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U-Pb SHRIMP detrital zircon ages from the Neoproterozoic Difunta Correa

**Metasedimentary Sequence (Western Sierras Pampeanas, Argentina): Provenance and
paleogeographic implications**

Highlights

- 1) The DCMS is Ediacaran and was laid down on Grenvillian basement of the MARA block
- 2) The basin was the MARA continental margin of the Puncoviscana/Clymene Ocean
- 3) Sediments came from the Grenvillian basement and more distal Laurentian sources
- 4) MARA was attached to Laurentia until the Iapetus ocean opening in the early Cambrian
- 5) The DCMS accreted to Gondwana prior to the Famatinian Orogeny

U-Pb SHRIMP detrital zircon ages from the Neoproterozoic Difunta Correa

Metasedimentary Sequence (Western Sierras Pampeanas, Argentina): Provenance and paleogeographic implications

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ABSTRACT

The central and eastern parts of the Sierra de Pie de Palo (Western Sierras Pampeanas, Argentina) are formed by a Mesoproterozoic basement and a Neoproterozoic sedimentary cover. Both were involved in an accretionary orogeny (penetrative deformation and metamorphism) along the southwestern margin of Gondwana in the Ordovician (i.e., Famatinian Orogeny). New U-Pb SHRIMP detrital zircon ages from the Neoproterozoic Difunta Correa Metasedimentary Sequence (DCMS), record the characteristics of this region at the time of sedimentation. Detrital zircon ages range from Neoarchean to Neoproterozoic, with main peaks at ca. 1.0-1.3 Ga and ca. 1.35-1.5 Ga. Geological and geochronological evidences from the DCMS suggest that the sediments were derived from both, the Grenville province and the Granite-Rhyolite province in the southeastern side of present Laurentia, and

from the nearby Grenville-age basement of Western Sierras Pampeanas. This latter basement has been interpreted as the result of the accretion and reworking of the South American Paleoproterozoic MARA craton to southeastern Laurentia during the Grenvillian Orogeny, which remained juxtaposed throughout the Neoproterozoic. The detrital zircon patterns of the DCMS support the hypothesis that this sequence was deposited in the Puncoviscana/Clymene Ocean during the Ediacaran at the southeastern passive margin of MARA. This craton eventually broke away from Laurentia in the late Neoproterozoic-early Paleozoic, which led to the opening of the Iapetus Ocean. MARA drifted along the Proto-Pacific Ocean, and finally collided against the southwest Gondwana margin during the Cambrian (i.e., Pampean Orogeny).

Keywords:

Neoproterozoic sedimentary rocks

Western Sierras Pampeanas

U-Pb SHRIMP detrital zircon ages

MARA craton

Laurentian paleogeography

1. Introduction

The paleogeographic position of Laurentia in the Neoproterozoic after Rodina break-up remains a subject of controversy. According to many authors (e.g., Hoffman, 1991; Dalziel, 1997; Johansson, 2014) Laurentia was probably juxtaposed to South American cratons (Amazonia and Río de la Plata) until the opening of the Iapetus Ocean in the early Paleozoic, coincident with the amalgamation of southwestern Gondwana through the

Pampean Orogeny in the early Cambrian (Casquet et al., 2012). This hypothesis can be tested in the Western Sierras Pampeanas (WSP) of Argentina, where a Mesoproterozoic basement and a Neoproterozoic sedimentary cover with Grenvillian and older detrital zircons were long recognized (McDonough et al., 1993; Vujovich and Kay, 1998; Casquet et al., 2001, 2008b; Varela et al., 2001, 2003; Galindo et al., 2004; Rapela et al., 2005, 2015). Thus, detrital zircon ages from the sedimentary cover along with other lines of geological evidence can be used to constrain sediment sources and to improve the Neoproterozoic paleogeography of continental blocks. Therefore, the Sierras Pampeanas of Argentina constitute a key area in southern South America for unravelling the timing of Rodinia break-up and how Laurentia, Amazonia and other continental blocks were related to each other afterwards.

The Sierra de Pie de Palo (SPP) in San Juan province is one of the westernmost ranges of Sierras Pampeanas (Fig. 1A). Like the other ranges of Sierras Pampeanas, the SPP is a pre-Andean crystalline block that underwent uplift in the Cenozoic in response to the Andean Orogeny. Rocks range in age from Mesoproterozoic to early Paleozoic. The oldest igneous and metamorphic rocks correspond to the dismembered Grenvillian orogenic belt of western South America. We use here the term Grenvillian in a wide sense to refer to the tectono-thermal events occurred between ca. 1.0-1.3 Ga. Post-Grenvillian and pre-Pampean Orogeny metasedimentary rocks were collectively named Difunta Correa Metasedimentary Sequence (DCMS) by Baldo et al. (1998) and dated as Ediacaran by Galindo et al. (2004) and Rapela et al. (2005). However, the DCMS remains poorly known because its outcrops are of difficult access. Moreover, the sequence underwent metamorphism and penetrative deformation during the accretionary Famatinian Orogeny in the early to middle Ordovician that hinder recognition and often make correlations and structural reconstructions difficult.

Contrasting paleogeographic models have been proposed for the SPP. The prevailing hypothesis holds that the whole SPP belongs to the worldwide known composite Precordillera/Cuyania terrane. This terrane consists of a Precambrian basement allegedly exposed in the SPP and in other minor outcrops, and a thick early Cambrian to middle Ordovician carbonate platform that widely outcrops in the Argentine Precordillera (for a review on the Precordillera/Cuyania terrane definition see Ramos, 2004). The Precordillera/Cuyania terrane was considered exotic to Gondwana and attributed to Laurentian provenance based mainly on paleontological and stratigraphic evidences (e.g. Astini et al., 1995; Benedetto, 1998). In this hypothesis, the Precordillera/Cuyania terrane rifted away from the Appalachian margin of Laurentia in the early Cambrian and collided against the proto-Andean margin of Gondwana in the middle Ordovician, after drifting across the Iapetus Ocean (e.g., Ramos et al., 1998; Thomas and Astini, 2003; Astini and Dávila, 2004). Conversely, some authors (Galindo et al., 2004; Mulcahy et al., 2011; Casquet et al., 2012; Ramacciotti et al., 2014a, 2014b) proposed that at least a part of the SPP (the central and eastern portions) did not belong to the Precordillera/Cuyania terrane and that it was already part of Gondwana in the early Cambrian. Moreover, the exotic-to-Gondwana origin of the whole Precordillera/Cuyania terrane has been questioned by several authors (e.g., Aceñolaza and Toselli, 2000; Finney, 2007). Therefore, we hereafter use the term Precordillera terrane to embrace only the western part of the SPP and the Argentine Precordillera.

In this contribution we provide the first mapping and stratigraphic description of the DCMS and we present new U-Pb SHRIMP detrital zircon ages in order to constrain the depositional age, source areas, and tectonic setting. We also propose an improved paleogeographic model of Laurentia and other South American cratons in the Neoproterozoic, strengthening the role of the MARA block (acronym of Maz, Arequipa, Río

Apa). This block is an alleged Paleoproterozoic continental fragment accreted to Amazonia in the middle Mesoproterozoic and further juxtaposed to Laurentia during the Grenvillian Orogeny (Casquet et al., 2012), where, apparently, the DCMS was laid down.

2. Geological setting

The SPP consists mainly of Mesoproterozoic rocks that underwent the Grenvillian Orogeny (chiefly in the western and central SPP) and of a Neoproterozoic metasedimentary cover (central and eastern parts of the SPP) (Fig. 1B). During the Ordovician, the SPP was affected by the Famatinian Orogeny, which produced an imbricate ductile thrust system with a general top-to-the-west sense of movement (e.g., Casquet et al., 2001; Mulcahy et al., 2011). Famatinian metamorphism was low- to medium-grade and peaked at ca. 465 Ma (Casquet et al., 2001). Pre-orogenic mafic dykes and sills, and syn-orogenic peraluminous granitoids have been recognized in the more accessible eastern side of the range (Panhkurst and Rapela, 1998; Mulcahy et al., 2011; Baldo et al., 2012; Ramacciotti et al., 2014a).

Five main lithological assemblages were recognized in the SPP, bounded by large shear zones and thrusts and internally imbricated. From west to east they are; the Caucete Group, the Pie de Palo Complex, the Central Complex, the DCMS, and the Nikizanga Group (Fig. 1B and 1C).

The Caucete Group (Borrello, 1969; Vujovich, 2003; Galindo et al., 2004; Naipauer et al., 2010; van Staal et al., 2011) is exposed along the western margin of the range, in the footwall of the large Piriquitas thrust (Fig. 1B), and consists of low to medium grade quartzites, marbles, and less common metavolcaniclastic rocks. A late-Neoproterozoic-Cambrian depositional age and a correlation with the Precordillera platform were suggested

for this unit based on Sr-isotope composition of marbles (Galindo et al., 2004) and U-Pb detrital zircon ages in metasandstones (Naipauer et al., 2010).

The Pie de Palo Complex (in the sense of Mulcahy et al., 2011) lies between the Pirquitas thrust and the structurally higher Duraznos thrust (Fig. 1B and 1C). It consists mainly of ultramafic and mafic rocks, chiefly metagabbros, garnet-amphibolites and serpentinites (Vujovich and Kay, 1998). Mesoproterozoic (ca. 1067-1204 Ma) U-Pb zircon crystallization ages were obtained for this Complex (Vujovich et al., 2004; Morata et al., 2010; Rapela et al., 2010; Mulcahy et al., 2011). Vujovich and Kay (1998) interpreted that the Pie de Palo Complex represents an ophiolite formed within a back-arc spreading environment. This complex has been correlated on the basis of similitude of common Pb-isotope composition and geochronology with the basement of the Precordillera terrane in the Argentina Precordillera. The basement here is only shown as xenoliths in Miocene volcanic rocks (Abbruzzi et al., 1993; Kay et al., 1996).

The Central Complex is a poorly known region because of the difficult access. It is defined here as a large extension between the Duraznos thrust and the eastern SPP where the DCMS is widespread. The boundary between the two assemblages is poorly known (Fig. 1B and 1C). The Central Complex consists of schists, quartzites, marbles, metavolcanic rocks, migmatites, orthogneisses, and amphibolites (Casquet et al., 2001; Mulcahy et al., 2011). The depositional age of the metasedimentary rocks in the Central Complex has to be older than the crystallization age of the orthogneisses that intrude them. One orthogneiss with A-type chemical signature was dated at ca. 774 Ma (Baldo et al., 2006) and was attributed to the early break-up of Rodinia. Ages of ca. 1025 Ma and ca. 1280 Ma were obtained for another two orthogneisses (Rapela et al., 2010; Garber et al., 2014, respectively). However, the allocation of those samples to the Central Complex remains uncertain because detailed geological mapping is still missing. Furthermore, some metasedimentary rocks assigned to

the DCMS (see below) were also recognized within the Central Complex, pointing to tectonic imbrication (Casquet et al., 2001; Vujovich et al., 2004).

The DCMS was first described by Baldo et al. (1998) as a complex succession of metapelites, Ca-pelitic schists, quartzites, quartz-feldspar metasandstones, marbles and para-amphibolites. The DCMS generally lies between the Central Complex and the Nikizanga Group and is separated from the latter by an extensional shear zone (Nikizanga Shear Zone; Fig. 1B and 1C). A Neoproterozoic depositional age for the DCMS was proposed based on Sr-isotope composition in marbles (Galindo et al., 2004) and U-Pb detrital zircon ages (Rapela et al., 2005; Rapela et al., 2015).

The Nikizanga Group consists of low- to medium-grade quartzites, marbles, graphitic schists, and less abundant amphibolites in the hanging wall of the Nikizanga shear zone in the southeastern margin of the SPP (Fig. 1B). An early Cambrian depositional age was obtained from Sr-isotope composition of marbles (Filo del Grafito marbles; Galindo et al., 2004) and recently supported by U-Pb detrital zircon ages from a quartzite (Ramacciotti et al., 2014b).

3. The Difunta Correa Metasedimentary Sequence (DCMS)

We distinguish four informal units within the DCMS. The stratigraphic order is based on younging criteria and structural considerations. They are from bottom to top: La Loma, Flores, Vallecito, and La Bomba units (Fig. 2). These units are affected by numerous shear zones and brittle Andean faults, which complicate its cartography. The La Loma Unit is found at the footwall of an extensional detachment, the Vallecito Shear Zone (Fig. 1B), whereas the other units are in the hangingwall. This suggests that the La Loma Unit is the older one, although no conclusive evidences have been found.

The La Loma Unit is widespread in the southeastern and central parts of the range, and in Loma La Chilca from which it owes its name (Fig. 1B). It consists mainly of massive dark quartzites and quartz-schists (Fig. 3A). The dominant lithology of this unit contains the assemblage Qtz-Grt-Bt-Ms-Pl $\pm$ Zrn-Op (abbreviations after Kretz, 1983), is fine-grained and shows a foliation defined by oriented micas.

The Flores Unit is mainly formed metasandstones and metaconglomerates (Fig. 3B) and less abundant marbles and Ca-pelitic schists. Ca-pelitic schists are remarkable rocks common in the DCMS, that consist of Ca-minerals (amphibole and/or epidote) in association with typical metapelite minerals (e.g., muscovite, staurolite, garnet), and are similar to the Alps garben-schist or garbenschiefer (e.g., Selverstone et al., 1984). The Ca-pelitic schists are porphyroblastic and contain the assemblage Hbl-Grt-Ep-Ms-Chl-Bt-Qtz-Pl $\pm$ Ap-Zrn-Op (Fig. 3C). Metaconglomerates are matrix-supported with monomineralic clasts of quartz and K-feldspar (2-15 mm) and scarce larger (5-15 cm) lithic fragments (Fig. 3D and 3E). They are lens-shaped, poorly sorted and usually grade quickly into sandstones (Fig. 3B). The mineral assemblage is Grt-Kfs-Pl-Qtz-Bt-Ms $\pm$ Ep-Zrn-Ap-Op. Some lithic fragments are fine-grained apatite-rich phosphorite (Fig 3E). Apatite is F-rich (2.2 wt% F) and its modal content in the phosphatic clasts can be up to 40%.

The Vallecito Unit is mainly composed of marbles and, to a lesser extent, of para-amphibolites, calc-silicate rocks and Ca-pelitic schists similar to those of the Flores Unit. The main outcrops occur near the Difunta Correa Sanctuary, close to Vallecito city (Fig. 1B). The mineral assemblage of marbles is Cal $\pm$ Dol-Qtz-Bt-Ms-Chl-Pl-Zo-Op, and they exhibit a granoblastic texture with Cal-Dol (2 mm) and a foliation defined by oriented micas. This unit is usually in contact with La Loma Unit through shear zones (Fig. 3F)

La Bomba Unit is well exposed in the southeastern side of the range. It consists of thick beds of metapelites, metasandstones (some of them containing calcite),

quartzites, and Ca-pelitic schists. Metapelitic staurolite schists with St-Grt-Bt-Ms-Qtz-Pl $\pm$ Zrn-Ilm have also been recognized within this unit.

The DCMS shows, at least in part, a marine origin evidenced by the Sr-isotope composition of marbles (i.e., the Vallecito Unit), which is compatible with the detrital zircon ages. In this context, the carbonates were probably deposited on a platformal setting (Galindo et al., 2004). Further, the phosphatic clasts of the Flores Unit suggest reworking of earlier platform deposits, which have not been recognized so far.

4. Sampling and analytical methods

Four samples from the DCMS were collected for U-Pb SHRIMP detrital zircon dating (Fig. 1B): three metasediments (SPP-22013, SPP-22019, and SPP-27003), and one metaconglomerate (SPP-22037). Table 1 shows the location and description of each sample.

Detrital zircons were separated from the four samples and concentrated using standard crushing, washing (to decant slime), heavy liquids, and paramagnetic separation procedures as described by Rapela et al. (2007). The zircon-rich heavy mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the Temora reference zircon, sectioned approximately in half, and polished. Cathodoluminescence images were used to describe the internal structures of the sectioned grains (Fig. 4). Three of the four samples (SPP-22013, SPP-22019 and SPP-22037) were analyzed with SHRIMP RG, as described by Williams (1998), at the Research School of Earth Sciences, The Australian National University (Canberra, Australia). Each analysis consisted of four scans through the mass range, and the reference zircon was analyzed once every five unknowns. Data were reduced using Isoplot/Ex (Ludwig, 2003). Sample SPP-27003 was analyzed at Centro de

Instrumentación Científica de Granada (Spain) with SHRIMP IIe/mc, following the method described by Montero et al. (2014). Results are shown in supplementary Table A.1.

Common lead corrections for ages older than 1100 Ma were made using ^{204}Pb and, for younger ages, by means of ^{207}Pb (Williams, 1998). Results are shown in the form of Tera & Wasserburg and probability density plots in Figure 5. Spots with high common lead (>5%), discordance >10%, and error age (one sigma) >5% were discarded and not considered in the probability density plots.

5. U-Pb detrital zircon ages

Zircon grains in all samples are generally up to 100 μm in size and have a variety of shapes, from anhedral rounded to euhedral prismatic with bi-pyramidal terminations, and oscillatory or irregular internal structures (Fig. 4). Most are igneous zircons that often show xenocrystic cores. Samples are described from bottom to top in the stratigraphic column (Fig. 5)

SPP-22019 (La Loma Unit). Sixty grains were analyzed and none was discarded. Ages vary between 612 (one grain) and 1674 Ma, with a main broad peak between ca. 1000 and 1300 Ma, and few zircons at ca. 950, 1500 and 1650 Ma (Fig. 5).

SPP-22037 (Flores Unit). Thirty five spots were analyzed and one was discarded. Ages range between 1022 and 2733 Ma, with a well-defined major asymmetric broad peak between ca. 1050 and 1200, and two grains at ca. 2700 Ma (Fig. 5).

SPP-27003 (La Bomba Unit). Sixty four spots were analyzed in fifty nine grains, and eleven were discarded. Zircon ages range between 937 and 2680 Ma, and can be grouped into two main peaks: the first one between ca. 950 and 1200 Ma, and the second is

an asymmetric broad peak between ca. 1400 and 1500 Ma (Fig. 5). Only one grain of ca. 2700 Ma was found.

Sample SPP-22013 (La Bomba Unit). Five analyses out of sixty were discarded. Ages range from 939 to 1640 Ma, and can be grouped into two main peaks: a broad peak between ca. 950 and 1200 Ma, and an asymmetric broad peak between ca. 1300 and 1500 Ma (Fig. 5). Two grains gave an age of ca. 1640 Ma.

6. Discussion

6.1. Age constraints and provenance

The youngest zircon age found in this work is 612 ± 8 Ma (only one grain). Similar Neoproterozoic zircon ages were reported by other authors in the DCMS (between 587 ± 25 and 641 ± 7 Ma; Rapela et al., 2005, Rapela et al., 2015). All these results are in concordance with ages obtained by means of Sr-isotope composition of marbles of the DCMS (Galindo et al., 2004). The Sr-isotope composition of these marbles (i.e., Vallecito Unit) suggests a sedimentation between ca. 620 and 640 Ma, by comparison with the oceanic secular Sr-isotope compilation of Halverson et al. (2010) as it was stated by Murra et al. (2014) and Rapela et al. (2015). Therefore, at least part of Vallecito Unit and the underlying units, and in consequence a large tract of the DCMS, were probably deposited in the early Ediacaran. The age of La Bomba unit remains unconstrained, but it could be as young as late Ediacaran or early Cambrian. The relationships between the DCMS and the younger (Cambrian) Nikizanga Group, referred above (Ramacciotti et al., 2014b), are obscured by intervening shear zones and thrusts of early Paleozoic age, and by Andean brittle faults.

Samples from La Loma Unit (SPP-22019) and Flores Unit (SPP-22037) show a main population of detrital zircon ages between ca. 0.95 and 1.3 Ga. On the other hand, samples from La Bomba Unit (SPP-22013 and SPP-27003) exhibit a main population of detrital zircons between ca. 1.3-1.5 Ga, besides that at ca. 0.95-1.2 Ga.

Structural and stratigraphic younging criteria suggest that the La Loma Unit and the Flores Unit are older than the La Bomba Unit, and therefore represent the lower part of the stratigraphic succession. On this basis we interpret that the source of zircons for the two lower units was a proximal Grenvillian basement, while the upper units were supplied from the same Grenvillian basement and from more distal sources, probably due to the increased extension of the drainage basin beyond the Grenvillian basement. The par-amphibolite (i.e., an amphibolite of sedimentary origin) analyzed by Rapela et al. (2005) belongs to the Vallecito Unit. It shows a detrital zircon pattern similar to La Bomba Unit (i.e., including zircon grains with ages between ca. 1.3 and 1.5 Ga), suggesting that the jump from a restricted Grenvillian source of sediments into a much larger drainage area took place at the end of the Flores Unit sedimentation. This evolution was apparently coincident with the turnover from a mostly high-energy siliciclastic sedimentation (Flores Unit) into a more stable carbonate platform, where the Vallecito Unit was deposited.

In order to constrain the source areas of the DCMS, the paleogeographic reconstructions of the Rodinia supercontinent and the possible location of the WSP basement during the Neoproterozoic must be considered. The hypothesis that Laurentia collided with Amazonia along the Appalachian margin as the result of the Grenvillian Orogeny has been long advocated by many authors (Dalziel, 1994, 1997; Sadowski and Bettencourt, 1996; Sadowski, 2002; Loewy et al., 2003; Tohver et al., 2002, 2004; Casquet et al., 2005; D'Agrella-Filho et al., 2008; Li et al., 2008, among others). Moreover, Casquet et al. (2012) suggested that the Grenvillian collision involved a missing Paleoproterozoic craton that they

called MARA and that had accreted to southern Amazonia at ca. 1.3 Ga. This hypothetical craton embraced the WSP basement, where isotope and zircon evidences exist for a hidden Paleoproterozoic basement (the Maz terrane), the Arequipa massif in southern Peru and the Rio Apa outcrop in southern Brazil (Casquet et al., 2012).

Sources for the two dominant populations of detrital zircon ages in the DCMS (i.e., ca. 1.0-1.3 Ga and 1.35-1.5 Ga) can be found not only in Amazonia (Sunsas and Rondonia-San Ignacio belt; e.g., Bettencourt et al., 2010), but also in Laurentia (Grenville and Granite-Rhyolite province; e.g., McLelland et al., 1996; Van Schmus et al., 1996). Besides, rocks of ca. 1.0-1.3 Ga occur also in WSP basement (e.g., Rapela et al., 2010). Southern Amazonia detrital zircon age patterns are shown in the work of Babinski et al. (2013; Figs. 6 and 7) on the Puga Hill and Bodoquena Ediacaran successions, along the western margin of the Paraguay belt in southern Brazil. Sediments were probably derived from a large area to the NW, embracing the Ventuari-Tapajos, Rio Negro-Juruena, Rondonia-San Ignacio and Sunsás orogenies between ca. 2.0 and 1.0 Ga (Tohver et al., 2004; Böger et al., 2005; Cordani et al., 2009). Although these patterns show similarities with the DCMS, there are also significant differences. The Amazonian patterns show remarkable peaks at ca. 1.75, 1.84 and 1.54 Ga, which are notably absent in the DCMS. Moreover, the peak at 1.0-1.2 Ga, although it is common in both areas, is subordinate in the Puga Hill and Bodoquena successions (Babinski et al., 2013), whereas it constitutes a dominant population in the DCMS. Thus, we consider Amazonia an unlikely source area.

Detrital zircon age patterns from Neoproterozoic sequences elsewhere in Argentina (e.g., the Sierras Bayas Group; Rapela et al., 2007; Gaucher et al., 2008; Cingolani et al., 2010) and in Uruguay (e.g., the Piedras de Afilar Formation and Arroyo Soldado Group; Gaucher et al., 2008) both far to the east of the WSP, are significantly different from the DCMS. Although they show Grenvillian zircons between ca. 1.0 and 1.2 Ga, the

dominant peaks are ca. 1.5, 2.0-2.2, 2.45 and 2.7-2.8 Ga. The latter are absent or poorly represented in the DCMS. Remarkably, the peak at 2.0-2.2 Ga is characteristic of the Río de la Plata craton (e.g., Hartmann et al., 2002; Santos et al., 2003, Rapela et al., 2007), which is the basement of the Sierras Bayas Group and the Piedras de Afilar Formation. In consequence, we argue that the Río de la Plata craton was not a source area for the DCMS. Paleogeographic location of the Río de la Plata craton in southern Gondwana, in the Ediacaran, remains poorly constrained but it was probably was much to the North of its present location and East of the Pucoviscana Ocean, which separated the WSP from southern Gondwana cratons at that time (Rapela et al., 2007, 2011; Casquet et al., 2012). Although some authors (e.g., Gaucher et al., 2008) suggest that the WSP and Amazonia were juxtaposed to the Río de la Plata craton in Neoproterozoic times, the detrital zircon patterns of the DCMS do not show evidence of that connection.

The third option is the Laurentian provenance. In this case, the dominant peaks of the DCMS (i.e., ca. 1.0-1.3 Ga, and ca. 1.35-1.5 Ga) could be correlated with the Grenville province (including the WSP Grenvillian basement) and the Granite-Rhyolite province, respectively, whereas the minor peak at ca. 1.6-1.7 Ga, recognized in three of the analyzed samples, could be attributed to the westernmost Mazatzal orogenic province (Fig.6). The scarce Neoproterozoic zircons of ca. 600 Ma, considered previously of Gondwanan provenance by Rapela et al. (2005), may be related to the extensional magmatism which preceded the opening of the Iapetus Ocean (Aleinikoff et al., 1995; Cawood et al., 2001; Tollo et al., 2004). Moreover, the absence of detrital zircon ages between 1.5 and 1.6 Ga in the DCMS, which are usually found in Gondwanan sequences, is consistent with the so called Laurentian magmatic gap (Fig. 6; e.g., Goodge and Vervoort, 2006). Detrital zircon patterns similar to the DCMS were found in Cambrian to Ordovician sequences of alleged Laurentian provenance in the Andean Precordillera and in the Caucete Group (i.e., West of the SPP)

(e.g., Thomas et al., 2004; Naipauer et al., 2010). Therefore, the DCMS detrital zircons age patterns analyzed in this work point towards a Laurentian source.

6.2. *Paleogeographic implications*

Our preferred model for the depositional tectonic setting of the DCMS in the Ediacaran, and the paleogeography are summarized in Figures 7 and 8 (see also Casquet et al., 2012). This model implies that, after the early break-up of Rodinia, Laurentia remained probably attached to MARA and Amazonia (and probably other still unconstrained cratons further south) across the Grenvillian orogenic belt during the Neoproterozoic. Protracted Neoproterozoic rifting occurred at least at ca. 845, 774 and 570 Ma, as indicated by A-type granitoids (e.g. Baldo et al., 2006; Colombo et al., 2009; Rapela et al., 2011) and carbonatite-syenite intrusions (Casquet et al., 2008a) in the WSP. Rifting eventually led to the separation of Laurentia + MARA + Amazonia from other Western Gondwana blocks and to the opening of the Puncoviscana/Clymene Ocean (for a review see Casquet et al. 2012) on the East. The Clymene Ocean was first defined by Trindade et al. (2006), who established, based on paleomagnetic grounds, that a late Neoproterozoic ocean existed between Amazonia + Laurentia on the one hand and West Gondwana cratons, such as Río de la Plata and Kalahari, on the other (see also Rapalini et al., 2015 for a recent paleomagnetical evidence). The Puncoviscana Ocean corresponds, according to this hypothesis, to the southeastern extension of the Clymene Ocean (present coordinates).

In contrast with the DCMS, which is, at least in part, marine (a carbonate platform), the Neoproterozoic rocks recognized along the southern Appalachian margin of Laurentia in the Blue Ridge province consist of continental rift-related sediments and volcanic rocks (e.g. Wehr and Glover, 1985; Thomas, 1991; Miller, 1994; Aleinikoff et al.,

1995; Tollo and Aleinikoff, 1996). This may indicate that the Appalachian margin was not the eastern continental margin of Laurentia at that time. Instead, the continental margin could be located still eastward (i.e., along the MARA margin that faced the Neoproterozoic Puncoviscana/Clymene Ocean on the East; Rapela et al., 2015). MARA remained attached to Laurentia (forming an enlarged Laurentia continent) until the early Cambrian when break-up took place and the Iapetus Ocean opened. We thus envisage that the DCMS was deposited on this passive margin during the Ediacaran (ca. 620 Ma and younger), prior to the Iapetus Ocean opening (Figs. 7 and 8). The continental margin was later involved in the Pampean Orogeny between 540 and 520 Ma, where an oblique collision with other western Gondwana cratons such as Kalahari, Río de la Plata, and Paranapanema occurred. This collision led to the final amalgamation of SW Gondwana. The inversion of the Puncoviscana/Clymene Ocean at ca 540 Ma (i.e., the beginning of subduction along the eastern margin), was almost coeval with the rifting-drifting of Laurentia away from MARA + Amazonia and the opening of the Iapetus Ocean (Casquet et al., 2012; Rapela et al., 2014; Rapela et al., 2015).

The western margin of MARA facing the Iapetus Ocean thus became the proto-Andean margin of Gondwana. It either remained hidden under the Paleozoic-to-present Andean sedimentary cover, or it was tectonically eroded throughout the Phanerozoic. Subduction at the proto-Andean margin started in the early Ordovician as evidenced by magmatic arcs of that age along western South America (e.g., Pankhurst et al., 2000; Coira et al., 1999; Steenken et al., 2006; Casquet et al., 2010) and it was followed by juxtaposition of the Precordilera terrane in the middle Ordovician (Ramos et al., 1998; Casquet et al., 2001).

This model addresses the possibility that the Precordillera terrane was also part of the western margin of MARA, after it drifted away from Laurentia in the early Cambrian. The terrane reached a position probably close to present after lateral displacement

along the Gondwana margin in the Ordovician, in concordance to an early proposal by Finney (2007).

7. Conclusions

Field evidence and geochronological data allow the recognition of four informal units within the Difunta Correa Metasedimentary Sequence in the Sierra de Pie de Palo (Western Sierras Pampeanas).

U-Pb SHRIMP detrital zircon patterns are compatible with a main input of sediments from the underlying WSP Grenvillian basement and from Laurentian sources, such as the Grenville (1.0-1.3 Ga), Granite-Rhyolite (1.3-1.5 Ga) and Mazatzal (1.6-1.7 Ga) provinces. Few zircons of Ediacaran age found in this work and by other authors in the DCMS may be related to anorogenic magmatism during a late rifting of Rodinia. Detrital zircon age evidence along with the Sr-isotope composition of marbles suggests that a large tract of the DCMS is early Ediacaran. However, the upper part of the succession may be as young as early Cambrian. The stratigraphic relationships with the Nikizanga Group are unknown.

We suggest that the DCMS was laid down in the Puncoviscana/Clymene Ocean on the southeastern margin of the MARA craton. The Puncoviscana/Clymene Ocean preceded the opening of the Iapetus Ocean in the early Cambrian (Fig. 8). After drifting away from Laurentia, MARA collided against other southwestern Gondwana cratons between 540 and 520 Ma (i.e., Pampean Orogeny). Subduction re-started in the early Ordovician at the western margin of MARA, which became the Proto-Andean margin of Gondwana, resulting in the Famatinian accretionary orogeny, widely recorded in Sierras Pampeanas.

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FIGURE CAPTIONS

Fig. 1. A) Geological map of Sierras Pampeanas showing the location of the SPP; B) Geological map of the SPP; C) East-west schematic section of the SPP showing the main geological units and structural boundaries.

Fig. 2. Structural and stratigraphic relationship of the main units of the SPP.

Fig. 3. A) Folded quartz-schist from La Loma Unit. B, D, E) Metaconglomerates from the Flores Unit. C) Calcipellitic schist (garben-schist or garbenschiefer) with hornblende-garnet from La Bomba Unit. This rock type is also present in Vallecito and Flores units. E) Phosphatic clast in metaconglomerate of the Flores Unit. F) tectonic contact between marbles from Vallecito Unit and La Loma Unit.

Fig. 4. Cathodoluminescence (CL) images showing morphology and internal structure of zircon grains from the DCMS. Uncertainties are quoted at one sigma level. *Discarded ages due to high common lead, large discordance, or errors > 5%.

Fig. 5. Tera-Wasserburg and probability density plots for U-Pb SHRIMP zircon ages showing the full range of ages from each DCMS samples. Errors are at one sigma. Red ellipses were discarded and not considered for the probability density plots.

Fig. 6. Tera-Wasserburg and probability density plots showing the full range of U-Pb SHRIMP zircon ages from our samples including the Vallecito Unit para-amphibolite from Rapela et al. (2005). Ordovician ages correspond to metamorphic rims and were only found in the para-amphibolite (Rapela et al., 2005).

Fig. 7. Geological setting for the DCMS (modified from Casquet et al. 2012) at ca. 620 Ma when the Vallecito Unit was probably laid down. ESP: Eastern Sierras Pampeanas.

Fig. 8. Paleogeographical reconstruction of Laurentia, Amazonia, Río de la Plata (RP) and Kalahary (K) showing the guessed position of MARA craton at ca. 620 Ma. Ages of Laurentian Precambrian orogenic belts and cratons according to Goodge et al. (2004) and Tohver et al. (2004) (Laurentia in its present position). Outcrops of basement with Grenvillian ages in MARA have been included: AM, Arequipa Massif (Peru); RA, Rio Apa (Brazil, Paraguay); WSP, Western Sierras Pampeanas (Argentina). Laurentia: TH, Trans-Hudson and related mobile belts; P, Penokean orogen; Y, Yavapay orogen; M, Mazatzal orogen; G-R, Granite-Rhyolite province. Arrows show the direction of sediment transport, and the source areas of the DCMS.

829 **Table 1.** Location (GPS coordinates), and description of the analyzed samples with U-Pb SHRIMP data.
 830 Mineral abbreviations after Kretz (1983).

Sample	Lat. (S)	Long. (W)	Unit	Rock type	Mineral assemblage
SPP-22013	31° 42' 24''	68° 01' 00''	La Bomba	Calcareous metasandstone	Qtz-Pl-Kfs-Cal-Ms
SPP-27003	31° 34' 46''	67° 52' 51''	La Bomba	Quartz metasandstone	Qtz-Ms-Bt-Grt
SPP-22037	31° 39' 34''	67° 53' 04''	Flores	Metaconglomerate	Qtz-Pl-Kfs-Bt-Ms-Chl-Ep
SPP-22019	31° 40' 32''	67° 51' 55''	La Loma	Quartz schist	Qtz-Pl-Bt-Ms

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Figure 1

Figure 4

Figure 6

Figure 7