Silurian-Devonian Land–Sea Interaction within the San Rafael Block, Argentina: Provenance of the Río Seco de los Castaños Formation

Carlos A. Cingolani, Norberto Javier Uriz, Paulina Abre, Marcelo J. Manassero and Miguel A.S. Basei

Abstract The Río Seco de los Castaños Formation (RSC) is one of the 'pre-Carboniferous units' outcropping within the San Rafael Block assigned to Upper Silurian–Lower Devonian age. We review the provenance data obtained by petrography and geochemical-isotope analyses as well as the U–Pb detrital zircon ages. Comparison with La Horqueta Formation is also discussed. The main components of this marine fine-grained siliciclastic platform are sandstones and mudstones. The conglomerates are restricted to channel fill deposits developed mainly at the Lomitas Negras location. A low anchizone for the RSC was indicated by illite crystallinity index. From the geochemical proxies described above (Manassero et al. in Devonian Change: Case studies in Palaeogeography and Palaeoecology.

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C.A. Cingolani (✉) · M.J. Manassero
Universidad Nacional de La Plata and Centro de Investigaciones Geológicas,
Diag. 113 n. 275, CP1904 La Plata, Argentina
e-mail: carloscingolani@yahoo.com

M.J. Manassero
e-mail: mj.manassero@gmail.com

C.A. Cingolani · N.J. Uriz
División Geología, Museo de La Plata, UNLP, Paseo del Bosque s/n,
B1900FWA La Plata, Argentina
e-mail: norjuz@gmail.com

P. Abre
Centro Universitario Regional Este, Universidad de la República,
Ruta 8 Km 282, Treinta y Tres, Uruguay
e-mail: paulinabre@yahoo.com.ar

M.A.S. Basei
Centro de Pesquisas Geocronologicas (CPGeo), Instituto de Geociencias,
Universidade de São Paulo, São Paulo, Brazil
e-mail: baseimas@usp.br

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Geological Society, 2009) a provenance from an unrecycled crust with an average composition similar to depleted compared with average Upper Continental Crust is suggested. T_{DM} ages are within the range of the Mesoproterozoic basement and Palaeozoic supracrustal rocks of the Precordillera-Cuyania terrane. ε_{Nd} values of the RSC are similar to those from sedimentary rocks from the Lower Palaeozoic carbonate-siliciclastic platform of the San Rafael Block. These data suggest an Early Carboniferous (Mississipian) low-metamorphic (anchizone) event for the unit. It is correlated with the 'Chanic' tectonic phase that affected the Precordillera-Cuyania terrane and also linked to the collision of the Chilenia terrane in the western pre-Andean Gondwana margin. As final remarks we can comment that the studied RSC samples show dominant source derivation from Famatinian (Late Cambrian-Devonian) and Pampean-Brasiliano (Neoproterozoic-Early Cambrian) cycles. Detritus derived from the Mesoproterozoic basement are scarce. U–Pb data constrain the maximum sedimentation age of the RSC to the Silurian–Early Devonian.

Keywords Silurian–Devonian · Provenance analysis · Río Seco de los Castaños unit · Chanic phase · Cuyania terrane

1 Introduction

The Río Seco de los Castaños Formation (González Díaz 1972, 1981) is one of the 'pre-Carboniferous units' outcropping within the San Rafael block (Fig. 1). This sequence was first part of the La Horqueta metasedimentary unit (Dessanti 1956), but it was redefined based on its sedimentary characteristics by González Díaz (1981) and was assigned to the Devonian by Di Persia (1972). Contributions by González Díaz (1972), Nuñez (1976) and Criado Roqué and Ibañez (1979) described other sedimentary features of this foreland marine sequence. Rubinstein (1997) found acritarchs and other microfossils assigned to the Upper Silurian age near the 144 Road (km 702) outcrops. Poiré et al. (1998, 2002) recognized some trace fossil associations that helped to interpret different sub-environments of deposition within a wide siliciclastic marine platform. More recently Pazos et al. (2015) record the presence of relevant ichnogenus along the Atuel River outcrops. Manassero et al. (2009) presented a sedimentary description and stratigraphy, geochemical and provenance facies analysis of this unit. Rapid deposition and storm action on the platform are suggested by the presence of hummocks and swaleys facies. Furthermore, plant debris (Morel et al. this volume) indicates that the continental source was not far away.

It is well known that the Upper Silurian–Lower Devonian is a time of great changes not only of ecosystems but of climates as well, caused probably by complex interactions between the fast-developing terrestrial biosphere, marine

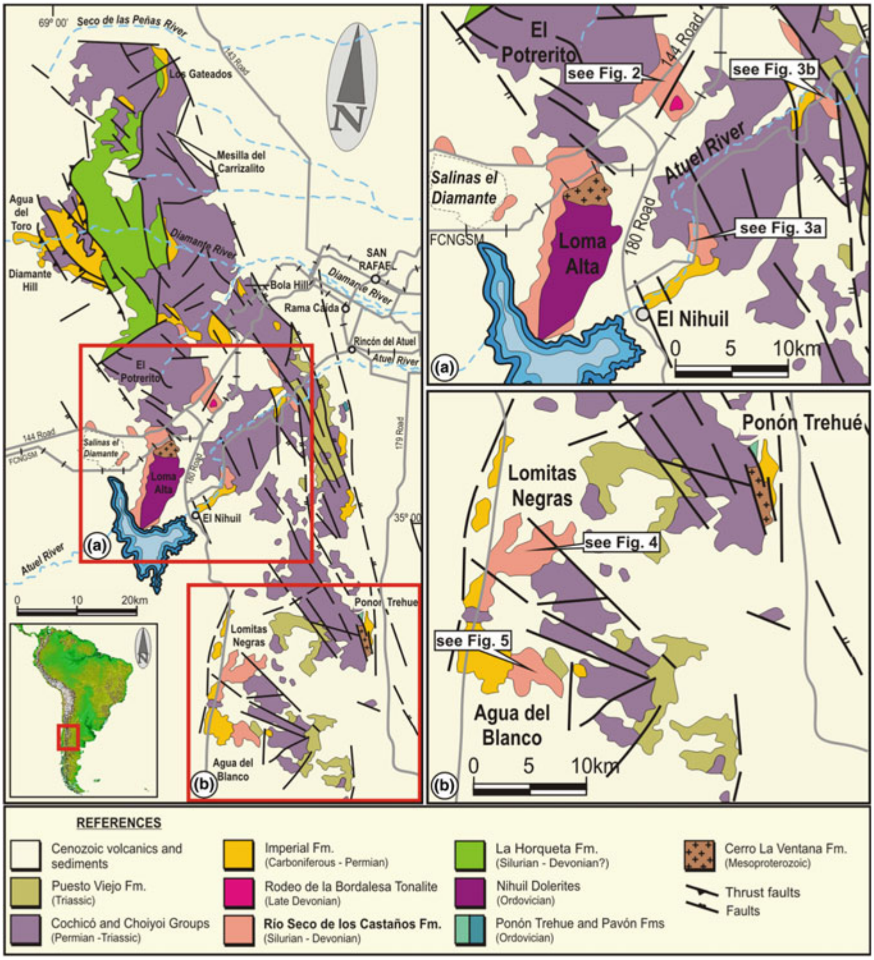

Fig. 1 Geological sketch map of the San Rafael Block showing different outcrops of the Río Seco de los Castaños Fm (RSC)

ecosystems and the atmosphere. Within this framework the Río Seco de los Castaños Formation (RSC) was deposited within a basin influenced by both, land and sea environments.

Based on these records, the main focus of the present paper is to review the provenance data obtained by petrography and geochemical-isotope analyses as well as to describe the recently acquired U–Pb detrital zircon ages. The data comparison with La Horqueta Formation is also discussed here.

2 Geological Aspects and Recognized Outcrops

Neither the base nor the top of the RSC are exposed. At the Loma Alta section this unit is separated by an unconformity or tectonic contact from the Mesoproterozoic mafic rocks (basement) and the Ordovician dolerite rocks. In other regions it is separated by unconformity from the Carboniferous-Lower Permian (El Imperial Formation) a fossiliferous marine-glacial/continental sedimentary unit locally forming deeply incised channels. The great angular unconformity is clearly showed at the Atuel River creek. The outcrops are rather isolated since they have been dismembered by Mesozoic and Cenozoic tectonism, according to Cuerda and Cingolani (1998) and Cingolani et al. (2003a) they are located at (Fig. 1)

2.1 Road 144-Rodeo de la Bordalesa

Trace fossils such as the *Nereites*-*Mermia* facies were mentioned (Poiré et al. 1998, 2002). Microfossils were described by Rubinstein (1997), although they were assigned to “La Horqueta Formation” (Fig. 2). In this region, the Rodeo de la Bordalesa Tonalite intruded the RSC. It has a magmatic arc geochemical signature and a crystallization age of 401 ± 4 Ma (Lower Devonian; Cingolani et al. 2003b, this volume), which also constrain the depositional age of the RSC.

2.2 Atuel River Creek

González Díaz (1972, 1981) described the type-section of the RSC in this region. Two main outcrops are recorded, one located about 12 km to the NE of the El Nihuil town (Fig. 3a) and the other near the Valle Grande dam (Fig. 3b), where the Seco de los Castaños River becomes an affluent of the Atuel River (González Díaz 1972). In the first locality the Formation comprises more than 600–700 m of tabular, green sandstones and mudstones with sharp contacts. It shows regional folding and dippings between 50° and 72° to the SE or NE. Above RSC inclined strata lay Upper Paleozoic horizontally bedded sedimentary rocks, displaying, therefore, a remarkable angular unconformity. In the Atuel Creek area fragments of primitive vascular plants are described and assigned to the Lower Devonian and marine microfossils such as prasinophytes, spores and acritarchs were found by D. Pöthe de Baldis (cf. Morel et al. 2006; this volume) in the RSC, indicating shallow water conditions near the coastline.

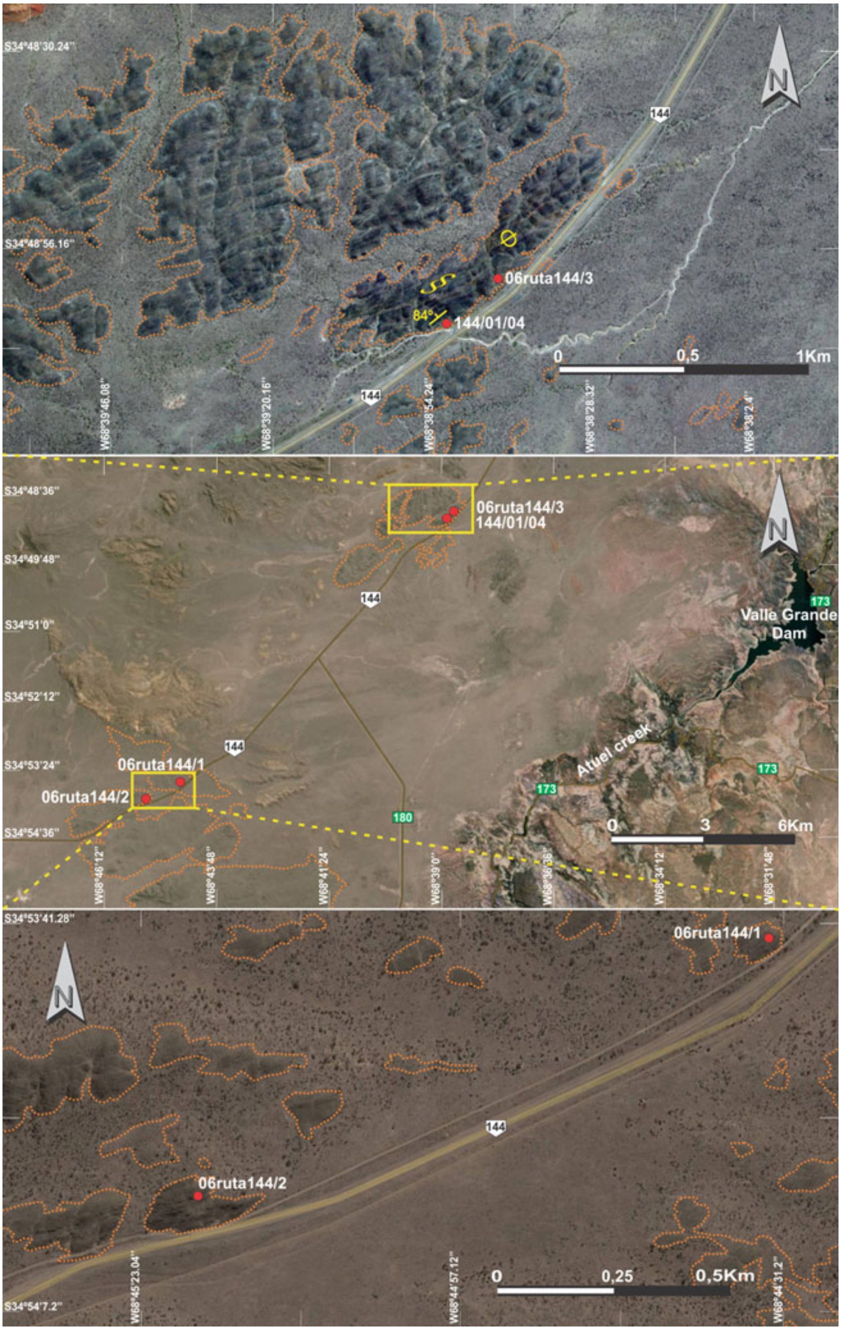

Fig. 2 Images showing the outcrops of the Río Seco de los Castaños Fm close to the 144 Road and position of the studied samples (*red dots*). The presence of microfossils and ichnofossils are denoted within the *upper image*

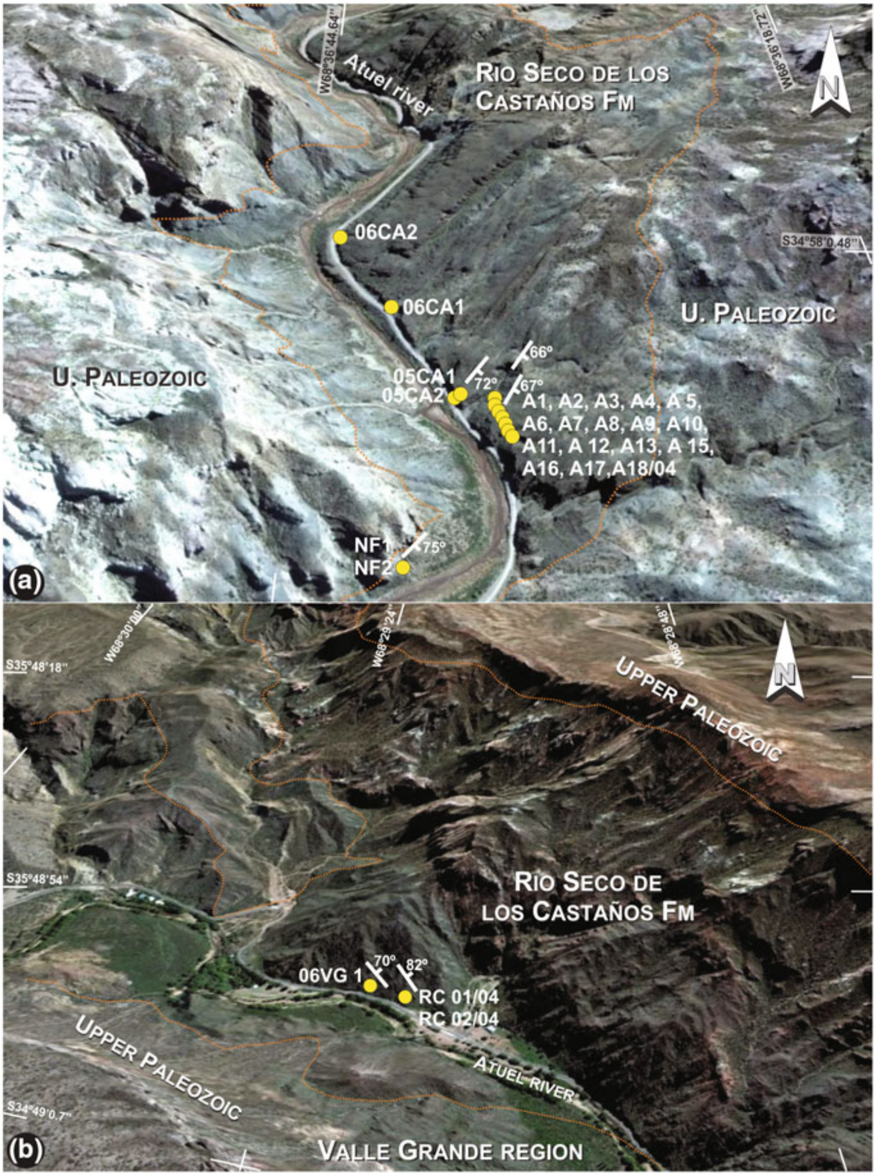

Fig. 3 Google-satellite images of **a** the Atuel River section and **b** Valle Grande region. The unconformity with the Upper Paleozoic succession is shown, as well as sampled locations (*yellow dots*)

2.3 Nihuil Area

The RSC (Fig. 1) is developed close to the Mesoproterozoic basement and Ordovician MORB-type dolerite rocks called 'El Nihuil mafic body' at the Loma Alta region (Cingolani et al. 2000; this volume).

2.4 Lomitas Negras and Agua del Blanco Areas

This region comprises the southernmost outcrops (Figs. 4 and 5). A Devonian coral known as '*Pleurodyctium*' was mentioned at Agua del Blanco, while conglomerates with limestone clasts bearing Ordovician fossils are described from the Lomitas Negras region (Di Persia 1972). Both successions are clearly folded and show substratal structures and wave ripples at the base of the sandy beds. After Di Persia (1972) the Lomitas Negras succession reaches a thickness of 2550 m.

3 Sedimentological Analysis

The main components of this marine fine-grained siliciclastic platform are sandstones and mudstones (Manassero et al. 2009). The conglomerates are restricted to channel fill deposits located mainly at the Lomitas Negras section. Main lithotypes recognized in the RSC platform are,

Mudstones: Comprise 50–90% of thin-beds, greenish in colour, usually with lamination and slight bioturbation commonly in repetitive sequences. The dark tonality and the scarcity of organic activity suggest anoxic conditions in low energy environments.

Heterolithics: Comprises thin-bedded sandstones and intercalated mudstones, with good lateral continuity and tabular-planar beds of few centimetres thick and grey to green colours. It is a very common facies, that exhibit sharp contacts and in many cases wave and current ripple structures, and also climbing ripples (Fig. 6). Normal grading and bioturbation are the dominant internal structures. Represents a well-oxygenated environment interpreted as a proximal or shallow marine platform, with dominance of a sub-tidal environment. The trace fossils are developed over a soft substrate with moderate energy.

Laminated siltstones: These rocks comprise bedded siltstones that range in thickness from several tens of centimetres to 1 m. They are intercalated with fine-grained sandstones with sharp contacts. Some coarser grained beds show small-scale ripple cross-lamination.

Sandstones: Comprise fine to medium-grained, grey and green, medium-bedded (10–15 cm thick) sandstones. They not only show massive and sharp contacts but also current and wave ripple marks (wave index 12–20) suggesting seawater-depths

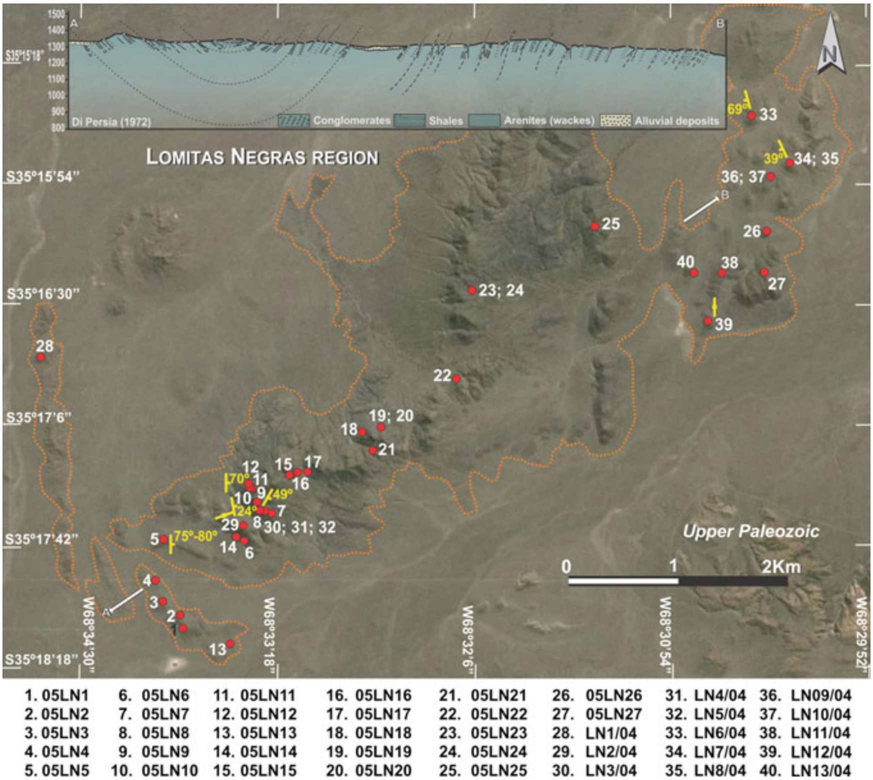

Fig. 4 Image showing the samples (*red dots*) along the Lomitas Negras section. At the upper part of the figure it is reproduced the SE-NW synclinal stratigraphic profile of RSC after Di Persia (1972)

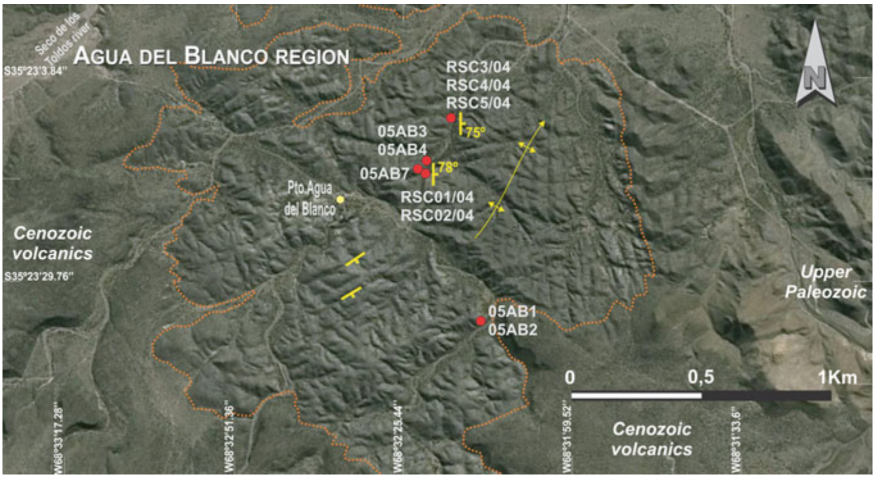

Fig. 5 In this image the folded structure and sampling (*red dots*) of the southernmost outcrops of the RSC (Agua del Blanco region) are shown. The contact with the Upper Paleozoic units is also shown

Fig. 6 Tabular facies of sandstones and mudstones showing the change from traction to suspension processes within the platform

of 20 m. Deformational structures such as contorted beds and dish structures are present and scarce flute marks can develop to the base of the beds.

Rapid deposition and storm action on the platform is recognized by the presence of hummocks and swales in this facies. Furthermore, plant debris (Morel et al. this volume) indicates that the continental source was not far away. The erosive base of some beds implies a high sedimentation rate and the dominance of thin-beds with fine sediments suggests the action of low density gravity flows in the platform. Within the last described facies a *charcoal bed* (10–15 cm thick) that might be a marker horizon, was also found (Fig. 7a). It is composed of a mixture of silty-quartz, illite-kaolinite clays and amorphous organic matter with a TOC (total organic carbon) of 1%. Its presence is restricted to the section of Atuel creek. Recently Pazos et al. (2015) record the ichnogenera *Dictyodora* Weiss, which constitutes one of the most diverse, documented outside Europe and North America. The ichnospecies recognised include *D. scotica* and *D. tenuis*—and a new ichnospecies, *D. atuelica*. The succession studied by Pazos et al. (2015) contains abundant microbial mats (wrinkle marks) as either extended surfaces or patches. Wave-dominated deltas have facies sequences that coarsen upwards from shelf mud through silty-sand to wave and storm influenced sands, capped with lagoon or strand-plains where these peat beds can develop to the top of each cycle. This seems to be the case for the Atuel section (Manassero et al. 2009) where several

Fig. 7 **a** The RSC outcrop show the intercalated charcoal bed at road 173 (km 12) at the Atuel River section; up sequence to the NE and **b** typical vertical and differentially weathered strata at Aisol creek outcrop (West located at the left side)

prograding sequences with intense wave action have been described. Deformation by 'Chanic' tectonic phase is evident (Fig. 7a, b).

Conglomerates: Both, clast- and matrix-supported conglomerates wtih erosive bases are usually restricted to 2–3 m wide and 1 m deep channels. This facies is only present at the Lomitas Negras section (Fig. 4), developing lenticular and laterally discontinuous beds. They are poorly sorted and the matrix is medium to coarse sand. Clasts range from 2 to 10 cm long and show chaotic disposition without stratification; they are mainly composed of wackes, marls, limestones, siltstones, phyllites, quartz and feldspars. Some limestone clasts bear Ordovician fossils (Nuñez 1976; Criado Roqué and Ibañez 1979).

To the top, the channels could reach several metres wide and two or three metres thick. The conglomerates tend to have a sub-vertical position, due to the regional folding of the sequence (Fig. 4). As they are harder than the associated fine-to-medium-grained sedimentary rocks, they result into a strong geomorphologic control. The thickness of sandstones and mudstones associated to this facies suggests high energy, a relatively instability of the coastline and close continental source areas bearing plant remains (Fig. 8).

Fig. 8 Plant remains from Lomitas Negras section. Distance between *white dots* is 1 mm

4 Petrography and Diagenesis Studies

25 thin section samples were analyzed under the microscope. The minerals recorded by point counting are quartz (monocrystalline, polycrystalline and metamorphic), K-feldspar (microcline), plagioclase, opaque minerals, hematite and sedimentary or metamorphic rock fragments (Fig. 9). The presence of detrital biotite and scarce muscovite suggest short transport and reworking of sediments (Manassero et al. 2009). Many of the medium-grained sandstones (2–1.5Φ) are wackes (more than 15% matrix) and are composed of subangular quartz, with normal and wavy extinction, feldspars and fragments of polycrystalline quartz. Samples from the Lomitas Negras section show higher proportions of polycrystalline quartz.

The rocks are classified as feldspathic-wackes and quartz-wackes. In the Q-F-L diagrams, the sandstones of the Río Seco de los Castaños Formation show a cluster of data in both the recycled orogen and continental block fields (Fig. 10). Feldspars and biotite are widespread altered to chlorite, giving the typical greenish colours to the rocks. In the Lomitas Negras section the abundance of polycrystalline quartz displace the data to the recycled field. Although the data is showing some dispersion, we assume an uplifted igneous-metamorphic basement or recycled orogen as source areas.

The clay minerals fraction was studied using XRD, and it shows a dominance of illite (40–60%), kaolinite (25–40%) and chlorite which ranges from 10 to 20%, although it can go up to 35% when interlayered with smectite (Manassero et al. 2009). Muscovite and interstratified chlorite/smectite are very scarce. The less than 2 μm fraction contains as well very small amounts of quartz and plagioclases. A low anchizone for the RSC was indicated by illite crystallinity index.

5 Geochemistry and Isotopic data

All the samples (n = 14) analyzed by geochemical methods from the RSC are claystones, except for one siltstone and sandstone (Manassero et al. 2009). CIA values are between 61 and 78. In the A-CN-K diagram the samples follow a general weathering trend which is broadly parallel to the A-CN join, regarding the average upper continental crust (UCC) composition, although K-metasomatism of some samples is evident. The RSC is moderately to highly weathered. Compared with Post-Archaean Australian Shales (PAAS) most of the samples are depleted in Th and U, although some samples are enriched in both. The Th/U ratios range from below to above the PAAS value of 4.7 but above the upper continental crust average indicating weathering processes, in accordance to CIA. The Zr/Sc and Th/Sc ratios indicate that recycling was not important for the RSC Formation, and an input from a source geochemically less evolved than average UCC. The Cr/V and Y/Ni ratios are 0.79 ± 0.33 and 0.86 ± 0.3 (average) respectively, indicating source rock(s) more mafic than the average UCC.

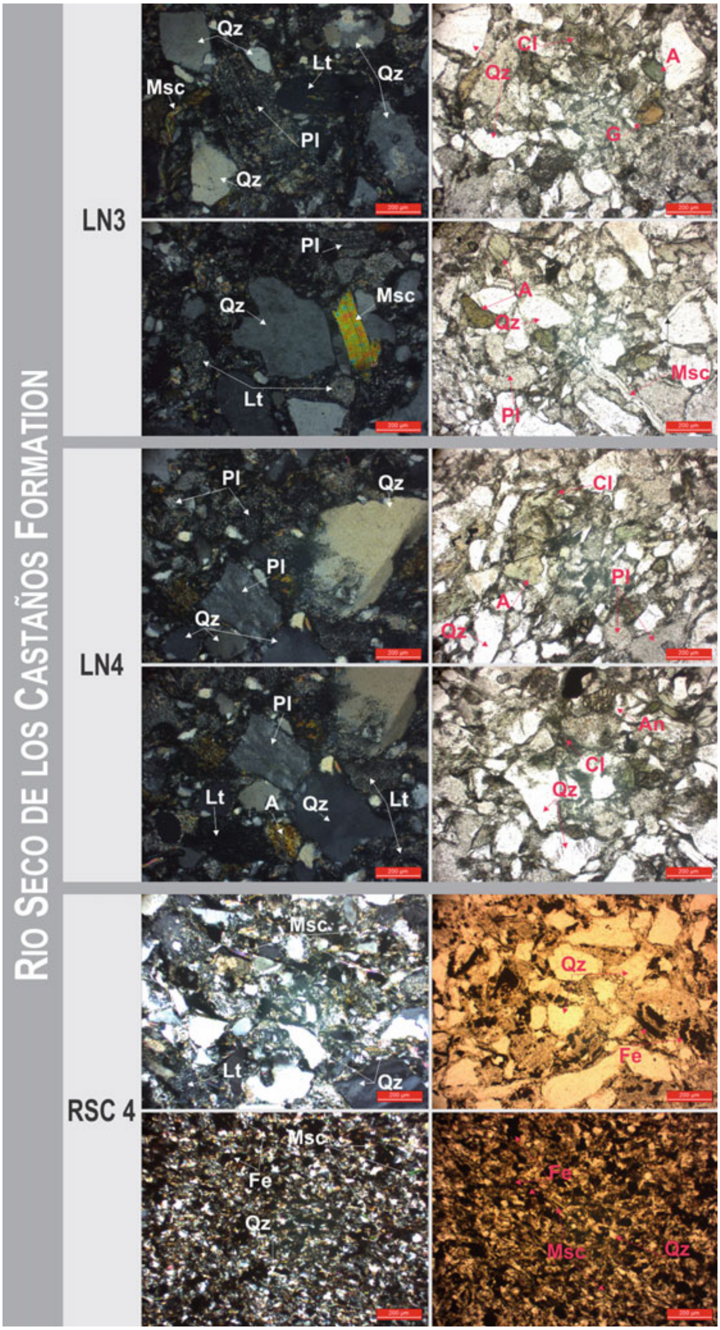

Fig. 9 Photomicrographs of medium-fine quartz-feldspathic wackes. RSC4: sample from Atuel River Creek. LN 3 and 4: samples from Lomitas Negras. On the left with crossed nicols. High matrix content and subangular character of minerals is shown. *Qz* quartz; *Pl* plagiocase; *Msc* muscovite; *Lt* lithics; *A* amphibole; *Fe* Fe oxides. Scale bar 200 µm

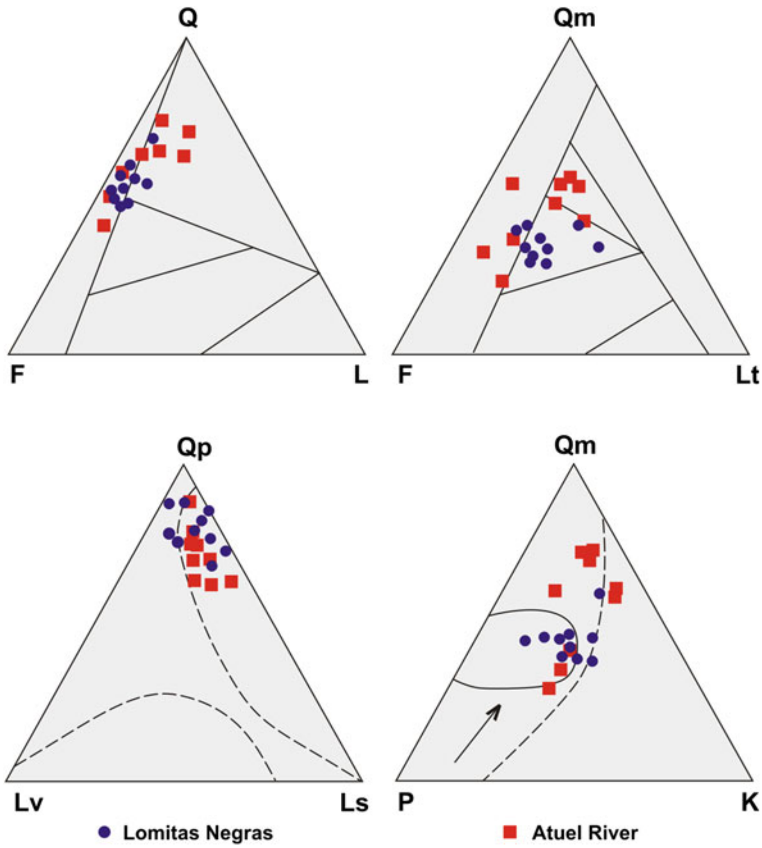

Fig. 10 Ternary diagrams after Dickinson and Suczek (1979) and Dickinson et al. (1979, 1983) plotting sandstone samples from the Atuel River Creek and Lomitas Negras sections. *F* feldspars; *FK* K-feldspars; *L* lithoclasts; *P* plagioclases; *Q* quartz (including polycrystalline quartz); *Qm* monocrystalline quartz; *Qp* polycrystalline quartz; *Ls* sedimentary lithoclasts; *Lv* volcanic lithoclasts (modified from Manassero et al. 2009)

The chondrite normalized REE diagram for the RSC is broadly similar to the PAAS pattern, showing a moderately enriched light rare earth elements pattern, a negative Eu-anomaly and a rather flat heavy rare earth elements distribution. Eu-anomaly of 0.81 along with Eu concentrations that double that from the PAAS supports the influence of a depleted source.

From the geochemical proxies described above (Manassero et al. 2009) a provenance from an unrecycled crust with an average composition similar to depleted compared with average UCC is suggested.

5.1 Sm–Nd Data

As were presented in Manassero et al. (2009) the RSC samples (n = 7) shows ε_{Nd} (t) values (where t = 420 Ma is the proxy age of sedimentation) ranging from −2.5 to −7.7 (average −4.5 ± 1.7). ε_{Nd} values are between those typical for the upper continental crust or older crust and those typical for a juvenile component (Fig. 11). Samples with the less negative ε_{Nd} (t) display the lowest Th/Sc ratios, indicating that the more juvenile the source the more depleted its geochemical signature. The $f_{Sm/Nd}$ against ε_{Nd} (t) diagram shows a data cluster between fields of arc-rocks and old crust. $f_{Sm/Nd}$ values out of the range of variation of the upper crust (−0.4 to −0.5) could be indicating Sm–Nd fractionations due to secondary processes.

T_{DM} ages are within the range of the Mesoproterozoic basement and Palaeozoic supracrustal rocks of the Precordillera-Cuyania terrane. ε_{Nd} values of the RSC are similar to those from sedimentary rocks from the Lower Palaeozoic carbonate-siliciclastic platform of the San Rafael Block, which show ε_{Nd} (t) between −0.4 and −4.9 (Cingolani et al. 2003a) and they are also in the range of variation of ε_{Nd} values of the Mesoproterozoic basement of the San Rafael Block (the Cerro La Ventana Formation; Cingolani et al. 2005) recalculated at 420 Ma. Although some $f_{Sm/Nd}$ values are below or above average values for the upper crust, all samples but one has $f_{Sm/Nd}$ values in the range of variation of the Cerro La Ventana Formation (Cingolani et al. 2005; Cingolani et al. this volume).

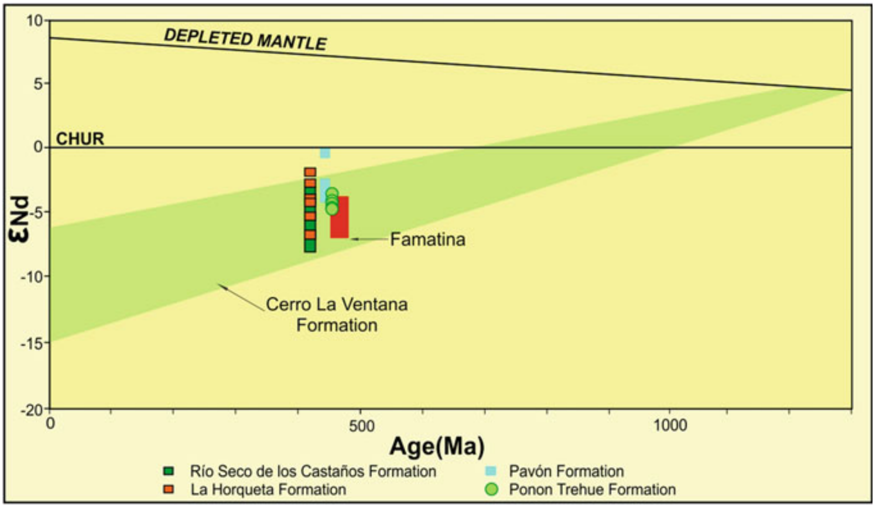

Fig. 11 Sm–Nd data of 7 whole rock samples from RSC that plot within the εNd range of Mesoproterozoic basement. For comparison the Pavón and Ponón Trehué Fms and Famatina arc (Ordovician) are also plotted (Abre et al. 2011, 2012)

5.2 Rb–Sr Whole Rock Data

Determination of Rb and Sr contents was performed by XRF, and the isotopic composition on natural Sr by mass spectrometry. The sample preparation, chemical attacks and Sr concentration with cation exchange resin were carried out in the clean laboratory of the Centro de Investigaciones Geológicas (CIG, University of La Plata, Argentina) and mass spectrometry was performed in the Centro de Pesquisas Geocronológicas (CPGeo), São Paulo, Brazil (Cingolani and Varela 2008). The results were plotted on isochron diagram, using the Isoplot model after Ludwig (2001).

Eight fine-grained samples were selected for analysis by Rb–Sr systematic; their location (all from the Atuel river type-section) is shown in Fig. 3. The Rb content varies between 165 and 312 ppm, while the Sr concentration ranges from 29 to 88 ppm. The $^{87}Rb/^{86}Sr$ ratios are between 7.5 and 24.4 in agreement with the relative high concentration of Rb and low contents of Sr. The expansion in the isochronic diagram (Fig. 12; Table 1) is acceptable for metasedimentary rocks. We interpret that during the low-metamorphic event Rb and Sr underwent isotopic homogenization, and therefore whole rock alignment is present (MSWD = 7.4). The high value of the initial isotopic ratio $^{87}Sr/^{86}Sr$ (0.7243) suggests a provenance for the sedimentary detritus from an evolved continental crust source. If we reject the sample A-02-04 that is out of the main alignment, the obtained Rb–Sr age is 336 ± 23 Ma.

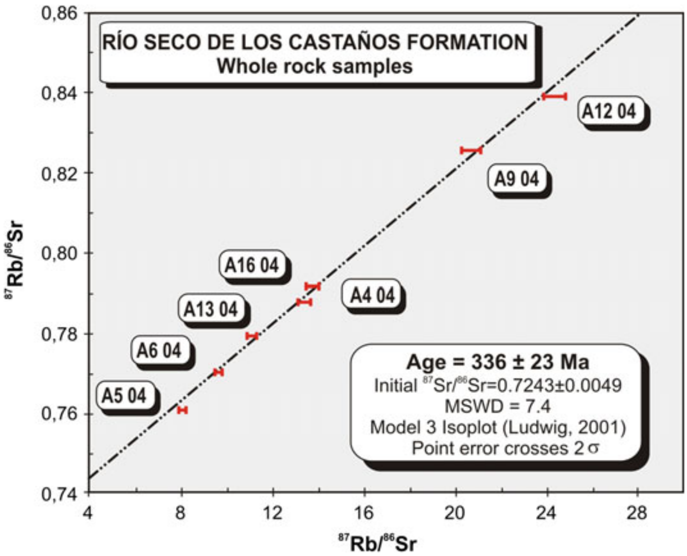

Fig. 12 Rb–Sr isochrone diagram for the RSC whole rock samples

Table 1 Rb–Sr systematic data

Lab. No. (1)	Field No.	Rb (ppm) (2)	Sr (ppm) (2)	^{87}Rb/^{86}Sr	Error	^{87}Sr/^{86}Sr (3)	Error
CIG 1350	A2/04	228.6	88.2	7.54	0.15	0.754476	0.000018
CIG 1351	A4/04	207.0	43.8	13.79	0.28	0.791519	0.000012
CIG 1352	A5/04	164.6	59.5	8.05	0.16	0.761021	0.000089
CIG 1353	A6/04	167.6	50.6	9.65	0.19	0.770341	0.000024
CIG 1354	A9/04	311.8	44.0	20.75	0.42	0.825325	0.000016
CIG 1355	A12/04	244.7	29.4	24.40	0.49	0.838778	0.000016
CIG 1356	A13/04	219.0	57.4	11.12	0.22	0.779242	0.000018
CIG 1357	A16/04	199.0	43.3	13.41	0.27	0.787614	0.000019

(1) CIG: La Plata; 1350 was eliminated, (2) FRX: CPGeo. São Paulo, and (3) mass spectrometer: CPGeo. São Paulo

These data suggest an Early Carboniferous (Mississipian) low-metamorphic (anchizone) event for the unit. Recalculating the data using all samples and following Isoplot 3.5 model 3 (Ludwig 2012), the obtained age is 346 ± 30 Ma, with enhanced error by using the eight samples. Another 'pre-Carboniferous' siliciclastic unit of the San Rafael Block, called La Horqueta Formation, which shows Rb-Sr whole rock ages (Tickyj et al. 2001) of 371 ± 61 and 379 ± 15 (Late Devonian), with an initial ^{87}Sr/^{86}Sr ratio of 0.7150, a considerable difference with respect to the RSC unit is evident, supporting the interpretation that both received detritus from different sources.

It is important to note that in the upper section of the Carboniferous-Lower Permian unconformable El Imperial unit, Rocha Campos et al. (2011) obtained U–Pb SHRIMP zircon ages of 297 ± 5 Ma (Carboniferous-Permian boundary) from tuff levels.

The Rb–Sr whole rock isotopic data of the metapelites record the very low-grade metamorphism during the Early Carboniferous. It is in correlation with the 'Chanic' tectonic phase that affected the Precordillera-Cuyania terrane (Ramos et al. 1986) linked to the collision of the Chilenia terrane in the western pre-Andean Gondwana margin. Rb–Sr data also help to constrain the depositional age and the discussion about the source areas of the RSC detritus.

5.3 U–Pb Detrital Zircon Age Data

U–Pb analyses of detrital zircons have been intensively used as an important tool to study the sedimentary provenance and the age of source(s) of detritus (Cingolani et al. 2014). Three samples from the RSC were analyzed by the U–Pb zircon systematic using LA-ICP-MS equipment, at the Centro de Pesquisas Geocronológicas, University of São Paulo (A-11-04; LN-10-04) and at Isotope

Laboratory of University of Río Grande do Sul, Porto Alegre, Brazil (LN-4-04). The obtained results are as follows:

Sample A-11-04 (Atuel river section, 34°57′47″S–68°36′40″W; Fig. 13; Table 3 in Supplementary Material): It is characterized by a main mode (61%) of detrital zircons of *Ordovician to Early Silurian* ages (433–480 Ma). In order of abundance, secondary records show the following age groups: *Mesoproterozoic*, with 1043–1392 Ma (10.5%), *Cambrian* with ages of 490 and 520 Ma (8.9%), *Neoproterozoic* with 548 and 731 Ma (7.5%), *Paleoproterozoic* with ages between 1686 and 1888 Ma (5.9%) and *Neoarchean* with ages between 2582 and 2628 Ma (5.9%).

Sample LN-10-04 (Lomitas Negras section, 35°15′52″S-68°30′19″W; Fig. 13; Table 4 in Supplementary Material): Shows also a dominance of *Ordovician* zircon grains (46.5%), with 435 and 486 Ma. A second group comprises *Cambrian* zircons (18.3%) with 493 and 537 Ma. In less proportion we found *Mesoproterozoic* grains (15.5%) with ages ranging from 1024 to 1352 Ma and *Neoproterozoic* zircons (12.7%) with ages from 543 to 956 Ma. Finally, we found two minor groups, one of *Neoarchean* zircons (4.2%) with ages of 2619–2686 Ma and another of *Paleoproterozoic* zircons (2.8%) with data of 1402–1530 Ma.

Sample LN-4-04 (Lomitas Negras section, 35°17′32.00″S–68°33′26.00″W; Fig. 13; Table 5 in Supplementary Material): *Ordovician* zircon grains (27%) are also dominant in this sample, with ages between 444 and 483 Ma. As a second group, we found Neoproterozoic grains (24%) with 545 and 997 Ma and Mesoproterozoic zircon grains (M3, M2, and M1; 25%) with ages ranging from 1019 to 1567 Ma. Upper *Cambrian* aged zircons show 9% and those of *Lower Cambrian* are 2%. Finally, two minor groups of zircons are present, one of *Paleoproterozoic* (8%) ages ranging from 1770 to 2425 Ma and another *Silurian–Devonian* (4%). In this sample most of the detrital zircons are coming from Ordovician, Neoproterozoic and Mesoproterozoic source ages in the same proportion.

As final remarks we can comment that the studied RSC samples show (Fig. 14) dominant derivation from Famatinian (Late Cambrian-Devonian) and Pampean-Brasiliano (Neoproterozoic-Early Cambrian) cycles. Detritus derived from the Mesoproterozoic basement are scarce. U–Pb data constrain the maximum sedimentation age of the RSC to the Silurian-Early Devonian.

5.4 Comparison with La Horqueta Formation

A comparison between RSC and La Horqueta Formation (Tickyj et al., this volume; Abre et al., this volume) is shown on Table 2. The RSC present low anchizone metamorphic grade dated by Rb–Sr as Lower Carboniferous; fossil (plants, acritarchs, ichnogenera) are preserved in different outcrops; a provenance from

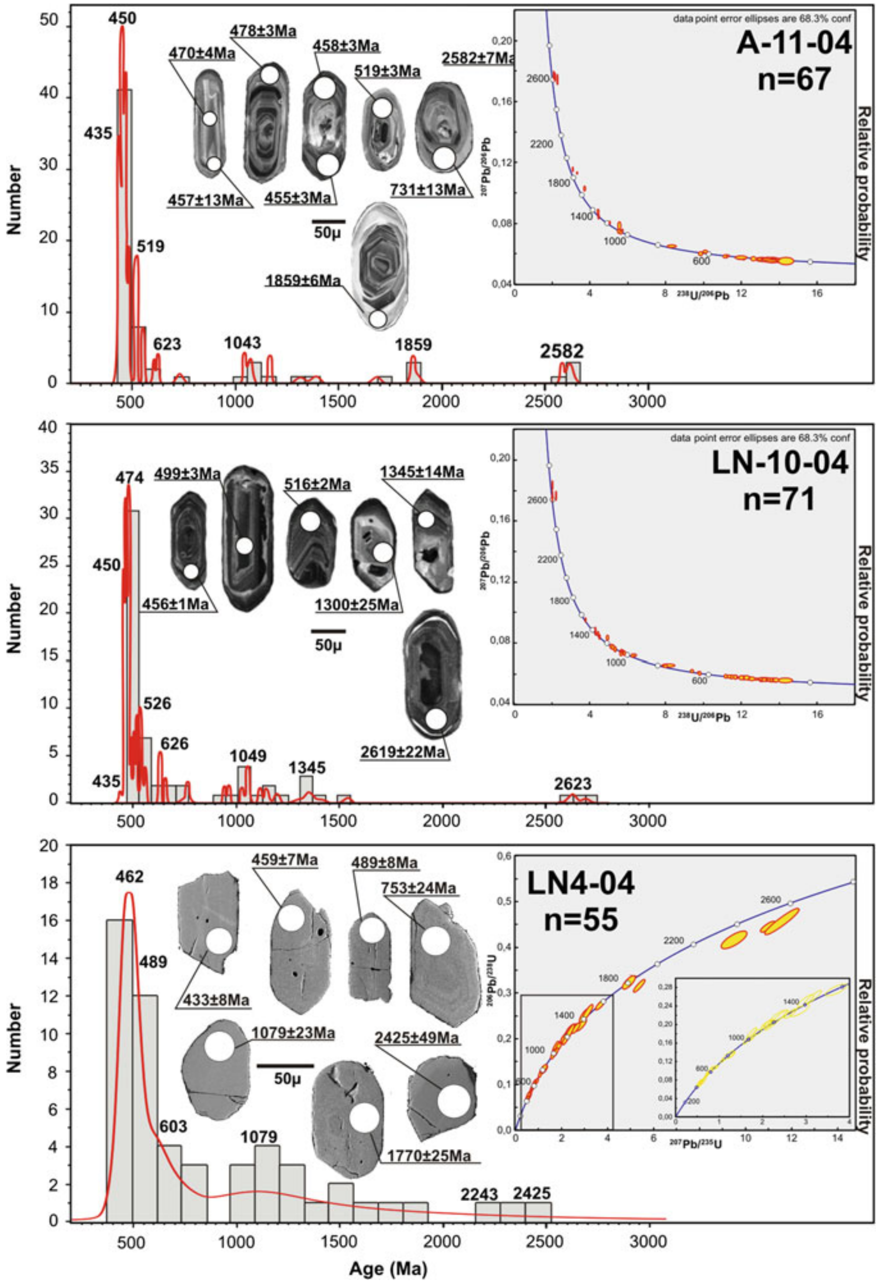

Fig. 13 Frequency histograms and probability curves of detrital zircon ages from RSC samples obtained by LA-ICP-MS. On each sample, the number of analyzed grains and obtained pattern ages was represented. On the right Tera-Wasserburg or Concordia diagrams for each sample is shown

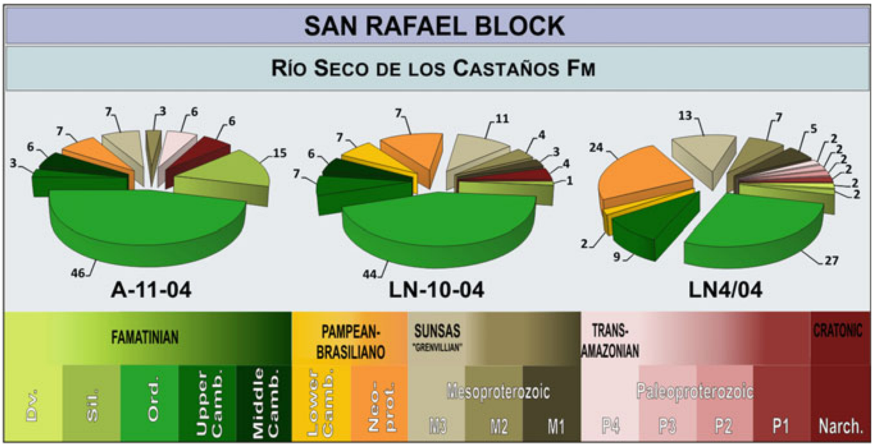

Fig. 14 Percentage of U–Pb detrital zircon ages of each sample represented in 'pie-diagrams'. Colours distinguished the main South American tectonic cycles

Famatinian rocks is accounted by U–Pb zircon patterns; it comprises conglomerate facies and a tonalite intrusive (401 Ma). On the other way, the La Horqueta Formation underwent a low grade of metamorphism, the fossil record is absent, Rb–Sr ages are older, as well as the main source rocks (determined by U–Pb detrital zircon ages), and it is intruded by a younger felsic plutonic body.

5.5 *Lu–Hf Systematic*

It is known that zircon preserves the initial $^{176}Hf/^{177}Hf$ ratio of the original magma, providing record of the Hf composition of their source environment at the time of crystallization. This ratio can be used to determine Hf model ages. Thus, the Hf isotopic composition of zircons can be utilized as a petrological tracer of a host rocks origin.

17 zircon grains (Table 6) were selected from the sample A-11-04 for Lu–Hf analysis by LA-ICP-MS at the Centro de Pesquisas Geocronológicas, University of São Paulo, Brazil. The $\varepsilon Nd(t)$ values of Ordovician and Neoproterozoic zircons range between −14.78 and −4.20 which reveal zircon derived from recycling old crust. Only one sample (Mesoproterozoic age zircon) show positive value 5.40 that linked with juvenile crust (Fig. 15).

Table 2 Comparison between RSC and La Horqueta Formation

Units	P–T conditions	Tectonic vergence	Fossil record	Rb–Sr (whole rock)	Detrital U–Pb zircon age cycles	Sedimentary environments	Intrusives	Sm–Nd data	Lithofacies	Ore deposits
Río Seco de los Castaños Fm	Low anchizone	East vergence folded	Ichnofossils: *Nereites-Mermia* *Dictyodora* Microfossils (acritarchs) Plants: Lycophythes	336 ± 23 Ma Lower Carboniferous	1. Famatinian 2. Pampean-Brasiliano 3. Mesoproterozoic	Marine platform-siliciclastic deltaic system Different facies	Devonian Rodeo Bordalesa Tonalite (401 ± 3 Ma)	εNd (t = 420 Ma) −2.5 to −7.7	Several from heterolithic to conglomerate	
La Horqueta Fm	Low-grade Hydrothermal veins	East vergence folded cleavage	No records	371 ± 61 Ma; 379 ± 15 Ma Upper Devonian	1. Mesoproterozoic 2. Pampean-Brasiliano	Turbiditic marine silicidastic	Permian Agua de la Chilena Granodiorite	εNd (t = 420 Ma) −1.49 to −6.53	Heterolithic	Sulphides La Picaza, Rodeo and others

Table 6 Lu–Hf systematic data of zircons from sample A-11-04 (Laboratory CPGeo SPL 846)

Sample SPL 846-A-11-04												
Grains/ spot	$^{176}Hf/^{177}Hf$	±2 se	$^{176}Lu/^{177}Hf$	±2 se	U–Pb Age (T1) Ma	ε Hf (0)	$^{176}Hf/^{177}Hf$ (T1)	ε Hf (T1)	$^{176}Hf/^{177}Hf$ DM ($T_{U\text{-}Pb}$)	T DM (Ma)	$^{176}Hf/^{177}Hf$ DM (T_{DM})	ε Hf (TDM)
1.1	0.282275	0.000036	0.001125	0.000021	1073	−17.56	0.282253	5.40	0.282446	1513	0.282122	10.68
3.1	0.282192	0.000050	0.002810	0.000059	447	−20.51	0.282168	−11.51	0.282902	2101	0.281685	8.56
5.1	0.282378	0.000032	0.000795	0.000009	453	−13.93	0.282371	−4.20	0.282898	1645	0.282024	10.21
25.1	0.282273	0.000026	0.001578	0.000033	456	−17.66	0.282259	−8.11	0.282896	1894	0.281840	9.31
37.1	0.282254	0.000170	0.003872	0.000055	450	−18.31	0.282222	−9.57	0.282900	1981	0.281774	9.00
46.1	0.282253	0.000027	0.001586	0.000033	454	−18.34	0.282240	−8.83	0.282897	1938	0.281807	9.15
46.2	0.282273	0.000029	0.001654	0.000021	459	−17.66	0.282258	−8.07	0.282894	1893	0.281840	9.31
11.1	0.282195	0.000041	0.002395	0.000045	462	−20.40	0.282174	−10.98	0.282891	2079	0.281701	8.64
18.1	0.282152	0.000036	0.002067	0.000053	460	−21.93	0.282134	−12.44	0.282893	2169	0.281634	8.31
58.1	0.282260	0.000028	0.001081	0.000017	460	−18.09	0.282251	−8.30	0.282893	1909	0.281828	9.26
19.1	0.282091	0.000043	0.003368	0.000052	521	−24.08	0.282058	−13.78	0.282849	2300	0.281536	7.84
7.1	0.282183	0.000031	0.001846	0.000061	519	−20.84	0.282165	−10.06	0.282850	2065	0.281712	8.69
21.1	0.282166	0.000028	0.002229	0.000043	453	−21.40	0.282147	−12.10	0.282898	2145	0.281652	8.40
22.1	0.282318	0.000028	0.000665	0.000022	465	−16.10	0.282312	−6.20	0.282896	1775	0.281928	9.70
36.1	0.282218	0.000035	0.000872	0.000011	450	−19.60	0.282211	−9.90	0.282900	2005	0.281757	8.90
50.1	0.282199	0.000030	0.001405	0.000017	454	−20.30	0.282187	−10.70	0.282897	2056	0.281718	8.70
53.1	0.282029	0.000032	0.002130	0.000064	459	−26.30	0.282010	−16.90	0.282894	2444	0.281428	7.30

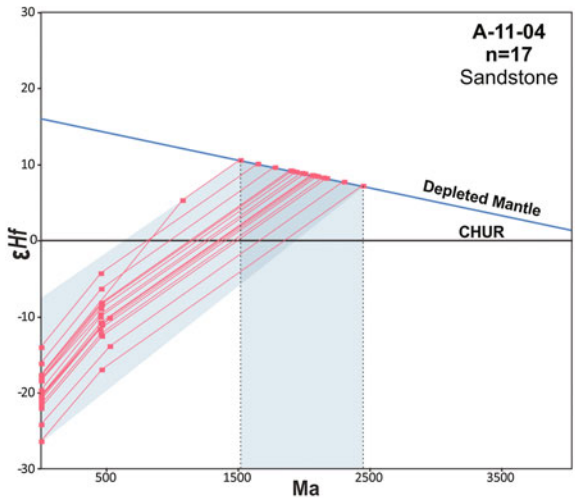

Fig. 15 εHf diagram obtained for A-11-04 sample

6 Discussion and Interpretation

As we concluded in Manassero et al. (2009) the relatively scarce diversity of sub-environments, dominance of fine-to-medium detrital grain sizes, lack of tractive sedimentary structures, and the important thickness of the beds associated with gravity flow processes are typical of a distal (below wave base) to proximal, silty-siliciclastic, marine platform-deltaic system. In this case, the sedimentary input was continuous, due to the absence of internal discontinuities. The dominant processes acting on this palaeo-environment were wave and storm action, prevailing the settling of fine material over the tractive processes. The presence of primitive vascular plant debris in the Atuel and Lomitas Negras sections (Morel et al. this volume) suggests closely related vegetated areas. The hydraulic regimes were moderate and the sea level changes in this sequence have generated very few sedimentary unconformities, but widespread lateral bed continuity.

Similar siliciclastic environments (and probably equivalent from a stratigraphical point of view), are interpreted as overfeed sedimentary foreland systems with great thickness (high sedimentary rates) and low textural maturity, e.g. the Villavicencio and Punta Negra Formations both from the Cuyania terrane. They have been described by other authors (González Bonorino 1975; Edwards et al. 2001, 2009; Peralta 2005, 2013; Cingolani et al. 2013). However, the channelled conglomerates and organic matter-rich beds lithofacies (charcoal) present in the RSC, allow us to distinguish this unit from other similar environments found within the Cuyania terrane.

The main detrital zircon age populations found in the RSC, indicate that two main sources are responsible for the vast majority of observed ages. The main peak corresponds to Ordovician ages that could have been derived from the Famatinian orogenic belt which is developed in the Pampia terrane (which major magmatic event is Ordovician). A second group of sources is characterized by Mesoproterozoic ages between 1000 and 1150 Ma that may confirm partial derivation from the easternmost igneous-metamorphic complex (Cerro La Ventana Formation).

The Sm–Nd signature of the Río Seco de los Castaños Formation agree well with the Mesoproterozoic basement and the carbonate-siliciclastic platform (same range of variation of the εNd (t) and T_{DM} ages), supporting both provenances (Fig. 11). The continental source areas (Cerro La Ventana Formation and the Ordovician sedimentary units) were located not far away towards the east within the San Rafael block (Fig. 1). The detrital material was westwards funnelled (conglomerate channels) from these positive areas into the outer platform areas also laterally associated with a progradating deltaic system along coastal sectors. The basin was deepening towards the west (open sea). Short transport is deduced from petrographical and sedimentological features. The limestone conglomerate-clasts support a provenance from rocks that belong to an Ordovician carbonate-siliciclastic platform, which is also located to the east.

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