5	-26.7	57.9	Sediments, Algeria	x	R	GPMDB 1794, 1470
310-318	11	-28.3	58.9	Ain Ech Chebbe Fm., Algeria	F?	R	GPMDB 1629, 1133
312-318	8	-28.2	55.5	El Adeb Larache Fm., Illizi basin, Algeria	x	R	GPMDB 3481, 8856
305-310	8	-30.3	57.4	Lark Hill Fm., Australia	F+	R	GPMDB 3463, 8822
310-315	5	-38.1	51.6	Rocky Creek Conglomerate, Australia	F+	R	GPMDB 3463, 8821
318 ± 3.4	3	-57.1	40	Peri Rhyolite, Australia	F+	R	GPMDB 3463, 8819
300-320 *b	12	-21.9	57.7	Itarare Subgroup, Brazil	x	R	GPMDB 798, 2369
300-320 *b	15	-19.2	47.4	Piaui Fm., Brazil	x	R	GPMDB 613, 3134
310-340 *c	16	-18	17.7	Tepuel Gr., Argentina	F+	R	GPMDB 2805, 7252

TABLE 4 | **Continued**

Age (Ma)	N	Lat S	Long E	Rock unit	Field tests	Pol.	Reference
				Late Carboniferous 1 (315-325)- 320 Ma			
290-320	22	-25	45	Dwyka System, South Africa-Tanzania-Zimbabwe	F+	MX	GPMDB 3489, 8894
299-318	9	-25.6	64	Abu Durba Sediments, Egypt	x	MX	GPMDB 2784, 7224
300-315	9	-26.6	44.7	Merkala Fm., Tindouf basin, Algeria	x	MX	Henry et al. (1999)
310-326	4	-28.4	56.9	Ain Ech Chebbi Fm., Reggane basin, Algeria	F+	MX	GPMDB 3402, 8653
315-325	11	-32.4	56.6	Djebel Reouina Fm., Tindouf basin, Algeria	x	R	Merabet et al. (1999)
315-326	2	-25	67	Ain Ech Chebbe Fm., Morocco	x	R	GPMDB 181, 3205
310-330	15	-34.4	42.7	Newcastle Range Volcanics, Australia	x	MX	GPMDB 3561, 9056
315 ± 5	13	-13.2	50.1	Connors Volcanics, Australia	x	R	GPMDB 3265, 8406
315-320	3	-13.5	45.2	Upper Clifden Fm./Lower Rocky Creek Conglomerate, Australia	F+	R	GPMDB 3463, 8818
				Early Carboniferous (325-340)- 330 Ma			
326-345	8	-7.6	52.5	Oued Draa Aftez Limestone, Morocco	x	R	GPMDB 1080, 2039
326-345	12	0.1	56.4	Djebel Hadid redbeds, Morocco	x	R	GPMDB 1080, 2040
326-360	4	-16.1	62.5	Basalts, diorite and contact, Morocco	C?	R	GPMDB 1080, 2038
310 ± 7 or 325 ± 6	33	-0.8	34.9	Bathurst Batholith, Australia	x	MX	GPMDB 3264, 8405
315-345 *c	1	-23.7	88.3	Percy Creek Volcanics, Australia	x	R	GPMDB 406, 1877
330-340 *c	3	-69.1	252.8	Yuendoo Rhyolite, Australia	F+	R	GPMDB 3463, 8816
				Latest Devonian - Early Carboniferous (340-360)- 350 Ma			
348 ± 8	12	-18.8	31.2	Tin Serririne intrusives	x	R?	Derder et al. (2006)
330-345	10	11.5	24.1	Mt Eclipse Sandstone, Australia	F+	MX	GPMDB 2866, 7471
340-370 *c	18	-39.1	33.3	Achala Batholith, Argentina	R+	MX	Geuna et al. (2008)
				Late Devonian (360-380)- 370 Ma			
360-375	3	-19.2	19.8	Beni-Zireg Limestones, Algeria	F+	R	GPMDB 2521, 6480
360-375	8	-4	3.6	Hervey Group, Australia	F?	MX	GPMDB 1579, 1031
360-375	13	-17.2	7.3	Worange Point Fm., Australia	F+	MX	GPMDB 2191, 5722
360-375	8	3.6	14	Brewer Conglomerate, Australia	F+	MX	GPMDB 2726, 7089
360-380	10	-11.6	4.2	Canning Basin Reefs, Australia	G+	MX	GPMDB 2942, 7659
360-385	7	1.7	11.9	Canning Basin Reefs, Australia	x	MX	GPMDB 1345, 452
370-390 *c	7	-40.8	338.4	Retreat Batholith, Australia	x	MX	GPMDB 3622, 9162

References as in table 3.
Gondwana margin, central western Argentina and Chile, means calculated separately (see Table 5).

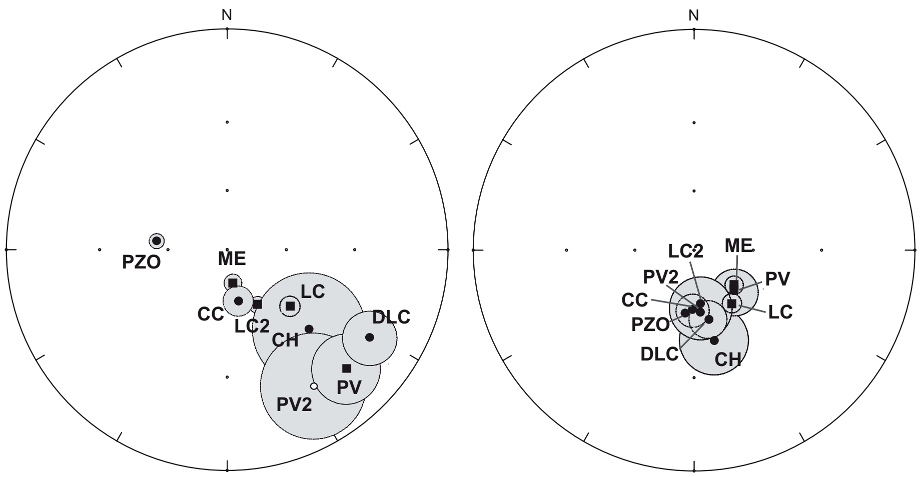

FIGURE 9 | **Locality mean directions of the characteristic remanent magnetisation for the Patquía Fm., before (left) and after (right) structural correction to restore them to paleohorizontal. The circle of confidence at 95% level (α_{95}) for each direction is shown. Lower/Upper Member directions as squares/circles. Locality codes as in table 3, symbols as in figure 7.**

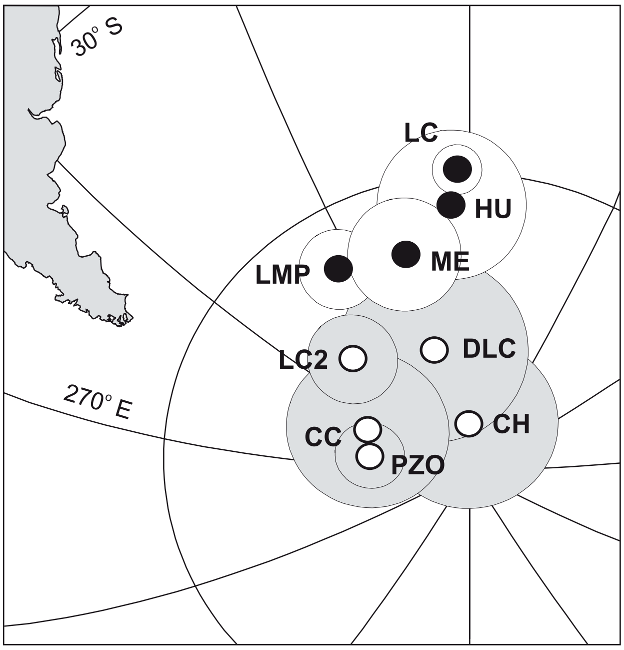

FIGURE 10 | **Paleomagnetic (south) poles of Patquía Fm. and equivalents in the Paganzo Basin, including A_{95} confidence circles. Locality codes as in table 3; Lower/Upper Member poles in black/white, with their confidence circles in white/gray colour. Schmidt-type projection.**

spanned from Middle Carboniferous to Permian rocks with no discrimination between them.

Some poles do not agree with those of similar age and were excluded from the means; that was the case for Retreat Batholith, Percy Creek Volcanics, Yuendoo Rhyolite, Tepuel Gr, and Achala Batholith (see table 4 for references). The disagreement might be explained as due to not having averaged the palaeosecular variation (for volcanics) or incorrect assessment of the palaeohorizontal (especially for plutonic rocks, but a critical point for every paleomagnetic study, as discussed before for Las Mellizas Mine). Also Bum Bum Mine pole disagrees, probably due to an undetected rotation or remagnetisation (see discussion in Geuna and Escosteguy, 2004), and was therefore excluded.

Table 4 summarises all the Palaeozoic pole positions from the Gondwana continents, given in NW Africa coordinates according to the reconstruction parameters of Lawver and Scotese (1987).

The poles were grouped in fixed 20Ma windows, following the ages proposed for the geological units and consequently for the acquisition of the primary remanences. Mean pole positions were calculated using the method of combining groups of poles of McFadden and McElhinny (1995). The method enables the mean pole position to be calculated from m pole positions where the poles are derived from widely different numbers of sites (N), therefore weighting the data according to N. The main drawback is that many of the poles have poorly constrained dating within intervals of 30Ma or greater, making difficult the discrimination of age groups. These poles were arbitrarily assigned to either one or other window based on similarity with the remaining poles. For example, the Early Permian

TABLE 5 | **Late Paleozoic APWP for Gondwana obtained from the data listed in Tables 3 and 4.**

				Pole in African coordinates		Pole in South American coordinates		
Age (Ma)	m	N	K	Lat. °S	Lon. °E	Lat. °S	Lon. °E	A95 (°)
250	4	62	9.8	-46.1	76.3	-85.4	7.4	6.1
270	3	38	63.4	-31.8	80.1	-71.7	37.9	2.9
290	15	266	21.5	-33.9	60.9	-68.8	349.2	1.9
310	8	68	30.0	-28.8	55.9	-62.2	347.5	3.2
320	9	88	13.6	-26.1	55.6	-59.8	350.0	4.2
330	4	57	10.8	-2.7	43.7	-33.8	351.6	6.0
350	2	22	15.1	-5.1	27.9	-27.7	334.4	8.2
370	6	49	20.7	-7.9	8.6	-18.3	315.9	4.6
				Southwestern South America paleopoles (mainly Paganzo basin)				
250	2	28	14.5	-51.9	86.7	-85.1	150.1	7.4
270	2	24	24.0	-44.2	63.8	-77.8	329.4	6.2
290	7	207	14.0	-46.8	58.6	-75.8	311.7	2.7
310	3	66	30.2	-29.1	58.6	-63.7	351.6	3.2

Means are calculated using the method of McFadden and McElhinny (1995) for combining groups of poles. m is the number of poles; N is total number of sites; k is the estimate of Fisher (1953) precision parameter; A95 is the radius of circle of 95% confidence about the mean pole position.

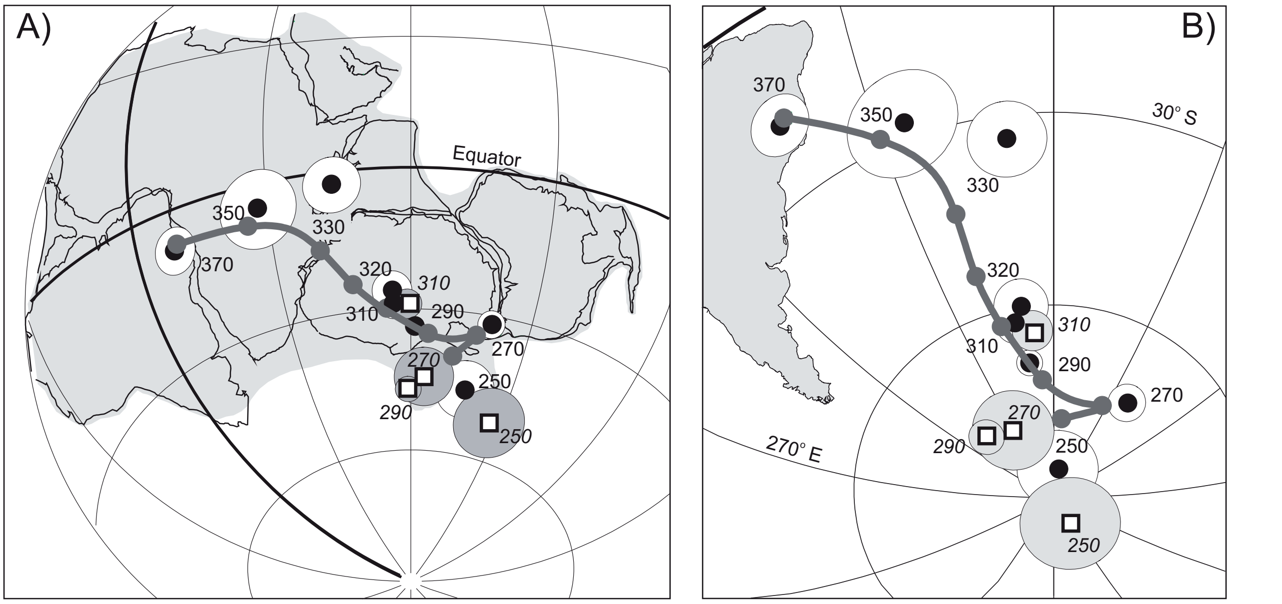

FIGURE 11 | **Apparent polar wander path obtained from selected poles from Gondwana. Black circles with white confidence cones: 20 Ma averaged windows; grey circles connected by grey lines: spline smoothed APWP (smoothing 50), data weighted according to age uncertainty. Numbers are ages in Ma. Paganzo basin mean poles are also shown as white squares. A) In African coordinates and B) In South American coordinates, using Lawver and Scotese (1987) reconstruction parameters. Schmidt-type projection.**

Floresta pole (Brandt et al., 2009) was placed at 290 Ma instead of 270 Ma as the loose age constraints allowed for it, and it was closer to other South American 290 Ma poles like Copacabana.

In some cases we used the auxiliary criterion of magnetic polarity, assuming that mixed polarity should be assigned either to pre 310 Ma or post 270 Ma windows. An additional window of 320 Ma was created to group many poles with geological age 320-300 (initially belonging to window 310 Ma) and very close to the 310 Ma mean, but with mixed polarity, what indicates they were magnetized immediately before the beginning of the PCRS (about 315 Ma; e.g., Dwyka System, Opdyke et al., 2001). For example, the mixed-polarity poles Bum Bum Mine (Late Carboniferous) and Majaditas Fm. (Late Carboniferous) were assigned to the pre-PCRS 320 Ma window; on the other side, mixed polarity poles Quebrada del Pimiento (K-Ar 263 ± 5 Ma,) and Río Chaschuil (Late Permian) were placed in the post-PCRS 250 Ma window. The K-Ar 254 ± 10 Ma for Choique Mahuida pole was considered a minimum age and the pole included in the 270 Ma window, due to its exclusive reverse polarity. Only poles calculated from all-reverse remanences were included in windows 310, 290 and 270 Ma corresponding to the PCRS.

The mean pole positions for each window are listed in table 5 in NW Africa and South America coordinates (Fig. 11). The mean poles for Paganzo basin are listed separately. Wider confidence cones for mean poles of ages higher than 320 Ma reflect the scarcity of data and the uncertainty in the age assignment; for example, none of the poles in the 330 Ma window reported field tests, and only one of the poles shows mixed polarity. No high quality paleomagnetic poles from South America appear in the windows 350-320 Ma.

An alternative approach to deal with ambiguities in assignment to fixed windows was to apply a spline smoothing to all of the poles, weighting data according to their age uncertainty. The agreement between the 20Ma-windows and the smoothed APWP obtained this way (Fig. 11) is acceptable, the outstanding exception being the 330 Ma window, reflecting the uncertainty discussed before.

The resulting Gondwana APW can be described in terms of linear segments and hairpins with geological significance, having in mind that movement described by paleomagnetic poles does not include the longitudinal component, but only latitudinal changes and rotations.

According to the obtained APWP, Paganzo basin in South America would have moved to the north during the Lower Carboniferous and up to ~ 330 Ma, in coincidence with the contraction of the Rheic Ocean that would culminate with the continental collision between NW Gondwana and south-eastern Laurentia at around 320 Ma (McElhinny et al., 2003).

A rapid counter clockwise rotation follows between 330 and ~ 320 Ma probably linked to the movement of Gondwana closing the Palaeotethys Ocean, though it is highly speculative because of the low quality of 350-330 Ma means. Conversely, there is no doubt of Gondwana having slowed down in terms of rotation or latitudinal movement from 320-300 Ma (Oviedo and Vilas, 1984).

Between 300-250 Ma the counter clockwise rotation resumes. A component of northward movement is indicated by the 270 Ma Gondwana pole; however, this mean is based on three poles calculated on red bed sequences, two from Africa (K3 beds in Tanzania) and one from South America (Tunas Fm.). Shallowing inclination could be an alternative to explain the apparent movement of Gondwana to lower latitudes depicted by these poles. The 250 Ma pole is based in just four poles with loose agreement among them; further research is needed to better precise this position.

The Paganzo basin paleomagnetic poles

Two mean poles were calculated from Paganzo basin coinciding with the two members of Patquía Fm., grouped in windows of 310 and 290 Ma for Lower and Upper Member respectively (Table 5). No 270 Ma poles were obtained in the eastern sector, as that was the time of basin inversion and a hiatus exists. Instead we calculated the mean of two 270 Ma poles on volcanic-volcaniclastic units from the western sector (Choiyoi Gr, Tambillos and Choique Mahuida Fm., see Table 4). Only the Río Chaschuil pole represents the 250 Ma interval, i.e. the post-PCRS, Permotriassic sedimentary sequences following Paganzo Group deposition and Late Permian inversion.

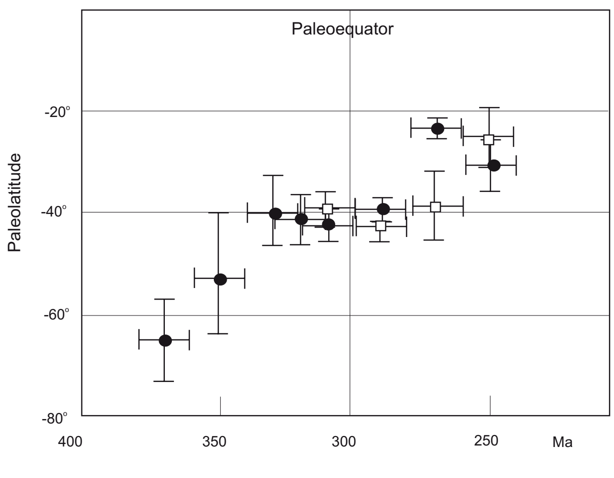

FIGURE 12 | **Diagram of latitude versus geologic time for the Paganzo basin according to the Late Paleozoic Gondwana and Paganzo poles. Horizontal and vertical bars indicate, respectively, the errors in age and paleolatitudes determinations. Black circles for Gondwana, white squares as deduced from Paganzo poles.**

While 310 Ma pole from the Patquía Lower Mb fits very well with the coeval pole for the rest of Gondwana, there is a clear misfit in the 290 Ma Upper Member pole (Fig. 11). The 270 Ma Paganzo pole calculated on Choiyoi Gr is also discordant, and resembles the older 290 Ma pole (Fig. 11). Coincidence with the APWP of the rest of Gondwana is again reached by 250 Ma (Permotriassic).

The Paganzo poles would indicate a rapid counter clockwise rotation of 30º at constant latitude of 40º for the basin (Fig. 11, 12); the movement occurred after the Lower Member of Patquía Fm. acquired its magnetisation but before the Upper Member did, supposedly between 310-290 if the acquisition occurred early during diagenesis.

Previous contributions attempted to explain the difference between poles of the two members of Patquía Fm. appealing to rotations around vertical axes, related to Andean deformation (Geuna and Escosteguy, 2004), or to incorrect age assignments or remagnetisations (Tomezzoli, 2009). A discussion on these hypotheses follows, in the light of available geological data.

Vertical-axis local rotations

Local rotations cannot explain the fact that both directions were recovered from an only continuous outcrop in Los Colorados, as it was already pointed out by Sinito et al. (1979b). Moreover, the basaltic flow interbedded in the Lower Member of Patquía Fm. in Paganzo Village and Las Torres (next to Las Mellizas Mine) was sampled in both localities by Thompson and Mitchell (1972) to calculate an only VGP based in 17 samples. The resulting VGP showed good statistical parameters and was coincident with the VGPs from the red beds surrounding it in Las Mellizas Mine (Fig. 8D). Not only is the vertical axis rotation hypothesis rejected based on the volcanic VGP, but also the possibility of shallowing inclination in the red beds.

Remagnetisation

An extensive remagnetisation of "Kiaman" age was documented by Rapalini and Tarling (1993) and Rapalini et al. (2000), affecting Lower Palaeozoic limestones of the Precordillera, as well as Ordovician ophiolites of the Alcaparrosa Formation. Recently its effects have been reported as far as in Proterozoic rocks of the Río de la Plata craton, in Uruguay (Rapalini and Sánchez Bettucci, 2008). This regional remagnetising event was tentatively linked to the migration of orogenic fluids during the SROP (Rapalini and Astini, 2005).

Tomezzoli (2009) invoked remagnetisation as one of the reasons for the discrepancy of supposedly Permian paleomagnetic poles from southern South America, and decided to compute them as Triassic poles, based on the position of the PPs in the proposed APWP.

The all-reversed remanence points to the PCRS as the moment of remagnetisation of Patquía Fm. This hypothesis is favoured by the coincidence of younger 270 Ma poles from the Choiyoi group in the same position. It is worth to note that a Late Permian unconformity truncates Permian sequences and marks the base of the Mesozoic over most Western Gondwana (Williams, 1995; Fernández Seveso and Tankard, 1995). The unconformity was attributed in western South America to the Amanaica Orogenic Phase (Aceñolaza and Toselli, 1981, Limarino et al., 1988), equivalent in age to SROP according to the new U-Pb dating (Gulbranson et al., 2008, 2010). Also many palaeosurfaces have been interpreted as of Gondwanian age (Rabassa et al., 1996). This makes a suitable scenario for widespread remagnetisations below long-lived surfaces, especially affecting lithologies more prone to fluid circulation, like aeolian facies in the upper Patquía Fm.

The upper section of Patquía Fm. differs from the lower one in being deposited in aeolian-evaporite environments, due to aridisation in the basin coeval with the inception of widespread volcanism in the western fringe of South America. Caselli and Limarino (2002) showed a change in the original mineralogy of sediment, with higher supply of lithic fragments and a shift to less mature assemblages. This should be added to a change in textures linked to the different depositional environment, and to warm arid climate favouring long-continued alteration. The high porosity shown by the aeolian interval, when compared with the fluvial sediments that form the Lower Member, could have favoured the redistribution of haematite by diagenetic solutions.

In the case haematite coating was responsible for the magnetisation, the upper section would be a good candidate for a "Type C" magnetisation (in the sense of Turner, 1980) acquired long after deposition, during a late stage of diagenesis/redistribution of haematite pigment. The multicomponent character for the remanence in Punta del Viento is an evidence of significant amount of time elapsed during the process of remanence acquisition.

Whatever the process affecting haematite in Upper Patquía Fm., it does not affect the overlying Amaná-Talampaya Fm., which shows a characteristically noisy magnetic signature, and incomplete oxidation of magnetite. If the remagnetisation hypothesis is to be accepted, it is reasonable to think it happened during the hiatus from ~253 - ~275 Ma, before deposition of the Amaná-Talampaya Fm. It means magnetisation was acquired when the Upper Patquía Fm. was virtually in horizontal position, as Permotriassic beds deposited in very-low-angle unconformity on it.

The hiatus represented by the Amanaica unconformity is contemporaneous with the end of the PCRS (267 Ma after Menning, 1995), which would be a good explanation for the all-reverse polarity isolated in the (remagnetised?) Upper Patquía Fm.

The remagnetisation hypothesis does not explain the discrepancy between Paganzo's and South American poles, though. The Upper Patquía Fm. pole falls in a position younger than the 250 Ma pole for Gondwana. Further research is needed to establish more precise and confidently the position of Gondwana 250 Ma pole. Meanwhile, and accepting the position calculated in Table 5 as valid, the Upper Patquía Fm. pole still represents a discordant position respect to the rest of Gondwana (Fig. 11), even if the magnetisation was acquired as a product of regional remagnetisation at ~ 260 Ma (not younger than 252 Ma, the age of a tuff in the overlying Amaná-Talampaya Fm.).

The paleomagnetic pole for the Upper Member of Patquía Fm. still can be interpreted as due to a primary magnetisation (acquired during early diagenesis, close to 290 Ma). It can also be due to a secondary magnetisation at about 260 Ma (not younger than 252 Ma), as discussed before. In any case, the pole is robust because: 1) it has a control on palaeohorizontal given by deposition of the overlying Amaná-Talampaya Fm., 2) the coincidence of magnetic remanence in red beds and the interleaved basaltic flow supports the absence of shallowing inclination, 3) rotation about vertical axes can be discarded as both groups of magnetic directions appear in the same section in two localities, named Los Colorados an Punta del Viento and 4) the coincidence of magnetic remanence directions coming from localities all around the basin is excellent (Fig. 9). This means that this pole can be confidently used to evaluate the tectonic displacements in the area of Paganzo basin respect to South America, as the two possibilities of age assignment would modify the velocity/timing of the movement, but not the sense.

Apparent polar wander (APW) for the western margin of South America including Paganzo basin vs. APW for Gondwana

Polar wander was already proposed for the whole West Gondwana by Oviedo and Vilas (1984), based on the grouping of all-reverse poles around an approximate direction Long. 300ºE, Lat. 80ºS (in South American coordinates). Rapalini and Vilas (1991, 1996) suggested a relationship among this period of fast APW, oblique convergence in the western margin of South America, tectonic rotations, and the SROP. If we accept as valid the 270-250 Ma poles for the rest of Gondwana (Fig. 11), then the paleomagnetic record in Paganzo represents a movement southwards and counter clockwise of the western margin of South America relative to the rest of Gondwana between 300-290 Ma (or 300-270 if remagnetisation is accepted). The relative movement would be reversed later, between 270 and 250 Ma, completing a cycle of opening-closure between the involved blocks.

If we do not accept the 270-250 Ma pole for the rest of Gondwana, then the position of Gondwana relative to Paganzo cannot be ascertained. The whole Gondwana might have moved together as marked by Paganzo poles. When transferred to South American coordinates, the Laurentia APWP (after McElhinny and McFadden, 2000) reflects a similar but delayed path, with Laurentia rotating slowly between 280 and 240 Ma (Fig. 13). The south-western margin of South America might have moved counter clockwise respect to the rest of Pangaea between 310-270 Ma, to be later caught up by Pangaea rotating at its time, between 250-220 Ma. Klootwijk (1979), Oviedo and Vilas (1984) and Rapalini and Vizán (1993) among others, proposed continental movements scenarios to explain the Early and Late Permian Paganzo paleomagnetic poles, assuming they were representative for the movement of Western Gondwana, and contrasting them with Eastern Gondwana poles. Unfortunately there are no high-quality poles for Eastern Gondwana for these critical periods, reported up to now.

The shifting in the Paganzo poles between 310 and 270 Ma coincides with San Rafael Orogeny, manifested as an event

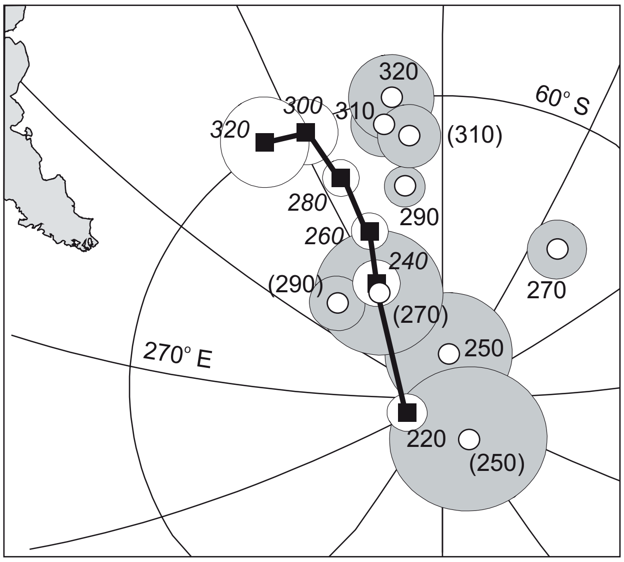

FIGURE 13 | **Comparison of the apparent polar wander path for Gondwana as in Fig. 11B, with the APWP for Laurentia after McElhinny and McFadden (2000), transferred to South American coordinates using the reconstruction parameters for Pangaea B as given by Vizán and Van Zele (2007). Numbers are age poles in Ma. Gondwana poles as white circles, Paganzo poles with ages in brackets. North American poles as black squares. Schmidt-type projection.**

of NNE (in present coordinates) shortening and regional sinistral transpression affecting central-western Argentina (Kleiman and Japas, 2009). Transpression lasted most of the Permian, presumably from 281 to 265 Ma, migrating to the SW to become linked to Gondwanide Orogeny in the Cape Fold Belt in South Africa (Kleiman and Japas, 2009). Crustal shortening and thickening, probably associated with a high geothermal anomaly (Llambías and Sato, 1990), was accompanied by widespread remagnetisation of carbonate and siliciclastic rocks in Precordillera (Rapalini and Tarling, 1993; Rapalini et al., 2000; Rapalini and Astini, 2005) and the Gondwanide orogen (Tomezzoli et al., 2006), and with large crustal block rotations in the Cordillera Frontal and westernmost Precordillera (Rapalini and Vilas, 1991). San Rafael orogeny was followed by an extensional (transtensional) period due to mechanical relaxation related to orogenic collapse (Llambías and Sato, 1995), characterized by voluminous rhyolitic volcanic rocks and granites in central western Argentina (Choiyoi Volcanic Province); transtensional phase began about 265 Ma in western Argentina (Kleiman and Japas, 2009). The whole Permian cycle of transpression-transtension was attributed to changes in the continental margin trend and/or in the direction of convergence (Kleiman and Japas, 2009), either of those factors probably linked to the collision of terranes in the southwestern end of Gondwana (Deseado terrane, Pankhurst et al., 2006; Patagonia, Ramos, 2008).

The modelling of continental movements clearly requires more constraints from confident paleomagnetic poles coming from geographically distributed localities. It is clear that Pangaea configuration in the Late Palaeozoic-Early Mesozoic was very far from rigid and static, but geological and paleomagnetic data point to a dynamic Pangaea model subjected to repeated fragmentation, opening and closure of seaways, active convergence/subduction and even intracontinental megashear (e.g. Morel and Irving, 1978; Irving, 1983; Ricou, 1995; Muttoni et al., 1996, 2003; Vai, 2003). Patquía Fm. palaeopoles are just one more piece to solve the puzzle in the south-western margin of South America.

CONCLUSIONS

The sequence of Carboniferous-Permian red beds sampled in Punta del Viento, Sierra de Umango, showed the classical magnetic behaviour for red beds, with haematite as the nearly exclusive magnetic mineral. That was not true for younger red beds in the area, as magnetite appeared as an additional carrier of remanence in Permotriassic and Cretaceous sections.

A multicomponent behaviour characterised the red beds; however, the NRM was dominated by a high-temperature

ChRM which could be easily separated. Even blanket cleaning at 450ºC was capable to resolve this component with enough confidence, what makes old paleomagnetic studies still useful. Poles from Paganzo Village and Las Mellizas Mine were recalculated based on new geological data.

A pattern of changes in the magnetic properties was observed, especially in the intensity of NRM and SIRM, which was correlated with lithological changes; the Upper Member of Patquía Fm., mainly aeolian-evaporite facies, showed systematically lower NRM and SIRM than the fluviatile Lower Member.

The Lower Member of Patquía Fm. provided paleomagnetic poles that were coincident with the reference APWP for the Late Palaeozoic of Gondwana, while the poles from the Upper Member did not agree with it.

Aeolianites from the Upper Member might have been a less faithful recorder of the geomagnetic field, as this lithology was more susceptible to redistribution of pigmentary oxides in porous sandstones. The different lithology of the Lower Member made it more suitable to complete its diagenesis earlier and to record the Late Carboniferous geomagnetic field.

Even if the Upper Member of Patquía Fm. is interpreted as remagnetised, the absence of remagnetisation in the overlying Amaná-Talampaya Fm. constrains the age of the remagnetisation to no younger than 252 Ma, coincident with a widespread remagnetisation reported in Precordillera by Rapalini and Tarling (1993) and possibly linked to the SROP. The paleomagnetic pole is still discordant with the Gondwana APWP, even considering a remagnetisation. Although Gondwana APWP is far from complete, at the present level of knowledge the Paganzo poles could be interpreted as recording a counter clockwise and southwards movement for the region respect to the rest of Gondwana, between 310-270 Ma, coeval with the transpressional event regionally linked alternatively to SROP and Gondwanide Orogeny. Palaeolatitude of Paganzo basin would have stayed constant at about 40º during all that time.

ACKNOWLEDGMENTS

This work was partially financed with research grants by ANPCyT (PICT 1074), and CONICET (PIP 1502). Argentine Geological Survey (SEGEMAR) provided assistance in the fieldwork. L. Fauqué contributed to the selection of the sites. R. Siqueira, D. Clark, P. Schmidt and M. Huddleston kindly helped during the laboratory work in Sao Paulo and North Ryde. SuperIAPD and GMAP programs were utilized in the analysis of paleomagnetic data and palaeoreconstructions, respectively. Comments by B. Henry, P. Schmidt and M. Garcés have contributed to substantially improve the original manuscript.

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Manuscript received July 2009;
revision accepted November 2009;
published Online July 2010.