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THE LATE NEOPROTEROZOIC-EARLY PALEOZOIC BASIN OF THE WESTERN ARGENTINE PRECORDILLERA: INSIGHTS FROM ZIRCON U-PB GEOCHRONOLOGY.

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ABSTRACT

In central-western Argentina, a belt including marine metasedimentary rocks and mafic-ultramafic bodies occurs throughout the western margin of the Precordillera. The belt is considered as the suture zone between the poorly known Chilenia terrane and the Cuyania terrane, part of the composite West Gondwana margin. It is assigned to the Late Neoproterozoic-Early Devonian based on fossil fauna and radiometric ages. In the southern sector of this belt, in the Peñasco area, two units crop out. The Peñasco Formation comprises metasandstone and metapelite spatially associated with mafic metavolcanic and metahyaloclastic rocks. Metagabbro bodies intrude the succession. The Garganta del León Formation consists of metasandstone and scarce metapelite where tractive and deformational sedimentary structures are preserved. Both units are affected by low-grade metamorphism, but the main foliation S_1 and crenulation cleavage S_2 are better developed in the Peñasco Formation rocks. U-Pb data on detrital zircon of two metasandstone samples from these units show a dominant detrital input from sources with 1.0-1.3 and 0.65-0.53 Ga ages. Detritus may come from reworked sedimentary units or from igneous/metamorphic complexes from the Cuyania terrane basement that was possibly exhumed in the Ocloyic orogen. A Gondwanan provenance for the late Neoproterozoic-Cambrian population would also be plausible. A *ca*. 460 Ma zircon population in the Garganta del León Formation is interpreted to be derived from the Famatinian Arc. This would imply that the deposition of the sediment occurred after the collision of the Cuyania terrane against West Gondwana, and that the Ocloyic orogen acted as a barrier for detritus from the Famatinian Arc and other rocks further east.

Key words: Mafic-ultramafic belt; Cuyania terrane; Chilenia terrane; Sedimentary provenance; Detrital zircon.

1. INTRODUCTION

Provenance studies based on the morphological and geochronological analysis of detrital zircon have proven powerful to solve some geological uncertainties. This technique provides estimates for a maximum depositional age and establishes characteristics of sediment source areas, including their composition and age. Provenance studies can, thus, define depositional age limits for sequences that lack fossils, exhibit strong deformation, and/or have been metamorphosed (*e.g.,* Gehrels, 2014). Throughout the Central Andes (28º-34ºS) it is possible to find such sequences of poorly specified age that are related to the accretion of different terranes (Pampia, Arequipa-Antofalla, Cuyania, among others) during the configuration of West Gondwana (current western margin of the South American Plate) during Late Neoproterozoic-Early Paleozoic time. One of these, the Cuyania terrane, is located in central-western Argentina (Fig. 1a). It is generally accepted to have been rifted from the southern margin of Laurentia during the opening of the Iapetus ocean and break-up of the Rodinia supercontinent during Late Neoproterozoic-Early Cambrian time (Thomas and Astini, 1996; Thomas *et al.*, 2012, among others), and that it was accreted onto West Gondwana during the Late Ordovician (Astini *et al.*, 1995; Ramos, 2004; among others).

During the past decades, the eastern margin of Cuyania has been the subject of numerous studies and strong debate, but little is known about its western margin and its relation to the poorly exposed Chilenia terrane to the west (Fig. 1a; Ramos *et al.*, 1986). There is a general consensus that the Cuyania and Chilenia terranes are separated by the Western Precordillera mafic-ultramafic belt, which can be traced for > 400 km north-south, and this is so far the main support for the existence of Chilenia as a separate terrane. Collision processes have been suggested by different studies carried out along this belt (Davis *et al.,* 1999, 2000; Robinson *et al.*, 2005; Massonne and Calderón, 2008; Willner *et al.,* 2011; Boedo *et al.,* 2016a-b), but still many aspects remain unsolved, including the provenance of the Chilenia terrane, such as whether all its Neoproterozoic-Devonian sedimentary successions were deposited in the same ancient marine basin, or whether the western margin of Cuyania was affected by the Ordovician Ocloyic orogeny, *i.e*. the collision of Cuyania with West Gondwana.

This contribution proposes the redefinition of two stratigraphic units from the southern sector of the Precordillera mafic-ultramafic belt (at the Peñasco locality, Fig. 1b) according to their geological features. We also provide U-Pb data for detrital zircon from these two units, estimate their maximum depositional ages, and characterize and assign possible source areas.

2. GEOLOGICAL FRAMEWORK

The Argentine Precordillera is a Miocene-aged fold-and-thrust belt located in central-western Argentina within the Cuyania terrane (Fig. 1a-b). The basement to this belt is indirectly known from studies of xenoliths of metamorphic rocks hosted in Neogene volcanic rocks (Leveratto, 1968). The xenoliths yielded U-Pb zircon ages between 1000 and 1100 Ma (Kay *et al.*, 1996; Rapela *et al.*, 2010).

The Early Paleozoic stratigraphic sequence of the Precordillera mainly consists of platform limestone to the east and marine siliciclastic sedimentary rocks to the west, where mafic and ultramafic bodies, which are affected by very low-grade to low-grade metamorphism, are intercalated (Haller and Ramos, 1984; Astini *et al.*, 1995; Thomas and Astini, 2003).

The western domain of the Argentine Precordillera consists of marine metasedimentary rocks. They occasionally host platform carbonate and siliciclastic olistoliths from the basement (Thomas and Astini, 2003, and references therein). These successions are spatially related to mafic and ultramafic bodies grouped together as the Western Precordillera mafic-ultramafic belt (PMUB).

The PMUB crops out between 28 and 33°S and consists of serpentinized ultramafic rocks, retrograded granulite, metagabbro and metabasalt that are tectonically juxtaposed and/or intrude the siliciclastic marine successions. The mafic rocks have mainly E-MORB (Enriched Mid-Ocean Ridge Basalt) signature and positive εNd values (+6 to +9.3), compatible with rocks from the oceanic crust (Haller and Ramos, 1984; Kay *et al*., 1984; Cortés and Kay, 1994; Fauqué and Villar, 2003; González Menéndez *et al.*, 2013; Boedo *et al.*, 2013). The belt exhibits strong polyphase deformation. The vergence of the Early Paleozoic deformation is still a matter of debate. Some authors postulate a westward vergence based on major structures (Ramos *et al.*, 1986; von Gosen, 1995; Cortés *et al.*, 1999), whereas others propose an eastward vergence on the basis of only localized kinematic indicators in allochthonous granulite lenses (Davis *et al.*, 1999; Gerbi *et al.*, 2002). These lenses may have been rotated, as they show different orientations along strike with respect to the main foliation (S_1) in metasedimentary rocks. Giambiagi *et al.* (2010) proposed a first event (D1) with east-west maximum shortening and westward vergence, and a second event (D2) with northwest – west-northwest maximum shortening direction and double vergence.

The PMUB can be divided into two sectors based on rock association and metamorphic grade: a northern sector, which comprises the localities of Jagüé, Rodeo, Tigre, Invernada, Calingasta, and Leoncito and a southern sector with the localities of

Peñasco, Pozos, Cerro Redondo, Cortaderas, and Bonilla (Fig. 1b). This latter sector of the PMUB can be correlated with the Frontal Cordillera mafic-ultramafic belt, which is located further south in the Cuchilla de Guarguaraz within the Argentine Frontal Cordillera (Fig. 1b). There, serpentinite, metaperidotite, massive orthoamphibolite, metagabbro, metabasaltic dikes, and pillow basalt are in contact with marble and schist (Villar, 1969, 1970; Gregori and Bjerg, 1997; López and Gregori, 2004; López de Azarevich *et al.*, 2009; Gargiulo *et al.*, 2011, 2013). The mafic bodies have N-MORB to E-MORB chemical signature (López and Gregori, 2004; López de Azarevich *et al.*, 2009), and the whole sequence is strongly deformed and metamorphosed.

Very low- to low-temperature and low-pressure metamorphic conditions (2-3 kbar, 250-350ºC) were estimated along the northern sector of the PMUB (Robinson *et al.,* 2005), whereas a low- to medium-temperature and high-pressure conditions affected the southern sector (7-9 kbar, 345-395℃, Boedo *et al.*, 2016a). Pressure-Temperature estimates by Davis *et al.* (1999) for the Cortaderas granulite yielded 850-1000℃ at 11 kbar, whereas even higher-pressure conditions were estimated for granulite from the Peñasco area (12-18 kbar, 650-910℃, Boedo *et al*., 2016b). Similarly, Massonne and Calderón (2008) and Willner *et al.* (2011) estimated high pressure conditions in metabasite and metapelite of the Guarguaraz area (Argentine Frontal Cordillera), followed by a decompression path with slight heating (clockwise metamorphic path). Dating of the metamorphic event generally yielded Middle-Late Devonian ages (Cucchi, 1971; Buggisch *et al*., 1994; Davis *et al*., 1999; Willner *et al*., 2011).

The PMUB, considered as an almost complete but dismembered ophiolite sequence, represents oceanic crust that may have been subducted shortly before the collision of the Chilenia terrane with the West Gondwana margin during the Middle Devonian (Haller and Ramos, 1984; Ramos *et al.,* 1986). Davis *et al.* (2000) challenged this interpretation and, based on U-Pb ages and geochemical data, proposed that the mafic and ultramafic bodies formed in different tectonic settings, such as a mid-ocean ridge setting (for E-MORB basalt), and the roots of a magmatic arc developed above a west-dipping subduction zone (for mafic granulite). In an earlier interpretation based on the detrital and geochemical features of the sedimentary rocks, Loeske (1993) postulated that the PMUB represents the floor of a back-arc basin.

3. METHODOLOGY

We studied two metasandstone samples from the Peñasco area, the northernmost locality of the southern PMUB (Fig. 1b). Metasandstone M-36 represents the Peñasco Formation and was taken west of the Cerro Pozo area (32°13'16.8"S-69°8'33.6"W, Fig. 2). Sample M-50 from the Garganta del León Formation was obtained in the Quebrada del Río Montaña (32°9'53.6"S-69°4'16.9"W, Fig. 2). Both samples were studied with a Nikon Optiphot2-Pol microscope, and protoliths were classified according to Folk *et al.* (1970).

The samples were prepared and analyzed following standard procedures. They were milled with a crusher and an agate mortar at the Departamento de Geología of the Universidad Nacional de Río Cuarto (Córdoba, Argentina). Detrital zircon grains were separated using standard preparation methods at the Departamento de Ciencias Geológicas of the Universidad de Buenos Aires (Argentina). Grains were randomly selected by hand-picking using a Leica EZ5 binocular microscope. Morphological analysis of detrital zircon grains was conducted with a FEI QUANTA 450 scanning electron microscope (SEM) at the Laboratório de Geoquímica Isotópica e Geocronologia of the Universidade de Brasília (UnB, Brazil). Different populations of detrital zircon grains were identified based on shape, habit, size, color, and aspect ratio. Back-scattered and secondary electron, and cathodoluminescence imagery obtained with the FEI QUANTA 450 SEM provided information about internal structures, fracture patterns, and solid inclusions.

U-Pb analyses of zircon were performed with a New Wave 213 µm Nd-YAG solid state laser attached to a Thermo Finnigan Neptune Multi-Collector Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICP-MS) at UnB following the procedure outlined by Bühn *et al.* (2009). The laser operated with a fluency of 2.0–2.3 J/cm^2 and a frequency of 10 Hz; ablation spots were about 30 µm in diameter. Blanks were measured before and after each sample analysis for blank correction. An external standard of 600.4 ± 1.8 Ma age (GJ1, Jackson *et al.,* 2004) was analyzed after every 8 unknown measurements to correct for mass bias and fractionation of U and Pb. An internal standard of 1063.4 ± 0.6 Ma was analyzed after 15 unknown measurements (reference zircon 91500; Wiedenbeck *et al.,* 1995, 2004) to check analysis reproducibility.

Data reduction was completed with an in-house Excel worksheet at UnB (Chronus, Valença, 2015). Analytical data for the analyzed zircon grains are listed in Appendix 1. Cumulative probability plots were constructed employing ISOPLOT v.3.70 (Ludwig, 2009), using analyses within 20% of concordance and reporting ^{207}Pb/^{206}Pb ages for analyses >1.0 Ga and ^{238}U/^{206}Pb ages for analyses < 1.0 Ga (Dickinson and Gehrels, 2003). Discordance was calculated as [1-(^{206}Pb/^{238}U age/^{207}Pb/^{206}Pb age)]·100 (Appendix 1).

A total of 96 analyses were performed on 80 zircon grains from metasandstone M-36, but 20 results were discarded due to $^{207}Pb/^{235}U$ error > 5%, Rho < 0.5, and ^{206}Pb contents > 3%. The remaining 76 zircon ages were concordant. For sample M-50, a total of 91 analyses were performed on 78 zircon grains. Ten results were discarded, and 81 zircon ages were concordant. To estimate the maximum depositional ages, we used (1) the youngest graphical peak and (2) the weighted mean of the coherent group of youngest ages that overlap at 2σ analytical error.

4. STRATIGRAPHY OF THE STUDY AREA

We propose a new nomenclature scheme for the upper part of the Villavicencio Group of the PMUB (Table 1). The unit names that are used throughout this study are based on this new subdivision.

Our proposal is based on the distinction of different lithological associations and structural features that were until now combined into one geological unit (Table 1). We redefined the Peñasco Formation after Cortés *et al.* (1999), which consists of a succession of metasandstone and metapelite spatially associated with mafic metavolcanic rocks and metahyaloclastite. Metagabbro dikes and sills frequently intrude the metasedimentary succession. The main metamorphic foliation (S_1) is conspicuous along sedimentary and igneous protoliths, and a crenulation cleavage (S_2) is generally well developed in fine-grained rocks. In contrast, the Garganta del León Formation, in part correlative to the Peñasco Formation after Cortés *et al.* (1999), includes metasandstone and scarce metapelite where tractive and deformational sedimentary structures are preserved. Metamorphic foliation S_1 is robust and S_2 is rarely developed.

We also suggest modifying the unit range of the lower part of the Villavicencio Group according to the Código Argentino de Estratigrafía (Comité Argentino de Estratigrafía, 1992), as the current name is not valid. Therefore, the former 'Cortadera facies' (Harrington, 1971) is renamed as 'Cortadera Complex' (Table 1). This modification is based on the different lithologies combined into this unit that also includes a complex structure without recognizable original rock succession. The Cortadera Complex crops out over *ca*. 30 km from the Cordón del Peñasco area to the Sierra de las Cortaderas area, where it reaches a maximum width of 3.6 km (Fig. 2). It comprises highly serpentinized ultramafic rocks (dunite, harzburgite, lherzolite, wehrlite and websterite), ultramafic cumulate, retrograded mafic granulite, and garnet-quartz-feldspar gneiss bodies that are in contact with gray to light blue phyllite and slate; the contact is marked by brittle, reactivated, ductile shear zones (Harrington, 1971; Davis *et al.,* 1999; Gerbi *et al.,* 2002). Metagabbro bodies intrude the serpentinite and phyllite. Listvenite is frequently associated with serpentinite margins (Boedo *et al.,* 2015). Mafic granulite and gneiss register a complex polymetamorphic evolution from high-pressure granulite facies to greenschist facies (Boedo *et al*., 2016b). The base, top and thickness of the unit are unknown due to intense deformation. The contacts with the Peñasco and Garganta del León formations are tectonic (Fig. 2, Table 2).

4.1. Peñasco Formation

The Peñasco Formation was earlier cataloged by Harrington (1971) as the Normal Facies of the Villavicencio Group (Table 1). Later, Cortés *et al.* (1999) defined the Peñasco Formation as the siliciclastic metasedimentary succession intruded by mafic bodies that crops out in the Cordón del Peñasco, Pozos and Cortaderas localities. We define the "Peñasco Formation" as the siliciclastic metasedimentary succession intruded by metagabbro bodies that is spatially associated with mafic metavolcanic and metahyaloclastite bodies. The formation crops out along the Cordón del Peñasco, to the west of the Cerro Pozo, and in the western part of the Sierra de las Cortaderas area (Fig. 2, Table 2).

The formation consists of olive-green, medium-fine metasandstone and metapelite intruded by metagabbro and/or metabasalt dikes and/or sills (Fig. 3a-c). Mafic metavolcanic and metahyaloclastite are frequently intercalated (Fig. 3d-f). The base, top and thickness of the unit are unknown due to intense deformation. The contacts with the Cortadera Complex are always tectonic. Metasedimentary rocks usually have a marked main foliation (S_1) that frequently coincides with original stratification (S_0). When recognized, crenulation cleavage (S_2) is better developed in fine-grained rocks (Fig. 3c).

Metagabbro and metabasalt bodies vary from a few meters to tens of meters in extent. They exhibit porphyritic to fine-grained texture, with 1-3 mm large plagioclase crystals, and dark green to black pyroxene crystals. Thicker bodies show margin-to-core crystal size variation. The primary assemblage of plagioclase, clinopyroxene and minor ilmenite, apatite and brown amphibole has been partially replaced by a high-pressure greenschist-facies mineral association (chlorite + albite + white mica (phengite) + epidote + titanite + actinolite + quartz + magnetite, Boedo *et al.*, 2016a). Ophitic and/or subophitic arrays and graphic texture are also recognized. They are tholeiitic in composition and have an E-MORB chemical signature (Boedo *et al.*, 2013).

The mafic metavolcanic and metahyaloclastic rocks are lenticular in shape and usually one meter thick. The mafic metavolcanic rocks are black, aphanitic, and composed of devitrified vitreous material and quartz-filled or carbonate-filled vesicles (Fig. 3d-e). Under the microscope, they have aphyric texture, whereby the groundmass of devitrified vitreous material is totally altered to a fine aggregate of albite, chlorite, opaque minerals and epidote. The metahyaloclastic rocks are groundmass-supported and brecciated. They consist of up to 7 cm large, angular to subangular, mafic metavolcanic and minor grey phyllite clasts (Fig. 3f) in a fine-grained matrix composed of deformed vitreous shards.

The depositional setting of the Peñasco Formation corresponds to a continental margin facing a shallow marine basin to the west (Harrington, 1971; Cortés *et al.,* 1999). A depth of < 200 m can be inferred from a high percentage of vesicles in mafic metavolcanic rocks (Moore and Schilling, 1973) and the presence of metahyaloclastic rocks (fragmentation due to cooling) in the Cordon del Peñasco area.

The metasedimentary rocks and mafic igneous bodies of the formation have been affected by a high-pressure greenschist facies metamorphism (345-395ºC, 7.0-9.2 kbar, Boedo *et al.*, 2016a).

4.2. Garganta del León Formation

We define the Garganta del León Formation as the siliciclastic metasedimentary succession that lies along the eastern sector of the Cordón del Peñasco (Fig. 2). Similar to the Peñasco Formation, it was early on grouped by Harrington (1971) into the Normal Facies of the Villavicencio Group and redefined by Cortés *et al.* (1999) as part of the Peñasco Formation (Table 1). We propose to separate it from the Peñasco Formation, as it consists only of metasedimentary rocks (see Table 2 for summary). Metamorphic foliations S_1 and S_2 are less developed than in the Peñasco Formation.

The Garganta del León Formation comprises up to 2 m-thick layers of olive-green, medium to fine-grained metasandstone that alternates with scarce olive-green metapelite (Fig. 4a-b). Occasionally, amalgamated medium-grained metasandstone, 1 m-thick coarse-grained metasandstone, and fine-grained metaconglomerate occur. In some places, up to 0.8 m-thick lenticular-shaped metasandstone layers occur. In other places, metasiltstone and 0.5 m-thick, tabular, massive, fine-grained metasandstone dominate. Fining-upward cycles and sedimentary structures such as flute and tool marks on bases, inverse grading, load casts, cross stratification, horizontal lamination and ripples are observed (Fig. 4c-d). Hummocky cross stratification-like structures are also recognized (Fig. 4e). Despite deformation, sedimentary features are still well-preserved along the Quebrada del Río Montaña. The main foliation S_1 is exclusively recognized in the fine-grained rocks and frequently coincides with stratification (S_0, Fig. 4b).

The top and thickness of the unit are unknown due to intense deformation and the absence of key beds. To the west, the contact with the Cortadera Complex is tectonic (Fig. 2). To the east, the formation conformably overlies the Alojamiento Formation (Banchig, 2006). This is consistent with the presence of limestone clasts in fine-grained metaconglomerate beds of the Garganta del León Formation (Fig. 4f).

The preserved strata and sedimentary structures suggest deposition in proximal areas, probably as a wave-modified turbidite (Myrow *et al.*, 2002). The strata belong to a continental margin facing a marine basin to the west (Harrington, 1971; Cortés *et al.*, 1999).

5. PETROGRAPHY AND U-PB GEOCHRONOLOGY

5.1. Petrography

Sample M-36 is a fine-grained metasandstone with an incipient spaced cleavage (S_1) (Fig. 5a-b). The lithology mainly consists of quartz grains (50%) up to 0.5 mm in size, with undulatory to patchy extinction. They appear rounded due to partial recrystallization during metamorphism and show pressure solution effects parallel to S_1. Lithic fragments (30%) correspond to low-grade metasedimentary rocks. Feldspar grains (10%) can reach 0.3 mm in size. Detrital white-mica laths (8%) reach 0.3 mm in size. Opaque minerals, zircon, tourmaline and pyroxene grains are also recognized (2%). The scarce matrix shows incipient recrystallization and consists of chlorite, white mica and opaque minerals. The protolith is classified as litharenite (Folk *et al.*, 1970).

Sample M-50 is a clast-supported metasandstone (Fig. 5c-d). It is composed of quartz grains (55%), with undulatory to patchy extinction and a size range from <0.1 to 0.9 mm. Lithic fragments (25%) are 0.2-1 mm in size and correspond to low-grade metasedimentary rocks (mainly phyllite and slate). Detrital feldspar (15%) is 0.1-0.4 mm in size. Detrital white-mica, zircon, apatite, biotite, and opaque minerals (5%) are also recognized. The scarce matrix has been affected by incipient recrystallization and is composed of chlorite, white mica, and opaque minerals. The protolith is classified as feldspathic litharenite (Folk *et al.*, 1970).

5.2. Detrital zircon morphology and U-Pb geochronology

The detrital zircon grains from both samples can be divided into 3 main groups according to color, aspect ratio, habit, length, and internal structure.

i) Colorless to light pink, subrounded grains of prismatic habit, with lengths of 110-210 µm. Aspect ratios are up to 2:1. Grains comprise homogeneous or faintly and broad oscillatory growth as internal structures, compatible with an igneous origin. Inclusions and microfractures are common. This is the most abundant zircon group in metasandstone M-36. It is less abundant in sample M-50.

ii) Colorless to light pink, idiomorphic grains with aspect ratios between 2:1 and 3:1. The length ranges from 150 to 300 µm. The grains have faint, broad oscillatory zoning, compatible with an igneous origin. This type forms the most abundant detrital zircon group in metasandstone M-50. Zircon grains from sample M-36 are prismatic, whereas those from sample M-50 are bipyramidal. Microfractures are recognized only in zircon grains of M-50. Both samples yield grains with acicular and/or prismatic inclusions.

iii) Pink, rounded grains with aspect ratios of about 1:1. Sizes range from 80 to 155 µm, with some exceptional cases up to 200 µm. This group of grains exhibits complex zoning compatible with a metamorphic origin. This type is more abundant in sample M-36 than in M-50.

Concordant zircon ages for sample M-36 define 3 main intervals (Fig. 6a): 530-830 Ma (55%, maximum age peak at *ca*. 630 Ma), 0.9-1.4 Ga (29%), and 1.7-1.9 Ga (13%). The *ca*. 630 Ma age peak is represented by grains from group (i). The youngest zircon population (*ca.* 530 Ma) is represented by idiomorphic zircons from group (ii). A weighted mean maximum depositional age is 533.9 ± 4.7 Ma. In contrast, concordant zircon ages for metasandstone M-50 define a bimodal distribution (Fig. 6b): 455-910 Ma (37%, maximum age peak at *ca*. 460 Ma) and 1.0-1.5 Ga (48%, maximum age peak at 1.2 Ga). The youngest maximum peak at *ca.* 460 Ma is given by idiomorphic zircon grains with bipyramidal habit and oscillatory zoning (group ii). This population is not registered in sample M-36. A weighted mean maximum depositional age of the cluster is 458.1 ± 1.5 Ma.

Mesoproterozoic zircon grains from both samples fall into the 1.0-1.3 Ga range. Both metasandstone samples exhibit a peak at *ca*. 1.2 Ga produced by zircon grains from groups (i) and (ii). Both samples also yield a Paleoproterozoic time interval (1.6-2.0 Ga) with a minor peak at *ca.* 1.9 Ga for zircon grains from group (ii) (M-36) and (iii) (M-50). Some of these grains are homogeneous or show faint, broad oscillatory zoning. Older zircon grains (*ca*. 2.5 and 3.2 Ga) recognized in metasandstone M-36 are rounded crystals with complex metamorphic zoning (group iii).

6. DISCUSSION

6.1. Source areas

The zircon ages show that the marine basin in the southern sector of the PMUB received sediment from areas where mainly rocks of Mesoproterozoic and Neoproterozoic ages were exposed. Paleoproterozoic and Early Paleozoic rock bodies were also exhumed and provided material to a lesser extent. These detrital ages can be compared with ages derived from the basement of the Cuyania and Chilenia terranes as well as from the basement of Gondwana.

The small proportion of Late Paleoproterozoic (1.6-2.0 Ga) zircons and its correlation with group (i) and (iii) morphologies (round to oval grain shapes with homogeneous and complex zoning) lead us to interpret this as reworked grains coming from rocks of previous sedimentary cycles. If we consider a Laurentian affinity for the Cuyania terrane, the detrital ages are comparable to the ages of the Yavapai-Mazatzal province (1.65-1.80 Ga) and/or the Trans-Hudson orogen (1.8-1.9 Ga; Whitmeyer and Karlstrom, 2007). A provenance from the Sierra de Maz (1.8-1.9 Ga) and further north, the Arequipa-Antofalla terrane (1.7-2.1 Ga) and the Río Apa block (1.77-1.95 Ga; Loewy *et al.,* 2004; Casquet *et al.,* 2012), can also be considered. However, the northern boundary of the Cuyania terrane has been a matter of debate, and its tectonic relationship with the Arequipa-Antofalla terrane is still not clearly determined. Similarly, a provenance from the Río de la Plata craton and other basement blocks of southern Brazil is not straightforward, as their typical 2.0-2.2 Ga age range (*e.g.*, Hartmann *et al.,* 2002; Rapela *et al.*, 2007) is practically absent in the analyzed samples. The 2.0-2.2 Ga detrital age has not been registered in other Early Paleozoic units of the Cuyania terrane either (Finney *et al*., 2005; Gleason *et al.*, 2007; Naipauer *et al*., 2010; Abre *et al*., 2012). This would imply the presence of an exhumed area (*e.g.*, the Pampean and/or Ocloyic orogen) that acted as a barrier for detrital input coming from cratonic areas (Augustsson *et al.*, 2015).

The dominance of Mesoproterozoic detrital zircon ages in the 1.0-1.3 Ga range is comparable to the age range of the presumably Grevillian basement rocks of the Cuyania terrane (*ca*. 1.24-1.03 Ga, Varela *et al.*, 2011, and others therein) and to the Las Yaretas gneiss exposed to the south of the study area at the Cordón del Portillo of the Argentine Frontal Cordillera, considered a part of the poorly exposed basement of the Chilenia terrane (1.07-1.08 Ga, Basei *et al.*, 1997). The 1.0-1.3 Ga detrital age is also comparable to ages from the Gondwanan Sunsás belt, located further north in the southwestern Amazonian craton, and also from the Arequipa-Antofalla terrane (Ramos, 2010, and others therein). However, considering the mostly elongated to oval zircon grains analyzed here, and their moderate degree of roundness, we interpret that they are derived from eroded or covered igneous/metamorphic complexes and/or recycled sedimentary rocks exposed in the vicinity of the depositional basin (*i.e*., the Cuyania basement) rather than from remote Gondwanan locations.

The strong presence of this 1.0-1.3 Ga population in the analyzed samples and also in other Neoproterozoic-Early Paleozoic units from the Cuyania and Chilenia terranes (Finney *et al.*, 2005; Gleason *et al.*, 2007; Willner *et al.*, 2008; Naipauer *et al.*, 2010;

Abre *et al.*, 2012; Ramacciotti *et al.*, 2015) suggests the existence of a constant source area that provided material throughout the basins that developed in the Cuyania terrane during the Neoproterozoic and Early Paleozoic.

The common late Neoproterozoic (*ca*. 650-600 Ma) and minor early Neoproterozoic (*ca*. 830-710 Ma) age population of both samples, as well as the age peak at *ca*. 530 Ma for the Peñasco Formation, are comparable to both Laurentian and Gondwanan sources, all related to the break-up of Rodinia. The typically subrounded grains with oscillatory magmatic zoning (group ii) are in accordance with igneous sources. The *ca*. 650-600 Ma population may have been derived from the igneous rock bodies related to the Brasiliano-Pan-African Orogen (*e.g.*, Brito Neves *et al.,* 1999), as interpreted for some Early Paleozoic Gondwanan units that show a similar detrital age (*e.g.*, Collo *et al.,* 2009; Adams *et al.*, 2011). A provenance from Late Neoproterozoic intrusive rocks from the Arequipa-Antofalla terrane (Loewy *et al.,* 2004) may also be possible. Another source for the Neoproterozoic populations could be reworked sedimentary units exhumed in the Ordovician Ocloyic orogen that host zircon related to the magmatic pulses during the opening of the Iapetus ocean (760-700 Ma, 620-550 Ma, Aleinikoff *et al*., 1995). A-type magmatism related to the early phase of the Rodinia break-up is registered both in the current Pie de Palo (774 Ma, Baldo *et al*., 2006) and Maz ranges (845 Ma, Colombo *et al.,* 2009). The peak of *ca*. 530 Ma in the Peñasco Formation is close to the time of the synrift volcanism along the Ouachita rift and Alabama-Oklahoma transform in the Ouachita embayment of Laurentia (539-530 Ma, Thomas *et al.,* 2012), where Cuyania supposedly rifted (Astini *et al.*, 1995; Thomas and Astini, 1996). However, the 530 Ma age peak is also similar to the time of the collision of the Pampia terrane with the Rio de la Plata craton (Pampean orogeny, 550-520 Ma, *e.g.,* Rapela *et al.*, 1998).

The youngest *ca*. 460 Ma zircon population only recognized in the Garganta del León Formation can be correlated to the late stages of the Famatinian Arc due to the presence of elongated and subrounded grains with igneous oscillatory zoning. The Famatinian Arc (530-460 Ma) developed due to east-dipping subduction of the ocean crust beneath West Gondwana, and magmatic activity ended with the collision of the Cuyania terrane (*e.g.,* Ramos *et al.*, 1986; Thomas and Astini, 1996). This detrital age is scarce along the Argentine Precordillera and points to the existence of a positive area, such as the Ocloyic orogen, that acted as a barrier for more important detrital input from the arc into the Ordovician to Silurian marine basins of central and western Cuyania (Gleason *et al.*, 2007; Abre *et al.*, 2012). The presence of this 'Famatinian' population suggests that deposition in a marine setting still occurred in the studied area after the collision of the Cuyania terrane with West Gondwana.

6.2. Tectonic implications

The extensional regime registered in the current southern PMUB and in the Frontal Cordillera mafic-ultramafic belt since the Late Neoproterozoic-Middle Cambrian (Basei *et al.*, 1997; Davis *et al.*, 2000; López and Gregori, 2004; Banchig, 2006; López de Azarevich *et al.,* 2009) was widespread along the PMUB and also further south (current San Rafael Block, Abre *et al.*, 2011) during the Ordovician.

This is evidenced by the dominant siliciclastic deposits that frequently host marine fauna and that are spatially related to E-MORB magmatism (Haller and Ramos, 1984; Kay *et al.*, 1984; González Menéndez *et al.*, 2013; Boedo *et al*., 2013). Extensional structures caused by gravitational collapse related to submarine sliding and carbonate olistoliths within Tremadocian slope facies register resedimentation processes along the margin of the basin (Benedetto and Vaccari, 1992; Banchig and Bordonaro, 1994; Alonso *et al.*, 2008).

The sediments of the Peñasco and Garganta del León formations were deposited in this extensional context. According to their lithological association, it can be interpreted that the studied formations were deposited in different sectors of the marine basin. Their Mesoproterozoic and Neoproterozoic detrital zircon ages are similar to those from other Early Paleozoic units of the Cuyania terrane (Finney *et al*., 2005; Gleason *et al.,* 2007; Naipauer *et al.,* 2010; Abre *et al.*, 2012). This implies that an important source area provided detritus of mostly Meso- and Neoproterozoic age to the entire Early Paleozoic marine basin. The transport of this material would have been mainly west-directed, as suggested by the east-west polarity of the Cuyanian Early Paleozoic successions (carbonate platform facing continental-slope and deep-water facies to the west) and paleocurrent directions (Abre *et al.*, 2012, and others therein). The Late Ordovician 'Famatinian' source registered in the Garganta del León Formation reinforces the hypothesis that the Ocloyic orogen prevented detrital input coming from the arc and also from other areas further east, such as the Pampean orogen or the cratonic areas. This also favors the interpretation of a Cuyanian source for Meso- and Neoproterozoic zircon over a population of Gondwanan origin.

7. CONCLUSIONS

During the Early Paleozoic, a continental margin facing a shallow (< 200 m-deep) marine basin to the west developed in the Peñasco area. The Peñasco and Garganta del León formations represent sedimentation in different parts of the basin.

Detrital zircon patterns of metasandstone from the Peñasco and Garganta del León formations show a dominant input from Late Mesoproterozoic (1.0-1.3 Ga) and Late Neoproterozoic-Cambrian (650-530 Ma) sources. Material may have been derived from eroded and/or covered igneous/metamorphic complexes and from recycled sedimentary rocks exposed in the vicinity of the depositional basin, such as the Ocloyic orogen.

The youngest zircon population of the Garganta del León Formation (*ca*. 460 Ma) can be correlated to the late stages of the Famatinian Arc. The presence of this 'Famatinian' population suggests that deposition of the sediment in a wave-dominated proximal setting still occurred in the studied area after the collision of the Cuyania terrane with West Gondwana.

The scarcity of a 'Famatinian' detrital age along the PMUB implies that the Ocloyic orogen prevented detrital input from the arc and from positive areas located further east.

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Highlights:

Two stratigraphic units are redefined: the Peñasco and Garganta del León formations.

Detrital zircon dating constrains source rock ages to the Meso- and Neoproterozoic.

The Ocloyic orogen acted as source and as a barrier for detrital input from Gondwana.

Cuyania accreted to Gondwana before the deposition of the Garganta del León Formation.

The Famatinian arc provided detritus to the western Cuyania marine basin.