Gondwana Research, V. 7, No. 4, pp. 1089-1104.
© 2004 International Association for Gondwana Research, Japan.
ISSN: 1342-937X

GR Gondwana Research

First Late Ordovician Paleomagnetic Pole for the Cuyania (Precordillera) Terrane of Western Argentina: a Microcontinent or a Laurentian Plateau?

Augusto E. Rapalini[1]* and Carlos A. Cingolani[2]

[1] *INGEODAV, Depto. Cs. Geológicas, Fac. Cs. Exactas y Naturales, Universidad de Buenos Aires-CONICET, Pabellón 2, Ciudad Universitaria, Buenos Aires, C1428EHA, Argentina*

[2] *CIG – Depto. Geología, Univ. Nac. La Plata, calle 1 n. 644, 1900-La Plata, Argentina*

* *Corresponding author: E-mail: rapalini@gl.fcen.uba.ar*

(Manuscript received August 30, 2003; accepted February 15, 2004)

Abstract

Time and tectonic processes involved in docking of the Argentine Precordillera (Cuyania terrane) against SW Gondwana has been a matter of much debate. A paleomagnetic study on the Early Caradoc Pavón Formation, exposed in the San Rafael block, province of Mendoza, Argentina, is presented. After detailed thermal and alternating field demagnetizations two geologically significant magnetic components were defined. A widespread post-tectonic component (A) is present in most sites of the Pavón Formation, with dual polarities, and is coincident with the characteristic remanence isolated from a Permo-Triassic rhyolitic dome intruding the sediments. Its pole position (83.7°S, 271.0°E, dp = 6.8°, dm = 9.0° N = 11 sites) falls on the Late Permian–Early Triassic South American reference poles suggesting that this component was acquired during the Choiyoi magmatic phase. A second component (B) also shows dual polarities and a positive fold test suggesting a primary origin. Unblocking temperatures and rock magnetic experiments indicate that B is carried either by hematite or magnetite at different sites. Anisotropy of magnetic susceptibility results suggest a depositional fabric and no remanence distortion due to deformation or compaction. A paleomagnetic pole computed from this remanence (PV) falls on 3.6°N, 346.4°E (dp = 2.9°, dm = 4.6° n = 22 samples). It indicates a paleolatitude around 26°S for deposition of Pavón sediments and constrains the paleogeographic evolution of Cuyania during the Ordovician, which was still at subtropical latitudes by the Early Caradoc. PV is consistent with the Laurentian Late Ordovician reference pole if Cuyania remains attached to SE Laurentia for the Early Caradoc, while it shows a significant cw rotation with no paleolatitude anomaly respect to the Gondwana reference pole when kept in its present position in SW South America. These comparisons are interpreted in three possible alternatives for the paleogeographic and tectonic setting of Cuyania in the Late Ordovician.

Key words: Paleomagnetism, Precordillera, Laurentia, Gondwana, Ordovician.

Introduction

The Argentine Precordillera has been interpreted as an Early Paleozoic Laurentian derived exotic terrane (e.g., Dalla Salda et al., 1992; Benedetto, 1993, 1998; Astini et al., 1995; Mahlburg Kay et al., 1996; Thomas and Astini, 1996; Dalziel, 1997; Keller et al., 1998). Ramos (1995) proposed that the Precordillera is part of a larger composite terrane that he named "Cuyania", and that includes the San Rafael Block and the Pie de Palo Range in the Western Sierras Pampeanas. All these areas are characterized by Grenvillian-age basement, which is consistent with the age of basement xenoliths in Tertiary volcanics in the Precordillera itself (Mahlburg Kay et al., 1996). Most authors agree in that Cuyania most likely originated from the Ouachita Embayment of North America. In particular, paleomagnetic data from the Early Cambrian Cerro Totora Formation (Rapalini and Astini, 1998) strongly support that origin. However, there are models that interpret the origin of the Precordillera to be autochthonous (Gonzalez Bonorino and Gonzalez Bonorino, 1991) or that it represents a parautochthonous displaced terrane (Baldis et al., 1989; Aceñolaza et al., 2002). This includes recent U-Pb ages from detrital zircons (Finney et al., 2003), interpreted as evidence in favour of an Early Gondwanan provenance, although these data has become invalid due to an error in the original labeling of the samples (Finney et al., 2004). In any case, Astini and Rapalini (2003) have argued that there is no serious challenge yet to the Laurentian-derived hypothesis.

Much less consensus exists, however, on how this terrane was transferred from Laurentia to Gondwana and the timing of its accretion. Basically, three different tectonic scenarios have been postulated for the transference of Cuyania. The first was postulated by Dalla Salda et al. (1992) and implied a continental collision between Laurentia and Gondwana in mid- (Late?) Ordovician times, followed shortly after by a separation leaving the Laurentian Precordillera attached to Gondwana as a tectonic tracer (Dalziel, 1993) of such collision. This hypothesis has been refuted, mainly on the basis of its incompatibility with the biogeographic evolution that suggests a progressive separation of Cuyania from Laurentia during Cambrian and Ordovician times and lack of mixture of Laurentian and Gondwanan faunas in mid-Ordovician times (e.g., Benedetto, 1998). Furthermore, Thomas et al. (2002) recently has also postulated that main Ordovician orogenesis in Eastern Laurentia (Taconic) and western South America (Ocloyic) is not coetaneous. A second model was proposed by Astini et al. (1995) and subsequently refined by numerous contributions (e.g., Thomas and Astini, 1996, 1999, 2003; Thomas et al., 2002; Astini, 1998; Benedetto, 1998; Benedetto et al., 1999), which basically proposes that the Cuyania terrane rifted apart from the Ouachita Embayment in the Early Cambrian and was transferred as a microplate across the Iapetus Ocean during Cambrian and Ordovician times to become accreted to the western South America (South-western Gondwana) margin. Cañas (1999) has suggested that instead of Early Cambrian, separation of Cuyania from Laurentia did not occur before the Early Ordovician. The Astini et al. (1995) model is compatible with the biogeographic evidence as well as stratigraphic and tectonic interpretations from both the southeastern Laurentian and southwestern Gondwana continental margins for the Early Paleozoic. However, it has been disputed by Dalziel (1997) indicating that it is not actualistic as it would imply a very large ridge jump during the rift-drift transition stage. To avoid this problem, Dalziel (1997) proposed and alternative model that can be viewed as a modified first model. It proposes that Cuyania was part of a Laurentian plateau during the latest Proterozoic and Early Paleozoic, in a fashion similar to the Malvinas-Falkland plateau respect to South America. According to this model, the progressive faunal diversity found between Precordillera and Laurentia would be due to extension along the plateau. Dalziel (1997) also suggested that accretion of Precordillera was produced by a "soft" collision between Laurentia and Gondwana in the Ordovician. Keller et al. (1998) modified the Laurentian plateau model in a way that it rests half way between those of Dalziel (1997) and Astini et al. (1995). In his proposal, Cuyania, as part of the so-called Texas plateau would have acted as the unknown source of sediments (Llanoria) already postulated for the Precambrian on Southeast Laurentia (see Keller et al., 1998). According to this model, this plateau would have undergone very significant crustal extension during Cambrian and Ordovician, reaching final break-up in the Caradoc, with formation of oceanic crust between Cuyania and Laurentia only at that stage. To avoid a Laurentia-Gondwana collision, this model proposes a Silurian to Devonian age for the accretion of Precordillera. Thomas and Astini (2003) have recently analysed the different proposals reaching the conclusion that the microcontinental hypothesis with Middle to Late Ordovician age for accretion is the more compatible with most evidence.

In any case, the controversy is still not settled. In particular, lack of paleomagnetic data for Cuyania between the Middle Cambrian and Devonian does not allow constraining the possible paleogeographic evolution of this terrane respect to Laurentia and Gondwana. This is partly due to failure in obtaining primary paleomagnetic directions in all analysed samples from the thick and widespread carbonate platform of the Argentine Precordillera and the San Rafael Block (Rapalini and Tarling, 1993; Rapalini, 1993; Truco and Rapalini, 1996; Rapalini et al., 2000; Rapalini and Astini, 2004). According to the quoted studies, a regional remagnetizing event affected several geologic units in Precordillera and the San Rafael Block in the Permian. This event has been labelled as the San Rafaelic remagnetization (Rapalini, 1993) and has strongly affected the Early Cambrian to mid-Ordovician calcareous units. With this in mind a paleomagnetic study was attempted on the well-dated clastic sedimentary rocks of the Early Caradoc Pavón Formation (Cuerda and Cingolani, 1998) exposed at Cerro Bola (34.6°S, 68.6°W) in the San Rafael Block, Mendoza Province (Fig. 1). As a result of this study we could determine for the first time the paleolatitude of the Cuyania terrane during the Late Ordovician. Its intriguing paleomagnetic pole position also suggests that the dispute between the microcontinent and plateau models may not be over.

Geologic Background

The San Rafael Block (Fig. 1a) as the southern extension of the Precordillera terrane (Fig. 1a) is located 200 km southwards of the Precordillera in the Mendoza province. Diverse igneous-metamorphic and sedimentary units of Precambrian to Middle Paleozoic age are present and known as "pre-Carboniferous units" due to their clear separation from the Upper Paleozoic beds by a regional unconformity. Very similar Grenvillian age basement and Early Paleozoic calcareous cover with similar paleontologic assemblies prove the continuity of the Early Paleozoic Precordillera terrane under the Mesozoic Cuyo Basin into the San Rafael Block (Ramos, 1995; Astini, 2003).

Among the Early Paleozoic sedimentary units exposed in the San Rafael Block is the Pavón Formation. It crops out in the central portion of this block at the eastern slope of the Cerro Bola (Fig. 1b). Outcrops of the Pavón Formation cover an area 3.5 km long and 1.2 km wide, and are composed of folded siliciclastic sediments, intruded by Permian-Triassic rhyolitic rocks and covered by Lower Permian volcaniclastics. A minimum thickness of 700 m has been measured for the Pavón Formation (Cuerda and Cingolani, 1998), its base being not exposed. The Pavón Formation consists of an association of massive green-reddish-grey sandstones, wakes, quartz-sandstones, siltstones and interbedded black shales. The sedimentological features suggest gravity flows in a relatively deep marine sedimentary environment. The presence of a rich Ordovician graptolite fauna (*Climacograptus bicornis* Biozone) indicates a Lower Caradoc age for the Pavón Formation. Composition, provenance and tectonic setting of the Pavón Formation were discussed by Cingolani et al. (2002). Based on paleocurrent data and Nd Tm model ages around 1.4 Ga, these authors interpreted that deposition of the Pavón Fromation siliciclastics took place in a foreland basin hypothetically generated by the accretion of the Precordillera terrane to Gondwana and the uplift of the Greenville age basement of the terrane to the East by thrusting.

A rhyolitic dome exposed at the Cerro Bola intrudes these rocks. Several old mineral and whole-rock K/Ar datings point to a Permo-Triassic (240–260 Ma) age for the rhyolitic dome (Linares et al., 1978, Fig.1b).

Paleomagnetic Study

Eighty-three oriented samples were collected at twelve sites in the Pavón Formation with a portable gasoline-power drill. An extra site (seven samples) was selected in the rhyolitic dome of Cerro Bola. Whenever possible, samples were oriented by means of both sun and magnetic compasses. In general, no significant declination anomalies were found. At the laboratory each core was sliced into one to three standard paleomagnetic specimens (2.2 cm high, 2.54 cm diameter). One or two specimens were processed from each sample. All specimens were submitted to detailed stepwise alternating field (AF) or thermal demagnetization (e.g., Butler, 1992) in twelve to seventeen steps up to 140 mT or 695°C. After demagnetization of 3 or 4 pilot specimens per site, the best cleaning procedure was selected for all remaining specimens. This consisted in detailed thermal demagnetization, identical to that performed on the pilot specimens up to temperatures of 695°C. Measurements of remanence intensity and directions were performed with a 2G® DC Squids cryogenic magnetometer (550R). AF cleaning was done with a three axis static degausser attached to the magnetometer, and thermal cleaning with a two-chambers ASC® oven.

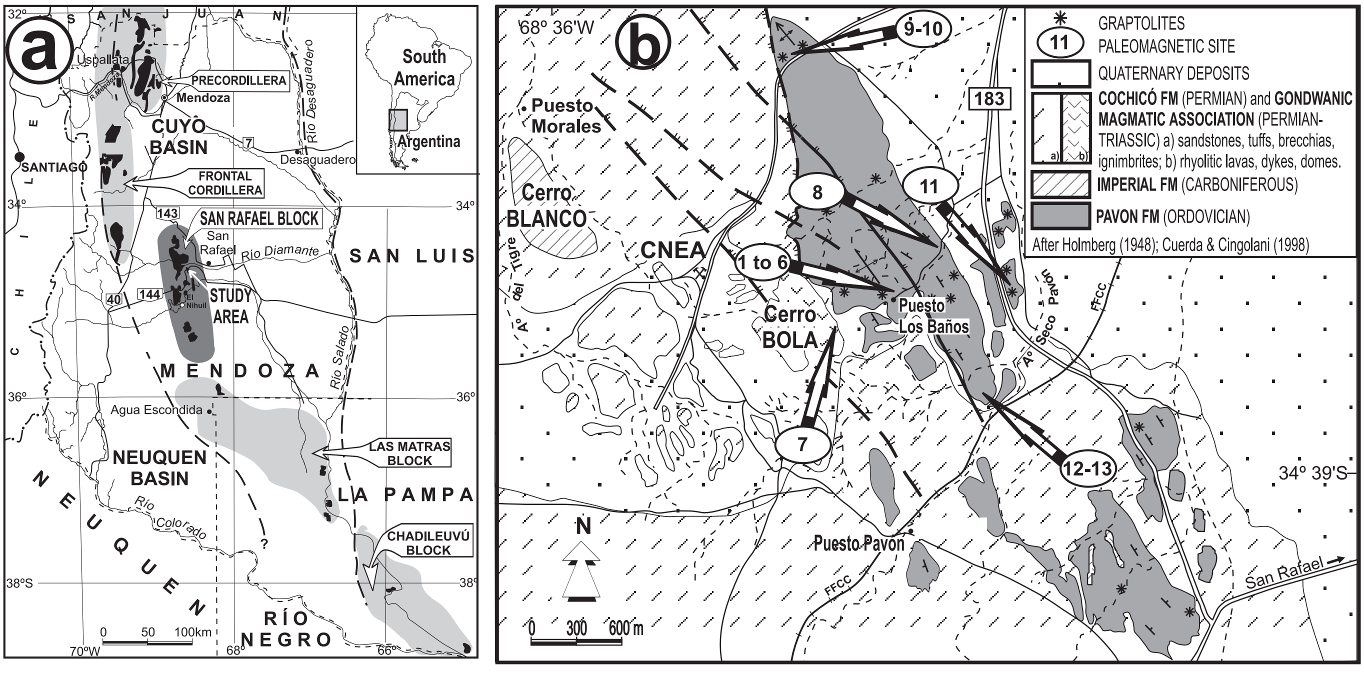

Fig. 1. (a) General location map of the outcrops of the study area and the main morphotectonic units of western Argentina. (b) Geologic map of the Pavón Formation outcrops at the Cerro Bola and location of the paleomagnetic sampling sites.

Possible chemical changes induced by heating were monitored by measurement of bulk magnetic susceptibility after each demagnetization step with an MS-2 Bartington® kappameter.

Magnetic behavior of each specimen was analyzed by visual inspection of As-Zijderveld plots, stereographic vectorial projections and intensity demagnetization curves. After visual selection, magnetic components were determined by principal component analysis (Kirschvink, 1980), with maximum angular deviation (MAD) values under 10°. In most cases components were determined with at least four consecutive demagnetization steps.

Component A (Permo-Triassic)

Typical demagnetization behavior is illustrated in figures 2 and 3. Most sites presented a characteristic component (A) with maximum unblocking temperatures between 620 and 670°C, suggesting hematite as the ferromagnetic carrier. This characteristic component was either upward directed to the North or downward directed to the South. Similar direction was isolated from the single site at the rhyolitic dome, although here unblocking temperatures were closer to that of magnetite (Fig. 2). This component showed very good within site consistency (Table 1) and was found at sites: PV1, PV2, PV3, PV4, PV7 (rhyolitic dome), PV8, PV9, PV10, PV11, PV12 and PV13. A low unblocking temperature component superimposed to component A at sites PV2, PV9 and PV10 unblocked at 400–450°C upward directed towards the North with lower inclination was assigned to a recent (viscous?) magnetization. Site mean directions for component A are shown in figure 4 both *in situ* and after restoring the beds to paleohorizontal (see also Table 1). Dispersal of directions upon bedding correction clearly indicates a post-tectonic nature for this magnetization. Directional coincidence with remanence isolated from the single site at the Permo-Triassic dome may be interpreted as coeval magnetization. The Cerro Bola rhyolitic dome has been dated as 240–260 Ma (Linares et al., 1978), this is to say a post-Kiaman magnetization age (Opdyke and Channell, 1996), which is consistent with the normal polarity observed at site PV7 on the dome and the dual polarities found for component A. A very large silicic igneous province developed in Permian to Triassic times in the San Rafael block and large areas of central and western Argentina known as the Choiyoi magmatic province (e.g., Mahlburgh Kay et al., 1989; Llambías et al., 1996, 2003). The rhyolitic dome at Cerro Bola is associated to this magmatic episode. A post-tectonic remagnetization associated to this magmatism is a likely origin for Component A. This is further tested by computation of a paleomagnetic pole for the *in situ* average direction of component A: 83.7°S, 271.0°E, dp: 6.8°, dm: 9.0°. This is plotted in figure 5 together with the reference paleomagnetic poles for South America for the Late Paleozoic–Early Mesozoic (McElhinny and McFadden, 2000). Its position is consistent with South American poles for 250 Ma (latest Permian) and 240 Ma (Early Triassic). This supports that component A is a secondary magnetization associated to the Permo-Triassic Choiyoi magmatic event. It also implies that no significant rotations are apparent for the study area since the Permo-Triassic.

Component B (Late Ordovician)

Component A is the most widespread and common characteristic remanence isolated in the Pavón Formation. However, a different component (B) was determined at 4 sites (PV5, PV6, PV9 and PV12). Sites PV5 and PV6 did not show the presence of component A, while it appears in some samples from PV9 and most from PV12. Magnetic behaviour of samples carrying this component is shown in figure 3. According to the unblocking temperature component B is subdivided into B1 (PV5, PV6, PV9) and B2 (PV12).

Very high unblocking temperatures up to 690°C, typical of hematite, characterize B1. In most cases this temperature was found to be some 20 or 30°C higher than typical unblocking temperatures of A. Its *in situ* direction is also different pointing downwards towards the East with moderate inclinations. However, one sample from site PV6 showed an antipodal direction and another an intermediate one, strongly suggesting that site PV6 recorded a reversal of the Earth Magnetic Field. Components A and B1 are never superimposed in the same sample. Component A is not present in sites PV5 and PV6, while in site PV9, samples carry either one or the other.

Component B2 is only present at site PV12 where it is represented by an almost vertical upward directed magnetic component isolated approximately between 250°C and 500°C (Fig. 3c), suggesting titanomagnetite as the carrier of the remanence.

Relation between components B1 and B2 is inferred from their perfect match (mainly antipodal) after bedding correction, which suggests that acquisition of both components was geologically coeval. Figure 6 illustrates the distribution of sample remanence directions for components B1 and B2 both *in situ* and after bedding correction. Visual inspection of the figure and comparison of statistical parameter K before and after bedding correction is conclusive of a prefolding origin for this remanence. The antipodal distributions of sample remanence directions indicate a positive reversal test. Therefore, a pre-tectonic paleomagnetic pole was computed for the Pavón Formation, both on site and sample bases (Table 1). Irrespective of the way the pole is computed, the position is virtually identical. Considering that both polarities of the Earth Magnetic Field are recorded in site PV6, it seems more appropriate to determine a sample basis for computing the mean remanence direction of the Pavón Formation. This implies to assume that each sample direction is an independent record of the Late Ordovician Earth Magnetic Field. Therefore, a paleomagnetic pole was computed on the basis of the bedding corrected remanence direction, PV: 3.6°N, 346.4°E, dp = 2.9°, dm = 4.6°, n = 22 (samples).

Anisotropy of Magnetic Susceptibility (AMS), Rock Magnetic and Petrographic Studies

Anisotropy of magnetic susceptibility (AMS, Tarling and Hrouda, 1993), was measured for a set of sites and samples of the Pavón Formation with a KLY-3 Kappabridge at the laboratory of the Universidad Nacional Autónoma de México (Campus Juriquilla). Since these measurements were performed after most of the paleomagnetic processing was over, only a reduced set of samples were available for measurement. AMS data was obtained from sites PV-2, PV-5, PV-6, PV-9, PV-11 and PV-12, which permits a comparison of the AMS pattern of sites with different paleomagnetic characteristics. Due to the small number of samples, sites PV5 and PV6 were combined into a single site, considering their similar lithologic content and paleomagnetic behavior, same bedding attitude and a stratigraphic separation of 1 meter between both. Anisotropy degree (P) varies between 1.016 and 1.055. In all cases but PV12, *K3* is coincident with the pole to bedding (Fig.7), while *K1* and *K2* tend to fall on the bedding plane. In the cases of sites PV5-6 and PV2, the very low anisotropy degree and distribution of AMS axes strongly suggest a depositional fabric (Hrouda and Jezek, 1999). This supports the case for a primary origin of magnetization as inferred from the positive fold test at sites PV5 and PV6, although with bulk susceptibility values in the paramagnetic range, other minerals than hematite may also influence the fabric. Higher values of P at PV-9 and PV-11 do not permit to rule out some superimposed deformational fabric. The very well defined triaxial pattern is consistent with that. In any case the anisotropy degree is still within the range of depositional fabric and in all cases is low enough to rule out any distortion of the paleomagnetic vector, in particular any inclination flattening that may induce anomalous paleolatitude determinations. Therefore, the paleomagnetic directions can be taken as reliable records of the Earth Magnetic Field at the time of remanence acquisition. The magnetic fabric of site PV-12 is somewhat anomalous as *K3* diverges from the pole to bedding towards the vertical. This may be due to a deformational fabric, but the very low P (1.03) argues against it. This site has a complex magnetic mineralogy, which may be influencing the magnetic fabric.

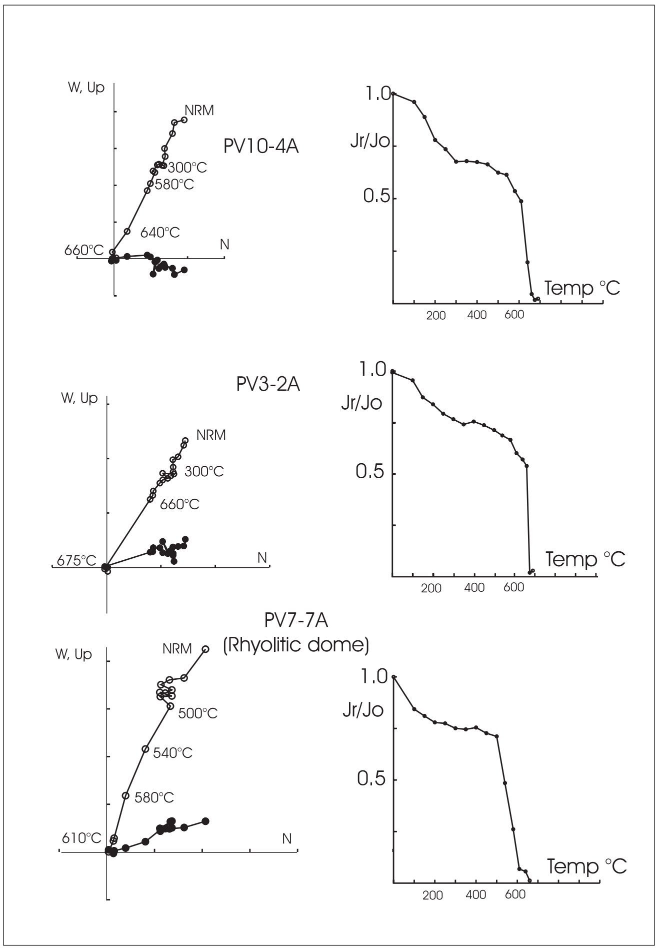

Fig. 2. Typical demagnetization behavior of samples carrying component A, represented by As-Zijderveld plots and demagnetization curves. In the vector diagrams closed (open) symbols represent projections on the horizontal (vertical) plane.

In order to better characterize the magnetic carriers some rock magnetic experiments were performed. They consisted in induction hysteresis cycles of some representative samples, examples of which are shown in figure 8, plus isothermal remanence acquisition and backfield curves. These experiments were performed with a Micromag® 2900 Alternating Gradient Magnetometer (Princeton Measurements Corp.) at the Instituto de Geofísica (Universidad Nacional Autónoma de México). The different hysteresis loops are remarkable. Sample from site PV-5 in which a presumably primary remanence carried by hematite was determined shows a very broad loop typical of this antiferromagnetic mineral as well as the highest values of Hc and Hcr. On the other hand, samples from sites PV8 and PV13 also show loops

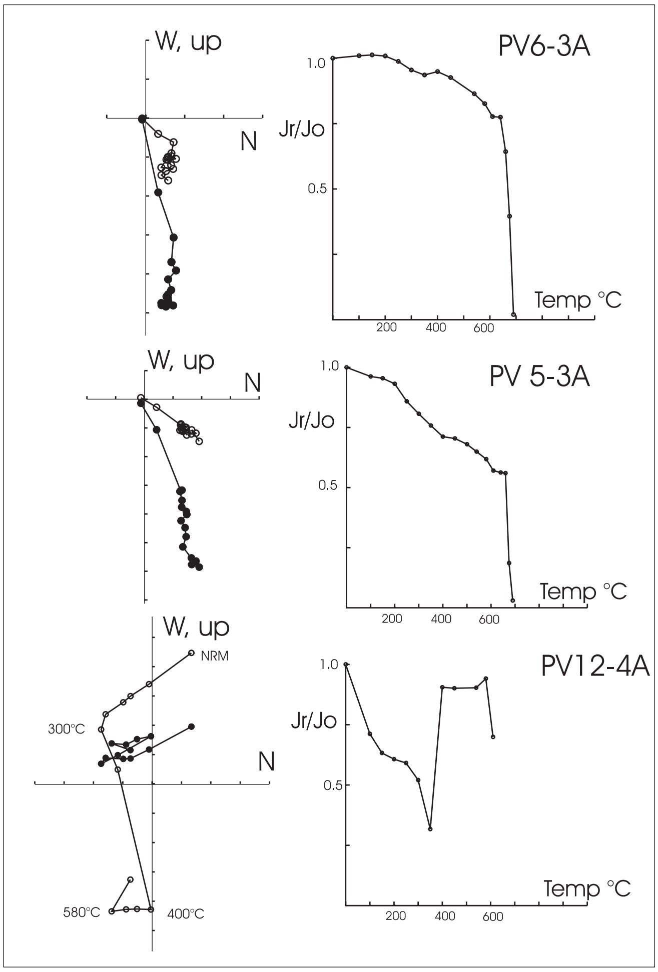

Fig. 3. Typical demagnetization behavior of samples carrying component B. PV-5 and PV-6 carry component B1 (hematite), PV-12 carries component B2 (magnetite). Symbols as in figure 2. For more explanations see the text.

compatible with hematite but with much lower Hc values. Hcr values are also smaller but not as much. Finally, the sample from site PV-12 shows a beautiful wasp-waisted loop indicating the presence of a ferrimagnetic phase (probably Ti?- magnetite). This kind of shape has been generally attributed to a mixture of grains in different domain state or mixture of two minerals. According to Dunlop and Ozdemir (1997) the mixture of magnetite and hematite can produce constricted hysteresis loops if both phases have comparable contributions to the magnetization. This is interpreted to be the case of site PV-12, consistent with a relatively large value of Hcr (194 mT, Fig. 8) and the observed demagnetization behavior (see above).

Preliminary microscopic observations of thin and polished sections of representative samples permitted the identification of hematite as the dominant ferromagnetic phase acting as cement in the sandstones. Textural observations suggest that poral spaces in the sandstones of site PV-6 (component B) are much reduced relative to others sites where component A dominates, possibly due to compaction. Polished sections also show a “cleaner” hematite at site PV6, while a “dirtier” one, with possible limonite intermixing, characterizes other sites. These preliminary observations are consistent with a different origin for the hematitic cement in those samples carrying components A and B1. A much-reduced poral space in the latter may have protected them from replacement of the original cement and promoted survival of the primary remanence.

Interpretation of Results

Paleolatitude of Cuyania in the Late Ordovician (ca. 455 Ma)

Paleomagnetic, rock-magnetic, AMS and petrographic studies are consistent with the interpretation that component B is a primary magnetization carry either by hematite (B1) or magnetite (B2) that accurately recorded the Earth Magnetic Field during the Early Caradoc (ca. 455Ma). The recording of both polarities also confirms that paleosecular variation was averaged out. Very low anisotropy degree and depositional fabric also indicates lack of remanence deformation. Therefore, the paleomagnetic pole of the Pavón Formation can be reliably used to compute the paleolatitude of the Cuyania (Precordillera) terrane in the Early Caradoc. Our results indicate that the sediments of the Pavón Formation were deposited at a latitude of 25.7°±2.9°S. This paleolatitude determination has important implications for most models of paleogeographic evolution of the Argentine Precordillera in the Ordovician. While there is general agreement of a low paleolatitude development of the main carbonate platform of the Precordillera in the Cambrian to Early Ordovician, abnormal carbonates of mainly Caradoc age of the Sassito Formation (Astini and Cañas, 1995; Keller and Lehnert, 1998) as well as graptolite (Mitchell et al., 1998) and conodont record (Lehnert et al., 1999) have been interpreted as evidence of cool waters (see also Astini, 2003). This was interpreted by Astini (1995) as evidence of a paleoposition of Precordillera (Cuyania) in mid to high southern latitudes, although Keller and Lehnert (1998) offered an alternative interpretation. Our results indicate that moderate to cool waters bathed Cuyania when it was still at nearly tropical latitudes (< 30°S). The possibility of cool oceanic currents reaching near tropical latitudes (18°–25°S) in Laurentia by the Early Caradoc, as proposed by Lavoie (1995), is confirmed by our data. Figure 9 shows a Late Ordovician paleogeographic reconstruction based on the Late Ordovician mean paleomagnetic poles for Laurentia and Gondwana (McElhinny and MacFadden, 2000). This figure

Table 1. Mean site remanence components determined in the Pavón Fm and the Cerro Bola rhyolite. n (N): number of samples (sites). Bedding attitude follows right-hand rule. Dec* and Inc* are declination and inclination values after bedding correction.

Comp	Geologic unit	Site	n (N)	Dec (°)	Inc (°)	α95 (°)	Bed Strike	Bed Dip	Dec* (°)	Inc* (°)	α95 (°)
A	Pavón Fm	PV-1	9	347.7	-52.9	6.9	259	48	173.1	-79.1	6.9
		PV-2	7	356.6	-53.6	4.8	221	45	74.0	-59.6	4.8
		PV-3	7	346.6	-60.2	7.6	208	46	74.7	-57.1	7.6
		PV-4	6	14.9	-62.8	10.5	160	23	37.5	-45.8	10.5
		PV-8	8	339.5	-61.4	8.3	320	69	260.6	-27.6	8.3
		PV-9	4	14.4	-55.1	11.7	271	51	156.2	-71.6	11.7
		PV-10	9	352.1	-64.7	6.7	271	51	189.6	-63.8	6.7
		PV-11	7	193.2	51.3	5.7	322	46	112.4	63.2	5.7
		PV-12	8	196.9	61.4	11.1	351	52	118.4	44.8	11.1
		PV-13	14	212.1	52.9	14.3	320	25	184.6	74.9	14.3
	Co. Bola Rhyolite	PV-7	8	346.6	-69.5	3.1	0	0	346.6	-69.5	3.1
	Mean all sites		**(11)**	**2.9**	**-59.7**	**6.0**			**332.5**	**-83.8**	**20.8**
B1	Pavón Fm	PV-5	8	77.6	16.6	5.1	198	39	61.6	47.9	5.1
		PV-6	6	74.7	11.9	6.7	198	39	61.3	42.4	6.7
		PV-9	3	107.5	40.8	11.3	271	51	63.8	35.3	11.3
B2		PV-12	5	131.8	-78.0	7.8	351	52	247.9	-44.9	7.8
	Mean all Sites		**(4)**	**81.3**	**40.6**	**52.3**			**63.7**	**42.7**	**6.6**
	Mean all Samples		**22**	**77.6**	**34.9**	**15.0**			**63.3**	**44.0**	**3.3**

Pole Positions: Comp A: 83.7°S, 271.0°E , dp=6.8°, dm=9.0°, N=11 sites; Comp B: 3.6°N, 346.4°E, dp=2.9°, dm=4.6° n=22 samples.

illustrates the paleolatitudinal band corresponding to the Cuyania terrane based on the Pavón Formation paleomagnetic pole and its uncertainties. The paleolatitude is coincident with that correspondent to Southeast Laurentia (Ouachita Embayment) and the present position of Cuyania in southwestern South America, although, the Late Ordovician paleoposition of Gondwana is loosely constrained by paleomagnetism (McElhinny and MacFadden, 2000). Our data is particularly significant from a paleogeographic viewpoint by constraining the position of Cuyania in nearly tropical latitudes by 455 Ma, while twelve million years later glacial deposits associated to the Hirnantian glaciation covered several areas of the terrane as well as other regions of South America (Peralta and Carter, 1990; Buggisch and Astini, 1993). Due to the paucity of Late Ordovician to

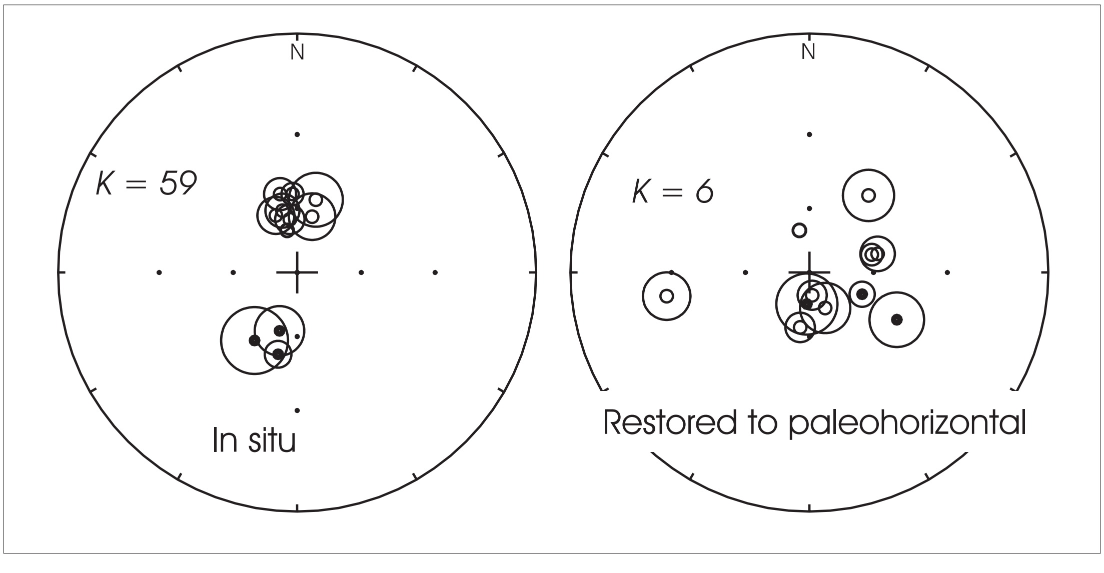

Fig. 4. Mean site component A remanence directions in situ and after bedding correction. Mean directions are plotted with their α95 confidence circles. Note the clear postectonic nature of component A and the presence of antipodal directions. Directional values are presented in table 1. Open (full) symbols correspond to upward (downward) directions. *K* is the Fisherian precision parameter.

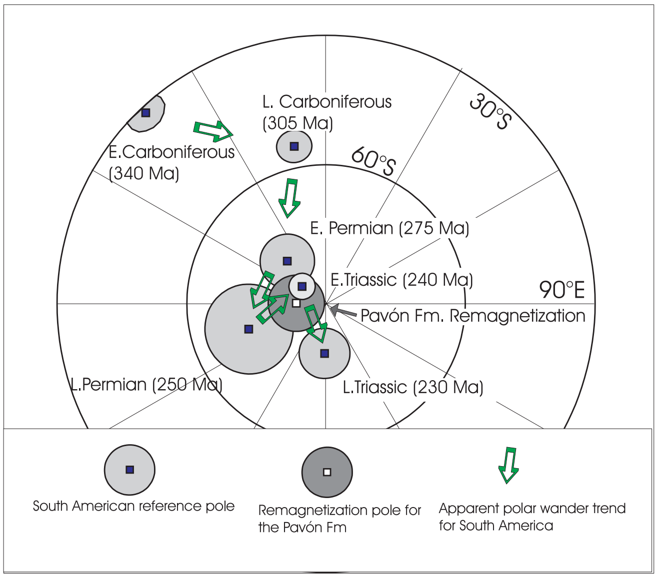

Fig. 5. Position of the postectonic paleomagnetic pole computed from component A in comparison with the South American apparent polar wander path from McElhinny and McFadden (2000). Note coincidence of the pole with the reference poles of 250 and 240 Ma.

Early Silurian paleomagnetic data for Gondwana, it remains controversial whether or not this glaciation was associated with a very fast drift of Gondwana and/or Cuyania towards polar latitudes by the end of the Ordovician.

Tectonic Implications

Figure 10A depicts the position of the Pavón Formation paleomagnetic pole (PV) in a Gondwana reconstruction after Lottes and Rowley (1990) and in North African coordinates. For comparison, Cambrian and Ordovician reference poles for Gondwana (McElhinny and MacFadden, 2000) are shown. The figure clearly shows the large confidence circle associated with the Late Ordovician (455 Ma) reference pole of Gondwana (15°) due to the paucity of reliable paleomagnetic poles of that age. This reduces the resolution of the paleomagnetic comparison between any suspect terrane and Gondwana for that age. It is evident, however, that PV is discordant with the reference Gondwana pole. Since the paleolatitude indicated by PV is within the error limits of the Gondwana pole, no significant paleolatitude anomaly can be claimed on paleomagnetic grounds for Cuyania respect to Gondwana. Therefore, PV's anomalous position can be explained by a simple clockwise rotation of around 30° about a vertical axis in post Early Caradoc times. However, since component A of Permo-Triassic age shows no rotation respect to the reference pole, this rotation is constrained between the Late Ordovician and the Late Permian.

Rapalini and Astini (1998) confirmed on paleomagnetic grounds that the Precordillera originated in the Ouachita Embayment in Southeast Laurentia. An Early Cambrian pole for this terrane perfectly matches the Laurentian Early Cambrian reference pole when the Precordillera is repositioned in the Ouachita Embayment following Thomas and Astini (1996). Figure 10B illustrates the Late Vendian to Ordovician reference poles for Laurentia with the Early Cambrian Cerro Totora and Early Caradoc Pavón formations poles when Cuyania is placed against the Ouachita Embayment using the rotation parameters of Rapalini and Astini (1998). It is striking that PV matches

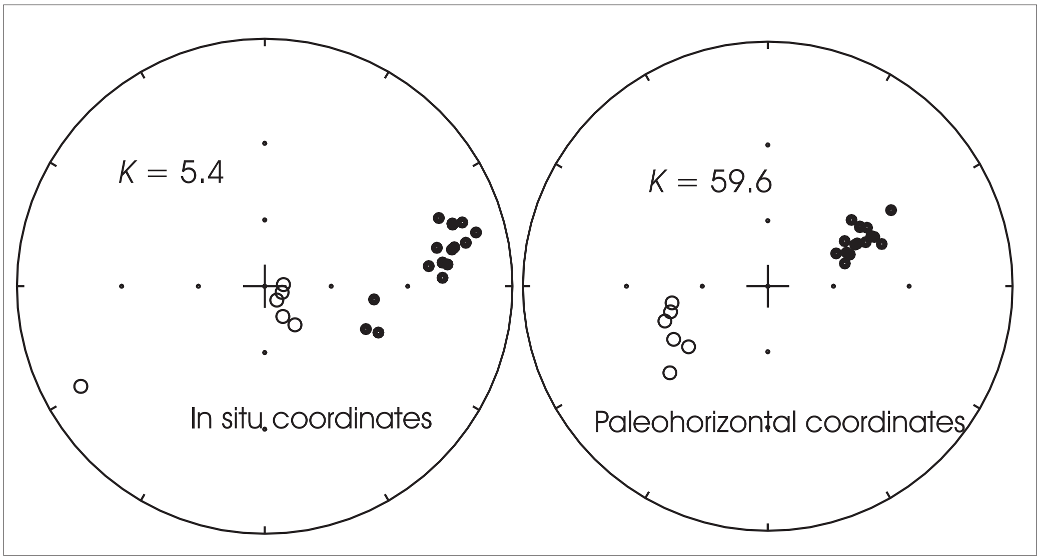

Fig. 6. Component B sample remanence directions in situ and after bedding correction. Note the clear pretectonic nature of the remanence and antipodal directions. For reference see caption of figure 4. Site means are presented in table 1.

the Laurentia Late Ordovician pole. Taking it at face value may suggest that both Cuyania and Laurentia shared a common apparent polar wander path between the Early Cambrian and Late Ordovician, which would imply that Cuyania stayed attached to Laurentia until Caradoc times. However, it must not be forgotten that only two poles represent Cuyania.

Evaluation of the paleomagnetic data depicted in figure 10 together with the geologic, stratigraphic and biogeographic available data from Cuyania has led us to

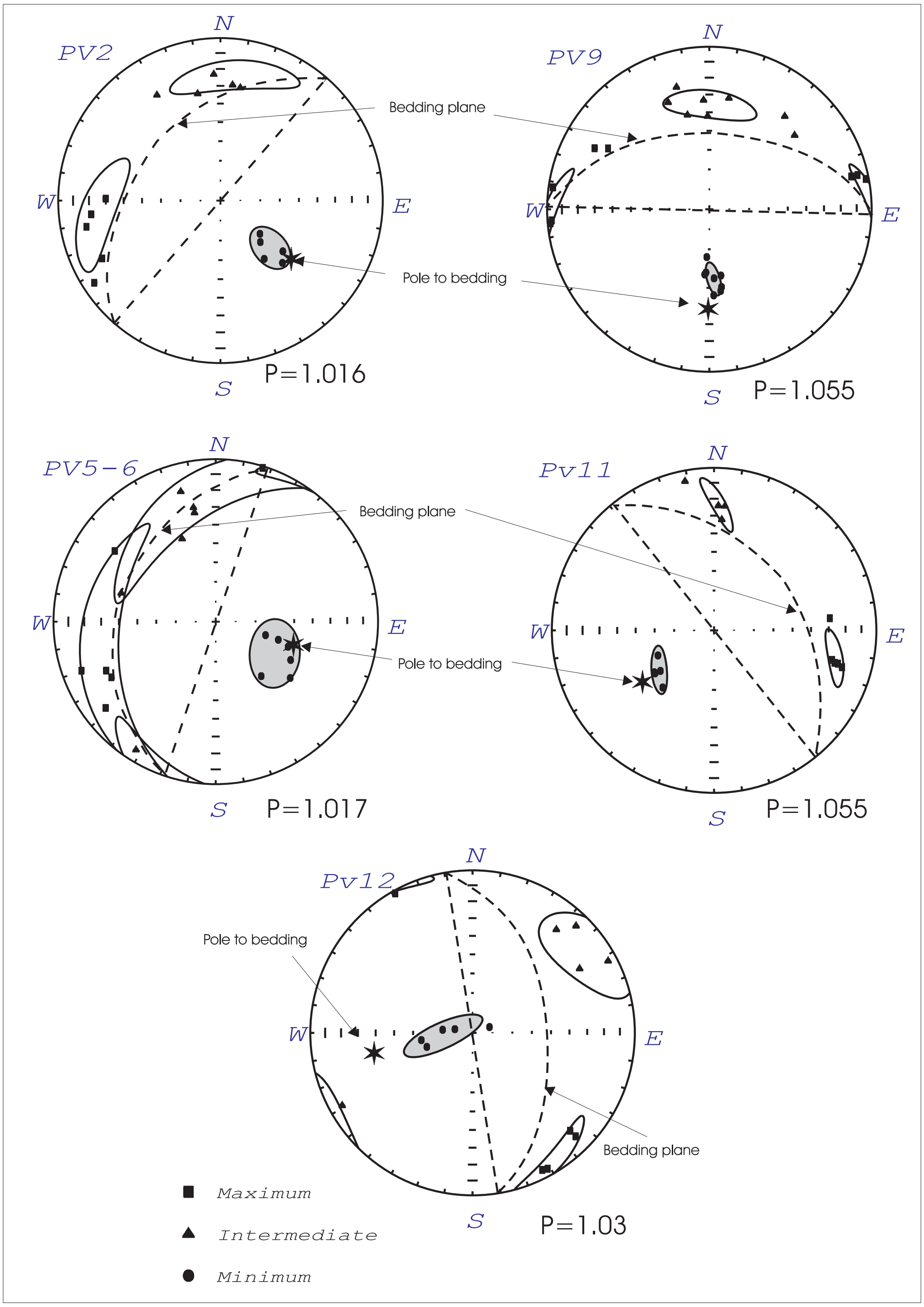

Fig. 7. Anisotropy of magnetic susceptibility (AMS) plots for some sites of the Pavón Formation. Note cluster of minimum (K3) directions around the pole to the bedding plane for most sites and low anisotropy values. More references in the text.

propose three different alternative models for the tectonic evolution of this terrane. All of them are supported by different data sets but conflict with others.

Alternative I (Texas Plateau)

The striking coincidence between PV and the Late Ordovician reference pole for Laurentia when Cuyania is kept at the Ouachita Embayment can be explained by the models that considered that Cuyania remained attached to Laurentia during Cambrian and most Ordovician times (Dalla Salda et al., 1992; Dalziel, 1997; Keller et al., 1998). The original proposal by Dalla Salda et al. (1992) has been ruled out on the basis of the comparative biogeographic evolution of the Precordillera terrane with Laurentia and Gondwana (e.g., Benedetto et al., 1999) as already mentioned in the Introduction. Thomas et al. (2002) has recently argued that the Taconic and Ocloyic tectonic phases in Laurentia and Gondwana were not coetaneous confirming that a continental collision between these two supercontinents in the Ordovician is unlikely. To avoid this problem, Dalziel (1997) proposed the existence of a large continental plateau that extended outboard of Southeast Laurentia, in a fashion similar to the present Malvinas-Falkland plateau in southern South America. According to this hypothesis the Precordillera Early Paleozoic deposits occurred on that plateau that was attached to southwest Gondwana in the Late Ordovician following a "soft" collision between Laurentia and Gondwana. Keller et al. (1998) modified the plateau model, suggesting that collision occurred in later times (Silurian-Devonian?) and was not related to any kind of supercontinental collision. According to this model, the plateau (Texas plateau) was the lost continent of Llanoria (see Keller et al., 1998) that hypothetically faced the Ouachita Embayment in the latest Proterozoic and Early Paleozoic. During the Early Paleozoic, this plateau underwent a significative crustal stretching that led to formation of ocean floor in the Caradoc-Ashgill and final separation of the Cuyania microcontinent from Laurentia. In favour of this model it has been presented that maximum endemism in the Precordilleran fauna was attained during the Caradoc (Benedetto et al., 1999), that depositional patterns in the Middle-Late Ordovician suggest an important paleotopography of horst and grabens consistent with prolonged crustal stretching (Keller et al., 1998), oceanic rocks no older than Caradoc to the west of Precordillera (Ramos et al., 1986), depositional patterns suggestive of continuous extension

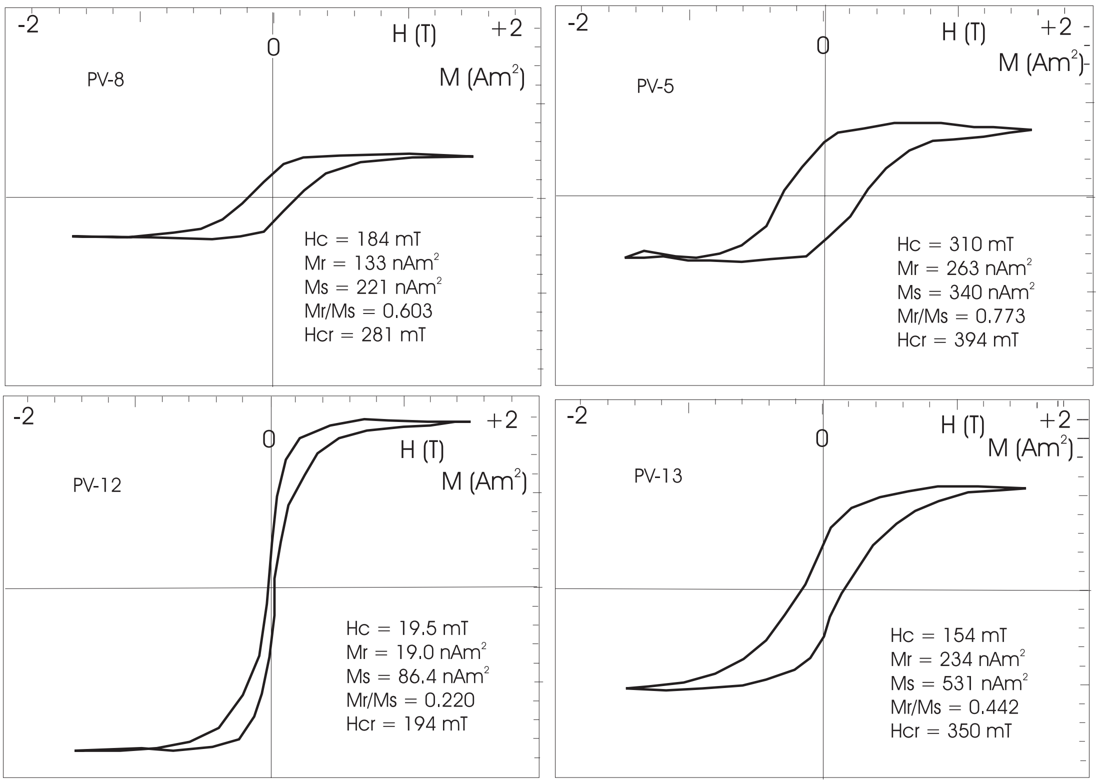

Fig. 8. Hysteresis loops for some samples of Pavón Formation. Note the different shapes and values. Dominance of antiferromagnetic fraction is evident in sample PV-5 and PV-8, while wasp-waisted loop of sample PV-12 is suggestive of combination of comparable contributions from ferrimagnetic and antiferromagnetic phases. Hc: coercive force, Hcr: remanence coercive force, Ms–saturation magnetization, Mr–saturation remanent magnetization. More references in the text.

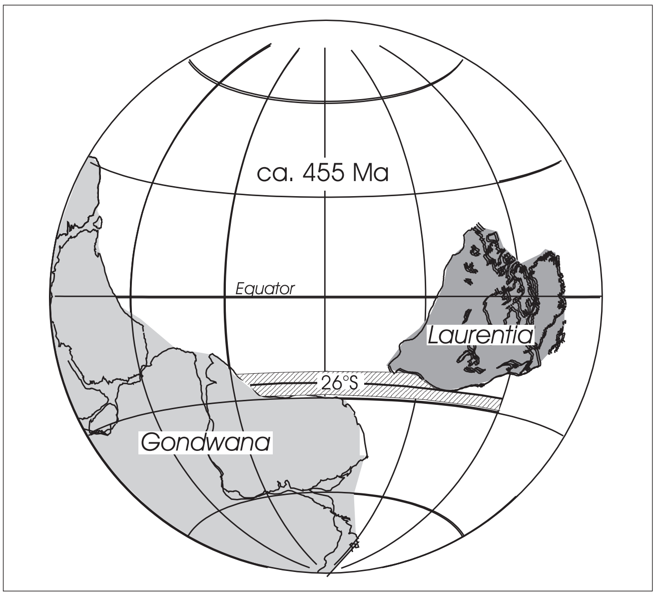

Fig. 9. Paleogeographic reconstruction of Laurentia and Gondwana for the Late Ordovician (ca. 455 Ma) according to their reference paleomagnetic poles (McElhinny and McFadden, 2000) and the paleolatitudinal band correspondent to deposition of the Pavón Formation. sediments as obtained from our paleomagnetic results.

in the western tectofacii of Precordillera (Spalleti et al., 1989; Keller and Lehnert, 1998), and some metamorphic and magmatic ages both in the western and eastern borders of Precordillera of Devonian age that were interpreted as the collision age (e.g., Rapela et al., 1998; Sims et al., 1998). However, biogeographic patterns suggest a close proximity of Cuyania to Gondwana by the end of the Ordovician (Benedetto et al., 1999), while important mixtures with Celtic faunas has been interpreted as Precordillera isolated in the Iapetus ocean during the Mid-Ordovician. Furthermore, a Silurian- Devonian collision is not favored by most authors, who preferred from structural and geochronological data a Middle to Late Ordovician age (Astini et al., 1995; Dalziel, 1997; Ramos et al., 1998; Thomas and Astini, 2003; etc.). Figure 10B depicts PV paleomagnetic pole in Laurentian coordinates keeping Cuyania in the same relative position than in the Early Cambrian. However, this position of Cuyania is not consistent with the crustal extension of the plateau for the Caradoc (Keller et al., 1998). In order to account for this, Cuyania was displaced 500 km to the southeast parallel to the Texas and Alabama-Oklahoma transforms (Thomas and Astini, 1999). Since the original reconstruction (Rapalini and Astini, 1998) already accounted for some 200 to 400 km separation between the southeastern margin of Laurentia and the western margin of Precordillera (due to rift stretching and compressive shortening in the Alleghenian and Andean deformation), the new reconstruction place the present borders of Precordillera and southeast Laurentia some 700 to 900 km apart which may represent a conservative estimate of stretching along the Texas plateau. Figure 11A shows the new position of PV after this displacement has been considered. The figure suggests that stretching of that amount is perfectly compatible with the paleomagnetic data. Despite this consistency, it must be remembered that Cuyania still lacks a proper apparent polar wander path that could allow testing whether Cuyania and Laurentia moved as a single plate until the Caradoc. New paleomagnetic data from Middle Cambrian to Silurian units of the Argentine Precordillera may have the potential to strengthen or rule out this hypothesis.

Alternative II (microcontinent in pre-accretion stage)

Astini et al. (1995) were the first to postulate a developed model in which Precordillera (Cuyania) behaved as an independent terrane or microcontinent between its departure from Laurentia and docking to Gondwana margin. This model is very consistent with the biogeographic evolution of the Precordillera in the Cambrian and Ordovician. This model has been developed further by many contributions (e.g., Thomas and Astini, 1996, 1999, 2003; Astini, 1998; Ramos et al., 1998; Benedetto, 1998; Benedetto et al., 1999; Huff et al., 1998) that focused not only on the biogeographic evidence but also on sedimentologic, stratigraphic and tectonic considerations. Among the main evidences put forward by this model, besides the biogeographic one, are the similarities in stratigraphic evolution of the Ouachita Embayment and Precordillera that can be interpreted as conjugate margins, with Precordillera as the lower plate; nearly identical subsidence curves that correspond to passive margin development and indicate rift to drift transition during the mid- to Late Cambrian; development of the Famatina volcanic arc in the Early Ordovician that is interpreted as the product of subduction along the Gondwana margin due to approach of Cuyania to Gondwana; widespread K-bentonites in Precordillera correlative to the Famatina arc and older than Laurentian K-bentonites in the Early Ordovician, suggesting proximity to Gondwana and no link to Laurentia for that time. Furthermore, different sedimentological and structural features of the Precordillera in the Mid- to Late Ordovician have been interpreted as evidence of approximation and collision of the terrane. A major tectonic phase in central western Argentina in the Late Ordovician (Ocloyic phase) is in general interpreted in this model as the collision of the terrane. Cessation of volcanic activity in Famatina in the Mid-Ordovician is also taken as evidence of the incoming collision.

However, some disagreements exist between advocates of this model. One concerns time of Cuyania separation from Laurentia. While a Middle Cambrian time is preferred by Thomas and Astini (1999), for example, an Arenig age is proposed by Cañas (1999). Similar disagreements appear with respect to accretion time. While Astini (1998) and Ramos et al. (1998) prefer a Mid-Ordovician collision, Benedetto (1998) and Benedetto et al. (1999) suggest that accretion did not occur before the end of the Ordovician.

Our paleomagnetic data will be analyzed regarding these different models. Our second alternative for interpretation of the PV pole considers that consistency of PV and the reference Laurentian pole shown in figures 10B and 11A is merely coincidental. Anyway PV is considered as representative of the Cuyania terrane. Consistent paleolatitudes within paleomagnetic error suggest that Cuyania, as a microcontinent, was close to its final position in the Southwest Gondwana margin by the Early Caradoc. However PVs 30° clockwise rotation respect to the Gondwana reference pole suggests that Cuyania was not still accreted, and that accretion involved a significant clockwise rotation in post early-Caradoc times. Conti et al. (1996), based on paleomagnetic data, postulated that Famatina and Eastern Puna Early Ordovician volcanic arc was a peri-Gondwanan terrane that was accreted in Mid- Ordovician times by a significant clockwise rotation. In our alternative II, final docking of Cuyania would involve a similar clockwise rotation that would follow that of Famatina-Eastern Puna magmatic arc (Fig. 11B). This alternative is supported by the highest endemism of Precordilleran fauna found in the Caradoc that would be difficult to explain if Cuyania was already an integral part of Gondwana, and most biogeographic evidence. It is also compatible with provenance data of the Pavón Formation rocks that indicate a Greenvillian uplifted basement to the East (Cingolani et al., 2002), which could be accounted for if initial stages of collision had already began by the early Caradoc. Problems with this model are widespread metamorphic ages around mid-Ordovician times to the east of Precordillera that suggest Mid-Ordovician accretion (Ramos et al., 1998) as well as stop of magmatism on the Gondwana margin by 455 Ma (Early Caradoc, Thomas et al., 2002) that has been interpreted as marking the accretion time.

New paleomagnetic data from other Caradoc units from Cuyania are necessary to test whether the rotation of the paleomagnetic pole observed is local or representative of the whole of Cuyania.

Alternative III (microcontinent already accreted)

Our third alternative (Fig. 11C) considers that the anomalous position of PV is due to an *in situ* local crustal block rotation and therefore is not representative of the whole of Cuyania. In this case the compatible paleomagnetically determined paleolatitudes for Cuyania and Southwest South America allows interpreting our data

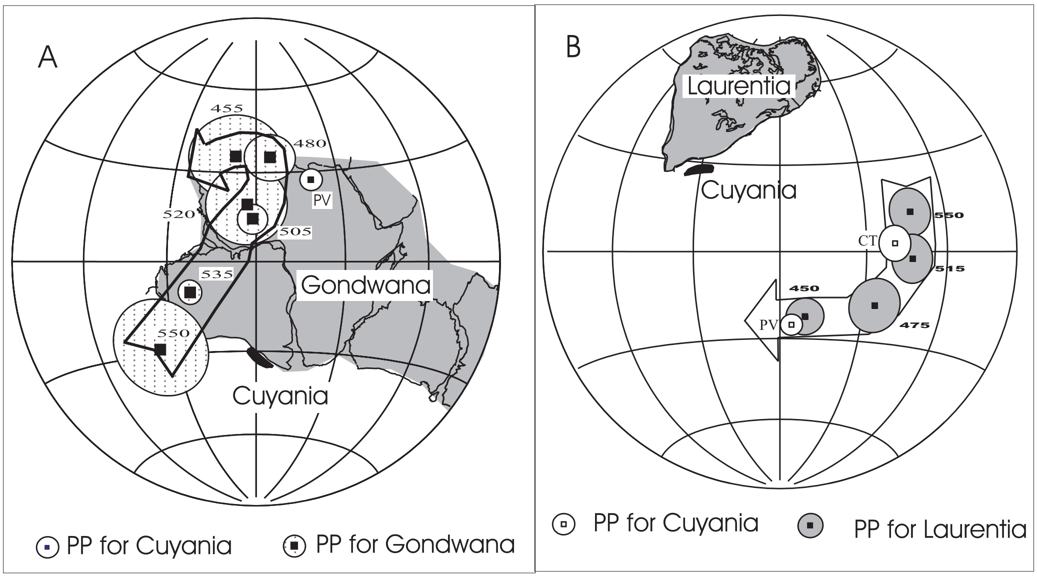

Fig. 10 (A) Position of the Pavón Formation paleomagnetic pole (PV) after rotation into a Gondwana paleoreconstruction (Lottes and Rowley, 1990) and latest Proterozoic Early Paleozoic reference poles for Gondwana. 455 and 480 Ma reference poles are taken from McElhinny and McFadden (2000), others have been computed based on the paleomagnetic poles from Africa, Antarctica, Australia, India, Madagascar and Sri Lanka, with A95≤16° selected by Meert (2001) plus recent poles from Madagascar by Meert et al. (2003) and South America by Sánchez Bettucci and Rapalini (2002). (B) Position of PV after rotation of the Cuyania terrane to match the Ouachita Embayment following rotation parameters by Rapalini and Astini (1998). The Early Cambrian Cerro Totora pole for Cuyania (CT) is also shown. Reference poles for Laurentia correspond to McElhinny and McFadden (2000) for 450 and 475 Ma poles, while those for 515 and 550 Ma have been computed according to the selection by Torsvik et al. (1996).

as supportive of an already accreted Cuyania in the Early Caradoc. This is consistent with cessation of magmatism ca. 455 Ma in the Gondwana margin as already mentioned, as well as with a source of Pavón Formation sediments in Greenvilian basement uplifted due to the collision to the East of Cuyania. There is however a time constraint for the *in situ* rotation, as it must have occurred in Paleozoic times, since the magnetization of Permo-Triassic age recorded in the same rocks show no evidence of rotation. The cause for such crustal block rotation is unknown but should be assigned to either the Chañic (Devonian) or the San Rafaelic (Permian) orogenic phases. An already accreted Cuyania is against the biogeographic evidence mentioned above and implies that the block rotation was by chance of the exact amount and sense to make the paleomagnetic pole coincident with the Laurentian pole when Cuyania is repositioned in the Ouachita Embayment. However, according to Ramos (2004) this alternative better explains most geologic and geochronological evidence. As in the previous alternative, further Caradoc

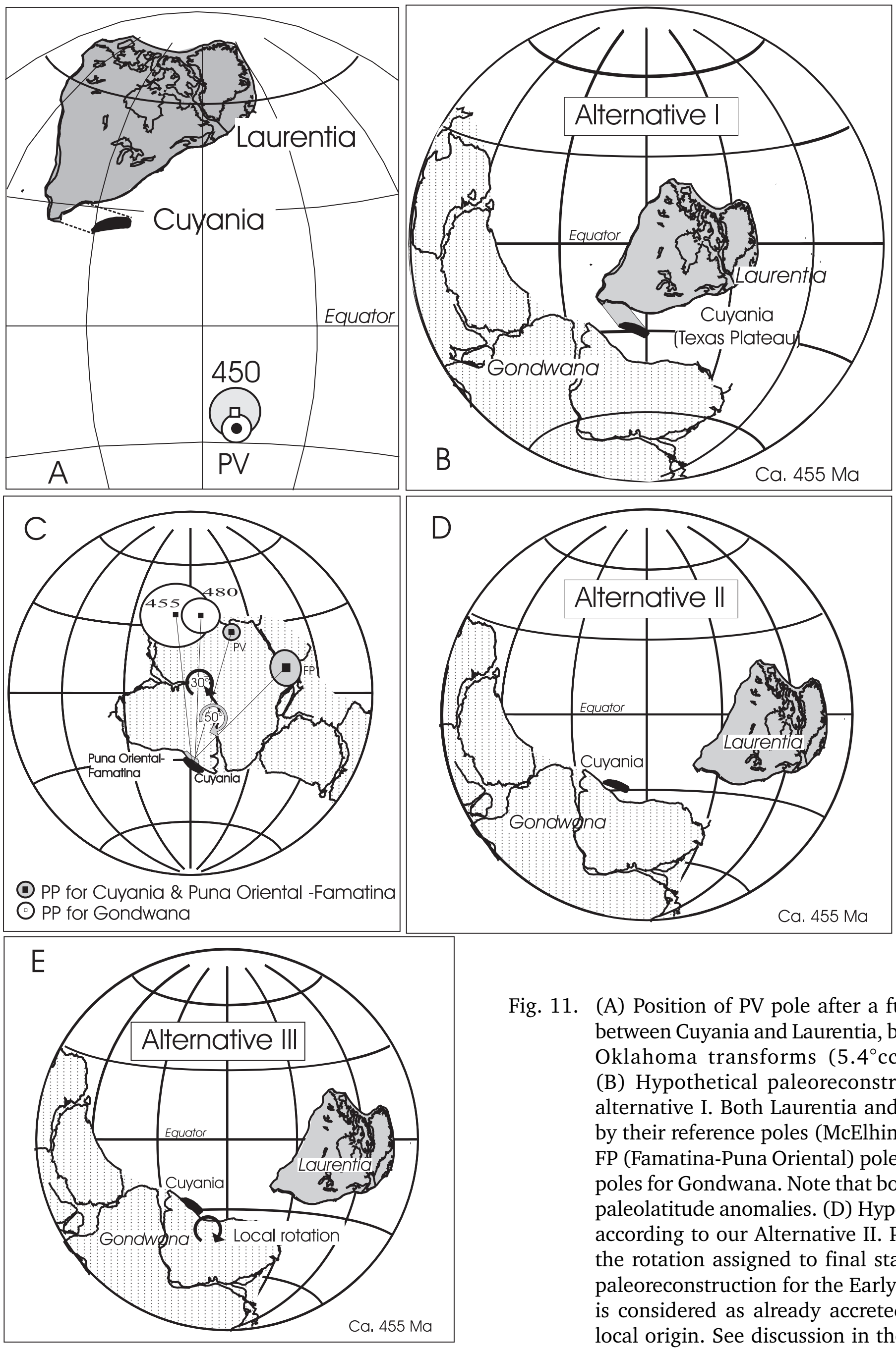

Fig. 11. (A) Position of PV pole after a further stretching of around 500 km is considered between Cuyania and Laurentia, by displacing Cuyania along the Texas and Alabama-Oklahoma transforms (5.4°ccw rotation around pole at 73.4°N, 11.3°E). (B) Hypothetical paleoreconstruction for the Early Caradoc according to our alternative I. Both Laurentia and Gondwana are placed within the limits imposed by their reference poles (McElhinny and McFadden, 2000). (C) Positions of PV and FP (Famatina-Puna Oriental) pole from Conti et al. (1996) and their coeval reference poles for Gondwana. Note that both show significant cw rotations and no significant paleolatitude anomalies. (D) Hypothetical paleoreconstruction for the Early Caradoc according to our Alternative II. PV is considered as representative of Cuyania and the rotation assigned to final stages of the accretional process. (E) Hypothetical paleoreconstruction for the Early Caradoc according to our Alternative III. Cuyania is considered as already accreted to Gondwana. Rotation of PV is considered of local origin. See discussion in the text.

paleomagnetic poles from Cuyania can test whether or not our study area underwent a local rotation in the Paleozoic.

In all cases, a better-defined Late Ordovician reference pole for Gondwana is of paramount importance to reduce the uncertainties.

Conclusions

A paleomagnetic study was carried out on the Early Caradoc clastic Pavón Formation exposed in the San Rafael Block, as part of the allochthonous Cuyania terrane. After standard demagnetization techniques, two components with geologic significance were determined.

The most frequent one was a post-tectonic remanence (component A) isolated at most sites of the Pavón Formation and at a Permo-Triassic rhyolitic dome that intrudes this formation. The paleomagnetic pole position consistent with the Late Permian reference pole for South America and the recordings of both polarities of the Earth Magnetic Field suggests that A is a secondary magnetization acquired in the latest Permian–Early Triassic during the widespread Choiyoi magmatic event that affected this region. A second magnetic component (B) was determined at 4 sites (22 samples) carried either by hematite or magnetite. It presented dual polarities and a positive fold test suggesting a primary detrital or early diagenetic origin. AMS studies indicated that most studied rocks show a very low anisotropy degree and depositional fabric, consistent with the primary origin of component B. These results also ruled out any significant inclination anomaly due to compaction. The computed paleomagnetic pole for the Pavón Formation indicates that this area of the Cuyania terrane was situated at latitude of around 26°S in the Early Caradoc, which means that models that sustained much higher latitudes on the base of sedimentological and paleontological evidence must be reconsidered. The paleolatitude computed is compatible with that expected from the Late Ordovician Gondwana reference pole, but the latter is ill defined and has very large error limits. Anyway, PV shows an anomalous position that can be reconciled with the Gondwana reference pole by assuming a 30° clockwise rotation of the sampling localities around a vertical axis located in the study area. However, if Cuyania is kept close to Southeast Laurentia, according to the proposals of Thomas and Astini (1996) and Rapalini and Astini (1998) for the Early Cambrian, PV agrees with the Late Ordovician reference pole of Laurentia. The agreement is even better if some 500 km further stretching is considered between Cuyania and the Ouachita Embayment along the Texas and Alabama-Oklahoma transforms.

Our results led us to propose three alternative interpretations. The first alternative is based on the above-mentioned coincidence between PV and the Laurentian reference pole and suggests that Cuyania remained attached to Laurentia, probably as part of the already proposed Texas plateau until the early Caradoc. The second alternative is to consider the consistency with the Laurentian pole as coincidental and that the rotation respect to the Gondwana reference pole is representative of the whole of Cuyania. In this hypothesis, our paleomagnetic data is interpreted as recording final approximation of Cuyania to the Gondwana margin but with accretion not yet produced by the Early Caradoc. The clockwise rotation expressed in the paleomagnetic pole position is interpreted as representing the accretion mechanism which would then be similar to that proposed by Conti et al. (1996) for the previous accretion of the peri-Gondwanic Famatina-Eastern Puna magmatic arc in the Mid-Ordovician. The third alternative proposes that compatible paleolatitudes for Cuyania with its present position in Southwest South America can be taken as evidence of accretion already occurred. Rotation of the paleomagnetic pole is then assigned to a local crustal block rotation that took place before the late Permian. There are different types of evidence both in favor and against all three alternatives. Solving the dilemma awaits the obtaining of new Early Paleozoic paleomagnetic data in Cuyania and improvement of the reference poles for Gondwana.

Acknowledgments

Financial support by the University of Buenos Aires (UBACyT X045), CONICET and Fundación Antorchas enabled this study. L. Ortiz collaborated during the field trip. S. Singer was very helpful with the analysis of thin and polished sections. C. Vasquez kindly performed the AMS measurements at the Unidad de Geociencias, UNAM, Querétaro, México. Hysteresis cycles were obtained at the Instituto de Geofísica, UNAM, México. Authorities of both institutions are acknowledged for allowing the use of equipments. Analysis of paleomagnetic samples were done with T.Torsvik's S-IAPD program, and paleoreconstructions were performed with Torsvik and Smethurst's GMAP program. Critical comments by reviewers I. Dalziel and V. Ramos improved the final version.

References

Aceñolaza, F.G., Miller, H. and Toselli, A.J. (2002) Proterozoic-Early Paleozoic evolution in western South America-a discusión. Tectonophys., v. 354, pp. 121-137.

Astini, R.A. (1995) Paleoclimates and paleogeographic paths of the Argentine Precordillera during the Ordovician: evidence from climatically sensitive lithofacies. In: Cooper, J.D., Droser, M.L. and Finney S.C. (Eds.), Ordovician odyssey. The Pacific Section Soc. Sediment. Geol., Book 77, pp. 177-180.

Astini, R.A. (1998) Stratigraphic evidence supporting the rifting, drifting and collision of the Laurentian Precordillera terrane of western Argentina. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc. London, Spec. Pub., v. 142, pp. 11-33.

Astini, R.A. (2003) The Ordovician Proto-Andean basins. In: Benedetto, J.L. (Ed.), Ordovician fossils of Argentina. Secretaría de Ciencias y Tecnología, Univ. Nac. Córdoba, pp. 1-74.

Astini, R.A. and Cañas, F.L. (1995) La formación Sassito, una nueva unidad calcárea en la Precordillera de San Juan: sedimentología y significado estratigráfico. Revista Asoc. Argentina Sediment., v. 2, pp. 19-37.

Astini, R.A. and Rapalini, A.E. (2003) Discussion to Proterozoic–Early Paleozoic evolution in western South America – a discussion. Tectonophys., v. 366, pp. 143-148.

Astini, R.A., Benedetto, J.L. and Vaccari, N.E. (1995) The early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted and collided terrane: a geodynamic model. Geol. Soc. Amer., Bull., v. 107, pp. 253-273.

Baldis, B., Peralta, S. and Villegas, C. (1989) Esquematizaciones de una posible transcurrencia del Terrane Precordillera. In: Proyecto IGCP 270, Univ. Nac. Tucumán, Serie Correlación Geológica v. 5, pp. 81-100.

Benedetto, J.L. (1993) La hipótesis de la aloctonía de la Precordillera Argentina: un test estratigráfico y biogeográfico. 12° Cong. Geol. Argentino, Actas, 3, pp. 375-384.

Benedetto, J.L. (1998) Early Palaeozoic brachiopods and associated shelly faunas from western Gondwana: their bearing on the geodynamic history of the pre-Andean margin. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc. London, Spec. Pub., v. 142, pp. 57-83.

Benedetto, J.L., Sanchez, T.M., Carrera, M.G., Brussa, E.D. and Salas, M.J. (1999) Paleontological constraints on succesive paleogeographic positions of Precordillera terrane during the Early Paleozoic. In: Ramos, V.A. and Keppie, J.D. (Eds.), Laurentia-Gondwana connections before Pangea. Geol. Soc. Amer., Spec. Paper, v. 336, pp. 21-42.

Buggisch, W. and Astini, R.A. (1993) The Late Ordovician Ice age: New evidence from the Argentine Precordillera. In: Findlay, R.H., Unrug, R., Banks, M.R. and Veevers, J.J. (Eds.), Gondwana eight, assembly, evolution and dispersal. Balkema Press, Rotterdam, pp. 439-447.

Butler, R.F. (1992) Paleomagnetism: magnetic domains to geologic terranes. Blackwell Sci. Pub., Boston, 319p.

Cañas, F.L. (1999) Facies and sequences of the Late Cambrian–Early Ordovician carbonates of the Argentine Precordillera: A stratigraphic comparison with Laurentian platforms. In: Ramos, V.A. and Keppie, J.D. (Eds.), Laurentia-Gondwana connections before Pangea. Geol. Soc. Amer., Spec. Paper, v. 336, pp. 43-62.

Cingolani, C.A., Manassero, M. and Abre, P. (2002) Geoquímica de elementos traza y tierras raras de las sedimentitas de la Formación Pavón, Ordovícico del Bloque de San Rafael, Mendoza. 15° Cong. Geol. Argentino, Actas, 1, pp. 667-673.

Conti, C.M., Rapalini, A.R., Coira, B. and Koukharsky, M. (1996) Paleomagnetic evidence of an Early Paleozoic rotated terrane in NW Argentina. A clue for Gondwana-Laurentia interaction? Geology, v. 24, pp. 953-956.

Cuerda, A. and Cingolani, C. (1998) El Ordovícico de la región del Cerro Bola en el bloque de San Rafael, Mendoza: sus faunas graptolíticas. Ameghiniana, v. 35, pp. 427-448.

Dalla Salda, L., Cingolani, C. and Varela, R., (1992) Early Paleozoic orogenic belt of the Andes in southwestern South America: Result of Laurentia-Gondwana collision? Geology, v. 20, pp. 617-620.

Dalziel, I.W.D. (1993) Tectonic tracers and the origin of the proto-Andean margin. 12° Cong. Geol. Argentino, Actas, 3, pp. 367-374.

Dalziel, I.W.D. (1997) Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. Geol. Soc. Amer., Bull., v. 109, pp. 16-42.

Dunlop, D.J. and Özdemir, Ö. (1997) Rock magnetism, fundamentals and frontiers. Univ. Press, Cambridge, UK, 573p.

Finney, S., Gleason, J., Gehrels, G., Peralta, S. and Aceñolaza, G. (2003) Early Gondwanan connection for the Argentine Precordillera terrane. Earth Planet. Sci. Lett., v. 205, pp. 349-359.

Finney, S., Gleason, J., Gehrels, G., Peralta, S. and Aceñolaza, G. (2004) Corrigendum to "Early Gondwanan connection for the Argentine Precordillera terrane" (Earth Planet. Sci. Lett., v. 76, pp. 1-11). Earth Planet. Sci. Lett., v. 219, p. 413.

González Bonorino, F. and González Bonorino, G. (1991) Precordillera de Cuyo y Cordillera Frontal en el Paleozoico temprano: terrenos bajo sospecha de ser autóctonos. Revista Geol. Chile, v. 18, pp. 97-107.

Hrouda, F. and Jezek, J. (1999) Magnetic anisotropy indications of deformation associated with diagenesis. In: Tarling, D.H. and Turner, P. (Eds.), Paleomagnetism and diagenesis in sediments. Geol. Soc. London, Spec. Pub., v. 151, pp. 127-138.

Huff, W.D., Bergstrom, S.M., Kolata, D.R., Cingolani, C. and Astini, R.A., (1998) Ordovician K-bentonites in the Argentine Precordillera: relations to Gondwana margin evolution. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc. London, Spec. Pub., v. 142, pp. 107-126.

Keller, M. and Lehnert, O. (1998) The Sassito sedimentary succession: A pinpoint in the geodynamic evolution of the Argentine Precordillera. Geol. Rundsch., v. 87, pp. 326-344.

Keller, M., Buggisch, W. and Lehnert, O. (1998) The stratigraphical record of the Argentine Precordillera and its plate-tectonic background. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc. London, Spec. Pub., v. 142, pp. 35-56.

Kirschvink, J. L. (1980) The least-squares line and plane and the analysis of paleomagnetic data. Geophys. J. R. Astron. Soc., v. 67, pp. 699-718.

Lavoie, D. (1995) A late Ordovician high-energy temperate carbonate ramp, southern Quebec, Canada: implications for Late Ordovician oceanography. Sedimentology, v. 42, pp. 95-116.

Lehnert, O., Bergström, S. M., Keller, M. and Bordonaro, O. (1999) Middle Ordovician (Llandeilian-Caradocian) conodonts from the San Rafael region, west-central Argentina: biostratigraphic, biogeographic and paleogeographic implications. In: Serpagli, E. (Ed.), Studies on conodonts-Proc. Seventh European Conodont Symp. – Boll. Soc. Paleontol. Italiana, v. 37, pp. 199-214.

Linares, E., Manavella, M. and Piñeiro, A. (1978) Geocronología de las rocas efusivas de la zona de los yacimientos Dr. Baulies y Los Reyunos, sierra Pintada de San Rafael, Mendoza. 7° Cong. Geol. Argentino, Actas, 2, pp. 13-21.

Llambías, E.J., Caminos, R. and Rapela, C.W. (1996) Magmatismo Gondwánico. In: Archangelsky, S. (Ed.), El sistema Pérmico en la República Argentina y en la República Oriental del Uruguay. Acad. Nac. Ciencias, Córdoba, pp. 267-288.

Llambías, E.J., Quenardelle, S. and Montenegro, T. (2003) The Choiyoi Group from central Argentina: a subalkaline transitional to alkaline association in the craton adjacent to the active margin of the Gondwana continent. J. S. Amer. Earth Sci., v. 16, pp. 243-257.

Lottes, A.L and Rowley, D.B. (1990) Reconstruction of the Laurasian and Gondwanan segments of Permian Pangaea. Geol. Soc. Mem., v. 12, pp. 383-395.

Mahlburg Kay, S.M., Orrell, S. and Abruzzi, J.M. (1996) Zircon and whole rock Nd-Pb isotopic evidence for a Grenville age and Laurentian origin for the basement of the Precordilleran terrane in Argentina. J. Geol., v. 104, pp. 637-648.

Mahlburg Kay, S.M., Ramos, V. A., Mpodozis, C. and Sruoga, P. (1989) Late Paleozoic to Jurassic silicic magmatism at the Gondwana margin: analogy to the Middle Proterozoic in North America? Geology, v. 17, pp. 324-328.

McElhinny, M.W. and McFadden, P.L. (2000) Paleomagnetism. Academic Press, San Diego, USA, 386p.

Meert, J.G. (2001) Growing Gondwana and rethinking Rodinia: a paleomagnetic perspective. Gondwana Res., v. 4, pp. 279-288.

Meert, J.G., Nédélec, A. and Hall, C. (2003) The stratoid granites of central Madagascar: paleomagnetism and further age constraints on neoproterozoic deformation. Precambrian Res., v. 120, pp. 101-129.

Mitchell, C., Brussa, E.D., Toro, B.A. and Astini, R.A. (1998) Late Ordovician graptolites from the Empozada Formation, Argentine Precordillera, an outer shelf, cool water, peri-Gondwanan assemblage? In: Gutierrez Marco, J.C. and Rabano, I. (Eds.), Proc. 6 Int. Graptolite Conf. & Field Meeting, IUGS Subcomm. Silurian stratigraphy. Temas Geológico-Mineros, v. 23, pp. 224-226.

Opdyke, N.D. and Channell, J.E.T. (1996) Magnetic stratigraphy. Academic Press, 346p., San Diego, USA.

Peralta, S.H. and Carter, C. (1990) La glaciación Gondwánica del Ordovícico tardío: evidencias en fangolitas guijarrosas de la Precordillera de San Juan, Argentina. 11° Cong. Geol. Argentino, Actas, 2, pp. 181-185.

Ramos, V.A. (1995) Sudamérica: un mosaico de continentes y océanos. Ciencia Hoy, v. 6, pp. 24-29.

Ramos, V.A. (2004) Cuyania, an exotic block to Gondwana: review of a historical success and the present problems. Gondwana Res., v. 7, pp. 1009-1026.

Ramos, V.A., Dallmeyer, R.D. and Vujovich, G. (1998) Time constraints on the Early Paleozoic docking of the Precordillera, central Argentina. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc., London, Spec. Pub., v. 142, pp. 143-158.

Ramos, V.A., Jordan, T.E., Allmendinger, R.W., Mpodozis, C., Kay, S.M., Cortés, J.M. and Palma, M. (1986) Paleozoic terranes of the central Argentina - Chilean Andes. Tectonics, v. 5, pp. 855-880.

Rapalini, A.E. (1993) Evidencias de un evento de remagnetización regional en Precordillera asociado a la Fase San Rafael. 12° Cong. Geol. Argentino, Actas. 3, pp. 415-422.

Rapalini, A.E. and Astini, R.A. (1998) Paleomagnetic confirmation of the Laurentian origin of the Argentine Precordillera. Earth Planet. Sci. Lett., v. 155, pp. 1-14.

Rapalini, A.E. and Astini, R.A. (2004) La Remagnetización Sanrafaélica de la Precordillera: Nuevas Evidencias. Revista Asoc. Geol. Argentina., submitted.

Rapalini, A.E. and Tarling, D.H. (1993) Multiple magnetizations in the Cambro-Ordovician carbonate platform of the Argentine Precordillera and their tectonic implications. Tectonophys., v. 227, pp. 49-62.

Rapalini, A.E., Bordonaro, O., and Berquo, T. S. (2000) Paleomagnetic study of Cambrian-Ordovician rocks in the Eastern Precordillera of Argentina: some constraints on the Andean uplift of this block. Tectonophys., v. 326, pp. 173-184.

Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J. and Galindo, C. (1998) Early evolution of the Proto-Andean margin of South America. Geology, v. 26, pp. 707-710.

Sánchez Bettucci, L. and Rapalini, A.E. (2002) Paleomagnetism of the Sierra de las Animas complex, southern Uruguay: its implications in the assembly of Western Gondwana. Precambrian Res., v. 118, pp. 243-265.

Sims, J.P., Ireland, T.R., Camacho, A., Lyon, P. Pieters, P.E., Skirrow, R.G., Stuart-Smith, P.G. and Miró, R. (1998) U-Pb, Th-Pb and Ar-Ar geochronology from the southern Sierras Pampeanas, Argentina: implications for the Paleozoic evolution of the western Gondwana margin. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc. London, Spec. Pub., v.142, pp. 259-281.

Spaletti, L.A., Cingolani, C.A., Varela, R.V. and Cuerda, A.J. (1989) Sediment gravity flow deposits of an Ordovician deep-sea fan system (western Precordillera, Argentina). Sediment. Geol., v. 61, pp. 287-301.

Tarling, D.H. and Hrouda, F. (1993) The magnetic anisotropy of rocks. Chapman and Hall, London, p. 217.

Thomas, W. and Astini, R.A. (1996) The Argentine Precordillera: a traveler from the Ouachita embayment of North American Laurentia. Science, v. 273, pp. 752-757.

Thomas, W. and Astini, R. A. (1999) Simple-shear conjugate rift margins of the Argentine Precordillera and the Ouachita embayment of Laurentia. Geol. Soc. Amer., Bull., v. 111, pp. 1069-1079.

Thomas, W. and Astini, R. A. (2003) Ordovician accretion of the Argentine Precordillera terrane to Gondwana: a review. J. S. Amer. Earth Sci., v. 16, pp. 67-79.

Thomas, W., Astini, R.A. and Bayona, G. (2002) Ordovician collision of the Argentine Precordillera with Gondwana, independent of Laurentian Taconic orogeny. Tectonophys., v. 345, pp. 131-152.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A. and Walderhaug, H.J. (1996) Continental break-up and collision in the Neoproterozoic and Palaeozoic – a tale of Baltica and Laurentia. Earth. Sci. Rev., v. 40, pp. 229-258.

Truco, S. and Rapalini, A.E. (1996) New evidence of a widespread Permian remagnetizing event in the Central Andean zone of Argentina. 3° Int. Symp. Andean Geodynamics, St. Malo, France, pp. 799-802.