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Paleomagnetic evidence for the origin of the Argentine Precordillera, fifteen years later: what is new, what has changed, what is still valid?

Augusto E. Rapalini

Laboratorio de Paleomagnetismo Daniel A. Valencio, Área Geofísica, del Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires. Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales. Universidad de Buenos Aires – CONICET

* Corresponding author, Email: rapalini@gl.fcen.uba.ar

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Abstract. The last two decades have experienced an outstanding interest in the origin of the Argentine Precordillera or its now accepted extension into the Cuyania terrane. Since the model published by Astini and co-workers in 1995, a great deal of evidence have been produced in favor of an Early Paleozoic Laurentian origin for this terrane. Almost fifteen years ago, the first paleomagnetic evidence in favor of such origin was published. A new analysis of the two available Early Paleozoic paleopoles versus an updated paleomagnetic databse for Gondwana and Laurentia is performed. The analysis also takes into account the "unorthodox" hypothesis of a para-authochtonous Gondwanan origin for Cuyania as a margin-parallel displaced terrane. The result of the analysis indicates that although the latter origin cannot be definitely rule out with the paleomagnetic data alone, this is more easily reconciled with the origin of this terrane as a fragment of the Laurentian crust rifted away from the Ouachita Embayment. Paleomagnetic constraints on the age and mode of accretion to Gondwana remain too ambiguous.

Keywords: *Paleomagnetism, Argentine Precordillera, Cuyania, Laurentia, Gondwana, Early Paleozoic*

Resumen. Durante las últimas dos décadas hubo un extraordinario interés en el origen de la Precordillera Argentina o su, hoy día aceptada, extensión en el terreno de Cuyania. Desde el modelo publicado por Astini y colaboradores en 1995, se ha obtenido una gran cantidad de evidencia a favor de un origen lauréntico en el Paleozoico temprano para este terreno. Hace casi quince años se publicó la primera evidencia paleomagnética a favor de este origen. Se presenta aquí un nuevo análisis de los únicos dos paleopolos eopaleozoicos disponibles para Cuyania versus una base de datos actualizada para Laurentia y Gondwana. El análisis también toma en consideración el modelo "no ortodoxo" sobre un origen para el terreno de Cuyania como un terreno para-autóctono a Gondwana desplazado a lo largo del margen continental. El resultado del análisis indica que aunque este último modelo no puede ser definitivamente descartado con la información paleomagnética exclusivamente, ésta se reconcilia mucho más fácilmente con el modelo que propone que Cuyania es un fragmento de corteza lauréntica que se separó del engolfamiento de Ouachita en el Paleozoico temprano. En cuanto a la edad y modo de acreción al Gondwana, las restricciones paleomagnéticas existentes son aún muy ambiguas.

Palabras claves: *Paleomagnetismo, Precordillera Argentina, Cuyania, Laurentia, Gondwana, Paleozoico Inferior.*

1 Introduction

The Argentine Precordillera is a morphostructural unit of about 400 km long located in central western Argentina (Fig.1). Its uplift is due to the Late Tertiary Andean tectonic activity (Jordan *et al*., 1983, Allmendinger *et al*., 1990, von Gosen, 1992, Cristallini and Ramos, 2000). Despite a complex Tertiary evolution, the Argentine Precordillera is probably better known due to its superb exposures of Paleozoic sedimentary successions (*e.g.* Ramos *et al*., 1986, Astini *et al*., 1995). In particular, it is widely known for the development of an extended Early Paleozoic (mainly Middle Cambrian to Middle Ordovician) carbonatic platform with a very abundant and varied fauna of invertebrates with striking similarities to that in the Appalachians of eastern North America. This fauna similarities were first described by Borrello (1965, 1971) and many subsequent studies have permitted an extremely detailed characterization of its paleontological content (*e.g.* Benedetto, 2003, Bordonaro, 2003, and references therein).

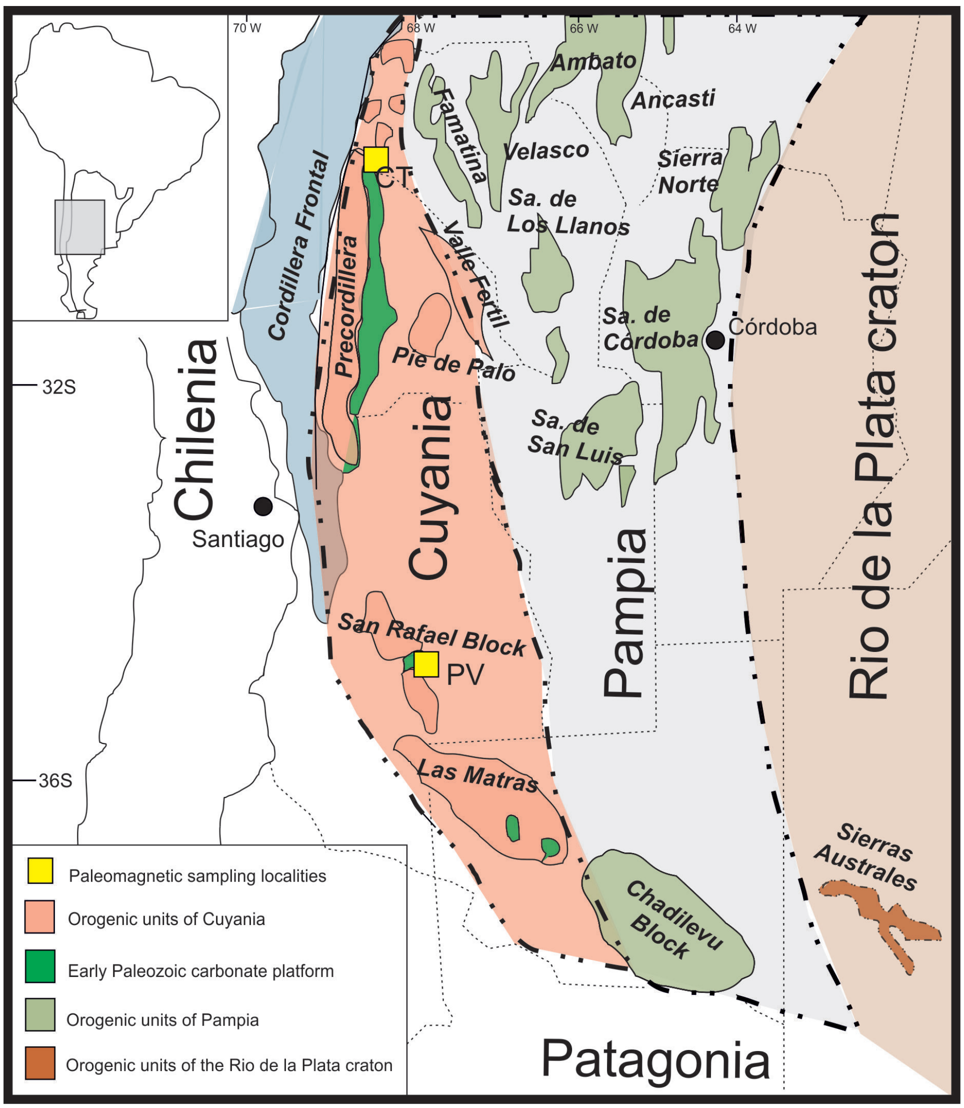

Figure 1. Simplified tectonic map of southern South America showing the main morphotectonic units and the extension of the Cuyania terrane and localities from which paleomagnetic results were obtained from Early Paleozoic rocks (simplified and modified from Ramos, 2004 and Finney, 2007). Boundary between Pampia and Rio de la Plata craton is modified from Rapela *et al*. (2007) and Ramos *et al*. (2010).

Astini *et al*. (1995) were the first to put forward a relatively complete tectonic model proposing that the Early Paleozoic carbonatic platform and related siliciclastic sediments of the Argentine Precordillera were deposited on an allochthonous terrane to Gondwana, that rifted apart from the Appalachian margin in Cambrian times; travelled across the southern Iapetus ocean and was accreted to the southwestern margin of South America in the Middle or Late Ordovician (Fig. 2). Previous suggestions of the Precordillera being a displaced terrane were published by Ramos *et al.* (1986) and Mena and Sellés-Martinez (1988) but without developing a proper tectonic model. Dalla-Salda *et al.* (1992) proposed that a very large strip of western South America, that included the Argentine Precordillera, was actually of Laurentian origin and called it the "Occidentalia" terrane. In their model this was accreted to Gondwana due to a continental collision between Laurentia and Gondwana in Ordovician times. Benedetto (1993) came closer to the tectonic model that was finally refined by the proposal by Astini *et al*. (1995). Short time later, Thomas and Astini (1996) completed the original model by proposing that the crustal fragment carrying the carbonate platform of the Argentine Precordillera rifted away from the Ouachita Embayment in the southern Appalachians in the Early Cambrian (Fig. 2a). The original publication by Astini *et al*. (1995) and a Penrose Conference on "The Argentine Precordillera: a Laurentian terrane?" held in the Argentine city of San Juan in 1995 (Dalziel *et al*., 1996) produced an extraordinary interest in its origin and fostered numerous studies in disciplines as different as biogeography, sedimentology, isotope geology, petrology, structural geology, paleomagnetism etc. This led to a decade (roughly 1995-2005) of huge advances in the

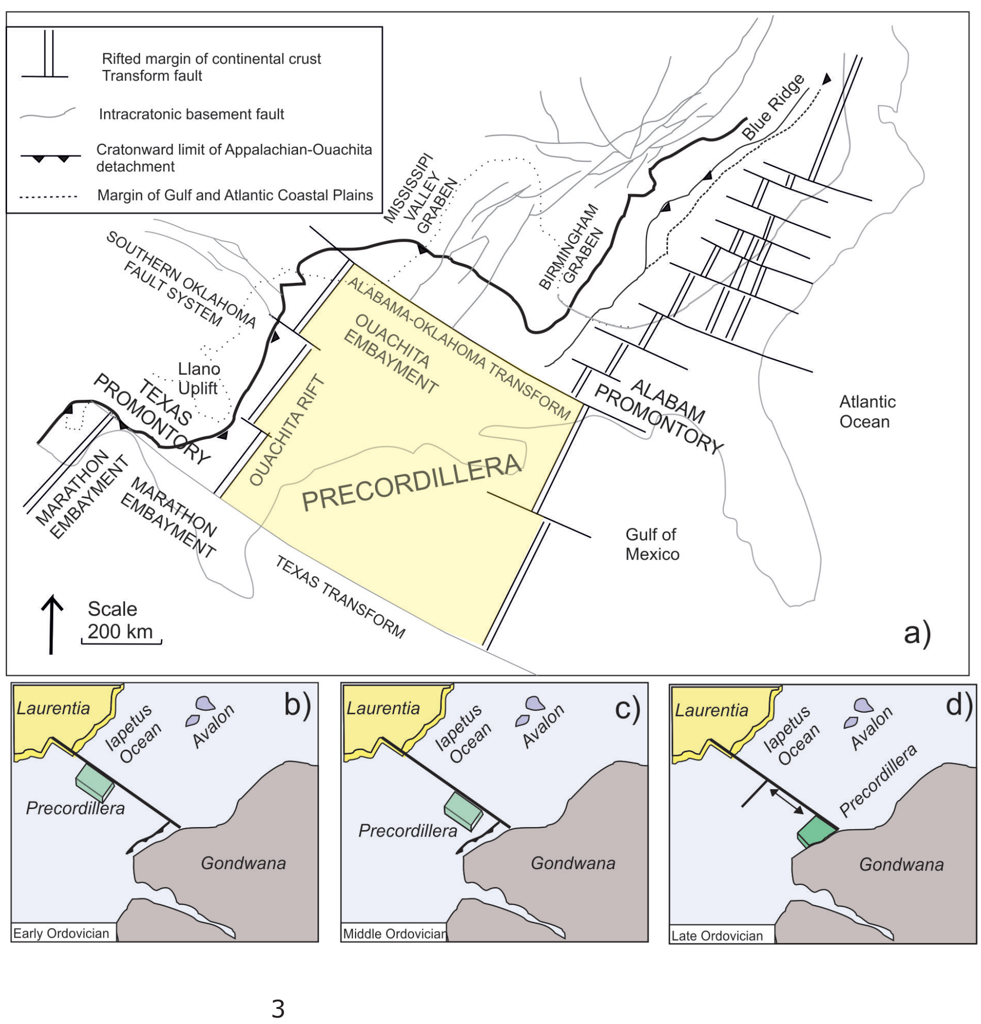

Figure 2. a) Tectonic sketch of southeastern North America with the modeled location of the Argentine Precordillera (or Cuyania) according to Thomas and Astini (1996). (Redrawn and simplified from the original authors). b), c) and d) Kinematic sketch of the hypothetical transfer of the Argentine Precordillera (or Cuyania) from Laurentia to Gondwana during Ordovician times (redrawn and simplified from Astini *et al.*, 1995).

knowledge of this region of western Argentina. Well over one hundred papers were published in that period dealing directly or indirectly with the origin of the Precordillera. Among many developments in this matter it is probably worth mentioning the near consensus reached in the fact that the Argentine Precordillera is just the best exposed part of a much larger terrane that was named "Cuyania" (Ramos *et al.*, 1998, see Fig. 1). Despite the fact that a majority of published articles since 1995 wholly or partially supported the original model of Astini et al. (1995) and Thomas and Astini (1996, Fig. 2), with minor or subtle modifications, controversies remained, particularly due to the fact that some researchers (*e.g.* Aceñolaza *et al*., 2002, Finney *et al.*, 2005) proposed a model that interpreted most evidence used to support the Laurentian origin of the Argentine Precordillera as evidence of a Gondwanan origin. In this alternative model the terrane was portrayed as para-authochthonous and displaced along the margin for about two thousands kilometers during the Early Paleozoic (Fig. 3), instead of "travelling" across the southern Iapetus Ocean. The literature published on the subject is too vast to be quoted in detail in this paper, but the reader can get good and detailed reviews of the "orthodox" and the "unorthodox" models in the review papers of Ramos (2004) and Finney (2007), respectively.

Rapalini and Tarling (1993) were the first to attempt recovering the original remanences from the thick Cambro-Ordovician carbonatic succession of the Argentine Precordillera. However, they failed due to the fact that the whole (or most) of it seems to be affected by a regional remagnetization ("the SanRafaelic Remagnetization") of Permian age. Further studies by Truco and Rapalini (1996), Rapalini *et al.* (2000) and Rapalini and Astini (2005) have better characterized this remagnetization process (see also the recent review by Font *et al.*, 2012). However, a successful paleomagnetic study was carried out on the Early Cambrian syn-rift red clastic successions of the Cerro Totora Formation exposed in the northern areas of Precordillera (Rapalini and Astini,

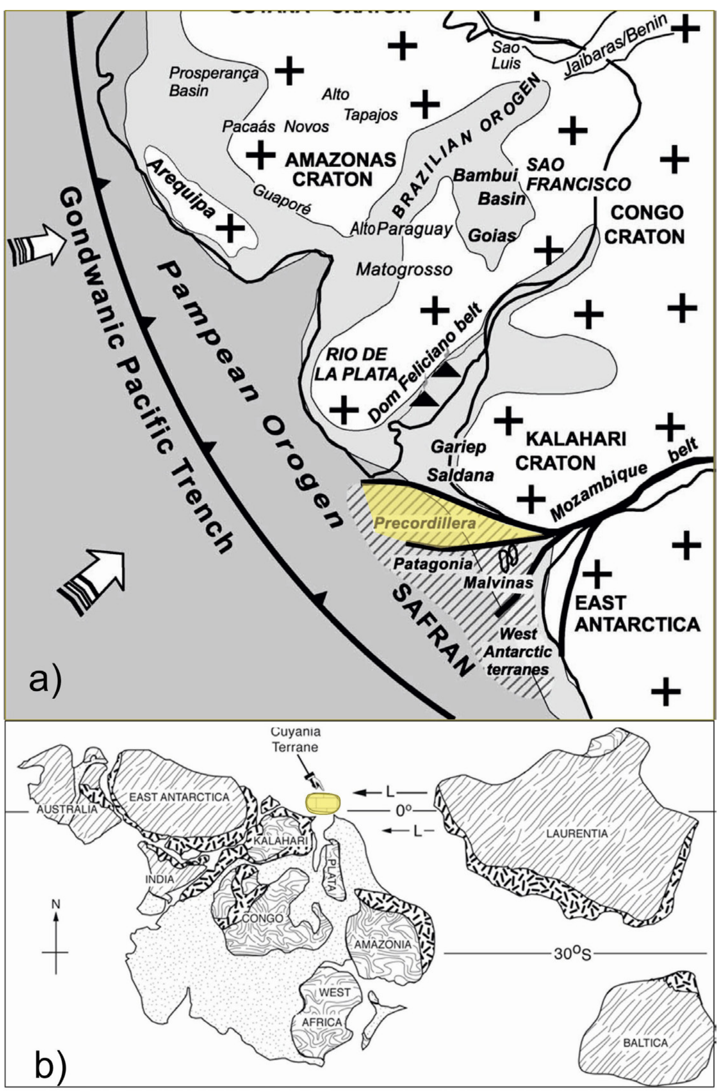

Figure 3. a) Sketch illustrating the proposed original position of the Argentine Precordillera (or Cuyania) in the SAFRAN hypothetical microcontinent (modified from Aceñolaza *et al.*, 2002). b) Paleogeographic reconstruction for Early Cambrian times with Cuyania located along the Gondwana margin, according to the SAFRAN hypothesis (modified from Finney *et al.*, 2005).

1997, 1998). This study provided the first reliable Early Paleozoic (Early Cambrian) paleomagnetic pole for the Argentine Precordillera. Its position was consistent with an origin of the Precordillera in the Ouachita Embayment of southern Laurentia and inconsistent with the position expected from the Gondwana apparent polar wander path known at that time (Fig. 4), and constituted a very robust evidence in favor of the Laurentian origin of this terrane, strongly supporting the model of Thomas and Astini (1996). Several years later, Rapalini and Cingolani (2004) obtained a second paleomagnetic pole for the Cuyania terrane, in this case of an early Caradoc age. Its interpretation respect to the time and way of transfer and accretion of this terrane to Gondwana was more ambiguous, in part due to the poor definition of the Late Ordovician paleomagnetic pole position for Gondwana (*e.g.* McElhinny and McFadden, 2000).

In part, the benign "fever" on "the origin of the Argentine Precordillera" has receded. It is probably a good time to re-assess the available paleomagnetic data in face of the new information that was produced since the original article by Rapalini and Astini (1998) was published and to analyze what constrains (if any) they place on the alternative models for the origin and evolution of this terrane in the Early Paleozoic.

2 Gondwana, Laurentia and Cuyania: Updated Paleomagnetic Data

Since the original publication by Rapalini and Astini (1998) the Ediacaran to Cambrian paleomagnetic pole data set for Gondwana (or several of its forming cratons) have significantly improved. Much effort has been devoted to try to determine time and kinematics of Gondwana formation in the last fifteen years which has led to a much larger and better data set of paleomagnetic poles. Table 1 presents a list of 22 paleomagnetic poles for different cratons of Gondwana between about 580 and 500 Ma. This has been updated from a previous compilation by Trindade *et al.* (2006). The new data set not only has significantly changed the

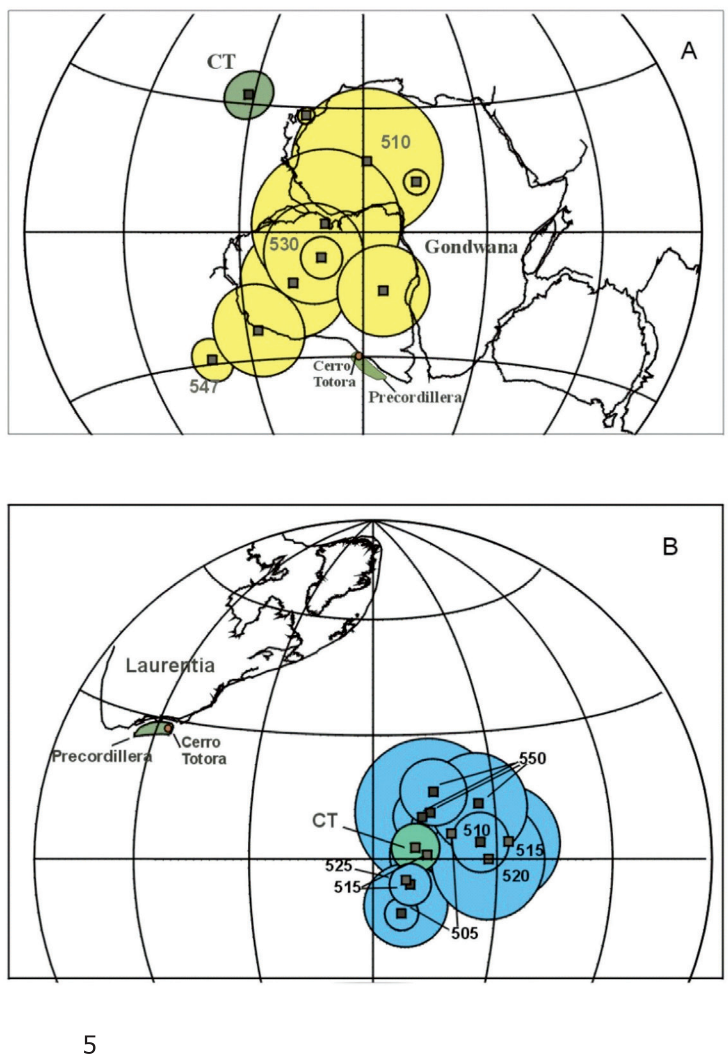

Figure 4. A) Comparison of the positions of the paleomagnetic pole from the Early Cambrian Cerro Totora Fm. (CT) with the available paleomagnetic poles for Gondwana, keeping the Argentine Precordillera in its present-day position in South America, as published by Rapalini and Astini (1998). B) Similar comparison of the Cerro Totora paleomagnetic pole position with respect to the coeval poles for Laurentia, if Cuyania is placed as the conjugate margin of the Ouachita Embayment, as published by Rapalini and Astini (1998). Numbers indicate approximate age of paleomagnetic poles for Gondwana and Laurentia in million of years.

Gondwana apparent polar wander path (APWP) for that time interval, but also has shed new light to the processes and time frame for Gondwana amalgamation. It is worth noting that the Gondwana APWP for this interval has become much better defined and it turned out to be significantly more complex than previously envisaged (compare figs 4a and 5b). It must be made clear now that what fifteen years ago was considered as a simple and single path for the whole of Gondwana (*e.g.* Meert and Van der Voo, 1996) since around 550 Ma, as shown in figure 4a, it is now considered only valid for some cratons, since amalgamation of Gondwana was well under way by the end of the Ediacaran. Trindade *et al.* (2006) provided strong evidence of a much longer and complex "Gondwana" APWP, as presented in Fig. 5b. According to these authors several Gondwana forming blocks were already united by the early Cambrian as suggested by the alignment of most paleomagnetic poles from different blocks, as Rio de la Plata, Congo-Sao Francisco, Arabia, East Antarctica and Australia, in a single path. The first two since around 580-570 Ma, while the others joining the path between 550 and 530 Ma. According to these authors the last big crustal block to assemble into Gondwana would have been Amazonia, which considering the Bambui B pole should have been part of the supercontinent by around 525 Ma. The complex process of Gondwana assembly is yet far to be known in detail but the main features of the APWP shown in Fig.5b seem to be robust enough to be used in paleogeographic and tectonic interpretations. Another interesting feature discovered by Trindade *et al*. (2006) is that the poles seem to agree much better into a single path if the "tight fit" Gondwana reconstruction proposed by Reeves *et al.* (2004) is used. A couple of new paleomagnetic poles have been published for the Gondwana forming blocks since the paper by Trindade *et al.* (2006). They belong to Ediacaran units in the Rio de la Plata (Los Barrientos, Rapalini, 2006) and Congo cratons (Nola dykes, Moloto-A-Kenguemba et al., 2008) which refine the older part of the path. As already mentioned, the new APWP for the "assembling Gondwana" is more complex than the one considered in the nineties. The new path shows a very long, fast and linear section from around 580 to 525 Ma. This is well determined by poles from Rio de la Plata and Congo between

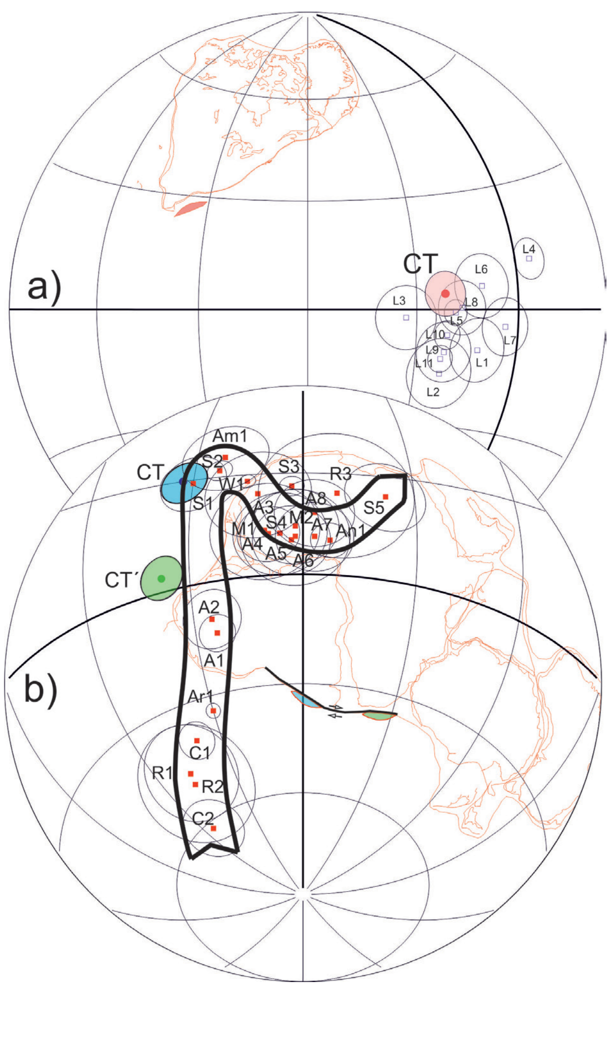

Figure 5. a) Updated comparison of the Cerro Totora (CT) paleomagnetic pole (ca. 515 Ma) with the approximately coeval poles for Laurentia placing Cuyania as the conjugate margin of the Ouachita Embayment. For identification of poles see Table 2. b) Updated comparison of the Cerro Totora paleomagnetic pole with the new apparent polar wander path for the "assembling Gondwana" (indicated with wide black lines). Cuyania is shown in two different positions: its present-day location in South America and the hypothetical position in the South American-African-East Antarctic (SAFRAN) embayment. CT (blue) and CT` (green) areas, are respectively the positions of the pole in each reconstruction. All poles are represented with their A95. For identification of poles see Table 1. See more references and discussion in the text.

Label	Geologic Unit	Pole Position			Age (Ma)
		Lat (°)	Long (°)	A95 (°)	
A1	Upper Arumbrera (Aus)	-14	336	5	545
A2	Todd River (Aus)	-10	335	8	528
A3	Hawker Group (Aus)	24	348	13	535
A4	Pertaoorta Group (Aus)	12	351	8	520
A5	Kangaroo Island (Aus)	12	354	12	519
A6	Billy Creek (Aus)	11	358	14	517
A7	Gilles Creek (Aus)	11	3	10	507
A8	Lower Lake Frome (Aus)	18	3	10	507
AM1	Araras Group B (Am)	36	338	10	525
AN1	Sor Rondane (Ant)	10	7	5	510
AR1	Mirbat Sandstone (Ar)	-34	330	2	550
C1	Sinyai Dolerite (C)	-40	321	5	547
C2	Nola Dykes (C) [1]	-62	305	8	571
M1	Madagascar Virgation Zone (M)	13	350	14	521
M2	Carion Granite (M)	14	358	11	508
R1	Los Barrientos (RP) [2]	-47	313	13	560
R2	Sierra de las Animas 2 (RP) [3]	-50	312	16	579
R3	Sierra de las Animas 1 (RP)	24	9	19	520
S1	Itabaiana dykes (SF)	29	330	8	525
S2	Bambui-Salitre C (SF)	32	337	3	525
S3	Bambui B (SF)	26	357	3	520
S4	Juiz de Fora Complex (SF)	10	357	10	510
S5	Piquete Formation (SF)	24	22	10	500
W1	Ntonya Ring (WA)	28	345	2	522

Table 1. Selected paleomagnetic poles from Gondwana cratons between ca. 580 and 500 Ma. Aus: Australia, Am: Amazonia, Ant: East Antarctica, Ar: Arabia, C. Congo, M: Madagascar, RP: Rio de la Plata, SF: Sao Francisco, WA: Western Africa. Table from Trindade *et al*. (2006) with the following modifications: [1] pole from the Nola dykes (Moloto A Kenguemba *et al*., 2008), [2] pole from the Los Barrientos claystones (Rapalini, 2006), [3] updated age for the Sierra de las Animas 2 pole from Oyhantzabal *et al*. (2007). Gondwana reconstruction in southern African coordinates according to Reeves *et al.* (2004) and Trindade *et al.* (2006). See representation of poles in Figure 5b.

580 and 560 Ma, followed by poles from Congo and Arabia of around 550 Ma and from Australia with ages between around 545 and 530 Ma. A conspicuous loop in the path, to the northwest offshore Africa, is dated at around 525 Ma from poles from Sao Francisco, West Africa and Amazonia. Since that, a dozen poles from several different continents (Table 1) define a path from about 525 to 510 Ma that enters NW Africa in a SE direction. A younger bend is suggested after 510 Ma so the pole reaches a position in the northern border of Africa by the Cambrian-Ordovician boundary (*e.g.* Grunow, 1999, Meert, 2001).

Improvements in Laurentia APWP for the latest Ediacaran – Cambrian has not been as significant as for Gondwana. Table 2 is based on the recent compilation by McCausland *et al.* (2011). Poles older than about 550 Ma have not been included since a long-standing controversy exists on the validity and interpretation of Laurentian paleomagnetic poles in the interval 580-560 Ma (see McCausland *et al.*, 2011 and references therein). Figure 5a shows distribution of these paleomagnetic poles. With the only exception of pole L4 (Mount Rigaud and Chatham), which seems somewhat discordant (undetected rotations?), all others seem to form a loose group with no evidence of significant polar wander. Whether Laurentia was at standstill near the equator for some 50 million years or experienced a very slow displacement relative to the rotation pole that cannot be resolved with the present database is still unknown. In any case it is quite clear that this continent was not affected by the fast displacements that experienced the "assembling Gondwana" at the same time.

No new paleomagnetic data from Cuyania has been published since the early Late Ordovician (ca. 455 Ma) paleomagnetic pole of the Pavón Formation (Rapalini and Cingolani, 2004). Therefore, the paleomagnetic database of this terrane consists in only two paleomagnetic poles (see Table 3), the early Cambrian Cerro Totora Fm (Rapalini and Astini, 1998) and the just mentioned Pavón Fm poles. Both are of high quality with positive fold tests and no resemblance to younger pole positions. In both cases, paleomagnetic data from younger units or magnetizations (see also Rapalini and Astini, 2005) indicate lack of local tectonic rotations since Permo-Triassic times at those localities.

3 Is Cuyania of Laurentian or Gondwanan Origin? An Updated Paleomagnetic Test

Rapalini and Astini (1998) provided the first paleomagnetic test for the origin of the Argentine Precordillera (Fig. 4). This was based on the Early Cambrian Cerro Totora pole (CT) that was compared with the available paleomagnetic poles of those days for Gondwana and Laurentia, keeping the suspect terrane in its present-day position within South America in a Gondwana reconstruction, and placing it in the Ouachita embayment, as proposed by Thomas and Astini (1996), respectively. At those times the comparison yielded a clear result in favor of a Laurentian origin for the Argentine Precordillera, since CT was inconsistent with the Gondwana APWP in the first alternative, while was consistent with coeval poles from Laurentia when placed as the conjugate margin of the Ouachita Embayment (Fig. 4). This was taken at those times as a robust support for the "orthodox" model of Laurentian origin of Cuyania (see for instance Ramos, 2004).

With the updated paleomagnetic database, particularly the Gondwanan one, and the newly proposed "unorthodox" model of Gondwanan para-authocthonous origin for Cuyania, it seems reasonable to perform the same test to confirm if the previously obtained conclusions still holds and if the paleomagnetic data available can be used to distinguish between both models.

Figure 5a presents a comparison of paleomagnetic pole positions between Laurentia (Table 2) and Cuyania (represented by CT, Table 3) when this terrane is positioned with its (present-day) western margin facing the continental margin of southeastern Laurentia represented in the Ouachita Embayment (see also Fig. 2a). Separation between both margins has been kept conservatively in the order of 200 km. Since in the

Label	Geologic Unit	Pole Position Lat (°)	Long (°)	A95 (°)	Age (Ma)
L1	Johnny Fm (rot)	-6	351	8	555
L2	Skinner Cove Fm	-10	337	9	550
L3	Wichita Granites	-2	327	8	533
L4	Mount Rigaud and Chatham	5	12	5	532
L5	Tapeats Sandstone (rot)	-1	341	3	508
L6	Florida Mountains aureole	6	349	8	503
L7	Tam Sauk Limestone	-4	356	7	500
L8	Moores Hollow	1	343	7	500
L9	Welge ss, Wiberns Fm.	-11	338	8	500
L10	Point Peak ss, Wiberns Fm.	-6	339	4	500
L11	Royer Dolomite	-13	337	4	500

Table 2. Selected paleomagnetic poles for Laurentia with ages between 550 and 500 Ma. Taken from McCausland *et al.* (2011). Poles L1 and L5 have been corrected for the Colorado plateau rotation (Molina Garza et al., 1995). See representation of poles in Figure 5a.

Label	Geologic Unit	Pole Position Lat (°)	Long (°)	A95 (°)	Age (Ma)
CT	Cerro Totora Fm (rotated to Gondwana)	30	327	6	525
CT	Cerro Totora Fm (rotated to Laurentia)	4	338	6	525
CT´	Cerro Totora Fm (rotated to SAFRAN)	4	322	6	525
PV	Pavón Fm (rotated to Gondwana)	27	18	4	455
PV	Pavón Fm (rotated to Laurentia)	-24	303	4	455
PV´	Pavón Fm (rotated to SAFRAN)	24	4	4	455

Table 3. Cuyania paleomagnetic poles. CT corresponds to the late Early Cambrian Cerro Totora pole and PV to the early Late Ordovician Pavón Fm. pole. Pole positions are presented 1) rotated to Gondwana (keeping present-day position of Cuyania in South America), following the rotation parameters of Reeves *et al*. (2004), 2) rotated to Laurentia (with Cuyania western margin placed as conjugate to the Ouachita Embayment): Lat: 9.9° N, Long: 311.4°, rot: 95.4° (cw), 3) rotated to a position in SAFRAN: Lat: 2.2° N, Long: 16.4°, rot: 32.6° (ccw), from its position in Gondwana. See representation of poles in Figures 5 and 7.

reconstruction the shape and size of Cuyania has been kept as it is today (Fig. 1), this separation can account for tectonic shortening of this terrane due to Andean deformation, which is of the order of 100 km in some areas of the Argentine Precordillera (*e.g.* von Gosen, 1992, Zapata and Allmendinger, 1996, Cristallini and Ramos, 2000), plus extension due to the postulated early Cambrian rifting event. CT corresponds to a pre-tectonic magnetization of red sandstones and siltstones deposited in a syn-rift environment. Age of these rocks is stratigraphically constrained as late Early Cambrian (Astini and Vaccari, 1996, Thomas *et al.*, 2001). Therefore, a most likely age for CT pole is considered as 515 Ma, due to the presence of *Olenellus* fauna in its top levels (Astini and Vaccari, 1996) and isotopic signatures of gypsum levels along the formation (Thomas *et al.*, 2001). As shown in figure 5a, CT pole is basically consistent with the Laurentian database for the 550-500 Ma interval. Since no APWP can be defined for such interval for Laurentia a more precise comparison cannot be done. Although it may be of no real significance, it is interesting to note that the Laurentian pole that shows the largest overlap of its confidence circle with that of CT belongs to the Tapeats sandstone of late Early to early Middle Cambrian age, resulting probably in the paleomagnetic pole with the closest age to that of the Cuyania pole. Also no statistically significant is the apparent position of CT on the "northern margin" of the group of Laurentian poles. This is very much dependent on the separation assumed between Cuyania and Laurentia by the late Early Cambrian. If later tectonic shortening (Devonian and Permian shortening of Precordillera has not been taken into account) as well as Early Cambrian stretching due to rifting have been underestimated, a displacement of CT towards the southeast is unavoidable, which will turn it closer to the center of the group of Laurentian poles. As evident from figure 5a, the western margin of Cuyania almost perfectly matches the southeastern margin of Laurentia in the Ouachita Embayment both in size, position and shape. This allows little room for significantly different relative positions of both continental masses beyond the already mentioned slightly larger separation.

Therefore, fifteen years later, the original conclusion by Rapalini and Astini (1998) that the Cerro Totora pole supports a Laurentian origin for the Argentine Precordillera, specifically from the Ouachita Embayment, still holds valid (compare figures 4b and 5a).

On the other hand, figure 5b shows the new "assembling Gondwana" APWP between 580 and 500 Ma (see above) and the position of CT if Precordillera is left in its present position in South America. The large change in the Gondwanan path has significantly changed the original conclusions by Rapalini and Astini (1998). As can be seen in the figure, CT is perfectly consistent with ca. 525 Ma paleomagnetic poles from Sao Francisco, West Africa and Amazonia. Following Trindade *et al.* (2006) we can accept that most cratons of Gondwana were already assembled by that time (however, see below further discussion on this). In particular CT falls exactly on top of the well-dated Itabaiana dykes pole of 525 Ma. This turns the original assertion by Rapalini and Astini (1998) that the Cerro Totora paleomagnetic pole constituted a robust evidence for the Precordillera to be allochthonous as apparently not valid anymore (compare figures 4a and 5b). However, this can only be sustained if a slightly older age for magnetization of the Cerro Totora sandstone (*i.e.* 525 Ma instead of 515 Ma) is accepted. Since no precise radiometric dating of this unit exists, the possibility of an older age for these rocks cannot be definitely ruled out, although this would contradict the only two available evidence to determine with some precision the depositional age of this formation. This difference of just 10 m.y. in the age of CT is crucial for testing the Gondwana origin of the Cuyania terrane, due to the very fast APWP experienced by the supercontinent during the whole Cambrian.

Thus, if a middle Early Cambrian age for the CT pole is accepted, an authochthonous origin for Cuyania cannot be ruled out on paleomagnetic grounds. However, no researcher has claimed in the last two decades (Gonzalez-Bonorino and Gonzalez-Bonorino, 1991) that the Precordillera is truly authochtonous, since a large spectrum of geologic evidence indicate that it must be "removed" from its present-day position in South America for at least Cambrian and Early Ordovician times. Some of the most compelling evidence is the presence of a wide and long-lived Middle Cambrian to Middle Ordovician stable carbonate platform (Fig. 1), indicative of a passive margin, side by side with a major Early to Middle Ordovician magmatic belt located to the east (The Famatinian Magmatic belt) that corresponds to a continental magmatic arc developed on top of an east-directed (present-day coordinates) subduction zone, and only possible if an active continental margin existed where the carbonate platform is located today (*e.g.* Pankhurst and Rapela, 1998). Completely different Cambrian faunas in the Precordillera respect to all neighbouring geologic provinces in Argentina (*e.g.* Benedetto, 1993), as well as the abrupt dissapearence of the carbonatic platform out of the Cuyania boundaries, are just other two of the extremely robust evidence that indicate that Cuyania must be displaced from its present position in South America for Cambrian times (for more details on these evidence see the review by Ramos, 2004 and references therein).

The alternative, "unorthodox", model of a Gondwanan para-authochthonous origin of Cuyania has been reviewed recently by Finney (2007). The original proposal of this model was published by Aceñolaza *et al*. (2002) who proposed that Cuyania was a terrane displaced along the Paleozoic Gondwana margin. According to these authors, this terrane originated in the "embayment" between South America, South Africa and East Antarctica (Fig. 3a). In this model Cuyania (quoted as Precordillera) was part of a relatively larger terrane that was labeled the SAFRAN microcontinent. This model lacks the detailed kinematics and paleogeographic relations of the Cuyania terrane with respect to its parental continent, that the "orthodox" model shows (compare figures 2a and 3a). However, some constraints from this model have been published by their advocates (Aceñolaza *et al*., 2002; Finney *et al*., 2005; Finney, 2007). The original position of Cuyania is clearly indicated to be immediately to the south (present-day coordinates) of the southern boundary of the Kalahari craton in South Africa. Displacement of the terrane towards its final position in Gondwana occurred from Late Ordovician to Devonian times. This displacement would have taken place along a major transcurrent (or transform) fault zone that would mark the eastern boundary (present-day coordinates) of the terrane. Following this, Cuyania has been displaced in figure 5b in such a way that its present-day eastern margin faces the southern margin of the Kalahari craton. The corresponding position of the Cerro Totora pole (CT´) is displaced now out of the APWP of the "assembling Gondwana" and towards an older section of it (ca 530 Ma?). Unless a later in situ counterclockwise rotation of around 30° is proposed for the Cerro Totora locality, the new pole position cannot be made consistent with the coeval paleomagnetic poles for Gondwana. The "unorthodox" model suggests that Cuyania experienced a dextral displacement of around

2000 km from its position as part of the hypothetical SAFRAN to its present-day position in South American Gondwana. Rapalini and Astini (2005) have proved that no tectonic rotations affected the Cerro Totora area since Permo-Triassic times, leaving the proposed intracontinental displacement as the main possible tectonic process to associate with the needed rotations in order to match the Cerro Totora with the coeval Gondwana poles. Although ccw rotations can be found associated to large dextral displacements, these areas are much more prone to undergo clockwise, and not counterclockwise, rotations (*e.g.* Luyendik *et al.*, 1980, Ron *et al.*, 1984, Nur *et al.*, 1986, McKenzie and Jackson, 1986, Lamb, 1988, Beck, 1991, etc).

In resume, the newly available APWP for the "assembling Gondwana" shows an striking coincidence of the Cerro Totora pole with the Gondwana poles of around 525 Ma. However, this age is older than independent determinations of the most likely age for this formation. Relocation of Cuyania along the Gondwana margin following the "para-authochtonous displaced terrane model" of Aceñolaza *et al*. (2002) and Finney (2007) produces a worse comparison of Cuyania`s early Cambrian pole with the coeval Gondwana APWP, unless ad hoc later tectonic rotations or a significantly different original position for Cuyania along the Gondwana margin are invoked.

Recently, Spagnuolo *et al*. (2011) have published the first Cambrian paleomagnetic pole for the Pampia terrane. Data come from the Middle to early Late Cambrian Mesón Group. The correspondent paleomagnetic pole is somewhat displaced from the expected late Cambrian Gondwana mean pole, and although different interpretations are possible, the authors have proposed a paleogeographic model to account for this paleomagnetic result that involves the strike-slip displacement of the Pampia terrane (plus Arequipa-Antofalla) from the southern tip of the Kalahari craton along the western margin of southwestern Gondwana (Fig.6). This model was based on an original speculation by Schwartz and Grommet (2004), later developed into a tectonic model by Rapela *et al.* (2007). With the important difference that in the Spagnuolo et al. (2011) model Pampia reached its final position along the Gondwana margin during the latest Cambrian – Early Ordovician, as opposed to the Devonian age proposed by Aceñolaza *et al*. (2002) and Finney (2007) for the Argentine Precordillera, both models share some similarities. Cambrian displacement of the Pampia terrane is mainly supported by the already mentioned paleomagnetic data as well as changes in the detrital zircons age patterns along the Pampia terrane from latest Precambrian to Ordovician times (*e.g.* Rapela *et al.*, 2007, Verdecchia *et al.*, 2011). It has been associated to final displacements of marginal terranes at the end of Gondwana assembly. In particular, Spagnuolo *et al.* (2011) have suggested that Pampia movement was associated to final collision of the Kalahari craton and the lateral escape of a marginal crustal slice. This model is still speculative and different lines of evidence, including further paleomagnetic data, are necessary to confirm it or rule it out (see Ramos *et al.*, 2010, for an opposite view to this model). If supported by future data, this model would turn the "unorthodox" model for the origin of the Argentine Precordillera invalid. To solve this problem the latter will have to be displaced even further south (in a Gondwana framework in African coordinates) near the TransAntarctic Mountains. No significant Early Paleozoic similarities exist between this region and the Argentine Precordillera and in any case a later displacement of around four thousand kilometers will turn this possibility highly unlikely.

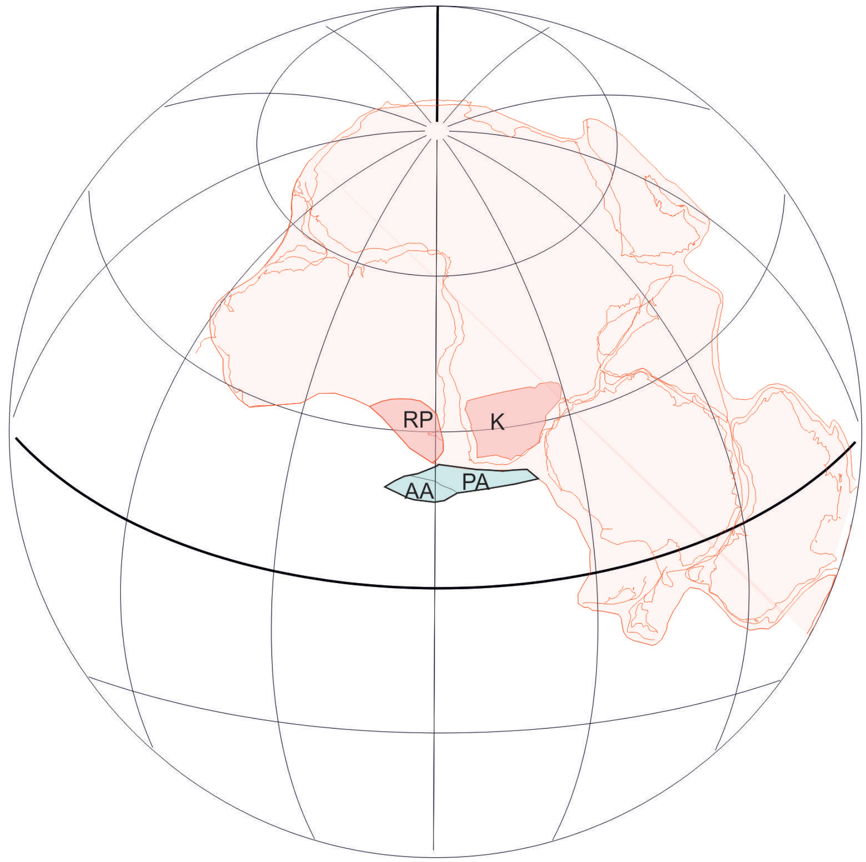

Figure 6. Paleogeographic reconstruction of Gondwana in middle to early Late Cambrian times according to Gondwana mean pole position of Meert (2001) and proposed location of the Pampia (PA) + Arequipa-Antofalla (AA) terranes according to Spagnuolo *et al*. (2011). More references in the text.

The other paleomagnetic pole available for Cuyania (Rapalini and Cingolani, 2004) belongs to the early Caradoc Pavón Fm. exposed in the San Rafael Block, some 500 km south from the Cerro Totora outcrops. The age of this unit is very well determined on the basis of a rich fossil fauna of graptolites (Cuerda and Cingolani, 1998). Positive fold and reversal tests as well as lack of resemblance to younger poles suggested that these rocks carry a primary remanence from which the paleomagnetic pole was computed (PV, table 3). The Late Ordovician reference poles for both Laurentia and Gondwana have remained unchanged since this pole was published, therefore very little can be add to the original interpretations of Rapalini and Cingolani (2004). Figure 7 illustrates the comparison of the PV pole with the coeval reference poles for Laurentia (450 Ma, McElhinny and McFadden, 2000) and Gondwana (455 Ma, McElhinny and McFadden, 2000) according to the different models for the origin of the Cuyania terrane. Rapalini and Cingolani (2004) pointed out that PV is strikingly coincident with the coeval reference pole for Laurentia if Cuyania remains attach to the Ouachita Embayment of Laurentia by the early Late Ordovician (Fig. 7a). Several lines of evidence suggest, however, that by that time connection with Laurentia had already ended (Astini *et al*., 1995; Ramos, 2004 and many others) or at least was very tenuous (Dalziel, 1997, Keller *et al.*, 1998). The latter authors proposed that connection between Cuyania and Laurentia remained until the Late Ordovician, and in particular Dalziel (1997) suggested that Cuyania was actually a fragment of stretched Laurentian continental crust that remained attached to the continent as a large plateau ("Texas plateau") similar to the present-day Malvinas plateau that is attached to South America. Figure 7b shows that the early Late Ordovician paleomagnetic pole from Cuyania is consistent with such model.

Most authors that support the "orthodox" model of Laurentian origin for Cuyania disagree with the "Texas plateau" proposal on the basis of several lines of evidence that would support collision of this terrane with Gondwana not later than Late Ordovician (see Thomas *et al.*, 2002 and references therein). If Cuyania was already part of Gondwana by Caradoc times, PV must be compared with the coeval reference pole for Gondwana. Unfortunately this is very ill defined (McElhinny and McFadden, 2000) as shown by its large confidence circle (Fig. 7c). Plotted in a Gondwana reference frame, PV is not consistent with the coeval pole for Gondwana. Their positions can be reconciled by an in situ clockwise local rotation of around 25° of the Pavón Fm sampling locality, since no significant anomaly in paleolatitude exists between the reference pole of Gondwana and PV (see PV rotated 25° as dashed circle in Fig, 7c). A secondary component from the same unit as well as paleomagnetic results from a Permo-Triassic rhyolitic dome intruding it constrain, however, any local rotation to be pre- Permo-Triassic. Rapalini and Cingolani (2004) proposed that the rotation could either be valid for the whole of Cuyania, in which case it would record the final stages of the terrane collision or it would represent a pre-Permian local tectonic rotation. Confirmation of any of these interpretations awaits the obtention of new late Ordovician paleomagnetic data from Cuyania as well as a better definition of the Gondwana reference pole.

Figure 7c shows the position of the PV pole (PV`) if rotated according to a position of Cuyania as part of the hypothetical SAFRAN microcontinent. According to the advocates of this model (Aceñolaza *et al*., 2002, Finney, 2007) Cuyania started its displacement along the margin of Gondwana by late Ordovician times. Therefore, the same position has been kept for Cuyania in this case as in the Early Cambrian. Placing Cuyania in such position virtually eliminates the need for a local in situ rotation, however PV´and the 455 Ma reference pole for Gondwana only overlaps partially, with a non-negligible difference in paleolatitude (anomalously high for Cuyania) indicated by both paleomagnetic poles taken at

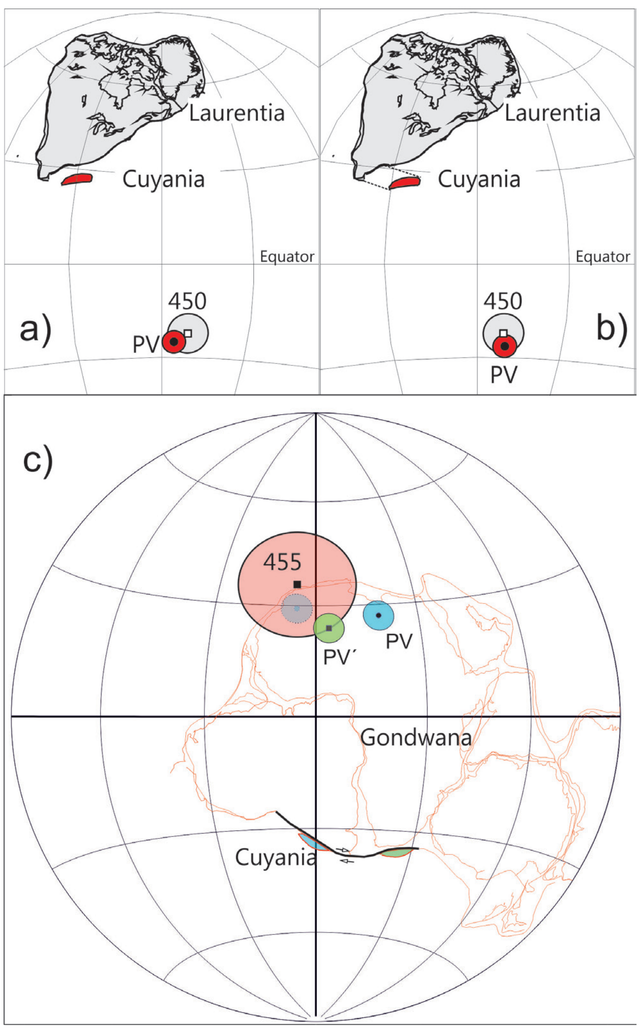

Figure 7. a) Comparison of the early Late Ordovician (ca. 455 Ma) Pavón Fm. paleomagnetic pole (Rapalini and Cingolani, 2004) for Cuyania with the reference mean pole for Laurentia of 450 Ma (McElhinny and McFadden, 2000) if this block is kept as the conjugate margin of the Ouachita Embayment. b) Idem *a)* but considering Cuyania as part of the Texas plateau (Dalziel, 1997). c) Comparison of the Pavón Fm. pole with the coeval mean reference pole of Gondwana with Cuyania in its present-day position in South America (PV, blue circle) and with Cuyania in the SAFRAN position (PV´, green circle). Dashed purple circle corresponds to the position of PV after an in situ ccw rotation of 25°. More references and discussion in the text. (Figures modified from Rapalini and Cingolani, 2004).

face value. However, this becomes barely significant when the statistical uncertainties are considered due to the very large confidence circle of the Gondwana pole.

4 Conclusions

Research on the origin of the Argentine Precordillera, and its extension in the composite Cuyania terrane, has produced great enthusiasm and debate during the last two decades. An enormous advance in the knowledge of the geology of this region of South America as well as in the global paleogeographic and tectonic evolution during the Early Paleozoic have been its main products. Nowadays most researchers seem to have reached a consensus in that this terrane rifted away from the Ouachita Embayment of Laurentia in Cambrian times to become accreted to the southwestern margin of Gondwana by the end of the Ordovician. However, some investigators have challenged the majority view and postulated that Cuyania originated in Gondwana, between the present-day South Africa and East Antarctic margins, and that was displaced along a major transform fault parallel to the continental margin to reach its present position in South America by Devonian times.

Almost fifteen years ago, Rapalini and Astini (1998) published the first Early Paleozoic paleomagnetic pole from the Argentine Precordillera, correspondent to the Early Cambrian Cerro Totora Formation. At that time comparison with the available paleomagnetic database for Laurentia and Gondwana seemed to provide very robust evidence that Cuyania originated in the Ouachita Embayment and was therefore allochthonous to Gondwana. A second pole was later obtained from early Late Ordovician rocks for Cuyania but its interpretation was more ambiguous and could be accommodated to different models.

Since those times, in particular the Gondwana paleomagnetic database between around 580 and 500 Ma have improved substantially, changing significantly the assumed APWP for this supercontinent used in the original comparisons. The Laurentian database for the latest Ediacaran-Cambrian, on the other hand, has barely changed since then. A new analysis of the available paleomagnetic poles for Cuyania with respect to the updated ones for Laurentia and Gondwana yield the following conclusions:

a) The Early Cambrian Cerro Totora paleomagnetic pole is most likely of 515 Ma and coincides with approximately coeval poles from Laurentia if Cuyania is placed as the conjugate margin of southeast Laurentia at the Ouachita Embayment; supporting the model that states that it is a Laurentian derived allochthonous terrane in Gondwana.

b) The position of the Cerro Totora pole, keeping Cuyania in its present-day position in South America, is no longer inconsistent with the APWP for Gondwana, although it matches pole positions slightly older (525 Ma) than the most likely age of the rocks from which it was computed.

c) Placing Cuyania next to the southern margin of the Kalahari craton, in a SAFRAN configuration, makes the Cerro Totora pole more discordant to the Gondwana APWP as it is displaced towards older sections of the path and out of it.

d) In such paleogeographic configuration, the pole can only be reconciled with the Gondwana coeval poles by assuming a significant ccw rotation of the Cerro Totora area, which has been determined not to have experience such rotation at least since Permo-Triassic times.

e) Since no changes have been produced in the last ten years in the Late Ordovician paleomagnetic poles for Gondwana and Laurentia, the interpretation of the early Caradoc pole for Cuyania from the Pavón Fm suffers similar ambiguities as those reported in the original publication (Rapalini and Cingolani, 2004).

f) While this pole position perfectly agrees with the Laurentian coeval reference pole keeping Cuyania attached to Laurentia or as part of the Texas plateau, the model that proposes that for Caradoc times Cuyania was already accreted to Gondwana can be reconciled with the paleomagnetic data if a post-Ordovician and pre-PermoTriassic in situ 25 °cw rotation is assumed either as a local crustal block rotation or for the whole of Cuyania as part of its acretionary process.

g) This rotation is not necessary in the SAFRAN model although this produces a larger paleolatitude anomaly, which is barely significant due to the large uncertainty in the reference pole for Gondwana.

h) If a recent tectonic model (Spagnuolo *et al.*, 2011), based on paleomagnetic data, that proposes that the Pampia and Arequipa-Antofalla terranes were displaced from the southern Kalahari margin in late Cambrian times on a major strike-slip system along the Kalahari and Rio de la Plata margins, is confirmed, the model of Gondwanan para-authochtonous origin of the Argentine Precordillera will become unsustainable.

i) After fifteen years of the first paleomagnetic test, the available paleomagnetic information is consistent with the Cuyania terrane rifting away from the Ouachita Embayment in SE Laurentia, and although the data itself cannot definitely rule out the alternative model of a Gondwanan para-authochtonous origin for this terrane, it would require to assume ad-hoc and apparently unlikely tectonic rotations associated to Cuyania displacement previous to its accretion.

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