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Reinterpretation of the Ordovician rotations in NW Argentina and Northern Chile: a consequence of the Precordillera collision?

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Abstract Early Paleozoic paleomagnetic data from NW Argentina and Northern Chile have shown large systematic rotations within two domains: one composed of the Western Puna that yields very large (up to 80°) counterclockwise rotations, and the other formed by the Famatina Ranges and the Eastern Puna that shows (~40°) clockwise rotations around vertical axes. In several locations, lack of significant rotations in younger rocks constrains this kinematic pattern to have occurred during the Paleozoic. Previous tectonic models have explained these rotations as indicative of rigid-body rotations of large para-autochthonous crustal blocks or terranes. A different but simple tectonic model that accounts for this pattern is presented in which rotations are associated to crustal shortening and tectonic escape due to the collision of the allochthonous terrane of Precordillera in the Late Ordovician. This collision should have generated dextral shear zones in the back arc region of the convergent SW Gondwana margin, where systematic domino-like clockwise rotations of small crustal blocks accommodate crustal shortening. The Western Puna block, bordering the Precordillera terrane to the north, might have rotated counterclockwise as an independent microplate due to tectonic escape processes, in a fashion similar to the present-day relationship between the Anatolia block and the Arabian microplate.

Keywords Paleomagnetism · Gondwana · Paleozoic · NW Argentina · Block rotations

Introduction

The Early Paleozoic tectonic evolution of the south western Gondwana margin (NW Argentina and N Chile) has been intensively discussed in the last two decades (e.g. Pankhurst and Rapela 1998; Ramos and Keppie 1999; Vaughan et al. 2005). Some authors, based on petrological and isotopic data, interpreted that between 20° and 26°S this margin had an evolution of an intra-cratonic mobile belt dominated by intracrustal recycling with minor contributions of juvenile magmatism for the Late Neoproterozoic and Early Paleozoic (Damm et al. 1990; Becchio et al. 1999; Lucassen et al. 2000). In a contrasting model, the evolution of the SW margin of Gondwana has been characterized as significantly influenced by the accretion of different allochthonous and/or para-authochthonous terranes that led to different orogenic cycles (e.g. Ramos et al. 1986; Astini et al. 1995; Rapela et al. 1998; Thomas and Astini 2003; Dávila et al. 2003; Ramos 2008). The Famatinian Cycle (Aceñolaza and Toselli 1976) developed along the southwestern Gondwana margin from the Early-Middle Ordovician to the Silurian with an enormous volume of magmatism associated to a subduction regime

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for over 1,000 km along this margin (e.g. Llambías et al. 1998; Pankhurst and Rapela 1998). This continental volcanic arc is particularly well exposed in the Famatina Ranges of Argentina, but it can be traced to the north, along the Western Puna (Astini and Dávila 2004; Kleine et al. 2004), and to the south along the Sierras Pampeanas and perhaps into the North Patagonian Massif (Pankhurst et al. 2006). Two contrasting interpretations have been given regarding the extent of this magmatism. One infers that the Famatinian Orogen developed crustal thickness in excess of 50 km, similar to the present day Andes (Becchio et al. 1999; Lucassen et al. 2000, 2001; Lucassen and Franz 2005). On the other hand, many authors interpreted the volcanic arc associated to a back-arc basin that accommodated a thick succession of Ordovician marine sedimentary and volcanic rocks (Astini 2003 and references therein). Widespread extensional features in the Famatinian back-arc have been described in several localities (Manheim 1993; Mangano and Buatois 1996; Esteban and Gutierrez-Marco 1997; Benedetto 1998; Esteban 1999; Esteban et al. 1999; Astini 2003; Bierlein et al. 2006), suggesting significant crustal stretching including the possibility of oceanic crust generation (Sims et al. 1998; Miller and Söllner 2005). The Late Ordovician to Early Silurian tectonic event (the "Ocloyic phase" of Mon and Salfity 1995) produced significant shortening (Astini and Dávila 2004), mainly through E-directed thrusts (Rapela et al. 2001; Astini and Dávila 2004) and shear zones (Perez et al. 1991; López and Toselli 1993; Sims et al. 1998; Miller and Söllner 2005), metamorphism (Rapela et al. 2001; Simpson et al. 2003; Steenken et al. 2004; Collo et al. 2008) and demise of the arc related magmatism (Durand and López 1996; Rapela et al. 1998, 2001; Dahlquist et al. 2008).

None of the former two alternative interpretations have thoroughly considered crustal kinematics which is the core of this paper. Paleomagnetism is an excellent method to establish the paleolatitudinal position and former orientation of crustal blocks. Early Paleozoic paleomagnetic data from NW Argentina and N Chile have shown large systematic rotations with limited to no paleolatitude anomaly (Valencio et al. 1980; Forsythe et al. 1993; Conti et al. 1996; Rapalini et al. 1999, 2002; Rakotolofo 2004; Spagnuolo et al. 2008; Spagnuolo 2009). These paleomagnetic poles were obtained in the Western Puna of Chile and Argentina, the Eastern Puna, the NW Pampean Ranges and the Famatina Ranges. All results from the latter three areas are consistent in showing large (i.e. around 40°) clockwise (cw) rotations around vertical axes, when compared with the coeval reference pole for Gondwana (e.g. Grunow 1995, 1999). On the other hand, the available data from the Western Puna yielded very large (up to nearly 90°) counterclockwise (ccw) rotations.

Published tectonic interpretations of these paleomagnetic results (Forsythe et al. 1993; Conti et al. 1996) proposed the opposite rotations of large para-authocthonous terranes (i.e. ccw for the Arequipa-Antofalla and cw for the Eastern Puna-Famatina) producing the closure of ocean floored backarc basins to the east and their subsequent accretion to the Gondwana margin (Fig. 1). Age of such collisions was loosely constrained by the paleomagnetic data, but from geologic interpretations it was speculated to be latest Ordovician for the Arequipa-Antofalla block and Mid-Ordovician for the Eastern Puna-Famatina terrane (see as review Ramos 2008). Both models were discussed by various authors (Pankhurst et al. 1998; Rapela et al. 1998; Saavedra et al. 1998; Rapalini et al. 1999; Quenardelle and Ramos 1999; Astini 2003), who generally pointed out several kinematic problems posed by those tectonic models.

The aim of this work is to present a new interpretation of the Ordovician paleomagnetic poles from NW Argentina and N Chile within a tectonic model that can integrate the geophysical (paleomagnetic), geological and magmatic evidence of the region.

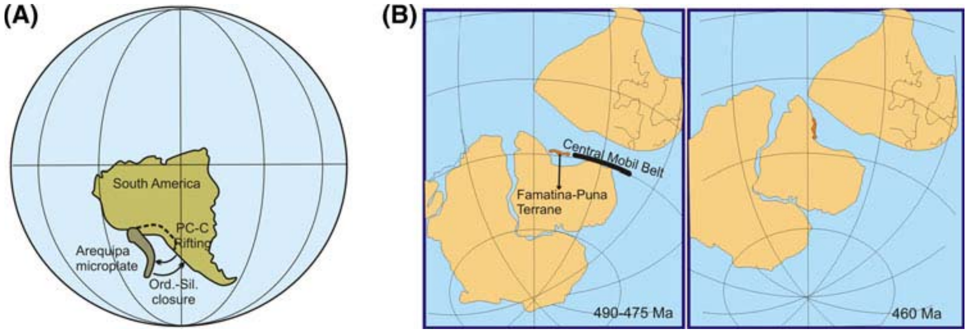

Fig. 1 Previous models to explain the Ordovician rotations. **a** Reconstruction of the Arequipa rotation, opening a basin during the Precambrian-Cambrian and closing it during the Ordovician–Silurian (Forsythe et al. 1993). **b** Paleogeographic reconstruction of Gondwana and Laurentia showing the position of the composed terrane of Famatina-Eastern Puna volcanic arc (Conti et al. 1996)

Paleomagnetic poles

Clockwise rotations (Famatina Range, NW Pampean Ranges and Eastern Puna)

Conti et al. (1996) carried out paleomagnetic studies in Lower-Middle Ordovician sedimentary and volcanic units (Susques and Acoite Fms) of the Eastern Puna, in the Early Ordovician Cuchiyaco Granodiorite of the NW Pampean Ranges (Table 1), and reassessed and reinterpreted the results of Valencio et al. (1980) in the late Early Ordovician volcanic and volcanoclastic Suri and Las Planchadas formations in the Famatina Ranges. All these rocks provided similar paleomagnetic results, despite the different lithologies, magnetic carriers and locations separated by several 100 km. In view of the consistent results in all these localities, the authors considered them as part of a several 100 km long coherent crustal block (The "Puna-Famatina terrane"; Fig. 1b), calculating a single paleomagnetic pole, PF: 21.8°S 1.3°W A95 = 7.5° $K = 57$ N (sites) = 16, from paleomagnetic directions obtained at the four different localities. When this pole is compared with the coeval reference pole of Gondwana for 475 Ma (Grunow 1995), a clockwise rotation of ~50° is evident (Fig. 2). The authors interpreted an Early Paleozoic age for the rotations, although no independent paleomagnetic data from younger rocks at the same localities were available at that time.

Spagnuolo et al. (2008) published robust paleomagnetic results from the Middle Ordovician Cerro Morado Group and the Molles Formation exposed in the Central Famatina Ranges. Rhyolite and ignimbrite flows of both units have similar magnetic behaviors, magnetite being the principal magnetic carrier. A magnetic component of high temperature/magnetic fields (400–580°C/15–100 mT) was isolated in most sites and samples. The fold test of Watson and Enkin (1993) indicated a pre-tectonic component. A paleomagnetic pole was obtained from these rocks, MCM1: 16.7°S 357.2°E A95 = 6.5° $K = 38.5$ N (sites) = 14 (Fig. 2; Table 1). In the same publication paleomagnetic results from the Permian De La Cuesta and La Veteada Formations, exposed in the same localities, were reported. AF and thermal demagnetization and IRM acquisition curves showed that hematite is the principal magnetic carrier in these rocks. A high temperature magnetic component characterized by southward declinations and positive inclinations was obtained, LC1: 76.9°S 345.2°E A95 = 9.4° $K = 21.1$ n (samples) = 29. On the other hand, in sedimentary sites of the Ordovician Molles Formation and a single site from the Cerro Morado Group a high temperature component carried by hematite was also found (see Spagnuolo et al. 2008 for the detailed analysis). After applying a Permian structural correction, a paleomagnetic pole was calculated for this magnetization, MCM2: 78.7°S 330.8°E A95 = 7.2° $K = 16.1$ $n = 27$. The similarity of the last two results after the structural correction suggests that both components were acquired at the same time (i.e. Permian). A composite paleopole was calculated LC3: 79.1°S 337.1°E A95 = 7.3° $K = 35.98$ (Fig. 3). The exclusive reverse polarity is consistent with

Table 1 Ordovician paleomagnetic poles of NW Argentina and N Chile

Paleomagnetic pole	Sampling area	Dec	Inc	PLat	PLong	A95 (dp/dm)	Rotations	Age (Ma)	References
Western Cordillera									
CHA	24.3°S 67.3°W	319.4°	57.4°	16.9°N	260.3°E	(20.4/27.8)	79.6 ± 18.6°	Early Ordovician; 469 ± 4	Rapalini et al. (2002)
CHO	24°S 68.5°W	9.6°	12.9°	58.1°N	309.3°W	(3.8/7.5)	41.8 ± 7.4	502 ± 10	Forsythe et al. (1993)
OP	24°S 68.5°W	320.6°	74.0°	0°S	271°E	(12.4/13.7)	76.9 ± 12.1	441 ± 8; 466 ± 44; 452 ± 4	Forsythe et al. (1993)
Famatina Ranges									
FS	27.8°S 68.1°W	90.5°	47.2°	13.0°S	3.7°W	6°	34.6 ± 7.4	Late lower-early middle Ordovician	Conti et al. (1996)
MCM1	28.7°S 67.8°W	93.4°	47.7°	16.7°S	357.2°E	6.5°	35.4 ± 7.8	Early-late middle Ordovician	Spagnuolo et al. (2008)
Eastern Puna									
PO	23.4°S 66.3°W 23.6°S 66.4°W	98.1°	47.9°	17.7°S	2.1°W	13°	38.1 ± 12.4	Lower-middle Ordovician	Conti et al. (1996)
Eastern Cordillera									
CY	26.1° 65.8°W	111.1°	50.9°	30.0°S	0.5°E	10°	52.4 ± 10.3	472 ± 15	Conti et al. (1996)

Dec declination, *Inc* inclination, *Plat* paleomagnetic latitude, *Plong* paleomagnetic longitude, *A95* (*dp*/*dm*) statistical parameters

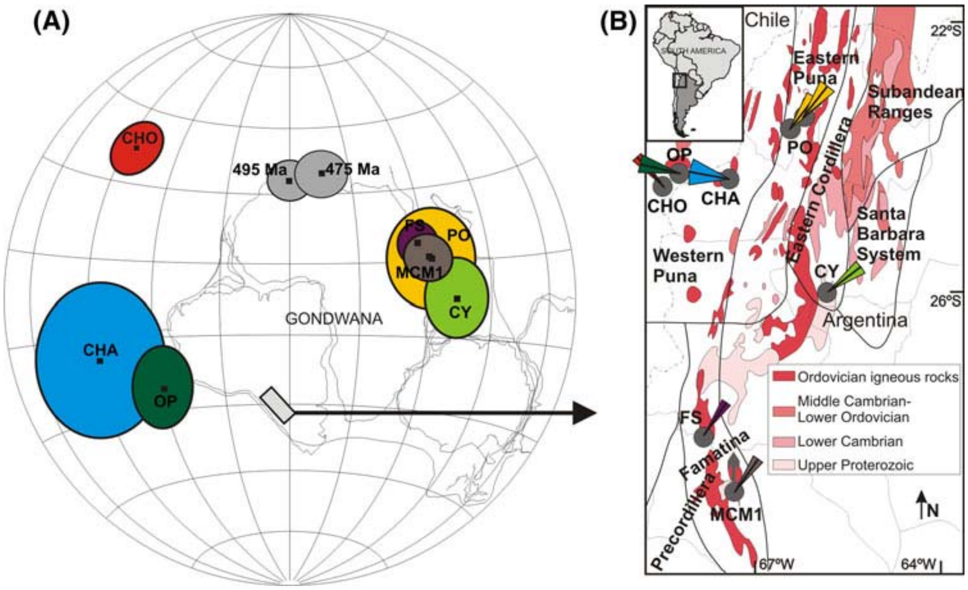

Fig. 2 **a** Ordovician poles in African coordinates: *MCM1* (Spagnuolo et al. 2008), *CY*, *PO*, *FS* (Conti et al. 1996), *CHA*, *CHO* (Forsythe et al. 1993), *OP* (Rapalini et al. 2002), 475 and 485 Ma (mean poles of Gondwana, Grunow 1995, 1999). **b** Map of NW Argentina, showing the paleomagnetic localities, with rotation values at each paleomagnetic study area with cones of 95% confidence limits

remanence acquired during the Late Paleozoic Reverse Superchron (or Kiaman, Opdyke and Channell 1996). The position of the combined pole in the South American APWP (Fig. 3; Tomezzoli 2001; Geuna and Escosteguy 2004; Rapalini et al. 2006; Brandt et al. 2009) suggests an age of magnetization around 270 Ma in the early Late Permian, and close to the end of the Kiaman superchron. The simplest interpretation indicates a primary (early diagenetic?) magnetization of the Permian De La Cuesta Formation and a coeval remagnetization of the Ordovician clastic sedimentary rocks of the Molles Formation. This has been interpreted as a regional diagenetic event that produced precipitation of hematite, perhaps through pervasive percolation of fluids associated with weathering and secondary leaching (Spagnuolo et al. 2008).

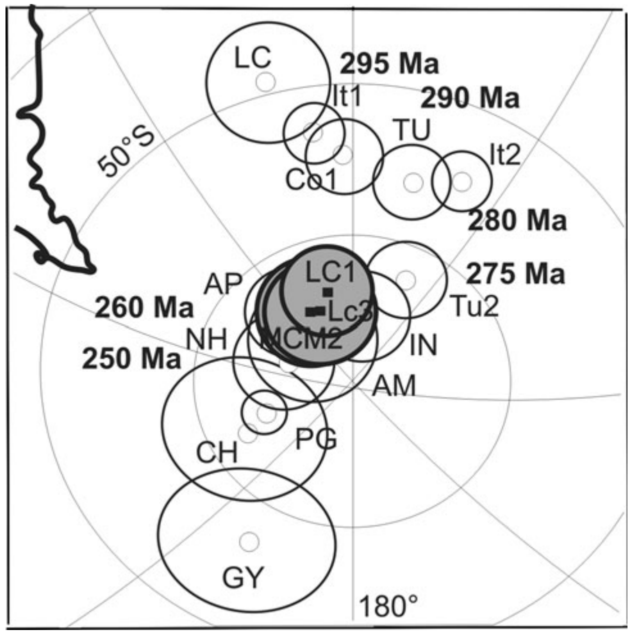

Fig. 3 Late Paleozoic South American paleomagnetic poles (Rapalini et al. 2006 and references therein), numbers indicate age. *LC1* De La Cuesta and La Veteada formations; *MCM2* sedimentary units of Molles Formation; *Lc3* mean pole (Spagnuolo et al. 2008). *LC* Sinito et al. (1979); *It1*, *It2* Pascholati (1983); *Co1* Embleton (1970); *TU* Tomezzoli and Vilas (1999); *Tu2* Tomezzolli (2001); *PG*, *AM* Valencio et al. (1977); *IN* Rapalini et al. (2006); *CH* Conti and Rapalini (1990); *AP* Ernesto (2005); *GY* Hargraves (1978); *NH* Creer et al. (1970)

These results allowed us to unambiguously date the rotations affecting the Ordovician rocks in that locality of the Famatina Ranges as pre-Permian.

Counterclockwise rotations (Western Puna)

Forsythe et al. (1993) carried out a paleomagnetic study in the Western Puna of Chile. Paleomagnetic poles were calculated from the Late Cambrian (ca. 500 Ma) Choschas pluton and associated lavas (CHO) and the Middle to Late Ordovician Tucucaro (441 ± 8 Ma), Alto del Inca (466 ± 44 Ma) and Tilopozo (452 ± 4 Ma) plutons (OP). The CHO and OP poles (see Table 1; Fig. 2) are anomalous with respect to the coeval reference poles of Gondwana (Grunow 1995, 1999). Very large, counterclockwise rotations are inferred from the data. Several years later, Rapalini et al. (2002) confirmed those results studying the Early to Middle Ordovician Chachas and Taca-Taca plutons and the Vega Pinato ignimbrites in the Argentine side of the Western Puna and obtained a paleomagnetic pole from those rocks (CHA; Table 1; Fig. 2).

Paleomagnetic constraints on the age of rotations

The Andean chain changes its strike from NW–SE to N–S at approximately 18°S. This region is generally known as the "Bolivian Orocline" (Fig. 4a) and comprises part of Bolivia, Perú and northern Chile and Argentina. It is characterized by counterclockwise rotations north of the bend and clockwise rotations south of it (e.g. Somoza et al. 1996; Beck 1998; Randall 1998) which affect many Mesozoic and Cenozoic units along the South American margin (Fig. 4b). Different tectonic models have been proposed to account for the systematic pattern of rotations observed along the Central Andes (Somoza et al. 1996; Beck 1998; Kley 1999; Arriagada et al. 2000; Roperch et al. 2000; McQuarrie 2002; Prezzi and Alonso 2002; Richards et al. 2004).

Since sampling localities are within the region affected by the Central Andes rotation pattern (CARP; Somoza et al. 1996) we need to test whether or not the rotations obseved in the Early Paleozoic rocks may be fully or partially assigned to the Andean deformation. Figure 4b shows the distribution of sampling localities of paleomagnetic studies in rocks younger than Ordovician in the Central Andes region under consideration. The database is quite extense (Beck 1998; Lamb 2001; Richards et al. 2004; Taylor et al. 2005; Ré 2008; Maffione et al. 2009; IAGA Paleomagnetic Database 2005). Rotated Mesozoic or Cenozoic units outcropping close to localities of rotated Ordovician rocks suggest that the rotations are Andean, while the lack of rotation of younger rocks would indicate an older age.

Poles CHO, OP and CHA from the Western Puna, show a very large ccw rotation. Paleomagnetic studies in younger rocks in nearby localities have shown negligible anomalies in declination (Fig. 4c), strongly suggesting a pre-Late Paleozoic age for the rotations. Furthermore, since only cw rotations are expected at these latitudes, according to the CARP, any Andean contribution would only increase the amount of Paleozoic rotations.

In the Famatina Ranges, the nearly 40° cw rotation shown by the Suri Formation paleopole (FS) is constrained by concordant paleomagnetic results on Permian rocks at the same locality (Thompson 1972; Rakotolofo 2004; Fig. 4d). Furthermore, paleomagnetic results in Neogene sediments exposed nearby (less than 30 km away) show rotation values under 5° (Reynolds 1987; Ré 2008; Fig. 4d). For the MCM1 paleopole, located some 100 km southwards in the Famatina Ranges, results from Permian red beds and interpreted remagnetization of Ordovician clastic sediments, already mentioned (Spagnuolo et al. 2008) at the same locality undisputably constrain the rotations as pre-Permian (Spagnuolo et al. 2008). This result is also confirmed by a paleomagnetic study in Miocene sediments that do not show any significant rotation relative to the reference direction (Zambrano 2006; Zambrano et al. 2010; Fig. 4e).

The age of rotation of the Early Ordovician units exposed in the Eastern Puna (Conti et al. 1996) is more loosely constrained. Data for the PO pole comes from two locations (Quebrada de las Burras at 23.4°S, 66.3°W and Huancar at 23.6°S, 66.4°W) located some 20 km from each other. No paleomagnetic study in younger rocks from the same two localities is yet available. Nevertheless, since the publication of this study, coverage of paleomagnetic data of the Puna of Argentina and Chile has significantly increased (Fig. 4f). The nearest published results on younger rocks are those from Prezzi and Alonso (2002) who observed a cw rotation of nearly 40° for the Late Cretaceous sediments of the Pirgua Group exposed in Coranzuli (~45 km to the north of the Ordovician locality), but very small to unsignificant rotations in Miocene rocks in a nearby locality. On the other hand, Coutand et al. (1999) found a cw rotation of around 20° in Early Miocene volcanic rocks outcropping ~60 km south. A very recent study by Maffione et al. (2009) on rocks exposed over 80 km to the NE showed significant cw rotations (around 45°) in Late Cretaceous sediments of the Pirgua Group, but with the occurence of some sites yielding no rotations. From the available data, therefore, no secure constraint can be placed on the age of rotation determined by Conti et al. (1996) in the Early Ordovician rocks. However, the widespread occurrence of large cw rotations of Meso-Cenozoic rocks in the region, suggests that it can partly relate to the Andean deformation (CARP of Somoza et al. 1996). Until new paleomagnetic data is obtained from younger rocks exposed closer to the Huancar and Quebrada de las Burras, the interpretation of the age of rotation of the Early Ordovician rocks is an open question.

The remaining pole published by Conti et al. (1996), the Cuchiyaco paleopole (CY), from the NW Pampean Ranges, also showed a very large cw rotation (over 50°). No paleomagnetic data was presented by the authors from younger rocks at the same locality in order to constrain the age of rotation. However, Aubry et al. (1996) published paleomagnetic results from four sites of the Late Cretaceous Pirgua Group exposed some 35 km to the north of the Cuchiyaco granodiorite (Fig. 4g). None of the sites recorded significant declination anomalies, suggesting lack of tectonic rotations since the Cretaceous, thus, supporting the case for a Paleozoic rotation.

Considering the analysis presented above, we suggest significant Paleozoic rotations in the Famatina Ranges (cw) and Western Puna (ccw), whereas a less certain Paleozoic age of rotation (cw) is suggested for the Cuchiyaco granitoid. The rotations recorded in the Early Ordovician units of the Eastern Puna could be Paleozoic as well as

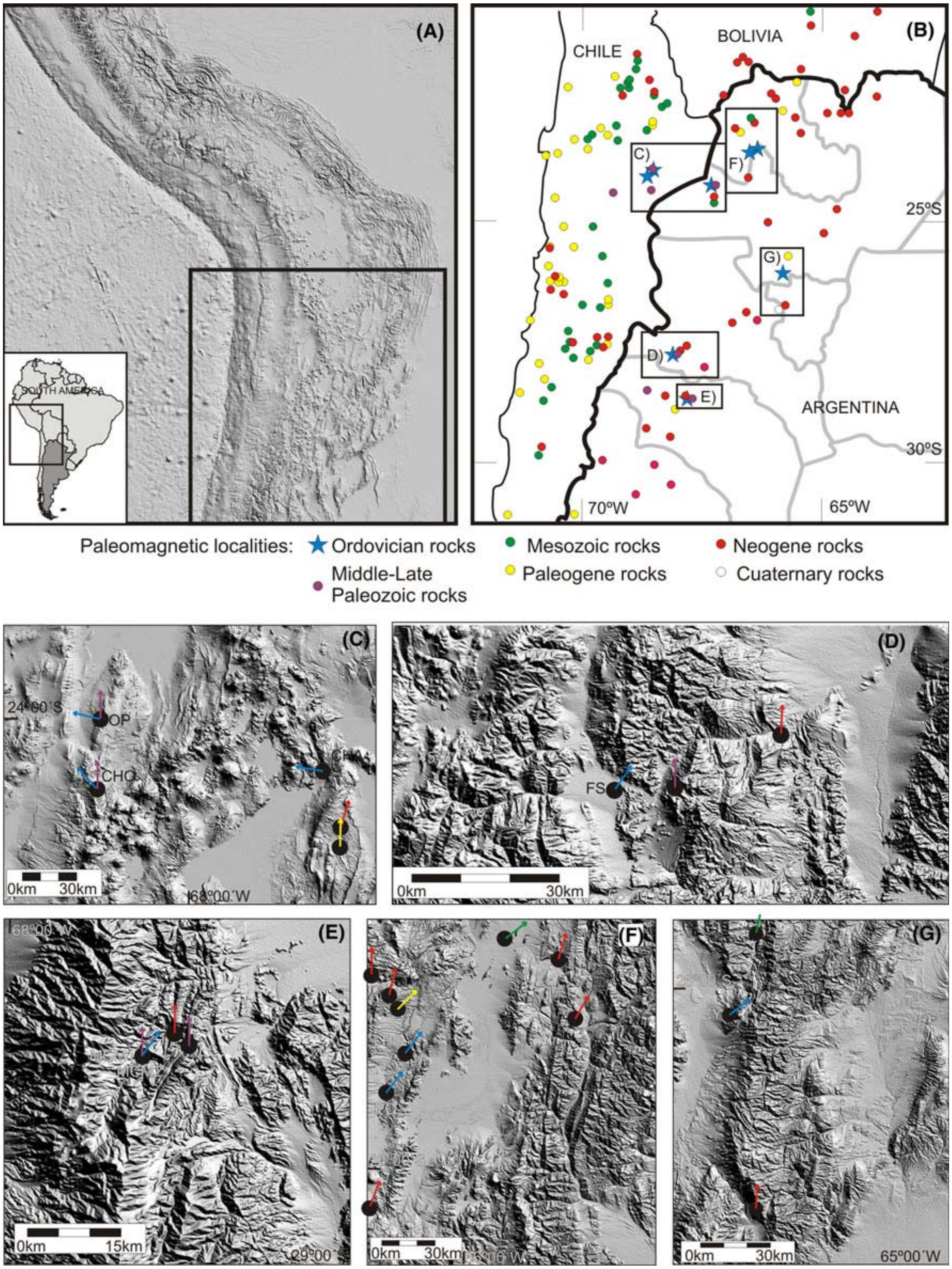

Fig. 4 **a** Digital elevation model (DEM) of Southamerican western margin. It can be seen the shape of the Bolivian orocline. **b** Map of NW Argentina and N Chile with the sampling paleomagnetic localities (Beck 1998; Lamb 2001; Richards et al. 2004; Taylor et al. 2005; Ré 2008; Maffione et al. 2009; IAGA Paleomagnetic Database 2005). **c**–**f** DEM of the Ordovician sampling localities and younger localities with the sense and value of rotation that everyone presents. **c** Western Puna (Forsythe et al. 1993; Coutand et al. 1999; Rapalini et al. 2002). **d** Famatina Ranges (Thompson 1972; Valencio et al. 1977; Conti et al. 1996; Rakotolofo 2004). **e** Famatina Ranges (Spagnuolo et al. 2008; Zambrano 2006; Zambrano et al. 2010). **f** Eastern Cordillera (Conti et al. 1996; Coutand et al. 1999; Prezzi and Alonso 2002; Maffione et al. 2009). **g** Pampean Ranges (Conti et al. 1996; Aubry et al. 1996)

Cenozoic. However, in the following analysis we interpret the Eastern Puna rotations as being of Paleozoic age.

Previous proposed models

The study localities described before are distributed in an area of several kilometers (400 km) in extent. Plots of rotation sign and magnitude vs latitude and longitude are presented in Fig. 5. They clearly show that all available paleomagnetic data obtained so far from Early Paleozoic rocks in the Famatina Belt and the Eastern and Western Puna show very large rotations. However, while the Western Puna shows ccw rotations of up to 80°, the Eastern Puna and Famatina Belt record clockwise rotations of around 40°. Except for this major difference in sign, no correlation is observed between the rotation values and the latitude or longitude of the sampling localities.

Similar rotation values in Eastern Puna and Famatina for over 400 km led Conti et al. (1996) to propose that the Famatina and the Eastern Puna constituted a single para-autocthonous block over which an Early Ordovician magmatic arc was emplaced during subduction of the southern Iapetus oceanic crust (Pankhurst and Rapela 1998; Quenardelle and Ramos 1999; Dahlquist and Galindo 2004; Ramos 2004, 2008). According to this interpretation this block rotated clockwise against the SW Gondwana margin in the Middle–Late Ordovician associated to the accretion process of the Precordillera terrane (e.g. Astini et al. 1995; Thomas and Astini 2003; Ramos 2004). Some limestones with calcareous algae of the Upper Cambrian-Tremadoc have been interpreted as suggesting a low latitude position of this place with tropical weather (Astini 2001a, 2003), indicating that the Famatina could be in some lower latitude than the conjugated coast of Gondwana according to its reference pole. Although this model could be reconciled with paleomagnetic (Conti et al. 1996), biogeographic (Benedetto 1998), magmatic (Quenardelle and Ramos 1999; Ramos 2008) and geophysical (Martínez and Giménez 2003) evidence, it has been disputed by several authors (Pankhurst et al. 1998; Rapela et al. 1998; Saavedra et al. 1998; Astini 2003). Major criticism has come from the petrologic evidence along the Famatinian arc that has been interpreted as an upper-plate continental magmatic arc developed on the Gondwana margin (Pankhurst et al. 1998; Saavedra et al. 1998; Rapela et al. 1998; Astini 2003). This model seems incompatible with a narrow para-autochthonous continental block with a back-arc oceanic basin behind it, unless important extension took place. Results from Spagnuolo et al. (2008) gave further support to the paleomagnetic results interpreted by Conti et al. (1996), expanding the rotated areas some 70 km southwards, and constraining the rotations to pre-Permian times. Several geologic problems remain unsolved by this model, which are briefly discussed below:

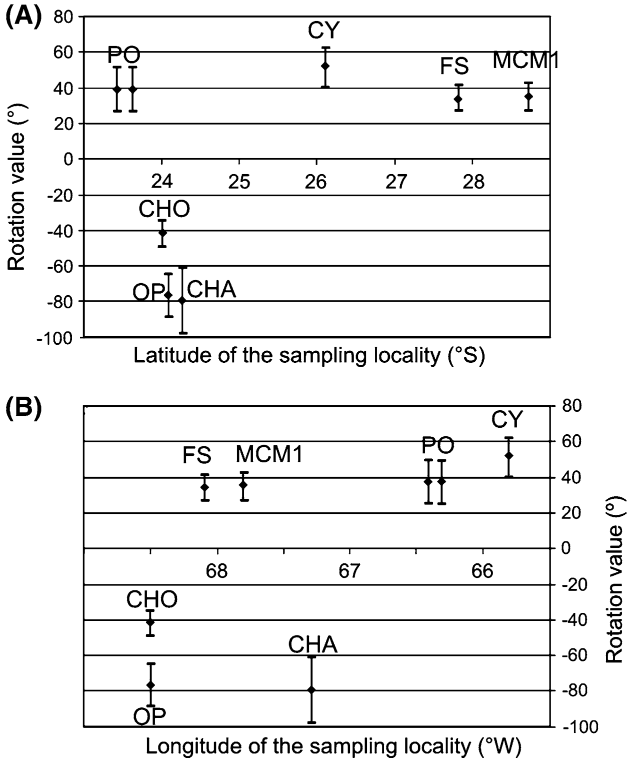

Fig. 5 Tectonic rotations of the paleomagnetic poles of lower Ordovician of the Famatina Ranges, the Western and the Eastern Puna. **a** Latitude of the sampling site vs. rotation. **b** Longitude of the sampling site versus rotation

1. The model of a para-autochthonous single block encompassing Eastern Puna and Famatina that rotated clockwise in the Mid-Late Ordovician implies some kind of V-shaped back-arc oceanic basin that was closed and inverted during rotation (Fig. 1b). Although there are reports of an Early Paleozoic oceanic back-arc basin, eastward (present-day coordinates) from the main magmatic arc in the San Luis Ranges (Las Termas Belt; Sims et al. 1998; Miller et al. 2003; Miller and Söllner 2005), no similar geotectonic feature has been reported associated to the Eastern Puna belt. Furthermore, considering that the back-arc basin should significantly increase its size towards the north (present-day coordinates) according to the paleomagnetic results, lack of evidence of such basin to the north is a major obstacle for this model.
2. Geologic (Astini and Dávila 2002, 2004), paleontological (Benedetto 2001, 2003) and geochemical (Rapela et al. 1992; Zimmermann et al. 2003; Kleine et al. 2004) considerations have suggested that the magmatism and the sediments exposed in the Famatina

Ranges does not continue towards the north into the Eastern Puna belt, but into the Western Puna.

3. Several lines of evidence suggest that magmatism in the Eastern Puna corresponds to an intraplate extensional setting and not to a magmatic arc (Balhburg 1990a, b; Coira et al. 1999, 2009; Ramos and Coira 2008). The Eastern Puna is composed by intraplate volcanics, masive flows, alcaline dykes (Coira et al. 1999) associated to a submarine bimodal volcanism in a transtensional retroarc setting (Coira et al. 1999; Astini 2003).
4. The presence of Cambrian-Tremadoc calcareous rocks in the Famatina Ranges should represent favourable climatic and stability conditions and not just necessarily a different paleogeographic position (Astini and Dávila 2004).
5. High-P/low-T metamorphism indicative of subduction-accretion regimes is absent in NW Argentina, the whole area shows rather uniform low-intermediate-P/high-T conditions (Lucassen et al. 2000). According to Lucassen et al. (2000), pressure was low as indicated by no or minor garnet in the gneiss and amphibolites. Upper amphibolite facies temperature (650 ± 7,508°C) at 5 ± 7 kbar pressure are reported from north of Chile (Lucassen et al. 1996; Lezaun et al. 1997), the Eastern Puna (Becchio et al. 1999) and the Quilmes Ranges (Toselli et al. 1978; Rossi de Toselli et al. 1987; Becchio et al. 1999) both in NW Argentina.

Similar to the above-mentioned model of Conti et al. (1996), but with an opposite sense of rotation, Forsythe et al. (1993) postulated that the Arequipa-Antofalla craton underwent a very large cw rotation in the Neoproterozoic opening a V-shaped oceanic basin from south to north followed by a ccw rotation in Early Paleozoic times, closing the basin and generating the Ocloyic deformation. This model is also supported by the fact that the Western Puna magmatic arc is approximately coincident with a positive gravity anomaly interpreted as a terrane boundary (Gangui and Gotze 1996; Omarini et al. 1999). A crustal discontinuity between the Western and Eastern Puna has been proposed by several authors (Ramos and Coira 2008), evidenced either as interpreted ophiolite remnants (Coira et al. 1982; Allmendinger et al. 1983; Blasco et al. 1996) or as a major strike-slip boundary (Coira et al. 1999), being an extensional retroarc setting (Astini 2008) the more accepted alternative nowadays. Although there are outcrops of peridotites, basaltic flows and pillow lavas of the Salar de Pocitos and Calalaste Ranges interpreted inicially as the opening of an oceanic basin (Allmendinger et al. 1983; Ramos 1988; Blasco et al. 1996), new geochemical results indicate that they were generated in an extensional arc-backarc setting (Balhburg et al. 1987; Balhburg and Furlong 1996; Zimmermann et al. 1999, 2009; Balhburg and Zimmerman 1999) emplaced in a thin crust. Another inconsistency is that the sence of movement (taking into account the paleomagnetic results of Forsythe et al. 1993) makes the basin wider and deeper to the south while the sedimentation is younger to the north but the paleocurrents are south-north directed (Niemeyer 1989; Balhburg 1990a, b, 1991). Lucassen et al. (2000, 2001) according to isotopic and geochemical results from Paleozoic and Precambrian igneous and metamorphic rocks, interpret that these mafic and ultramafic rocks are the result of recycling of continental crust with repeated similar characteristics and minimum addition of juvenile components inconsistent with any evidence of terrane acretion. There are no evidence of high pressure-low temperature metamorphic rocks (blue schists, eclogites), ophiolites and other rocks typical of collison zones (Lucassen and Franz 2005; Bierlein et al. 2006), and nor the isotopical composition of the Neoproterozoic and Early Paleozoic rocks show evidence of exotic cortical fragments (Lucassen and Franz 2005).

Alternative model for understanding opposite block rotations

To account for the paleomagnetically determined (Fig. 2), clockwise rotation of Ordovician rocks in the Famatina Range, NW Pampean Ranges and Eastern Puna (Valencio et al. 1980; Conti et al. 1996; Spagnuolo et al. 2008), and counter-clockwise rotations of those in the Western Puna (Forsythe et al. 1993; Rapalini et al. 2002), we propose a model of systematic crustal block rotations produced by crustal shortening and tectonic escape during and immediately after the collision of Precordillera in the Middle-Late Ordovician (Astini and Dávila 2004; Ramos 2004). The time of collision of the Precordillera terrane has been independently suggested from cooling ages of the metamorphic basement of ca. 464 Ma (Ramos et al. 1998; Rapela et al. 2001; Ramos 2004 and references therein), by the foundering of the carbonate platform in Early Middle Ordovician (Dalla Salda et al. 1992a, b; Astini et al. 1995; Dalziel 1997; Ramos et al. 1998), the finding of K-benthonites (Huff et al. 1998), the cesation of arc related magmatism in the upper plate (Quenardelle and Ramos 1999; Durand and López 1996; Rapela et al. 1998, 2001; Dahlquist et al. 2008), the appearance and dispersal of typical Gondwanan faunas into the Precordillera (Benedetto 2003) and by the development of a peripheral foreland thrust-belt associated to synorogenic conglomerates in the lower plate (Thomas and Astini 2007) and opposite vergence deformation within the upper plate (Astini and Dávila 2004). The evidence for continuous along-strike Hirnantian (Late Ordovician) glacial deposits across the boundary of the

Precordillera and the Central Andean basin, including those in the Puna region (Astini 2001a, b, 2003), is strong evidence for considering the accretion had largely ended by the Late Ordovician.

The subduction of oceanic crust under the Gondwana margin during the Early Paleozoic generated the Famatinian arc since around 490 Ma (Pankhurst et al. 1998; Rapela et al. 1998) extending from the Puna to the San Luis Ranges (Fig. 6a) and probably into northern Patagonian Massif (Pankhurst et al. 2006). Isotopic and geochemical analysis of Lower Ordovician granitoids in the Famatina Ranges indicate that they were emplaced in a thick continental crust (Rapela et al. 1999, 2001; Pankhurst et al. 2000; Rubiolo et al. 2002). There is also, significant evidence of an important back-arc basin developed by crustal stretching to the East of the main arc and characterized by normal faults (Mangano and Buatois 1996; Astini et al. 1995; Astini 1998). Thick sequences of volcanic and sedimentary rocks (Allmendinger et al. 1983; Mangano and Buatois 1996; Astini 2003; Astini and Dávila 2004) including deep marine facies (black shales) with marine faunas (Mangano and Buatois 1996; Benedetto 1998; Esteban and Gutierrez-Marco 1997; Esteban 1999; Esteban et al. 1999; Astini 2003) characterize this basin. This apparent contradictory situation in the Famatina Ranges was compared by Astini (2003) with the hot orogens of Collins (2002) that can favour the growth of the upper plate without the need of terranes separation and amalgamation (Astini 2003; Astini et al. 2008). Many authors suggested the presence of two magmatic arcs within this region (Mangano and Buatois 1996; Astini and Benedetto 1996; Rapela et al. 1998, 2001; Pankhurst et al. 2000; Astini and Dávila 2002) partially submerged in a marine setting with a thin crust (Bierlein et al. 2006). Gravity studies indicate a residual positive anomaly under the Famatina Ranges that can be explained with a thin crust (Manheim 1993; Martínez and Giménez 2003). It is likely that the Famatinian magmatism was the result of the subduction of an oceanic plate under the continetal crust of Gondwana with negative roll-back generating a lot of extensive structures in the continental upper plate up to the occasional production of quasi-oceanic to oceanic (?) rocks (Sims et al. 1998; Miller and Söllner 2005). In the Late Ordovician to Silurian the back-arc basin was finally closed and inverted through thrusting and development of mylonitic belts (Astini and Dávila 2004) and S-type plutons associated to shear zones between 447 and 435 Ma (Rapela et al. 1998; Steenken et al. 2004). In the Famatina Ranges this deformation is also characterized by dextral (Hongn et al. 1999; Rapela et al. 2001; Höckenreiner et al. 2003; Whitmeyer and Simpson 2004; López et al. 2007) and sinistral (Steenken et al. 2004; López et al. 2007) transpressive movements with associated normal faults (Dávila 2001). The development of a faulted back-arc basin within a thin continental crust (in some places almost quasi-oceanic, e.g. Miller and Söllner 2005) must have been a key factor controlling deformation. Being an extremely weak region, most of the displacement was probably concentrated along shear belts in the back-arc, that worked as lateral detachment surfaces (Fig. 6). This may have promoted displacement and rotation of smaller crustal blocks encompassing the magmatic arc, plus the fore-arc as well as some fragments of the back-arc (Willner et al. 1987).

Domino system pattern

Systematic crustal block rotations are common in continental margins, whether associated to transform boundaries (e.g. Pluhar et al. 2006), oblique subduction (e.g. Beck et al. 1986) or collisional belts (e.g. Thöny et al. 2006). Isseven and Tuysuz (2006) describe two models to explain rotational kinematics around vertical axes in the upper crust: continuum (ductil deformation distributed along a wide area) and discrete (rotation of blocks without internal deformation). Since the pioneering work of Freund (1974) it is well known that rigid body rotations around vertical

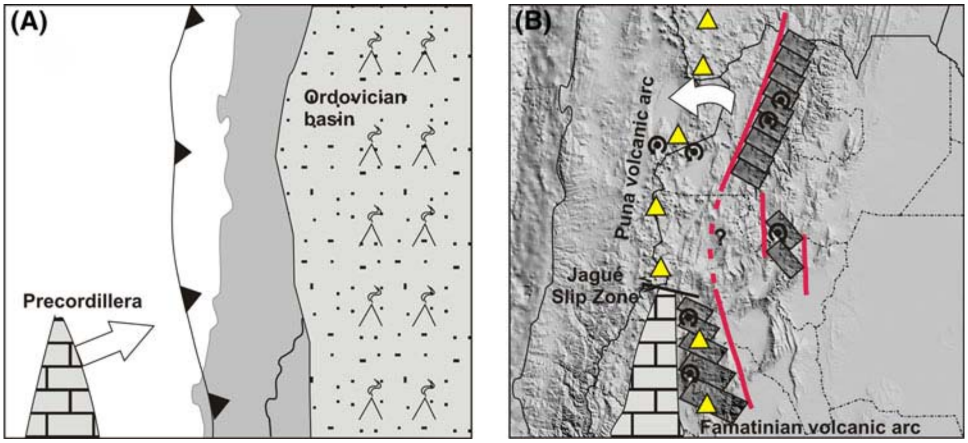

Fig. 6 Tectonic evolution model of the southwestern margin of Gondwana in the early Paleozoic. **a** Subduction in the western margin of Gondwana, generation of the Famatinian magmatic arc (*triangles*) and the associated sedimentary basin (*dotted shadow*). **b** Collision of the Precordillera, the magmatic arc stopped and there is deformation in the retroarc with development of shear zones (*red lines*) and rotation of the blocks

axes are a very effective mechanism to achieve significant crustal shortening creating compression/extension in various quadrants. The cw rotations of the Famatina Ranges and the Eastern Puna probably developed in a domino system pattern (Fig. 6). Considering these tectonic conditions, crustal shortening due to nearly orthogonal collision of Precordillera may have been at least in part accomodated through rigid body rotations of discrete crustal blocks or through ductil deformation accomodated by shear zones (Fig. 6). Between the convergene zone and those shear zones basement partitioning would have occured separating blocks bounded by strike-slip faults (cf. Kuhn and Reuther 1999). The development of such structures would generate coeval compressive and extensive deformation in the boundaries of the blocks. Both types of structures have been respectively mapped in the Famatina Ranges (e.g. Höckenreiner et al. 2003; Dávila 2001). Thöny et al. (2006) proposed a rotational domino pattern in the northern Alps generating a mega shear zone along which rotations of near 60° have been determined. Such amount is more likely within a soft domino system instead of the rigid blocks model (Peacock et al. 1998). A similar setting was probably placed in the Famatina Ranges during the collision of Precordillera. The Ordovician back-arc basin would have acted as a weak zone along which rotations and displacements were promoted during deformation (Miller and Söllner 2005). Similar rotation values at different localities is consistent with a domino-rotation pattern. Martina and Astini (2009, see also references therein) described a major NW shear zone, the Jagué left slip zone (Astini and Dávila 2004), that is interpreted as the northern boundary of the Precordillera terrane. This is approximately coincident with the northern limit of the Famatina Range. Sub-vertical N–S to NNW-SSE regional-scale shear zones have long been known between the Famatina and the Pampean Ranges which were likely generated during inversion and deformation of the stretched continental crust along the Famatinian back-arc basin. The best known of these is the Tipa shear zone (López and Toselli 1993; Höckenreiner et al. 2003) which extends in a NNW-SSE direction for several 100 km and shows high angle mylonitic belts of up to 2 km wide. In the San Luis Ranges also there is evidence of dextral ductile deformation (Sims et al. 1998; Whitmeyer and Simpson 2004). These structures developed between the Ordovician and the Devonian and have apparently accommodated a significant crustal shortening between the Famatina and the Pampean Ranges blocks, during and after the collision of the Precordillera Terrane. These shear zones must have acted as a major crustal boundary between the Famatinian arc and the foreland to the East promoting cw rotations of discrete crustal blocks in a domino-pattern as a way to accommodate significant amounts of crustal shortening during collision of the Precordillera (Fig. 6). Considering the evidence in favour of continuation of the Famatinian magmatic arc in the Western Puna (Astini and Dávila 2004), a significant displacement of the arc towards the East is observed to the south of the Jagué shear zone (Fig. 6b) which is likely due to crustal shortening associated to the collision of the Precordillera. The fact that a different sense of rotations have been paleomagnetically determined in the Western Puna (Rapalini 2005) is consistent with our model.

Escape tectonics model

We propose that the rotations in the Western Puna are also related to the deformation generated by the collision of the Precordillera. Location of the Westen Puna block immediately to the north of the Precordillera strongly suggests the possibility of strike slip involving tectonic escape of the former due to indentation of the latter onto the Gondwana margin. Astini and Dávila (2004) proposed that Precordillera was an indented block in the western margin of Gondwana as pointed by the displacement between the Famatinian and the Western Puna arcs. The large ccw rotations found in the Western Puna can, therefore, be explained as associated to the main tectonic process that caused the rotations in the Famatina Range. There are numerous modern examples of tectonic escape processes associated to collision, i.e. the Dead Sea region (Piper et al. 2002; Adiyaman and Chorowickz 2002), northwestern South America (Trenkamp et al. 2002; Backé et al. 2006), southeast Asia (Morley 2007; Rutherford et al. 2001), Himalayas (Molnar and Tapponier 1975; Lin et al. 2008), Taiwan (Lacome et al. 2001; Ching et al. 2007) and others.

An analogy between the present Anatolian plate and the Western Puna is suggested (Fig. 7). In the region of Turkey, the Arabian plate is moving to the north while Eurasia to the south. The Neogene continental collision between them generated faulting in the Bitlis zone and the extrusion to the west of the Anatolia microplate producing its ccw rotation (Adiyaman et al. 2001; Adiyaman and Chorowickz 2002; Aksu et al. 2005; Isler et al. 2005; Koral 2007). This plate was divided into smaller fragments that further rotated counter-clockwise (Wong et al. 1995; Piper et al. 2002). In our Ordovician example, the collision of the Precordillera against the Gondwana margin would have generated the tectonic escape of the Western Puna (possibly also subdivided in several smaller blocks), which rotated in a counter-clockwise sense. A major crustal discontinuity between the Western and Eastern Puna was inferred by Coira et al. (1999) associated to dextral transcurrent movements in a fashion similar to the present day North Anatolian fault (Taymaz et al. 2007). Structural work further supports a transpressive deformation in the northwestern Argentina (Willner 1990; Hongn et al. 1999).

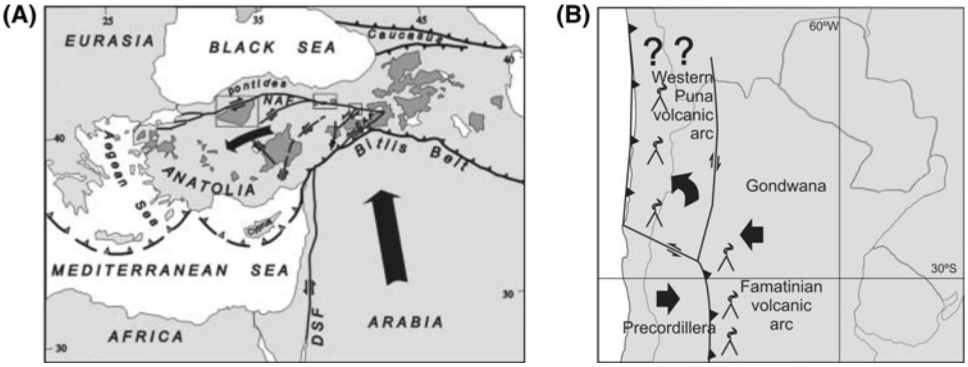

Fig. 7 Proposed correlation between **a** the present tectonics of the eastern Mediterranean region (Adiyaman et al. 2001) and **b** Ordovician tectonics (Famatinian Orogeny) in NW Argentina

Balhburg (1990b) recognized foliations associated to shear zones and interpreted pull-apart basins with alcaline volcanism (Coira et al. 1999). To the East of this major crustal discontinuity, clockwise rotations were observed in Ordovician rocks in the Eastern Puna and NW Pampean Ranges (Conti et al. 1996). This is similar to what has been found to the north of the North Anatolia Fault, as indicated for the Black Sea region, by Yaltirak et al. (1998). Piper et al. (2002) found much smaller ccw rotations to the north of the North Anatolia Fault than those to the south. They explained them as large ccw rotations previous to development of the fault, which triggered cw rotations that are balancing the original ones. The concept of escape tectonic referred to the movement of a block through the free margin in a compressive setting and has been widely described as the product of orthogonal collisions (Indochina: Taponnier et al. 1982; Alps: Ratschbacher et al. 1991) and oblique convergence (Pubellier et al. 1996). These structures can not be used to delucidate the angle of approach of the Precordillera to the margin of Gondwana. More data in the northern segment of Western Puna will help in defining whether this movement was through discrete blocks (as proposed by Isseven and Tuysuz 2006 for Anatolia) or just as one single plate. Further detailed work will also allow testing if in our Ordovician case study the rotations are bigger closer to the indentor.

Conclusions

A new kinematic model supporting escape tectonics that is consistent with opposite block rotations related to collision and emplacement of the Precordillera terrane against Gondwana is suggested from the analysis of Ordovician paleomagnetic poles from NW Argentina and N Chile. Clockwise rotations around vertical axis were observed in Ordovician rocks of the Famatina Ranges (Valencio et al. 1980; Conti et al. 1996; Spagnuolo et al. 2008), the NW Pampean Ranges and the Eastern Puna (Conti et al. 1996), whereas counter-clockwise rotations have been found in the Western Puna (Forsythe et al. 1993; Rapalini et al. 2002). The Famatinian magmatic arc, created by subduction of the Iapetus oceanic plate under the southwestern Gondwana margin that eventually led to the collision of Precordillera probably developed a negative roll back that caused the formation of an important back arc basin with significant extension that led to production of quasi-oceanic crust at some places. This region acted as a significant rheologic discontinuity promoting the rotation of rigid crustal blocks around vertical axes as an efficient mechanism of crustal shortening during and immediately after the collision of Precordillera. This also produced the tectonic escape of the large crustal block of the Western Puna along a major strike-slip zone that marks its boundary with the Eastern Puna. During its escape the Western Puna rotated counterclockwise reproducing a tectonic scenario very similar to the modern North Anatolian fault system and neighbouring regions in the Eastern Mediterranean.

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