The Famatinian Orogen Along the Protomargin of Western Gondwana: Evidence for a Nearly Continuous Ordovician Magmatic Arc Between Venezuela and Argentina

Victor A. Ramos

Abstract The continental protomargin of Western Gondwana in South America records an important Early-Middle Ordovician magmatic activity associated with the development of the Famatinian orogen. Almost the entire margin has evidence of a magmatic arc preserved as orthogneisses in the high-grade metamorphic domains up to volcanic rocks of the same age interfingered with sedimentary facies. These subduction-related calcalkaline rocks have new U-Pb zircon dates that show striking similar ages bracketed between 490 and 460 Ma. The different domains along the continental margin are compared taking the western Sierras Pampeanas as the type locality, showing an alternation among high-grade metamorphic—greenschist facies—sedimentary facies. There are three deeply exhumed segments preserved as orthogneisses in high-grade amphibolite facies, the Sierras Pampeanas, the Marañón, and the Santander-Mérida domains. These domains are flanked by greenschist facies such as the Quetame in Colombia, the Vilcabamba in Perú, and the Puna Eruptive Belt in northern Argentina. Some segments are characterized by sedimentary facies as the Altiplano domain of Bolivia and the Olmos-Loja domain between Perú and Ecuador. The location and metamorphic grade are controlled by the amount of shortening and uplift, responsible for the different crustal levels exposed, as a consequence of the characteristics of the distinct terranes that collided against the continental margin. As a final remark, the time span of the Famatinian episode when globally compared has a widespread development in Laurentia, Baltica, and Australia, as a consequence of a period of high mobility of the plates during Early-Middle Ordovician times.

Keywords Magmatic arc · Terrane collision · Subduction related
Metamorphic grade · Protomargin · Paleozoic orogen

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A. Folguera et al. (eds.), *The Evolution of the Chilean-Argentinean Andes*,
Springer Earth System Sciences, https://doi.org/10.1007/978-3-319-67774-3_6

1 Introduction

Along the protomargin of Western Gondwana, there is evidence of subduction-related arc rocks during the Early Paleozoic (Fig. 1). These rocks are emplaced in the present metamorphic basement exposed along the western continental margin of South America. Although numerous authors described the geology, the geochemistry, and the geochronological data in different segments of Venezuela, Colombia, Perú, Chile, and Argentina, there is not a comprehensive view of their importance, time constraints, and paleogeographic significance. The understanding of these magmatic rocks of mainly Ordovician age is important to constrain the tectonic setting of the protomargin of Western Gondwana and several processes that have affected almost the entire margin at that time.

The reconstruction of the Paleozoic protomargin requires the recognition of the different episodes of terrane accretion that affected the margin during Mesozoic and Cenozoic times. The accretion of oceanic terranes is very conspicuous in the Northern Andes, and the ancient continental margin has to be reconstructed by removing the terranes accreted after the Ordovician (Restrepo and Toussaint 1988; Aleman and Ramos 2000; Ordóñez-Carmona et al. 2006; Ramos 2009; Gómez Tapias et al. 2015). The Early Paleozoic restoration of Western Gondwana also needs the removal of Patagonia, which is considered an allochthonous terrane accreted during the Late Paleozoic (Ramos 1984, 2008; Pankhurst et al. 2006). Although these last two proposals have different paleogeographic boundaries for northern Patagonia, after the finding of Early Cambrian archeocyatids in northern Patagonia, there is more consensus in the boundary indicated in Fig. 1 based on the correlation proposed by González et al. (2011) and Ramos and Naipauer (2014).

The objective of the present study is to review and correlate the different segments where Famatinian rocks have been recognized along the continental margin of South America in order to understand the tectonic evolution of the Early Paleozoic protomargin, based on previous work of the author, and recent data and new geochronological studies performed along the Andes by different research groups.

2 The Famatinian Orogen in Its Type Locality

The Famatinian orogenic cycle was defined in northwestern Argentina by Aceñolaza and Toselli (1976). The original definition encompasses a larger time span, which included all the sequences above the Tilcárica angular unconformity at the base of the Cambrian produced by their Pampean orogeny, up to the Late Devonian, leaving out the Late Paleozoic lesser deformed successions. However, the evidence provided by later tectonic studies demonstrated that a major orogeny

Fig. 1 Reconstruction of the Paleozoic protomargin of Western Gondwana (modified from Ramos 2009). Note the occurrence of oceanic terranes obducted during Mesozoic and Cenozoic times in the Northern and Southern Andes. The southern limit of the South American platform sensu Almeida et al. (1976) coincides with the Patagonia terrane as defined by Ramos and Naipauer (2014)

ended at Middle Ordovician times, and as a consequence, subsequent studies restricted the Famatinian orogeny from the base of the Cambrian up to the Middle Ordovician (Haller and Ramos 1984; Astini and Benedetto 1993; Astini et al. 1995; Pankhurst et al. 1996, 1998). This time span is generally accepted nowadays (Chew et al. 2007; Romero et al. 2013; among others).

The type locality for the Famatinian orogeny and the Famatinian magmatic arc is well exposed in the Sierra de Famatina, located in the western side of Sierras Pampeanas (Fig. 2) in central western Argentina (Ramos 1988; Astini et al. 1995). The tectonic evolution of this area comprises the docking and amalgamation against the protomargin of Western Gondwana of the allochthonous Cuyania terrane, derived from Laurentia (Ramos et al. 1986; Astini and Benedetto 1993; Astini et al. 1995, 1996; Ramos 2004).

As a consequence of the approach and accretion of Cuyania, the Famatinian orogen recorded a subduction-related magmatic arc, where mainly plutonic and metamorphic rocks were described along the western Sierras Pampeanas (Aceñolaza et al. 1996; Pankhurst et al. 1998; Quenardelle and Ramos 1999; Otamendi et al. 2008, 2009a, b, 2010). The magmatic arc was active from 490 to 460 Ma with a magmatic peak at about 470 Ma; main deformation took place close to 460 Ma, and postectonic granites were emplaced in Late Ordovician and Early Silurian times (see Chernicoff and Ramos 2004, and cites therein).

There are many studies that characterize the geochemical and petrological behavior of these magmatic arc rocks. In the Famatinian magmatic belt of the Sierras Pampeanas, Pankhurst et al. (2000) identified three distinct granite types: dominant I-type, S-type, and small-scale tonalite–trondhjemite–granodiorite (TTG) type which were confined further to the east in the Sierras de Córdoba, as pointed out by Dahlquist et al. (2013). These three granite types were emplaced within the 484–463 Ma interval, which characterizes the Famatinian rocks (Dahlquist et al. 2008). Detailed petrological and geochemical studies have been presented by Rapela et al. (1990), Aceñolaza et al. (1996), Saavedra et al. (1998), Pankhurst et al. (1998, 2000), Dahlquist et al. (2005, 2007, 2008), Ducea et al. (2010), and Otamendi et al. (2012), among others.

These igneous rocks were emplaced in a metamorphic basement characterized by typical low-P and high-T conditions reported all along the Famatinian belt of the Sierras Pampeanas (e.g., Toselli et al. 1987; Pankhurst et al. 1998; Dahlquist et al. 2005, 2007; Otamendi et al. 2008; Collo et al. 2009; Verdecchia et al. 2011).

These rocks are limited to the west by a basic and ultrabasic belt (Fig. 3) described as the Famatinian ophiolites (Ramos et al. 2000) associated with paired metamorphic belts, with high pressure—low temperature belts ocean-wards (see Boedo et al. 2016).

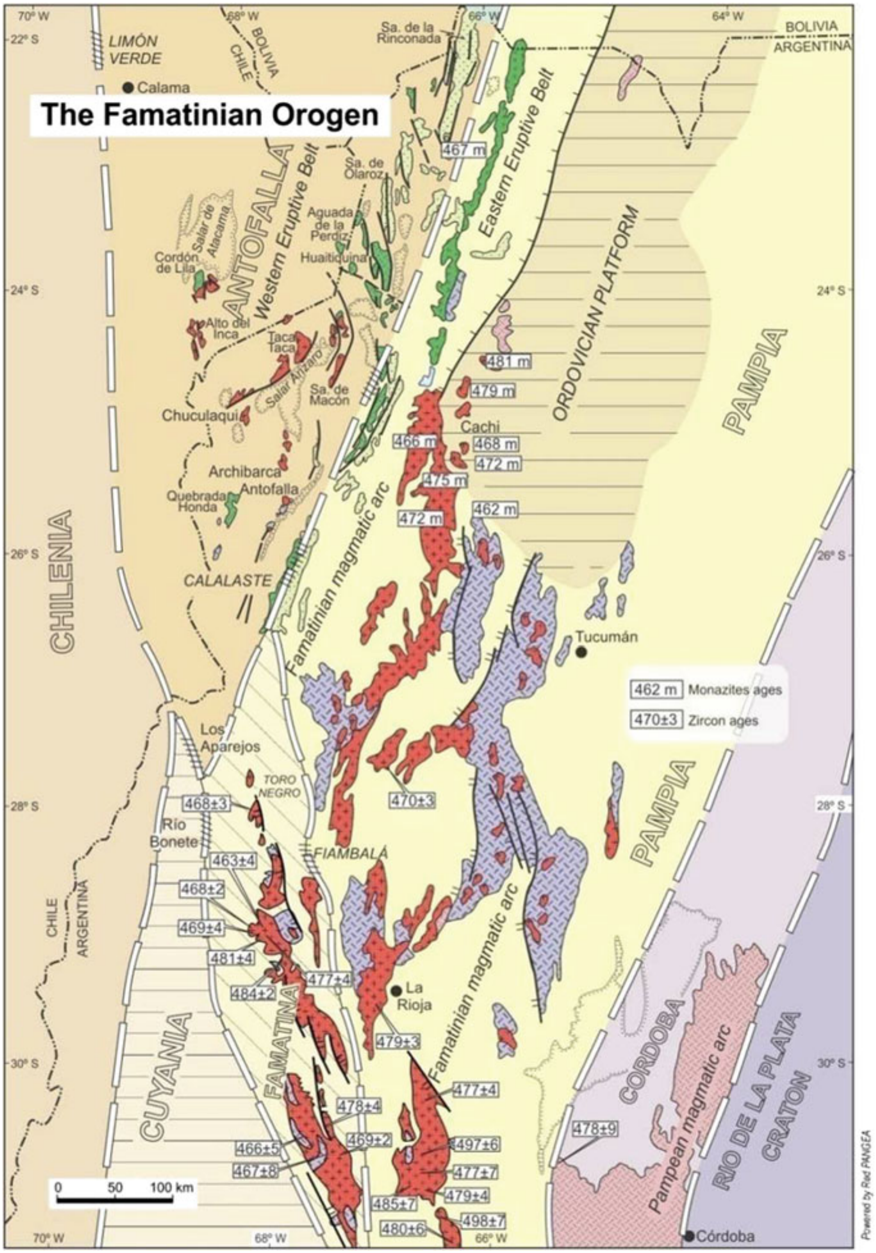

Fig. 2 Type locality of the Famatinian orogen in Sierras Pampeanas. Some ages are indicated in millions of years (Ma) as a guide based on different data sets (see Pankhurst et al. 1998; Quenardelle and Ramos 1999; Otamendi et al. 2008, 2009a, b, 2010). The terrane boundaries are based on Ramos (2009) and Ramos et al. (2010)

Fig. 3 Metamorphic rocks of the sole thrust in Cortaderas ophiolitic belt, Mendoza Province (after Haller and Ramos 1984). Foliation is enhanced by spinel minerals in the serpentine

3 The Famatinian Orogen Along the Protomargin of Western Gondwana

The previous description of the Famatinian orogen, although very succinct, will be used to correlate the type locality with other igneous and metamorphic rocks recognized along the continental margin of South America during the 490–460 Ma time interval. The description will be from the best known type locality in the south toward the north. The margin has been divided into a southern segment along northern Argentina and Bolivia, a central sector comprising central and northern Perú, and a northern sector from Ecuador to Venezuela, in order to have coherent segments with similar evolution.

3.1 Southern Sector

Since the early work of Coira et al. (1982), it is known that the Famatinian Ordovician arc granitoids of Sierras Pampeanas transitionally pass to the *Faja Eruptiva de la Puna* (Eruptive belt of the Puna). These igneous rocks defined by

Méndez et al. (1973) have been divided by Niemeyer (1989) in two volcanic belts: the eastern and western eruptive belts (see Fig. 2). A complete description of the geological, geochemical, and isotopic characteristics of these rocks is presented by Coira (2008), who interpreted these rocks as having a weak arc signature. The eastern belt of volcanic rocks is interbedded with clastic sediments bearing graptolites of Floian (Arenig) age. The biostratigraphic control, based on the graptofauna, indicates that these volcanic rocks span between 470 and 477 Ma (ICS-IUGS Geological Time Table, 2016). This belt has also some minor intrusives ranging in age from 476 ± 1 and 478 ± 3.5 Ma (U-Pb in monazite, Lork and Bahlburg 1993; Coira 2008).

The new data presented by Bahlburg et al. (2016) show two discrete phases of intrusion in the *Faja Eruptiva de la Puna Oriental* (Eastern Eruptive Belt). The first phase coincides with the main Famatinian activity, which according to these authors is around 465 Ma old. This phase is related to mafic and intermediate volcanic rocks that are interfingered with graptolite bearing sediments which have been recently revised by Brussa et al. (2008). Several studies confirm the old Arenigian age of the fauna, but with more detailed work, it is now known that the time span of these graptolites can be assigned to different biozones ranging from Late Floian to mainly Dapingian–Early Darriwilian age (Brussa et al. 2008; Toro et al. 2006; Martínez et al. 1999). These biozones encompass a time interval between 477 and 465 Ma (Ogg et al. 2016), which coincides with the main activity of the Famatinian arc. The second main phase of Bahlburg et al. (2016) corresponds to 444.9 ± 2.3 Ma, almost at the Ordovician-Silurian boundary (443.8 Ma, according to Ogg et al. 2016). Based on the new precise data, the second phase is attributed by Bahlburg et al. (2016) to the Ocloyic phase, which according to Turner and Méndez (1975) and Ramos (1986) occurred at the end of the Ordovician. It is worth mentioning that this phase was disregarded by Moya (2015) that after a complete analysis of the present evidence, assumed that the main orogenic phase occurred in Northern Argentina in Dapingian times, and not along the Ordovician-Silurian boundary as previously proposed. Based on this regional evidence, the second phase of Bahlburg et al. (2016) is assumed to be a reactivation, probably controlled by extension or transtension along a crustal weakness zone. The occurrence of large amounts of ultrahigh temperature melts in the eastern eruptive belt was interpreted by Fernández et al. (2008) as evidence of extension in the back-arc of the western eruptive belt. The control of this extension is linked to the crustal weakness zone, which was interpreted as an Ordovician suture by Coira et al. (1982). However, this Ordovician suture has been put to rest by Bahlburg et al. (2016) based on the demonstration of Zimmermann et al. (2014) that gabbros on this suture were emplaced at 543.4 ± 7.2 Ma. These authors interpreted the Calalaste mafic and ultramafic rocks as Precambrian, failing to recognize the Late Cambrian age of a rhyolite dated by U-Pb in zircons and associated with the mafic and ultramafic complexes (Pinheiro et al. 2008). This important weakness zone, which continues further north in Pocitos (see Zappettini et al. 1994), is interpreted here as the Grenville suture between Antofalla and Pampia, which has been partially reactivated by extension in Famatinian (and possibly in Pampean) times.

The geochemical characteristics of the rocks of *Faja Eruptiva de la Puna* indicate a typical arc-related plutonism and volcanism (Niemeyer 1989; Coira 2008), with strong arc affinities in the western belt, which weaken eastward in the eastern eruptive belt. This activity ends by the end of the Floian (Ramos and Coira 2008), and the final products at the end of the Ordovician are probably related to extension (Bahlburg et al. 2016). The country rocks of these volcanic and sub-volcanic products are clastic sediments or metasedimentary rocks with very low metamorphic grade. The anchimetamorphism field of these rocks indicates temperatures of about 275–300 °C and pressure near 1.5 kbars (Toselli 1982).

As illustrated in Fig. 4, there is a conspicuous change from south to north in the metamorphic conditions between the Sierras Pampeanas and the Eruptive Belt of the Puna, indicating shallower crustal levels, exposed to the north. The arrow at the latitude of the city of Jujuy (Fig. 4) points out the occurrence of volcanic rocks to the north, in contrast with the dominant intrusive rocks to the south of the Famatinian orogen. A second arrow along the boundary between Argentina and Bolivia (Fig. 4) coincides with the last evidence of volcanic rocks to the north. The entire Ordovician rocks of the Altiplano domain of Bolivia and southern Perú have neither arc volcanism nor metamorphism at all (Ramos 2008). However, some minor occurrences have been reported by Bahlburg et al. (2006) in the Ollantaytambo Formation and in the Umachiri beds of Early to Middle Ordovician age and interpreted as back-arc rocks.

At these latitudes, the volcanic arc is developed closer to the continental margin of northern Chile and southern Peru during Ordovician times (Fig. 4). This proximity could be a consequence of crustal erosion by subduction that affected this margin during the Andean cycle, when more than a hundred kilometers were eroded away (Kay and Coira 2009). Relics of the Famatinian arc have been identified along the present continental margin (Loewy et al. 2004; Boekhout et al. 2013; among others).

The southern segment has two regions with different tectonic evolution. The Sierras Pampeanas segment exposes the lower crust as a consequence of the collision of the Cuyania terrane against the Western Gondwana margin (Ramos 2004). This collision deformed and uplifted the continental margin uncovering the lowermost levels of the crust as described by Otamendi et al. (2012). The Altiplano domain preserves clastic deposits of the Ordovician retroarc platform without igneous rocks and no metamorphism. This fact is explained by a different Early Paleozoic tectonic setting. The Altiplano domain was the retroarc basin of an arc developed along the continental margin of northern Chile and southern Perú (see Fig. 4) and did not record any collision at Middle Ordovician times (Bahlburg 1990; Bahlburg and Hervé 1997; Egenhoff 2007; Ramos 2008; Ramos and Coira 2008).

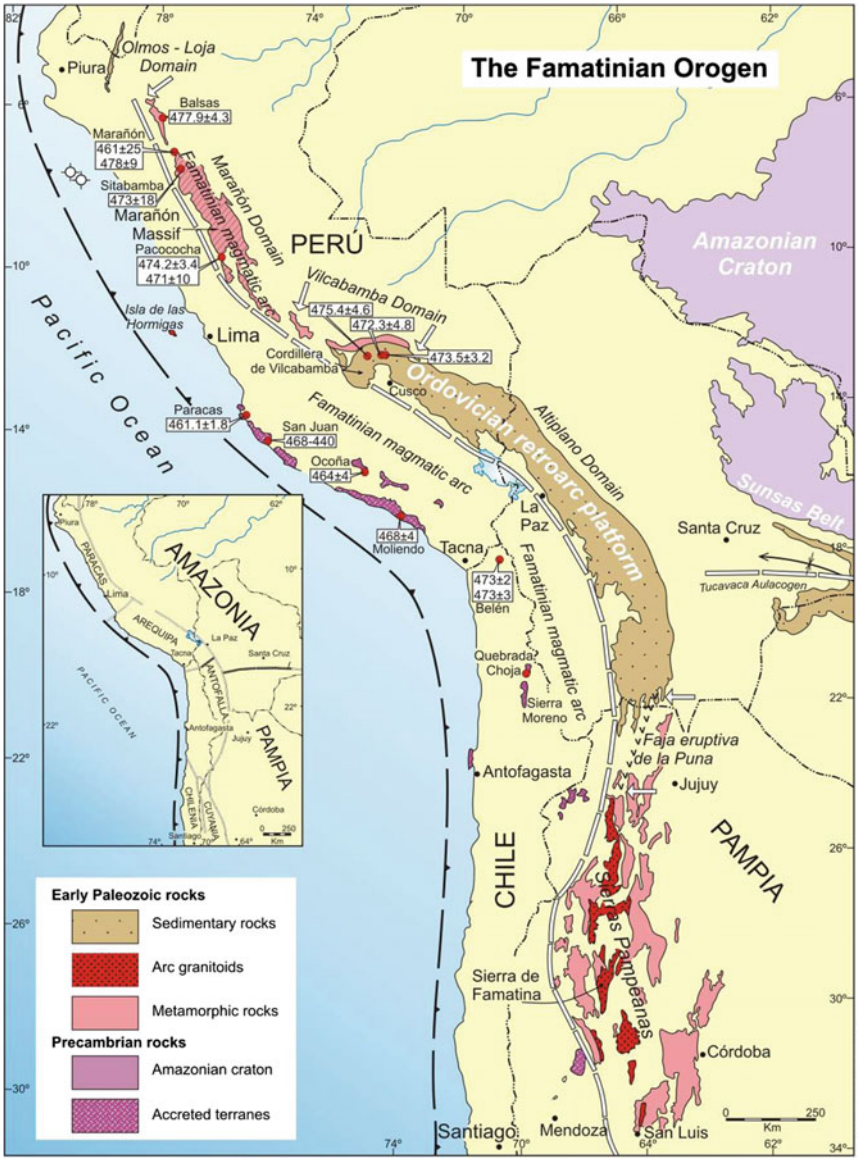

Fig. 4 Famatinian orogen along the central western part of South America shows different segments with distinct behavior. It can be recognized a southern segment where the Sierras Pampeanas, the type locality of the orogen, has been described, the Altiplano domain where an Early Paleozoic retroarc platform is well developed without magmatic arc rocks, and a central segment, where metamorphic and igneous arc rocks are again exposed in northern Perú. The inset shows the different terranes identified along the continental margin after Ramos (2010) and Romero et al. (2013). Some representative ages in millions of years (Ma) are based on Loewy et al. (2004), Cardona et al. (2006), Chew et al. (2007), Reitsma (2012), Boekhout et al. (2013). The broad dashed line between the Ordovician retroarc platform and the Famatinian magmatic arc represents the approximate location of the Grenvillian suture between the Arequipa and Antofalla terranes after Ramos (2010), which has been only partially reactivated by extension during the Famatinian orogeny

3.2 Central Sector

North of the Altiplano domain, the clastic sedimentary sequences of Ordovician age widely exposed in Bolivia and southern Perú have been described by Reimann et al. (2010, 2015). These sedimentary rocks toward the north give place to the low-grade metamorphic rocks of the Cordillera de Vilcabamba (see Fig. 4). These metamorphic rocks in greenschist facies, exposed around the city of Cusco, were attributed to the Early Paleozoic, but new ages of the granites emplaced in these rocks constrained their ages to the pre-Late Ordovician. In fact, the recent U-Pb zircon ages presented by Reitsma (2012) and Spikings et al. (2016) from the Vilcabamba domain show some Famatinian granites with several ages between 475.4 ± 4.6 and 472.3 ± 4.8 Ma.

This segment is well represented in the Marañón Massif, where the Famatinian magmatic arc has been identified by Cardona et al. (2006) and Chew et al. (2007). The geochemical data presented by these authors show a typical arc-related cal-calkaline signature. The metamorphic grade of these basement rocks corresponds to the amphibolite facies, and the arc rocks are mainly preserved as orthogneisses (Chew et al. 2007). Along this segment, Willner et al. (2014) have recognized a paired metamorphic belt, a western belt of medium pressure and high temperature coinciding with the magmatic arc, and an eastern belt with high pressure and low temperature, coinciding with the contact between the Paracas terrane and the protomargin of Gondwana, typical of collision zones. The age of the magmatic arc was precisely dated in several localities ranging between 471 ± 10 and 477.9 ± 4.5 Ma (Fig. 4). Although there is consensus that this suite is subduction related, the tectonic setting proposed by Chew et al. (2007) differs from the proposal of Ramos (2008). The first authors have interpreted the presence of this magmatic arc as an open embayment during Ordovician times, while Ramos (2008, 2009) favored the subduction and later collision of a Grenvillian block, identified as the Paracas terrane. This last proposal is getting support in later local studies (see Carlotto et al. 2009; Chew et al. 2016), mainly after the identification of remnants of this basement block in Isla de las Hormigas and in several oil wells offshore of Trujillo (Romero et al. 2013).

3.3 Northern Sector

This sector encompasses the Famatinian rocks from Ecuador to Venezuela. In recent years, many studies provided new ages that allowed identifying the extension of the Famatinian magmatic arc up to the Cordillera de Mérida in Venezuela. In this sector, several domains with different metamorphic facies have been recognized.

A segment characterized by Ordovician sedimentary and low-grade metamorphic rocks is exposed north of the Cordillera de Marañón, which continues into Ecuador at the latitude of Loja. This segment has been identified by Carlotto et al. (2009) as the Olmos-Loja domain. The metamorphic grade of the Marañón domain drops north of

Balsas (Fig. 4) to the Ordovician phyllites and schists of the Olmos Complex, and the metasedimentary rocks of the Salas Group (Reyes and Caldas 1987).

North of the Olmos-Loja domain in the Cordillera Real of Ecuador, there are some inliers where Paleozoic rocks were identified based on the work of Herbert (1977), who studied the geochemistry of the exposed black phyllites and quartzites. The rocks of these greenschist facies were grouped in the Chiguinda and Agoyán units. These rocks are exposed north of Loja in a belt along the western margin of the Cordillera Real for more than a hundred kilometers (Litherland et al. 1994). Similar rocks crop out again north and south of Papallacta (see location in Litherland et al. 1994), but in this northern part they are associated with orthoamphibolites derived from basaltic precursors. These rocks have important ductile deformation near Cuyuga, where Trouw (in Litherland et al. 1994) has identified a conspicuous nappe tectonics. We had the opportunity to examine the structure of these exposures along the Papallacta Valley, confirming a pre-Jurassic intense deformation (Figs. 5 and 6). No precise ages are available, but there are some old K-Ar ages from Agoyán low-grade rocks, which yielded 417 Ma, probably indicating a cooling age of an older metamorphic rock (Litherland et al. 1994).

The Paleozoic rocks of Papallacta, southeast of Quito (Fig. 7), have K-Ar ages in biotite and hornblende that vary from 881 ± 20 to 306 ± 10 Ma (Litherland et al. 1994), but U-Pb ages have yet to be measured. The highly deformed Paleozoic rocks of the Cordillera Real have been tentatively grouped as the Cuyuga domain (?) in Fig. 7, but it is still uncertain if they are some remains of the Famatinian orogen or they are correlative with the younger Tahamí terrane of the Central Cordillera of Colombia as Martens et al. (2014) have proposed.

The basement of the Eastern Cordillera of Colombia has been interpreted as an allochthonous terrane accreted during Late Paleozoic times (Restrepo and Toussaint 1988). These authors proposed that the Chibcha terrane included the continental basement of the easternmost part of Central Cordillera, the Eastern Cordillera, the Santander Massif, and part of the Santa Marta Massif (Toussaint and Restrepo 1989). Aleman and Ramos (2000) proposed that this continental terrane was accreted by the end of the Ordovician, founded on some preliminary dates available from the Santander Massif and the age of the main deformation of the Quetame low-grade metamorphic rocks. The southern segment of the Chibcha terrane exposed the Quetame Massif (Fig. 7), composed of low-grade metamorphic rocks attributed to the Early Paleozoic.

Based on the stratigraphic relations between the greenschists and the overlying quartzites and conglomerates with intercalated shales, and the palynological assemblage described in these deposits, Grösser and Prössl (1991) separated this unconformable unit as Silurian, restricting the age of the Quetame Schists to the Ordovician. Ordóñez-Carmona et al. (2006) interpreted the collision of the Chibcha terrane to the autochthonous margin of Gondwana at around that time and defined the Quetame event as the main deformation of these metamorphic rocks. Horton et al. (2010) reported a U-Pb age in zircons of 483 ± 10 Ma from a granitic boulder

Fig. 5 Cuyuga nappes in the Papallacta Valley of the Cordillera Real of Ecuador described by Litherland et al. (1994). Red dashed line indicates the base of the overthrust

derived from La Mina Granodiorite, intruded in the phyllitic rocks of the Quetame Group. This group further south passes to Ordovician sedimentary rocks.

There is no reliable data on the age of the metamorphism in Quetame, but based on the preliminary ages obtained in the Santander Massif, Restrepo-Pace and Cediel (2010) recognized three important events in the Chibcha terrane. A Grenvillian age metamorphism ($\sim$1.0 Ga) in the basement is intruded by foliated granitoids of $\sim$477 Ma and non-foliated granites of $\sim$471 Ma. These authors identified the deformation of the Chibcha basement as produced by the Caparoensis orogenic episode, but derived from the evidence obtained in the Santander Massif. Recently, the main peak of metamorphism of equivalent rocks in the Santander Massif has been assigned to the Middle and Late Ordovician by Mantilla Figueroa et al. (2016) and correlated to the Famatinian deformation.

The low-grade metasedimentary rocks exposed in the Floresta Massif, located between the Santander and the Quetame massifs in the Eastern Cordillera (Figs. 7 and 8), have been interpreted by Forero Suárez (1990) as part of the Grenvillian basement of his allochthonous terrane. Recent studies by Horton et al. (2010) described some monzogranitic rocks intruded in this basement with U-Pb zircon ages of 482 $\pm$ 15 Ma and 464.2 $\pm$ 8.2 Ma. These zircons have inherited cluster ages at 1200–1140 Ma and 1050–1000 Ma, consistent with the assumed ages of Forero Suárez (1990).

Fig. 6 Detailed view of pyrophyllite schists of the Cayuga nappes with top-to- the-east deformation in the Papallacta Valley, Cordillera Real of Ecuador

The new studies of Van der Lelij (2013) in the Santander Massif of Colombia and in the Mérida Andes of Venezuela, further north, dated the crystalline basement exposed on these regions. The new ages in the main Mérida basement as well as in the Caparo block show that both units belong to the same terrane, modifying the original proposal of Bellizzia and Pimentel (1994) of the allochthonous Mérida terrane and the autochthonous Caparo block, followed by several authors (see Aleman and Ramos 2000). The new data indicate that the metamorphic basement protolith of the Mérida terrane, including the Caparo block of Bellizia and Pimentel (1994), has mean Grenvillian ages of 1008.6 ± 6.7 Ma and 1018.3 ± 8.9 Ma (Van der Lelij 2013). This study together with the new work of Mantilla Figueroa et al. (2016) and Van der Lelij et al. (2016) shows that the Northern Andes basement of Colombia and Venezuela was affected by an important Ordovician metamorphism. Van der Lelij et al. (2016) recognized a Barrovian metamorphism in upper amphibolite facies with peak conditions between ~489 and ~472 Ma, and a subsequent anatexis that partially melt the orthogneisses at ~454 ± 10 Ma.

The new ages bracketed an important deformation in the Mérida Andes and in the Santander Massif that fit in general terms with the Famatinian orogeny. The deformation is also constrained by the age of the Caparo Formation, a clastic sequence of Late Ordovician age that unconformably covers the metamorphic rocks (Aleman and Ramos et al. 2000; Ordóñez-Carmona et al. 2006).

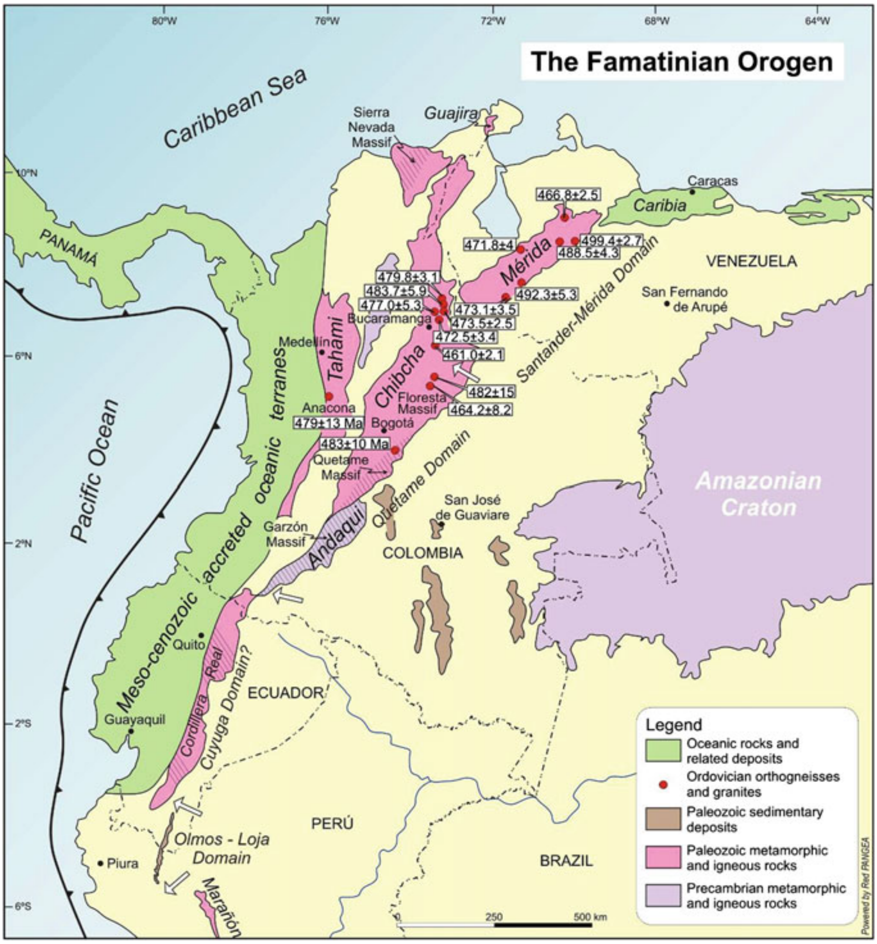

Fig. 7 Famatinian orogen in the Northern Andes. Some representative ages in millions of years (Ma) of the magmatic rocks are indicated (based on Van der Lelij 2013; Martens et al. 2014; Mantilla Figueroa et al. 2016). Note that the reconstruction of the protomargin of Gondwana requires eliminating the oceanic terranes accreted after the Cretaceous

4 The Grenvillian Suture Between Arequipa and Amazonia

There is indirect evidence of an important weakness zone between Arequipa and Amazonia. The data presented by Loewy et al. (2004) have demonstrated that on the Arequipa Massif a magmatic arc during Mesoproterozoic times was developed. Ramos (2008, 2009) has interpreted this juvenile arc as a Grenville arc coeval with the Sunsas arc, which at about ~1,000 Ma has been amalgamated during the formation of the Rodinia supercontinent. The collision between Arequipa

Fig. 8 Deformed Ordovician quartzites in the Quetame Massif, Arroyo Susumuco, Eastern Cordillera

(Antofalla) and Amazonia (Pampia) cratonic blocks produced a prominent suture between these terranes. That suture is interpreted based on the three-dimensional inversion model of the seismic profile of Dorbath et al. (1993) and the structural interpretation of Martínez et al. (1994) depicted in Figs. 9 and 10.

The boundary between the Arequipa terrane and the Amazonian craton has been interpreted as the Grenvillian suture between this continental blocks (Ramos and Jiménez 2014). This weakness zone has been several times reactivated, mainly as a extensional zone controlling the emplacement of igneous rocks during the Pampean, Famatinian, Late Paleozoic, and Andean times (Fig. 10).

This suture continues further south between Antofalla and Pampia cratonic blocks, and is responsible of the emplacement of volcanic and subvolcanic bodies of the eastern eruptive belt in the Puna (see location along the Altiplano as indicated in Fig. 3). This suture probably controlled the Calalaste, Pocitos, and other mafic and ultramafic rocks of different ages (see Pinheiro et al. 2008; Zimmermann et al. 2014). It has also controlled the emplacement of the Frailes Ignimbrite in Quaternary times (Kay and Coira 2009) and the Miocene volcanic rocks of Potosí in Bolivia. This important suture was actively controlling the inception of the Puncoviscana basin in Neoproterozoic times, the *Faja Eruptiva Oriental* of the Puna, and even is still actively controlling the present delamination in the Altiplano (see Beck and Zandt 2002).

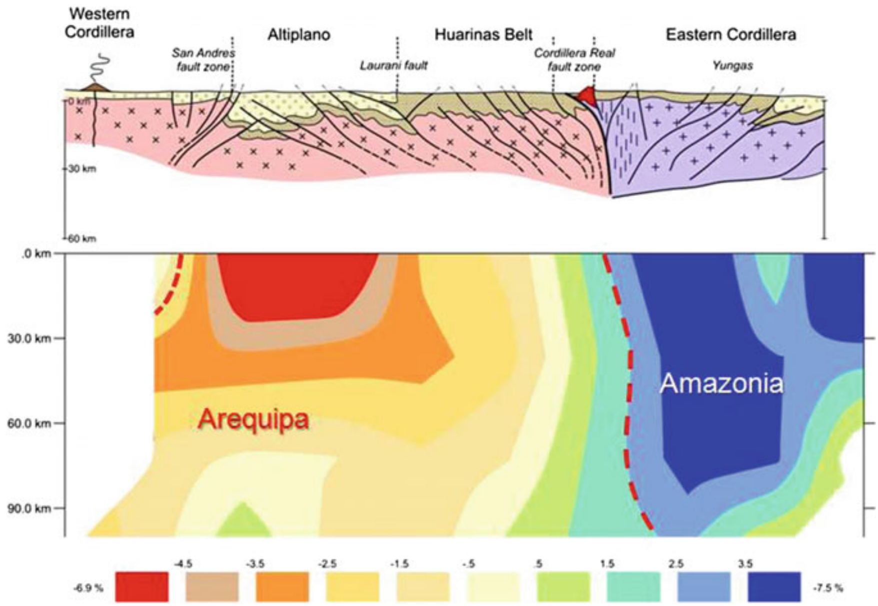

Fig. 9 Geological and structural cross section from the Altiplano to the Eastern Cordillera at the latitude of La Paz, Bolivia. Vertical cross section down to 90 km through the three-dimensional inversion model beneath a seismic profile. Notice that the high-velocity zone (> +2.5%) is limited to the southwest, at least in the crust by the Cordillera Real fault system (after Dorbath et al. 1993). This crustal contrast is interpreted as the boundary between Arequipa and Amazonia

5 Tectonic Setting of the Famatinian Orogen

There is evidence of several segments with calcalkaline magmatic activity along the protomargin of Gondwana during latest Cambrian–Middle Ordovician times. As depicted in Fig. 11, the magmatism is not continuous along the margin and the different sectors have distinctive tectonic settings. The type locality, the Famatinian magmatic arc, is the best known on petrological, geochemical, and isotopic grounds (Ramos 1988; Pankhurst et al. 1998; Fernández et al. 2008; Otamendi et al. 2012). It has an extensive development between Bolivia in the north and the northern boundary of Patagonia to the south. Arc magmatism has been described during Ordovician times in Patagonia, but it is older than Famatinian and it has been correlated by Chernicoff et al. (2013) with the Ross Orogeny developed in the Transantarctic Mountains during Cambrian to Early Ordovician times.

Lower crust levels are exposed in the central part of the Famatinian arc, as described by Otamendi et al. (2012), and these deepest levels are associated with the central part of the collision with the Cuyania terrane around 465–460 Ma. Northward, the magmatic rocks have more superficial volcanic and subvolcanic levels, up to its end in southern Bolivia.

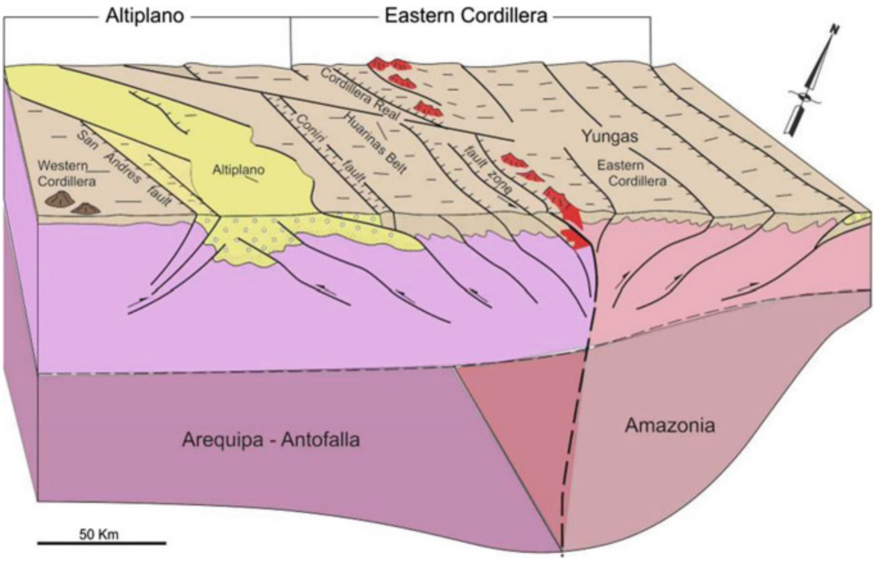

Fig. 10 Structural interpretation showing the Huarinas structural belt developed with a top-to-the-west vergence, between Amazonia and Arequipa (Antofalla) (after Martínez et al. 1994). Late Paleozoic and Oligocene granites that constitute the Cordillera Real are emplaced along the suture (see details in Ramos and Jiménez 2014)

The intense ductile deformation observed in both margins of the Cuyania exotic terrane has kinematic indicators showing a top-to-west vergence (Ramos et al. 1986; Martino et al. 1993), which together with the ophiolitic belt along the western boundary clearly points out to an east-dipping paleosubduction zone (present coordinates). This fact indicates that the magmatic belt developed on the autochthonous protomargin of Gondwana (Ramos 2004).

A branch of the Famatinian arc toward the north developed on the Arequipa-Antofalla terrane along the present margin. A large part of this margin has been eliminated by crustal erosion by subduction (Stern 1991). Along this segment, isolated patches of the magmatic arc were identified by several authors in northern Chile and along the boundary with Bolivia (Wörner et al. 2000; Coira et al. 1999, 2009; Ramos 2009). Geochemical and isotopic characteristics indicate the continuation of the Famatinian arc (Chew et al. 2007; Coira 2008). The old Grenville suture has been extensionally reactivated during Ordovician times and controlled the western slope of the clastic platform (Fig. 11) and the location of submarine tholeiitic rocks and turbiditic deposits along the Grenvillian suture in the Altiplano of Bolivia (Ávila Salinas 1992; Ramos 2008).

The location of the Grenville suture was based on geophysical grounds. The lithospheric model of Dorbath et al. (1993) based on teleseismic data from southern Peru and Bolivia, together with the tomography of Dorbath and Granet (1996) led to the structural interpretation of Martínez et al. (1994) of Figs. 9 and 10. Based on

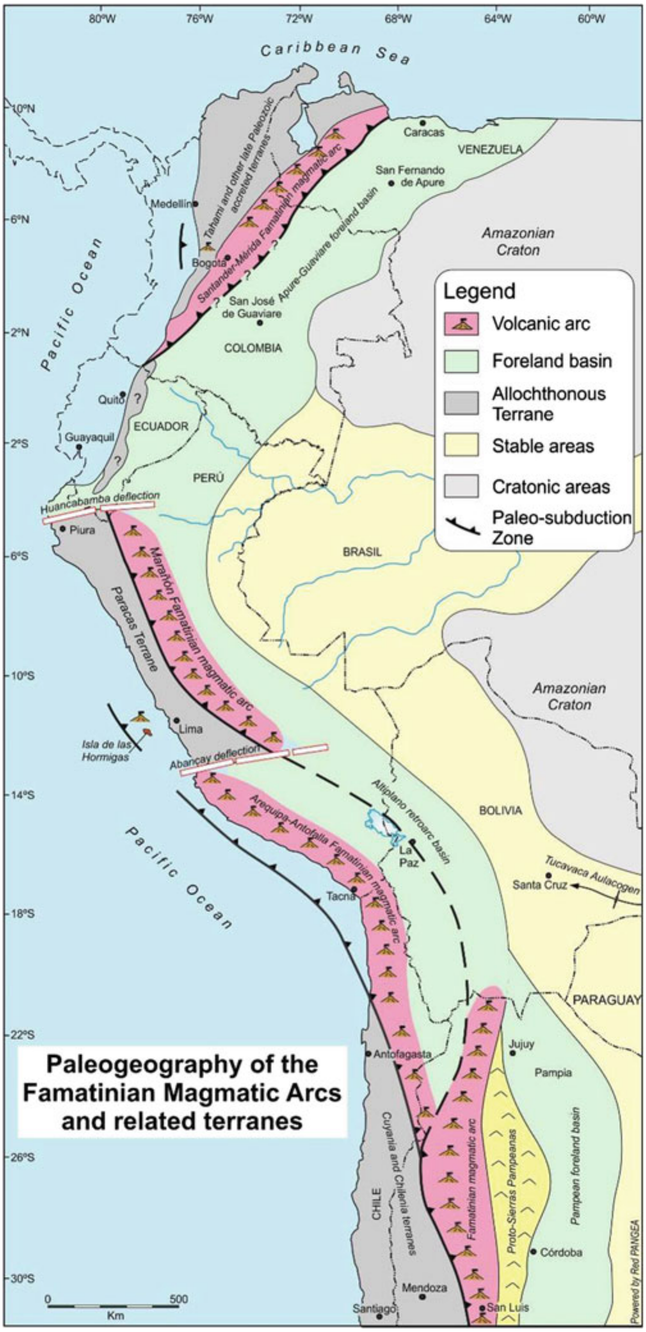

Fig. 11 Paleogeography of the Early Paleozoic along the reconstructed protomargin of Western Gondwana (based on Toussaint and Restrepo 1989; Ramos 2004, 2009; Chew et al. 2007; Coira 2008; Restrepo-Pace and Cediel 2010). Note the relationship between the Huancabamba and Abancay deflections with the paleogeography of the magmatic arc

these data, Ramos and Jiménez (2014) interpreted the location of the suture as traced in Fig. 3. It is worth noting that this weakness zone is controlling the inception of present delamination along the proposed suture east of the Titicaca Lake (Beck and Zandt 2002).

North of the Abancay deflection, Chew et al. (2007) and Cardona et al. (2009) described again the magmatic arc and correlated these rocks with the Famatinian orogen. The magmatic activity prior to the collision has similar ages as the orthogneisses of the type Famatinian locality. Again in this area, the collision with the Paracas terrane is constrained by the metamorphic pair described by Willner et al. (2014). These authors identified high-pressure conditions of 11–13 kbar/ 500º540 ºC during maximum burial derived from a garnet amphibolite in the Tapo Ultramafic Massif, west of the magmatic arc. The Famatinian arc in the western Marañón Complex has low-PT conditions at 2.4–2.6 kbar and 300–330 °C estimated for a phyllite-greenschist assemblage, representing for Willner et al. (2014) contrasting metamorphic conditions characteristic for a magmatic arc environment. The age of the peak metamorphism is 465 ± 24 Ma dated by Sm–Nd mineral-whole rock isochrone. The associated Tapo Ultramafic Complex was interpreted as a relic of oceanic crust which was subducted and exhumed in a collision zone along a suture (Castroviejo et al. 2009, 2010). Structural studies of these ophiolitic relics in Huánuco and Tarma, along the western Marañón Massif, have demonstrated the development of phyllonites and mylonites along the contacts that rule out a previous interpretation of these rocks as peridotite igneous intrusives (Rodrigues et al. 2010a). The ductile deformation D3 that affected the peridotites and serpentinites in Huánuco has a southwest vergence (Rodrigues et al. 2010b).

Based on these data, it is likely that the Paracas microcontinent, a para-utochthonous terrane, collided against the protomargin of Gondwana with a subduction zone dipping to the east (present coordinates) as depicted in Fig. 11 (Ramos 2008, 2009; Carlotto et al. 2009; Willner et al. 2014; Chew et al. 2016, among others).

North of the Huancabamba deflection, there are many uncertainties in the Cordillera Real of Ecuador derived from poor exposures due to the dense vegetation, the conspicuous strike-slip deformation that truncates the continuity of the different units, and the lesser amount of data available in comparison with the Central Andes. However, there is incomplete evidence in two different sectors of the Cuyuga domain (see Fig. 7) where deformed Paleozoic rocks are exposed (Litherland et al. 1994).

Geochronological data only indicate possible Early Paleozoic rocks, but these are not precise enough to correlate these rocks with other known areas either to the north or to the south. Martens et al. (2004) correlated these rocks with the Tahamí terrane, because they share common characteristics with some of the rocks exposed in the Central Cordillera of Colombia. One of the few unambiguous facts is that the deformation of the Cuyuga nappes has a clear vergence to the east (Trouw in Litherland et al. 1994), which may offer some clues in reconstructing the subduction polarity.

The Chibcha and Mérida terranes are important in reconstructing the Famatinian orogen in the Northern Andes (Figs. 7 and 11). The Chibcha terrane has been divided into two different domains. The southern Quetame domain has a lower metamorphic grade and absence of orthogneisses of Famatinian age, when compared with the Santander-Mérida domain (Fig. 8). The relationship between these two domains is similar to the transition among Sierras Pampeanas-Puna Eruptive Belt-Altiplano domains, the Marañón- Vilcabamba-Altiplano domains, or the Marañón-Olmos-Loja domains (Figs. 3 and 7). These transitions are characterized by different crustal levels exposed in each domain, varying from lower crust high-grade metamorphic rocks to upper crustal levels with low-grade metamorphism or just sedimentary and volcanic rocks. These different structural levels have been explained by the amount of shortening and uplift, and subsequent exhumation related to the collision that has affected some segments.

The tectonic setting of the Quetame domain has not consensus. Toussaint and Restrepo (1989) interpreted it as the result of collision of Chibcha terrane with the Gondwana protomargin, proposal that was followed with some little differences by Restrepo-Pace (1992), Restrepo-Pace et al. (1997), Aleman and Ramos (2000), Ordóñez-Carmona et al. (2006), Ramos (2009), and Restrepo-Pace and Cediel (2010). Others interpreted the Chibcha terrane as an autochthonous part of the Gondwana margin (Van der Lelij et al. 2016).

In order to evaluate the tectonic setting of the Quetame domain, it is important to understand the evolution of the Early Paleozoic protomargin. There is good evidence that during Early to Middle Cambrian times the Los Llanos Basin in Colombia and the Apure Basin in Venezuela were part of a continental passive margin, possibly a conjugate margin of the West Avalonia terrane (Murphy et al. 2006). The occurrence of the typical Acado-Baltic trilobite *Paradoxides* in the Cambrian carbonates of Serranía de Macarena, known since the early work of Harrington and Kay (1951), was confirmed by later studies of Rushton (1962), who accepted his provincialism as part of the Atlantic Realm. *Paradoxides* can also be found within the Carolina Slate belt, in eastern New England, eastern Newfoundland, New Brunswick, and in the Avalon Peninsula (Restrepo-Pace and Cediel 2010). Murphy et al. (1999, 2006) assumed that West Avalonia was detached from northern South America, based on the basement characteristics (see also Benedetto and Ramírez 1985; Benedetto et al. 1999; Benedetto 2004). As a result of that, the foreland sector of the Northern Andes was a passive margin during Cambrian to Early-Middle Ordovician times as described by Aleman and Ramos (2000), Restrepo-Pace and Cediel (2010), among others. The change to a contractional tectonic regime occurred in Middle-Late Ordovician times, when the Guaviare–Apure foreland basin was formed (Fig. 11), and for that reason the basal conglomerates of the Darriwilian Caparo Formation are unconformably overlying the Early Ordovician metamorphic rocks of the Mérida Andes. The seismic data on the westernmost Llanos Basin show a fold and thrust belt developed between Late Ordovician to Devonian times, beneath the truncation of the Cretaceous flat lying unconformity.

The Santander-Mérida domain shares in common a high amphibolite grade of its basement, and the occurrence of Famatinian orthogneisses (Restrepo-Pace et al. 1997; Van der Lelij 2013). Main deformation and important uplift took place during the Caparoensis-Famatinian orogeny in Early to Middle Ordovician times. However, two different processes have been invoked to explain the tectonic evolution. Recently, Van der Lelij et al. (2016) challenged the exotic nature of the Mérida terrane, postulating that Chibcha and Merida terranes were formed through a period of alternating compression and extension in an Andean-type setting. The Laurentian nature of the basement proposed by Forero Suárez (1990) was questioned based on a Pb isotope correlation diagram, which shows that the isotopic composition of the basement of Merida terrane was distinct from the eastern Laurentian Grenville Province (Van der Lelij 2013). A similar conclusion was obtained for the Central Andean terrane of Colombia by Ruiz et al. (1999). Cuyania seems to be the only truely exotic terrane for Gondwana, when the Pb isotope compositions of the different Grenvillian terranes associated with the continental margin are compared (Ramos 2004, 2010). Most of the terranes are para-utochthonous to Gondwana and have collided and detached from the margin several times (Ramos 2009).

Another important point is the high-grade Ordovician metamorphism of the Santander Massif and the Mérida Andes, and the subsequent uplift, which are hard to explain in Andean-type settings. The subduction along an Andean margin never exposes the lower crust, unless some extraordinary process occurs, such as the collision of a terrane. Based on these facts, we agree with Restrepo and Toussaint (1988), Toussaint and Restrepo (1989), Restrepo-Pace (1992), Aleman and Ramos (2000), and Ordóñez-Carmona et al. (2006) among many others that considered the Chibcha and Mérida terranes as continental blocks that collided with the continental margin in the Paleozoic.

The polarity of the paleosubduction zone is still a matter of debate. When all the Famatinian arcs along the protomargin are compared, the only one that has a reverse polarity is the Santander-Mérida domain. This is based on the vergence of the structure on the eastern side of the Chibcha and Mérida terranes, the location of the magmatic arc on the hanging wall of the paleosubduction, and the potential sutures described along this limit. However, more data are needed to confirm this assertion.

There are two intriguing facts which have not yet a reasonable justification. One of them is the Anacona terrane in the Central Andes of Colombia south of Medellín (Martens et al. 2004). A typical Famatinian orthogneiss (Figs. 7 and 11), known as La Miel orthogneiss, has xenocryst zircons with igneous overgrowths with ages varying from 479 to 470 Ma, very distinct from other gneisses from the Tahamí terrane. The occurrence of lower Paleozoic metamorphosed granitoids in the Central Cordillera of Colombia, although scarce, has been interpreted as an Ordovician arc formed along the margins of the Rheic Ocean, previous to the amalgamation of Pangea (Villagómez et al. 2011). Another hypothesis for these igneous rocks is that the zircons are fingerprints of the lower crust formed during the rift-related opening of the Iapetus Ocean and could be related to the bimodal igneous domain now in south Mexico and Central America (Martens et al. 2004).

The second intriguing fact is from Isla de las Hormigas along the western margin of Paracas terrane near Lima, where igneous zircons of 467.9 ± 4.5 Ma age in high-grade orthogneisses of Grenvillian age record a Famatinian igneous episode (Romero et al. 2013). The interpretation of this isolated example has the same alternatives as the Anacona terrane previously discussed.

6 Concluding Remarks

The analyses of the occurrence of Famatinian magmatic arcs along the protomargin of Western Gondwana indicate complex and variable tectonic settings, far from a unique simple Andean margin. The status of the present knowledge, although uneven, allows some interesting remarks.

1. There is an almost semicontinuous belt of arc-related rocks with ages varying from 490 to 460 Ma, which correlates with the time span of the Famatinian orogen in its type locality in western Sierras Pampeanas.
2. The metamorphic grade of these rocks has some noticeable variations controlled by the crustal levels exposed. The high-grade domains are flanked by transitional segments where the metamorphic grade changes from greenschist facies to sedimentary facies, as between the Vilcabamba and Altiplano domains, Puna Eruptive Belt and the Altiplano domains, or Marañón and Olmos-Loja domains.
3. The deep crustal level exhumed in some segments seems to be controlled by shortening and uplift produced by collision of different accreted terranes. The large, old, and exotic Cuyania terrane, which has a thick Precambrian cold crust, produced one of the most prominent uplifts and deformations.
4. The variable location of the Famatinian arcs, from far to near the continental margin, is controlled by the presence or absence of terranes colliding against the margin. The Altiplano domain is a good example of a suture of the old Grenville margin, which was not reactivated during Early Cambrian extension.
5. The quasi-uniform ages of all these episodes are not unique, as episodes of “Famatinian” age are registered in the Caledonides in Europe, the Appalachian in North American, and in the Lachlan belt of Australia. This fact obviously indicates a period of fast drift of the Ordovician plates that produced subduction-related igneous rocks all around the globe.

Acknowledgements This paper is the result of many field trips, meetings, and symposia held along the Andes from Venezuela to Patagonia. The author thanks numerous colleagues for livid discussions, hard debates, and generous friendship that fed during the years my interest to learn how the Andes work. The critical reviews of the manuscript by Juan Otamendi, *Universidad de Río Cuarto*, Roberto Martino from *Universidad Nacional de Córdoba* and Heinrich Bahlburg from *Universität Münster* are deeply acknowledged. This is the contribution R-208 of the Instituto de Estudios Andinos Don Pablo Groeber (UBA-CONICET).

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