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From source-to-sink: The Late Permian SW Gondwana paleogeography and sedimentary dispersion unraveled by a multi-proxy analysis

Luciano Alessandretti [a,*], Rômulo Machado [a], Lucas Veríssimo Warren [b], Mario Luis Assine [b], Cristiano Lana [c]

[a] Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562, Cidade Universitária, São Paulo, SP CEP 05508-080, Brazil
[b] Instituto de Geociências e Ciências Exatas, Departamento de Geologia Aplicada, Universidade Estadual Paulista, Avenida 24-A, Bela Vista, Rio Claro, SP CEP 13506-900, Brazil
[c] Departamento de Geologia, Escola de Minas, Universidade Federal de Ouro Preto, Morro do Cruzeiro, Ouro Preto, MG CEP 35400-000, Brazil

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ABSTRACT

The Late Permian sedimentary succession of the Paraná Basin, southern Brazil, provide a valuable source of information about sediment provenance, tectonic processes and, consequently, the paleogeography of the southwestern Gondwana supercontinent. In order to understand the patterns of sedimentary dispersal and reconstruct the Late Permian source-to-sink dynamic, we report a complete series of U-Pb ages and Hf isotopic compositions of detrital zircons from the Rio do Rasto Formation sandstones allied with detailed paleocurrent and sedimentologic data. Our integrated provenance study reveals a consistent sediment transport from the south to the north and northwest. According to the evaluation of zircon ages and Hf isotopes, it was possible to determine four distinct source areas: (i) a distant Late Paleozoic active magmatic arc located in the southwestern Gondwana margin (i.e. Gondwanides Orogen), corresponding to the North Patagonian Massif; (ii) recycling of orthoquartzites from the uplifted Paleozoic Ventania Fold Belt and immature sandstones from the Claromecó Foreland Basin in central-eastern Argentina and the Silurian-Devonian successions of the southern Paraná Basin (central-northern Uruguay) and North Patagonian Massif; (iii) exhumed areas of the Archean-Paleoproterozoic basement and Neoproterozoic to Early Paleozoic mobile belts of the Damara in southwestern Africa and Ribeira Fold Belt in Uruguay and southern Brazil; and (iv) southeastward provenance of Grenvillian (1.2–1.0 Ga) zircons coming from the mafic to intermediate Mesoproterozoic igneous units of the Namaqua-Natal Belt in South Africa and Namibia. These data allow us to argue that sediments deposited in the Paraná Basin during the Late Permian come from both short- and long-distance source areas. In this context, an important population of Permian detrital zircons comes from the Gondwanides Orogen in the south, probably carried by transcontinental alluvial systems. Close to the source area, antecedent river channels would have eroded older sedimentary rocks of the Ventania Fold Belt, Claromecó and Chaco-Paraná basins and North Patagonian Massif, crosscutting a peripheral bulge and flowing towards the alluvial plain of the intraplate setting to areas further north. Concomitantly, these sediments are reworked by strong winds that even helped carrying the grains to the Paraná Basin depositional site.

1. Introduction

The U-Pb ages and Hf isotopic compositions of detrital zircons obtained in clastic sedimentary rocks identifies the isotopic characteristics of source areas, providing powerful information on paleogeography and sediment-dispersal patterns (Dickinson et al., 1983; Ross et al., 1992; Gehrels et al., 2000; Lindsay, 2002; Cawood et al., 2003; Sears et al., 2004; DeCelles et al., 2007). Although there exists a significant number of isotopic investigations on volcanic zircons from Late Paleozoic tuffaceous beds in the Paraná Basin (Matos et al., 2001; Guerra-Sommer et al., 2005, 2008a, 2008b; Santos et al., 2006; Rocha-Campos et al., 2006,

* Corresponding author.
E-mail address: luciano.geors@gmail.com (L. Alessandretti).

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2007; Mori et al., 2012; Cagliari et al., 2014), little progress was made on the provenance of the sedimentary terrigenous deposits. Historically, the ages of the Permian strata in the Paraná Basin have been determined based on paleontological data obtained especially from palinomorphs assemblages (Daemon and Quadros, 1970; Souza and Marques-Toigo, 2005; Souza, 2006) and tetrapods (Dias da Silva, 2011). Due to the faunal endemism (Simões et al., 1998, 2015) and the lack of worldwide-distributed index fossils, such as ammonoids or conodonts, the age of the Permian strata of the Paraná Basin is poorly constrained. This fact makes this geotectonic unit an especially interesting target for the application of U-Pb geochronology coupled with Lu-Hf method. The abundance of fine-grained deposits can provide ancient detrital zircons that contain valuable information about the source areas and exhumation processes, erosion and transport of sediments and evidences about the tectonic processes that took place in the marginal portions of Gondwana during the Permian times. In this way, as observed by Ramos et al. (2013), geochronologic and provenance studies can provide evidence for the accretion of the Patagonian terrane along the southwestern Gondwana, an issue that has generated intense debate in the last decades (Ramos, 1984, 2008; Kay et al., 1989; Sellés-Martinez, 1989; Cobbold et al., 1991; Kostadinoff and Labudía, 1991; López-Gamundí and Rossello, 1998; Von Gosen, 2003; Chernicoff and Zapettini, 2004, Kostadinoff et al., 2005; Pankhurst et al., 2006; Ramos and Naipauer, 2012; Ramos et al., 2013; Rapalini et al., 2013; Pángaro et al., 2015; among others).

Current studies suggests that the collision of the Patagonian terrane against the southwestern Gondwana margin during the Lower Permian (allochthonous hypothesis of Ramos, 1984, 2008; Naipauer et al., 2010; Ramos et al., 2013) was responsible for the deformation and metamorphism of the Ventania Fold Belt (VFB) (Varela et al., 1986; Buggisch, 1987; López-Gamundí et al., 1995). According to Ramos (1984) hypothesis, Patagonia was an exotic terrane separated from Gondwana by a marine basin before the Carboniferous. Prior to the collision between Patagonia and South America (SW of the Gondwana supercontinent), a north-south subduction would have been responsible for the closure of this oceanic basin. During the subduction stage in the Permo-Triassic, a widespread arc-related magmatism took place in the North Patagonia Massif, while the Patagonia docking produced intense folding and thrusting in the VFB (Ramos, 1984, 2008). Notwithstanding, no outcrops of basic and ultramafic rocks of oceanic crust (ophiolites) have been found; and gravimetric and magnetic anomalies nearby the supposed regional boundary are inconsistent with a belt of high-density rocks (Kostadinoff and Labudía, 1991; Kostadinoff et al., 2005). Rapalini (1998), based on paleomagnetic data from the Sierra Grande Formation of the North Patagonian Massif, suggested that the Patagonian terrane has not subjected to latitudinal displacements since Devonian times. Some authors also propose that the VFB is an intracratonic basin inverted by contraction and strike-slip tectonics related to oblique subduction (Cobbold et al., 1991; López-Gamundí et al., 1994, 1995; Rossello et al., 1997; Gregori et al., 2008). Additionally, Rapalini and Vizán (1993) and Rossello et al. (1993) have interpreted the deformation in the VFB as a resulted of the intraplate compression. Furthermore, other hypothesis based on paleogeographic and paleoclimatic reconstructions refute Patagonia as an allochthonous terrane (López Gamundí and Rossello, 1998).

Considering any hypothesis cited above, the formation of the Gondwanides Orogen in southern Gondwana in the Upper Permian, promoted closure of the intracratonic basin located to the north, isolating the Paraná Basin Epeiric Sea from the Panthalassa Ocean (Milani, 2007). The formation of a mountain range with altitudes between 1000 and 2000 m (Ziegler et al., 1997) reordered the whole arrangement of drainages and catchment areas and changed the sedimentary dispersion pattern (Ramos et al., 2013). These paleogeographical modifications resulted in changes in the stratigraphic architecture recorded in the succession of the Rio do Rasto Formation (Warren et al., 2008; Alessandretti et al., 2015).

Here we investigate sediment provenance, dispersion and final deposition (source-to-sink) of upper Permian sequences of the Paraná Basin based on new U-Pb ages ($n = 426$) and Hf isotopic compositions ($n = 194$) of detrital zircons and extensive paleocurrents measurements ($n = 130$). We focus our observations on fluvio-deltaic deposits of the Rio do Rasto Formation that are distributed along a 700 km exposure range in the eastern border of the Paraná Basin (Fig. 1). The samples were collected in the Rio do Rasto Hill and the Lages Dome, a positive anticlinal structure near the homonymous city in Santa Catarina State, southern Brazil. This approach revealed an unexpected pattern of sedimentary dispersion with important implications for the southwestern Gondwana paleogeography at the end of the Paleozoic.

2. Geological setting

The sedimentary succession of the Rio do Rasto Formation comprises the upper portion of a transgressive-regressive cycle developed on the Upper Permian-Early Triassic of the Paraná Basin, southern of South America (Schneider et al., 1974; Lavina, 1991; Warren et al., 2008; Milani, 2007). This unit is about 180–250 m thick and is exposed along a narrow strip in the eastern border of the basin (Fig. 1). The Rio do Rasto Formation stratigraphically corresponds to the upper portion of the Passa Dois Group and is delimited at the base and the top by transitional contacts with the Teresina and Pirambóia formations, respectively (Lavina, 1991; Warren et al., 2008; Holz et al., 2010). Gordon (1947) formally subdivided the unit into the Serrinha (lower) and Morro Pelado (upper) members composed of an alternating succession of gray-to-red sandstones, siltstones and mudstones. The progradational architecture of the succession is attested by the tendency of increase in frequency and size of the sandstones bodies to the top. The sediments of the basal Serrinha Member are characterized by fine sandstone facies with swaley/hummocky stratifications interbedded with heterolithic and laminated pelitic gray-colored facies. This arrangement suggests an alternation of day-by-day sedimentation by suspension with episodic deposition by storms in offshore conditions (Rohn, 1994; Warren et al., 2008). The fossil concentrations (bone beds and rarely coquinas) are mainly composed of teeth, bivalve fragments, scales and fish coprolites and present taphonomic similarities with the storm-generated deposits (Rohn, 1994; Simões et al., 2015). Lenticular and sigmoidal meter-size layers of fine sandstones occasionally occur interbedded with this succession and are interpreted as distal deltaic mouth bars deposits (Lavina, 1991; Warren et al., 2008). A notable change of gray pelitic facies to red and purple colored mudstones occur at the intermediate portion of the Rio do Rasto succession. This variation is accompanied by the appearance of deltaic architectural elements, such as mouth bars, inter-distributary channels and crevasse splay lobes (Warren et al., 2008; Schemiko et al., 2014) pointing to a deposition in different physiographic positions inside a shallow water body. This interpretation is reinforced by the alternation of nearshore and offshore deltaic architectural elements and can be associated with the auto-cyclicity dynamic characteristic of the deltaic depositional environment (Fig 2); (Warren et al., 2008; Alessandretti et al., 2015). In the Morro Pelado Member, the massive presence of eolian facies is a definitive evidence of the continentalization and the possible transition to the Pirambóia desert system (Lavina, 1991; Rohn, 1994; Warren et al., 2008). Paleocurrent measures previously obtained in fluvial and eolian

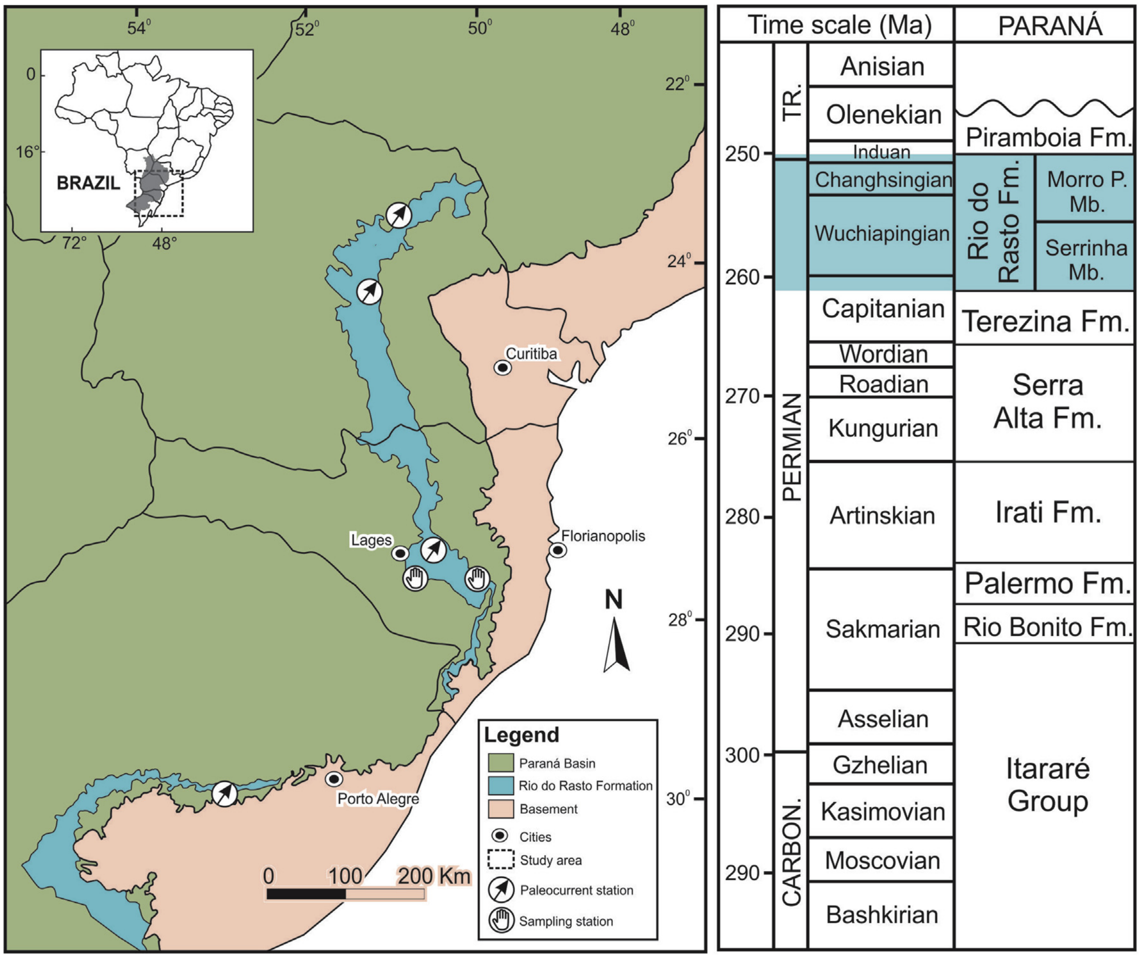

Fig. 1. Location map of the Rio do Rasto Formation within the eastern border of the Paraná Basin showing the sampling and paleocurrent stations.

facies of the Morro Pelado Member indicate a sedimentary transport from the southeast to northwest and from the east to west, respectively (Warren et al. (2008)). Sedimentary facies and depositional interpretations of the Rio do Rasto Formation are reported in Table 1.

3. Material and methods

We collected four samples of fine-grained sandstone from the Rio do Rasto Formation at the southeastern flank of the Paraná Basin, near the Lages and Lauro Müller municipalities, Santa Catarina State. The sampling campaign proceeded a systematic reconnaissance of the different Rio do Rasto Formation facies that involved: (1) documentation of vertical and horizontal facies patterns of the Rio do Rasto Formation, (2) analysis of stratigraphic sections, and (3) stratigraphic profiles (1:20-scale) across the Rio do Rasto (present study), Rio do Sul and Espigão hills. At Lages and surroundings, stratigraphic sections were measured, coupled with detailed facies description following Walker's method (1992), acquisition of paleocurrents data according the Miall's protocol (1999) and interpretations of architectural elements based on Miall (1985, 1996).

The samples from the Serrinha (PLA-09 and PLA-18) and from the Morro Pelado (PLA-01 and PLA-19) members were processed by standard methods for zircon grain separation including heavy liquids, Wilfley table, Frantz isodynamic magnetic separator and manual selection. Zircons grains were handpicked under a binocular stereo microscope, arranged on double-sided tape, and cast in epoxy mounts. After this first preparation stage, the zircon grains sections were observed with a FEI-QUANTA 250 scanning electron microscope equipped with secondary electron and cathodoluminescence (CL) detectors at the Centro de Pesquisas Geocronológicas (CP-Geo) of the Instituto de Geociências (IGc), Universidade de São Paulo (USP), Brazil. The conditions used in CL analysis were as follows: 20 kV of accelerating voltage, 4 μm of beam diameter and 200 μs of acquisition time.

The Pb/U and Pb isotope ratios in zircon grains were measured in *Element II* LA-SF-ICP-MS coupled to a 213 CETAC laser at the Laboratório de Isótopos at Universidade Federal de Ouro Preto (UFOP, Brazil), following the analytical procedures presented in Farina et al. (2015) and Takenaka et al. (2015). The analyses were conducted using a laser energy density of ca. 8 J/cm2 at a repetition rate of 10 Hz, and a 20 μm spot diameter. In the U-Pb Laboratory at UFOP, the primary reference material employed was the GJ-1 zircon (608 ± 0.4 Ma; Jackson et al., 2004) and for quality control, as a secondary standard, the Plešovice zircon (337.1 ± 0.4 Ma; Sláma et al., 2008). The background data were acquired for 20 s followed by 40 s of laser ablation signal. The relevant isotope rations ($^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$, $^{208}Pb/^{232}Th$, $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$, where ^{235}U is calculated from ^{238}U counts by abundant natural reason $^{235}U = ^{238}U/137.88$) were processed using the Glitter software package and plotting and age calculations were done using the Java-based DensityPlotter program (http://densityplotter.london-geochron.com) (Vermeesh, 2012). All U-Pb data were

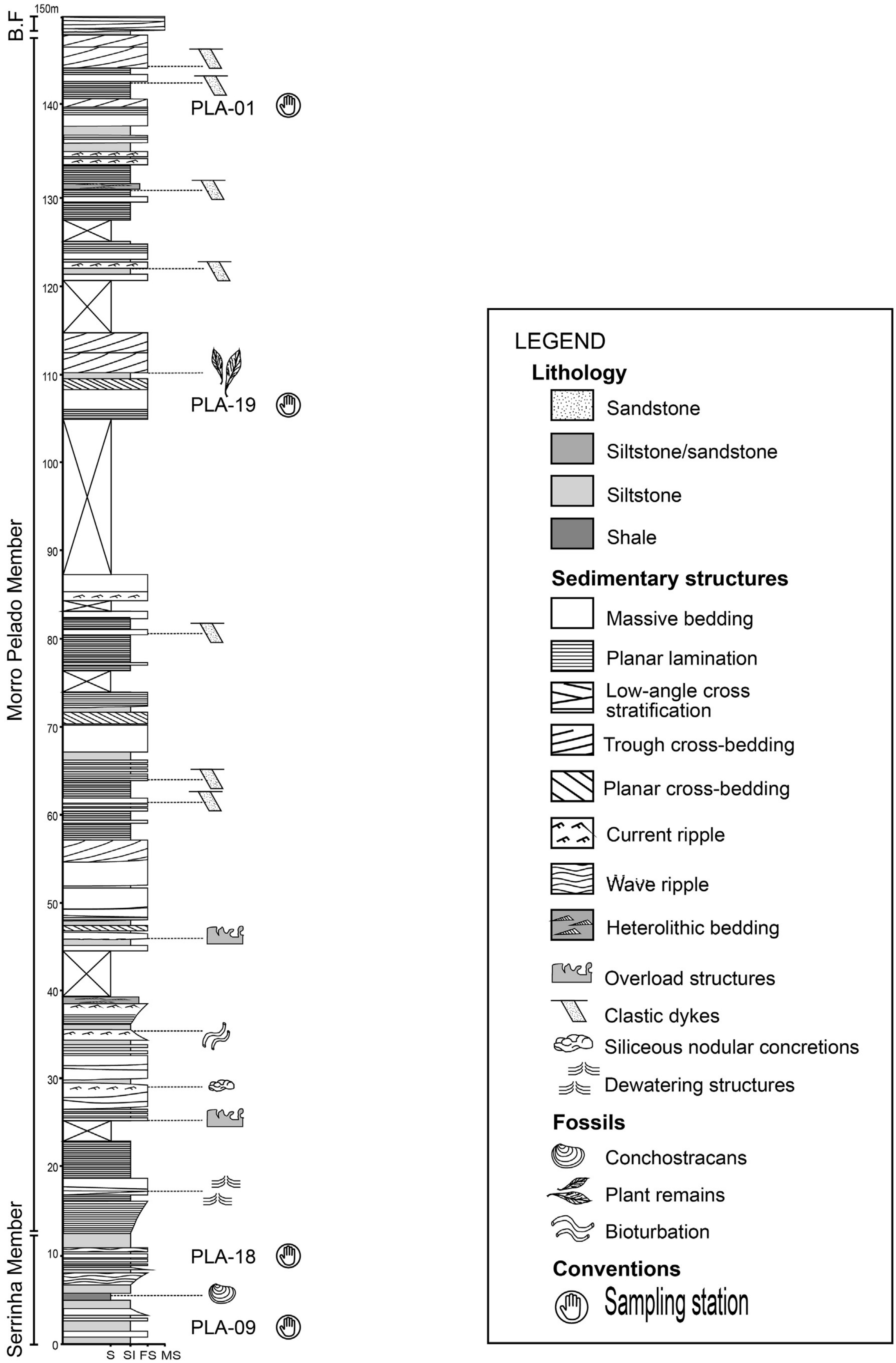

Fig. 2. Columnar section of wave influenciated shoreface deposits of Serrrinha Member and deltaic/alluvial deposits of Morro Pelado Member, Rio do Rasto Formation. Serra do Espigão, Santa Catarina State, Brazil. Note the position of the samples collected for detrital zircon analysis.

Table 1
Sedimentary facies and depositional interpretations.

Code	Facies	Description	Depositional process
M	Siliciclastic massive and laminated mudstones	Centimeter to decimeter thick tabular beds of gray, green, yellow and red shales, mudstones and massive or laminated siltstones. Occasionally with *Diploclaterion* vertical tubes.	Deposition by decantation under oxygenated and calm water without action of bottom currents.
H	Heterolithic bedding	Decimetric tabular thick beds of heterolithic facies characterized by intercalation between quartz very fine sandstone and red to pink siltstone. The sandstone usually presents wave ripples and the pelitic facies is massive.	Facies deposited by alternation of traction currents and decantation
Sm	Massive sandstones	Centimeter to meter thick scale tabular and lenticular beds of very fine to fine massive sandstones. Punctual presence of pelite intraclasts.	The massive structures is related to the lack of granulometry contrast and occasional bioturbation
Sp	Sandstones with planar lamination	Centimeter to meter thick tabular beds of very fine to fine sandstones with planar lamination	Deposition by traction currents (lower flow regime) in horizontal bottom
Sr	Sandstones with climbing ripples	Centimeter to meter tabular thick beds of very fine sandstones with subcritical symmetric to asymmetric climbing ripples. Occasional presence of complex and chevron accretion suggesting deposition by wave orbitals.	Migration of ripples under unidirectional and oscillatory lower-flow regime
Sh	Sandstones with hummocky cross stratification	Fine to very fine sandstones with hummocky cross stratification disposed in centimeter to decimeter thick tabular beds. The concave-convex stratification has centimeter in amplitude and wavelength.	Interaction between storm wave orbitals and unidirectional rip currents in distal conditions.
Ss	Sandstones with swaley cross stratification	Centimeter to decimeter thick tabular beds of fine sandstones with swaley stratification.	Deposition by oscillatory flux and unidirectional rip currents in proximal conditions during storm events
Sl	Sandstones with low-angle cross stratification	Fine to very fine sandstones with low-angle ($<10^{\circ}$) cross stratification disposed in decimeter to meter-scale thick tabular beds	Deposition by traction currents in a low gradient bed
St	Sandstones with through cross stratification	Decimeter to meter thick, tabular and lenticular beds of very fine to medium sandstones with small to large through cross stratification. The largest stratifications present granular segregation (fine to medium size grains) in the foreset.	Migration of subaqueous sinuous (3D) crested dunes. The sandstones with large through cross stratification are interpreted as a product of migration of eolian dunes

filtered for 10% discordance. Paleozoic zircons are reported from $^{206}Pb/^{238}U$ ages, whereas zircons older than Mesoproterozoic (1000 Ma) rely on $^{206}Pb/^{207}Pb$ ages. This procedure is appropriate because to the $^{206}Pb/^{238}U$ ages are usually more accurate for younger ages, whereas $^{207}Pb/^{206}Pb$ is more precise for older ages. We measured a total of 426 zircon and obtained representative ages for all grains.

Lu, Yb and Hf isotopic data were acquired on a Thermo-Finnigan Neptune multicollector ICP-MS coupled with a Photon-Machines 193 nm laser system at the Universidade Federal de Ouro Preto. The standards used during Hf analysis were GJ1 zircon, Temora zircon and Plešovice zircon. Laser energy of ca. 8 J/cm2 with a repetition rate of 10 Hz, in which the ablation of zircon was made in static mode during 60 s of ablation with a laser spot of 40 μm was used for all analyses. Each analysis was driven on the same site dated by the U-Pb method. An Aridus nebulization system was used to introduce nitrogen (~0.080 l/min) into the Ar sample carrier gas to improve transport efficiency. The isotopes ^{172}Yb, ^{173}Yb and ^{175}Lu were simultaneously monitored during analysis to allow for correction of isobaric interference of Lu and Yb isotopes on mass 176. The ^{176}Yb and ^{176}Lu concentrations were calculated using a $^{176}Yb/^{173}Yb$ of 0.796218 (Chu et al., 2002) and $^{176}Lu/^{175}Lu$ of 0.02658 (Goethe University of Frankfurt am Main in-house value). The data were corrected for instrumental mass bias using an exponential law and used the reference $^{179}Hf/^{177}Hf$ value of 0.7325 (Patchett et al., 1981). The mass bias of Yb isotopes commonly differs slightly from that of the Hf isotopes with a typical offset of the βHf/βYb of ca. 1.04 to 1.06 when using the 172Yb/173Yb value of 1.35274 from Chu et al. (2002). The mass bias behavior of Lu was assumed to follow that of Yb. Lu-Hf T_{DM} ages for zircon grains were calculated based on a depleted mantle source with $^{176}Lu/^{177}Hf$ of 0.0388 and $^{176}Hf/^{177}Hf$ of 0.28325 (Griffin et al., 2000; updated by Andersen et al., 2009). Model ages of individual zircons from mafic and felsic sources were calculated assuming the following parental magma compositions: felsic, Lu/Hf = 0.010; mafic, Lu/Hf = 0.022. The εHf(t) values were calculated assuming chondritic values (CHUR) of $^{176}Hf/^{177}Hf = 0.0336$ and $^{176}Lu/^{177}Hf = 0.282785$ (Bouvier et al., 2008) and the decay constant of $\lambda^{176}Lu$ (1.867 × 10−11/yr) of Söderlund et al. (2004). The Hf isotopic measurements were performed for 194 zircon with acceptable concordance. The analytical results are given in the electronic Supplementary material.

4. Results

4.1. Paleocurrents

The paleocurrent data were acquired along the eastern border of

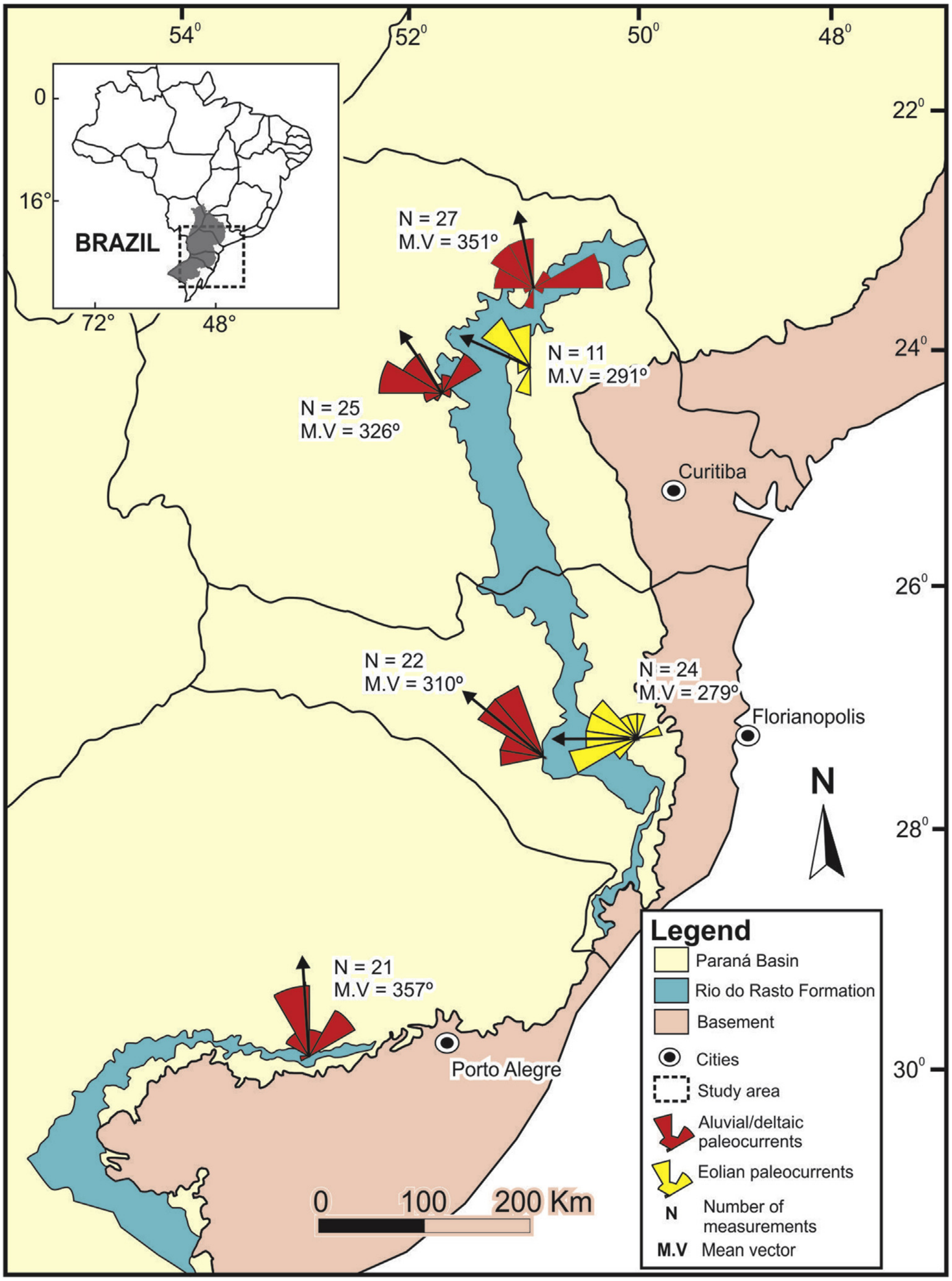

Fig. 3. Paleocurrents of the Morro Pelado Member of the Rio do Rasto Formation. North and northwesterly fluvial paleocurrents indicate sediment-source from south and southeast of the basin, while eolian paleocurrents point to contemporaneous winds reworking fluvial sediments and moving them towards west.

the Paraná Basin in the Rio Grande do Sul, Santa Catarina and Paraná States (Fig. 1). A total of 95 paleocurrent measurements were acquired in alluvial and deltaic facies of the Serrinha and Morro Pelado Members (Fig 3). Eolian paleocurrents ($n = 35$) were obtained exclusively in the Santa Catarina and Paraná sections from the upper succession of the Morro Pelado Member (Fig 3).

The alluvial and deltaic paleocurrents were obtained in sandstone facies from deltaic bars in the upper portion of Serrinha Member and in distributary channels of all succession of the Morro Pelado Member. Fluvial paleocurrents show consistent direction of sedimentary transport from the SSE to NNW, indicating that the fluvio-deltaic systems prograded from south-southeast toward north and northwest (Fig 3). It is important to note that the data presented by Schemiko et al. (2014) suggest fluvial progradation from W to E. This direction is consistent with the eolian paleocurrents measured in this work (Fig. 3) and probably represents local variations in the direction of fluvial/deltaic distributary channels. The fluvial paleocurrents, measured over 700 km along the outcrop area of the Rio do Rasto Formation, are consistent with the previously paleocurrents measured by Nowatzki et al. (2000) and Warren et al. (2008) and corroborates with the main depositional area of the Paraná Basin during the Upper Permian (Milani and Ramos, 1998; Artur and Soares, 2002). The fluvial sediment transport points to depositional dip towards northwest and sediment-source area in highlands located southeast of the depositional setting in Brazilian territory. In fact, paleogeography data

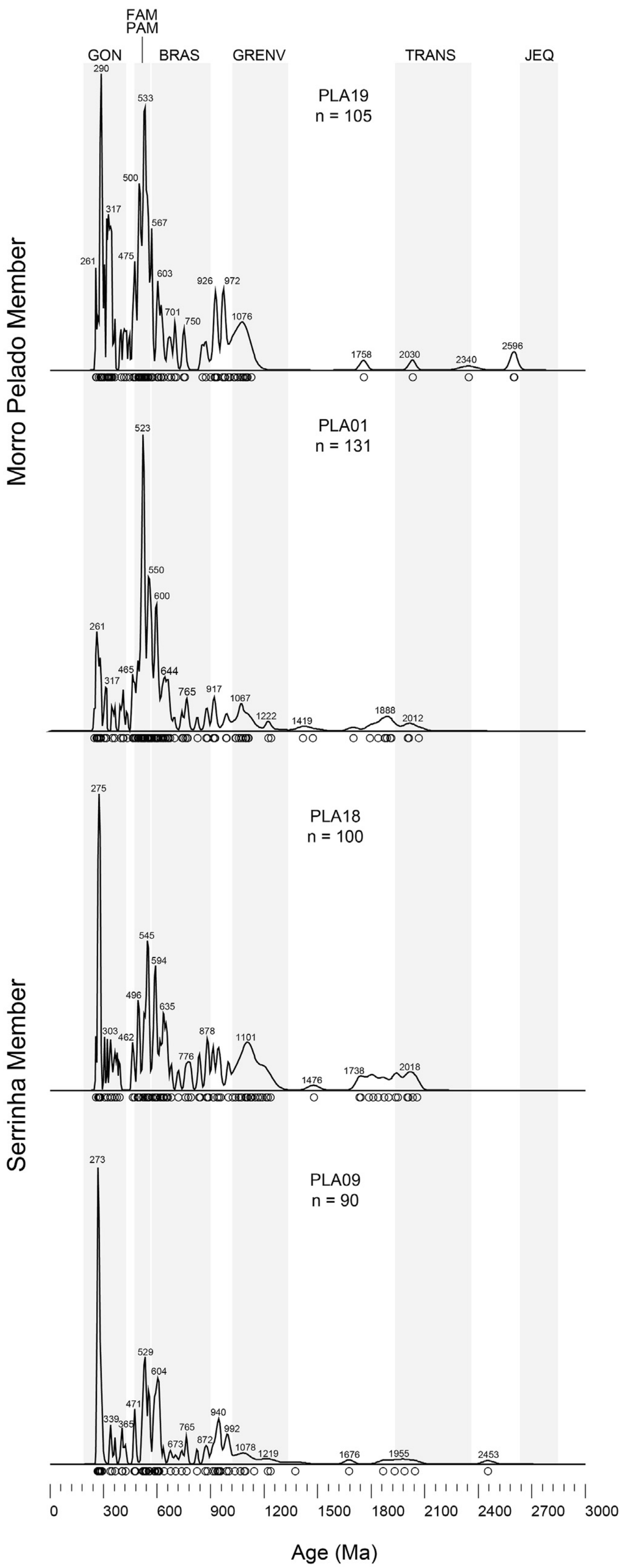

Fig. 4. U-Pb frequency plot ages from detrital zircons of the fine sandstones of the Rio do Rasto Formation.

from the Hesperides basin in Argentina reinforce the tendency of sedimentary transport from the northern Patagonia volcanic arc to the Paraná Basin (Pángaro et al., 2015).

4.2. *U-Pb ages and Hf zircons compositions of the Rio do Rasto Formation*

Fluvio-deltaic sandstones of the Rio do Rasto Formation were sampled in two sections in the Santa Catarina State (Fig 1), and detrital zircons were analyzed in order to identify possible source-areas and provenance, and evaluate how far the sediments were transported before the sink in the Rio do Rasto depositional settings. The complete list of the U-Pb and Hf isotopic data obtained for detrital zircons are given in the Tables 1 and 2 in the electronic supplementary material. All samples show major input from Permian (ca. 261–290 Ma) sources. In addition peaks at ca. 303–339 Ma (Gondwanian), 462–475 Ma (Famatinian), 523–545 Ma (Pampean), 600–878 Ma (Brasiliano), 992–1222 Ma (Grenvillian), ca. 2018 Ma (Transamazonian) are present, albeit in variable proportions. The zircon age spectra for the fine-grained sandstones of the Morro Pelado member are remarkably similar from those of the Serrinha Member. Ages versus probability density diagrams for the four samples are presented in Fig. 4. The Hf isotopes have been analyzed in 96 detrital zircons from the Serrinha Member and 117 from the Morro Pelado Member, in order to trace potential source(s) and understand their nature. In the Morro Pelado Member, 70 zircons have been analyzed from sample PLA-01 and 47 from sample PLA-19 (Fig. 5). A total of 42 zircons were analyzed from sample PLA-09 and 54 from sample PLA-18 from the Serrinha Member.

4.2.1. *Sample PLA-09 (Serrinha Member – Lages Dome)*

The sample PLA-09 of the Serrinha Member is a greyish, well-sorted, very fine-grained, massive sandstone deposited in the wave influenced coastal system with deltaic influence (Fig. 1). In the Serrinha Member 42 zircons have been analyzed from sample PLA-09. The euhedral and subhedral zircons have grain sizes ranging from 60 to 300 μm, and are rounded to well-rounded grains. A dominant peak at ca. 273 Ma, with subordinate peaks at ca. 529, 552 and 604 Ma, characterizes this sample. Subordinate frequency peaks occur at ca. 339, 365, 405, 471, 765, 940 and 992 Ma with scattered Mesoproterozoic to Neoarchean grains is also observed.

The $\varepsilon Hf_{(t)}$ vs. time diagram for the sample PLA-09 shows that the oldest group of zircons with ages between 1.63 and 2.43 Ga is characterized by mainly negative values between −7.7 and −0.8 and T_{DM} ages from 2.92 to 2.34 Ga. One Paleoproterozoic zircon has an $\varepsilon Hf_{(t)}$ of +1.6 with T_{DM} age of 2.72 Ga. The group of zircon with ages around ca. 1.0 Ga is almost entirely characterized by positive $\varepsilon Hf_{(t)}$ values ranging between +1.6 and + 8.3 and T_{DM} ages from 3.77 to 1.42 Ga. Two Greenvillian-aged zircons yielded negative values of $\varepsilon Hf_{(t)}$ of −17.9 and −3.9 and T_{DM} ages 3.77 and 2.46 Ga. The Ediacaran to Cryogenian zircons have variable characteristics, with a group of slightly positive $\varepsilon Hf_{(t)}$ +2.6 and + 0.1 and model ages between 1.34 and 1.25 Ga; a second group has negative $\varepsilon Hf_{(t)}$ values between −7.2 and −2.3 and older T_{DM} ages between 2.47 and 2.25 Ga. The Paleozoic source can also be grouped in two clusters: a group of Permian zircons with negative $\varepsilon Hf_{(t)}$ values (−4.4 and −0.9) and T_{DM} ages between 1.31 and 1.14 Ga; the other group, composed of Devonian, Carboniferous and Permian zircons, has positive $\varepsilon Hf_{(t)}$ values (+0.7 and + 6.9) and T_{DM} ages (1.64 and 1.09 Ga).

4.2.2. *Sample PLA-18 (Serrinha Member – Rio do Rasto Hill)*

The sample PLA-18 of the Serrinha Member is a grayish, very fine-to fine-grained, well-sorted, massive sandstone bed deposited

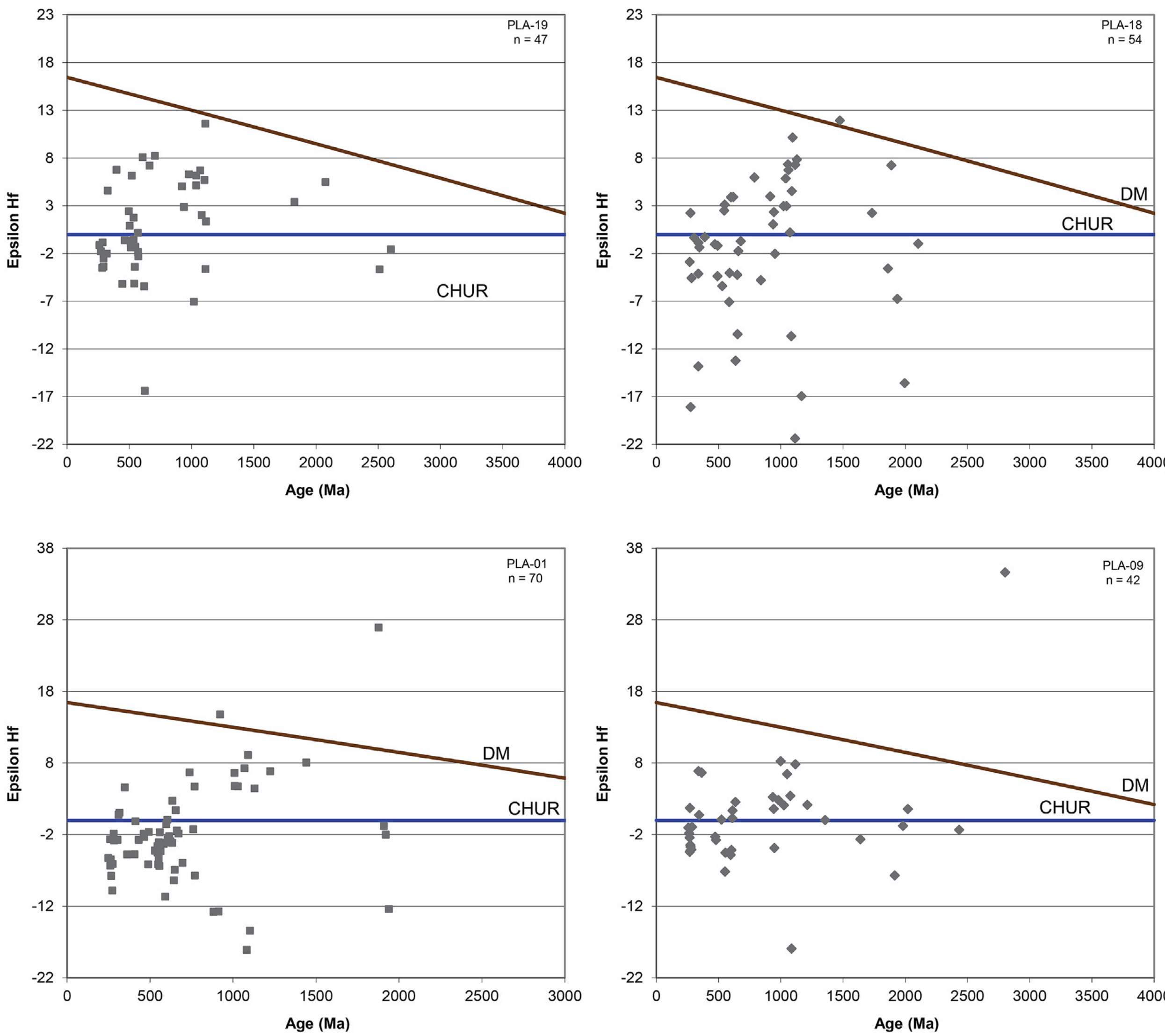

Fig. 5. Lu-Hf isotope analyses of samples from the Rio do Rasto Formation.

in the prodeltaic depositional system of the upper Serrinha Member. This sample correspond to a very fine-grained sandstone collected in the Rio do Rasto Hill (Fig. 1). The zircon grains are rounded to subrounded, euhedral, subhedral and their sizes vary from 60 to 185 μm. This sample is characterized by prominent Permian (ca. 275 Ma) and Neoproterozoic (ca. 545–999 Ma) prominent age peaks, followed by significant zircon grain populations with Carboniferous (ca. 303–360 Ma), Devonian (ca. 370–390 Ma), Ordovician (ca. 462–496 Ma) and Mesoproterozoic (ca. 1105–1476) age peaks. The data of the Serrinha Member show that Paleoproterozoic zircons are very rare and the youngest zircon yields an age of 269 ± 2 Ma (Late Permian).

Several zircons from distinct sources have been analyzed for Hf isotopes in the sample PLA-18 of the Serrinha Member. Four Paleoproterozoic zircons yielded negative εHf(t) values of −15.6 and −1.0 and model ages between 3.29 and 2.57 Ga; whereas another two yielded positive εHf(t) values of +7.2 and + 2.2 and TDM ages of 2.12 and 2.46 Ga. Almost all Grenville-age zircons yielded positive εHf(t) values from +0.2 to +10.1 and TDM ages ranging from 2.19 to 1.32 Ga; other four zircons have negative εHf(t) values (−29.2 to −2.0) with age models oscillating between 3.18 and 1.74 Ga. The Neoproterozoic sources can be divided into negative εHf(t) values from −59.2 to −0.7 with TDM ages between 4.36 and 1.19 Ga; positive εHf(t) values range from +3.9 to +2.5 and TDM ages restricted between 1.19 and 1.15 Ga. One Ordovician zircon has εHf(t) of −1.0 with a TDM age of 1.88 Ga; another Silurian zircon has εHf(t) of −0.3 with model age of 1.19 Ga. The Permo-Carboniferous source yielded negative εHf(t) values from −51.8 to −0.3 with Hf model ages 3.75 to 1.13 Ga. One Permian zircon (ca. 275 Ma) has an εHf(t) of +2.2 with a TDM age of 1.46 Ga.

4.2.3. Sample PLA-19 (Morro Pelado member – Rio do Rasto Hill)

Sample PLA-19 is a reddish, fine-grained and well-sorted sandstone with planar stratification deposited in the deltaic plain setting, characteristic of the upper portion of the Morro Pelado Member (Warren et al., 2008). Zircon grains are rounded, subhedral and their sizes vary from 70 to 175 μm. The probability density plots of the sample PLA-19 collected in the Rio do Rasto Hill section, shows main Permian and Neoproterozoic peaks at approximately 261–290 and 533 Ma, respectively. Another important Neoproterozoic peaks range between ca. 567, 603, 926 and 970 Ma. A significant contribution of Grenvillian-aged zircons also occurs at ca. 1076 Ma associated with rare Paleoproterozoic and Neoarchean ages. Carboniferous and Ordovician clusters have approximate ages of 317 and 475 Ma, respectively.

The scarce Neoarchean zircon grains from the sample PLA-19 have εHf(t) values of −3.7 and −1.6 with TDM ages of and 3.1 and 3.6 Ga. The Paleoproterozoic zircon grains (U-Pb ages between 1827 and 2076 Ma) show a wider range of εHf(t) values, which vary from −12.4 and +5.5, with TDM model ages between 3.08 and 2.41 Ga. The majority of Grenvillian-age zircon grains yielded positive εHf(t) values between +1.4 and +11.6 with TDM ages 2.12 and 1.2 Ga. However, four zircons yielded negative εHf(t) values of −18.1 to −3.6 and Hf model ages varying between 2.86 and 1.96 Ga. The Neoproterozoic zircon grains (U-Pb ages between ca. 520 and 979 Ma) show mainly negative εHf(t) values, which vary from −16.4 to −0.5, with TDM model ages between 2.39 and 1.2 Ga. The Carboniferous grains show slightly negative and positive εHf(t) values. Three grains yielded negative values between −4.7 and −2.0, and Hf model ages ranging from −1.40 and −1.22 Ga. The Permian zircon grains, which represent the main peak of this sample, have all negative εHf(t) values between −7.8 and −0.8 with TDM model ages restricted between 1.58 and 1.12 Ga.

4.2.4. Sample PLA-01 (Morro Pelado — Lages Dome)

Sample PLA-01 was collected at Lages Dome and corresponds to a reddish very fine-to fine-grained sandstone that is moderately sorted with planar internal stratification deposited in the deltaic plain setting of the Morro Pelado Member. Zircon grains are rounded to subrounded, euhedral, subhedral and their sizes vary between 68 and 273 μm. The sample yielded dominant Neoproterozoic (ca. 523–600 Ma) and Permian (ca. 261–281 Ma) age peaks. Subordinate age peaks between ca. 1890, 1067, 917, 874, 820, 765, 641, 465, 409, 348 and 317 were also obtained (Fig. 4). Three Paleoproterozoic-age zircons analyzed from sample PLA-01 have negative εHf(t) values between −12.4 and −0.8 with TDM ages between 3.08 and 2.46 Ga. The Grenville-source has principally positive εHf(t) values between +9.1 and + 4.5 with TDM ages constrained between 1.85 and 1.41 Ga. Two Mesoproterozoic grains (U-Pb ages of 1083 and 1102 Ma) yielded negative εHf(t) values of −18.0 and −15.4 and TDM ages of 2.67 and 2.55. The Neoproterozoic zircon grains, which represent the main peak in this sample show variable characteristics with a main group with negative εHf(t) values between −34.0 and −0.51 with Hf model ages varying from 3.7 to 1.4 Ga. The scarce Cambro-Ordovician zircon grains have εHf(t) values between −6.15 and −1.64 with TDM ages bracketed between 1.57 and 1.33 Ga. Four carboniferous grains yielded slightly negative and positive εHf(t) values, which vary from +4.6 to −2.73. Permian zircons indicate mainly Meso to Paleoproterozoic model ages (1.58–1.18 Ga) with negative εHf(t) values ranging from −9.79 and −1.87.

5. The SW Gondwana sedimentary dispersion during the Late Permian

The U-Pb ages and Lu-Hf isotopes combined with robust paleocurrent data from the Rio do Rasto Formation indicates variable sedimentary transport distances from the source areas to the final depositional site during the Late Permian. During this period, the main depositional site of the basin was located in the southwestern Gondwana hinterland (Milani, 2007). The depositional dip to the north is suggested by the paleocurrents (Milani and Ramos, 1998; Artur and Soares, 2002) indicating that the intracratonic basin was probably flanked by topographic highs developed on old Archean-Paleoproterozoic cratons and Neoproterozoic-Early Paleozoic mobile belts located at south and east. Compounding the Upper Permian paleogeographic and geotectonic scenario, the allochthonous terrane of Patagonia was being accreted to the south margin of Gondwana (Ramos, 1984; 2008; Ramos et al., 2013). Paleotopographic models indicate that the orogen that resulted from this collision (the Gondwanides Belt *sensu* Keidel, 1916), reached maximum elevations of about 1000–2000 m above the Panthalassa Ocean sea level at the Permo-Triassic limit (Ziegler et al., 1997). This newly uplifted orogen affected the oceanic connections of the Paraná Basin and prevented the marine incursion of the Panthalassa seaways through the continent (Milani, 2007). The orographic barrier also imposed extreme climatic changes characterized by increasing aridity from the Late Permian to Lower Triassic (Limarino et al., 2013). Pángaro et al. (2015) proposed an inter-continental connection (the Hesperides Basin) of the Upper Paleozoic to Lower Triassic southwestern Gondwana basins based on correlation of well log data and 2D seismic lines. This link implies in a huge sedimentary wedge extending from more than 1000 km to the north from the Gondwanides orogen core. Sediment wedge proposed by Pángaro et al. (2015) would have extended from the Gondwanides belt to the southern depositional area of the Paraná Basin.

As shown in the Fig. 3, the paleocurrent data were acquired over 700 km of the eastern border of the Paraná Basin. The paleocurrent readings obtained indicate a consistent sedimentary transport from southeast to northwest, suggesting a depositional dip to northwest and highland areas located to the southeast. Paleocurrents from eolian sand-dune facies indicate a general wind direction from ESE to WNW (Fig. 3). The sedimentary dispersion pattern suggest that the main source areas of the Rio do Rasto Formation were located southeast of the depositional site during the upper Permian, but with important eolian sediment contribution derived from exposed areas located to the east.

5.1. Paleozoic sources: magmatism and sedimentary recycling

The ages here analyzed, reveal that the Rio do Rasto Formation has an expressive contribution of Early Permian-age zircons both in the Serrinha and Morro Pelado members. The dominant peaks at ca. 290, 275 and 273 Ma found in the Rio do Rasto Formation are similar to those peaks at ca. 291 and 282 Ma found in the Tunas Formation of the Claromecó Basin (Ramos et al., 2013). The upper stratigraphic layers of this Argentinian unit register an abrupt change in the paleogeography and sedimentary dispersal patterns, evidenced by dominant paleocurrents from the southwest to northeast (Andreis and Cladera, 1992; López-Gamundí and Rossello, 1998), volcanic debris (Andreis and Cladera, 1992) and the presence of abundant metamorphic/volcanic lithic fragments (López-Gamundí et al., 1995; López-Gamundí, 2006; Alessandretti et al., 2013) together with magmatic zircons (Ramos et al., 2013). Such drastic depositional dip change is related to the development of a Late Paleozoic magmatic arc located in the actual northern Patagonia, which released the magmatic zircons to the Claromecó Basin and further areas to the north (Ramos et al., 2013). The Gondwanides Orogen and the uplifted Ventania Fold Belt were considered by Ramos et al. (2013) as the main source areas providing immature detritus to the Claromecó Basin. The isotopic data presented by the authors is reinforced by conventional petrographic, geochemical and paleocurrents studies performed by Andreis and Cladera (1992), López-Gamundí and Rossello (1998) and Alessandretti et al. (2013). For the Late Paleozoic of the Karoo Basin in South Africa, Andersen et al. (2016) showed that this succession are also characterized by Permian-age zircons derived from the Gondwanides Orogen and recycling grains derived from older sedimentary rocks (Cape Fold Belt).

The Permian igneous rocks in northern Patagonia along the Somún Cura Massif, have negative εNd(t) values (see Pankhurst et al., 2006), suggesting a strong crustal participation for the genesis of the granitoid rocks. Such values are consistent with the mostly negative εHf(t) values found in the Permian detrital zircons of the Rio do Rasto Formation, which also revealed a major crustal contribution (Fig. 5). The Late Paleozoic ages coupled with several paleocurrent data from the Rio do Rasto Formation show that the source areas were located to the south and related with igneous and metamorphic rocks of the Somún Cura Massif, considered the core of the Gondwanides belt in southwestern Gondwana (Ramos, 2008).

Another possible (but improbable) alternative as source area is the Permian Choiyoi rhyolitic province in Chile and Argentina (Kleiman and Japas, 2009; Rocha Campos et al., 2011). However, the dominantly northward sediment-routing system evidenced by paleocurrents of the Rio do Rasto Formation allows refuting this hypothesis. The morphologies of the Permian-age zircons in the Rio do Rasto Formation point to magmatic rather than volcanic origin for these grains (see cathodoluminescence images in the electronic Supplementary material).

The Late Carboniferous peaks of ca. 303, 317 and 320 Ma found in the Rio do Rasto Formation are very similar with the 304, 315 and 322 Ma peaks obtained in zircons of the Pillahuincó Group, Claromecó Basin (Ramos et al., 2013). U-Pb-Hf data from detrital zircons of the Claromecó Basin presented by Ramos et al. (2013) indicate a Late Carboniferous source from the northern Patagonia along the Somún Cura Massif. Late Carboniferous A-type granites occur as small scattered plutons in the Sierras Pampeanas of NW Argentina, making this region a potential source area for sediment supply to the Paraná Basin during Permian times. Dahlquist et al. (2013) reported U-Pb ages of 322 ± 3 Ma for the Los Árboles pluton, with and εNd(t) values of −5.6 and −1.2, respectively. The Early Carboniferous peak at ca. 340 Ma found in the Rio do Rasto Formation can also be correlated with granitic rocks from Sierras Pampeanas. The Zapata granitic complex yielded a U-Pb zircon age of 340 ± 3 Ma, with εHf(t) = −6.4 and εNd(t) = −3.2 (Dahlquist et al., 2013). For the Cerro de La Gloria pluton, Alasino et al. (2012) obtained an U-Pb zircon SHRIMP age of 349 ± 3 Ma, whereas Dahlquist et al. (2013) presented an U-Pb zircon LA-ICP-MS age of 353 ± 4 Ma. The εHf(t) and εNd(t) yielded values of 1.6 and −0.5, respectively. Thus, the similarities between Early and Late Carboniferous age peaks in the Rio do Formation (ca. 317, 322 and 340 Ma) and granitoids in the Sierras Pampeanas, and the complete lack of fluvial and/or deltaic paleocurrents indicating transport from W to E, lead us to discard a direct sedimentary transport for these zircons. Rather, these peaks may reflect a sedimentary recycling of older successions bearing carboniferous zircons, such like the Ventania Fold Belt and the Chaco-Paraná, Paganzo and Paraná basins.

The Rio do Rasto Formation detrital zircon ages yielded Middle-Upper Devonian peaks at ca. 392 Ma and 360 Ma, comparable with the 389 and 375 Ma peaks found in the Tunas Formation sandstones of the Claromecó Basin (Ramos et al., 2013). The Devonian zircons population in the Tunas Formation point to an origin in the Eastern Sierras Pampeanas, where late-to post- orogenic granites yielded U-Pb crystallization ages ranging from 393 ± 5 and 368 ± 2 Ma (Dorais et al., 1997; Stuart-Smith et al., 1999). These ages are suggestive of long distance sedimentary transport from the Sierras Pampeanas to the Claromecó foreland basin (Fig. 6). The Middle-Upper Devonian Achala granite is the most expressive batholith in Sierras Pampeanas and has a U-Pb zircon SHRIMP age of 379 ± 6 Ma and εNd(t) = −4.0 (Rapela et al., 2008b). These authors also dated a small scale tonalitic intrusive at 369 ± 6 Ma, with εNd(t) values between −1.3 and −1.9. The recent work of Dahlquist et al. (2013), presented new U-Pb *in situ* LA-ICP-MS ages of 372 ± 6, 377 ± 3, 368 and 366 ± 6 Ma for the granitic rocks of the Achala Batholith. The εHf(t) values for these granitoids are at around −4.8 (Dahlquist et al., 2013). The Devonian detrital zircons with crustal affinities of the Rio do Rasto Formation yielded negative εHf(t) values at around −3.5, consistent with those obtained for the Achala Batholith. Over again, the paleocurrent measures presented here and in the works of Warren et al. (2008) and Nowatzki et al. (2000) are not consistent with a direct transport from the Sierras Pampeanas to the intracratonic depositional site. Rather, it seems that the Devonian detrital zircons found in the Rio do Rasto Formation were probably reinserted into the sedimentary cycle mainly by erosion of the uplifted Ventania Fold Belt (Ramos et al., 2013).

The Ordovician age peaks between ca. 462 and 475 Ma found in the Rio do Rasto Formation can be chronocorrelated with the frequency peaks of 469 Ma found in the pre-Carboniferous rocks of the Cape Fold Belt (South Africa) (Fourie et al., 2011), the 478 Ma peak in the Balcarce Formation (Tandilia System) (Rapela et al., 2011) and the 475 Ma peak obtained for the Lolén Formation in the Ventania System, Argentina (Ramos et al., 2013). Recent U-Pb detrital zircon ages from the Devonian Durazno Group (Cerrezuelo and La Paloma formations) in the southern Paraná Basin of Uruguay (Uriz et al., 2016), indicating that the main source areas are Neoproterozoic, with minor contributions derived from Mesoproterozoic and Archean-Paleoproterozoic rocks. It is important to note that the youngest detrital zircons of the Durazno Group are Ordovician-age, defining a maximum sedimentation age of 485 and 484 Ma for the Cerrezuelo and La Paloma formations, respectively (Uriz et al., 2016). These ages are similar to those found in the Upper Devonian Lolén Formation of the Ventania Fold Belt (Ramos et al., 2013), the Balcarce Formation (Rapela et al., 2011) of the Tandilia System and in the Rio do Rasto Formation (this paper). The provenance at this epoch has two candidate source areas: the Early-Middle Ordovician granites from the Sierras Pampeanas and the Early Ordovician granitoids from basement of the Patagonia terrane. Early-Middle Ordovician (Famatinian) calc-alkaline granitoids are widespread in the Sierras Pampeanas of Argentina. They are interpreted as granitoids intruded in an active continental margin (Dahlquist et al., 2013). The available geochronological data indicate ages of 489 ± 4 Ma (Cerro Toro granite), 476 ± 6 Ma (Mazán granite), 466 ± 6 Ma (La Cañada granitic complex) and 464 ± 5 Ma (Valle Fértil granite) (U-Pb LA-ICP-MS ages) (Dahlquist et al., 2013). Pankhurst et al. (2006) reported ages of 478 ± 4 Ma for the Valle Fértil granite, 481 ± 4 Ma for the Cerro Toro granite and 484 ± 3 Ma for the Mazán granite (U-Pb SHRIMP ages). The Cerro Toro granite has εNd(t) and εHf(t) of −6.3 and −14, respectively. The Mazán granite has εHf(t) = −10.2. The La Cañada granite yielded εNd(t) and εHf(t) values of −5.0 and −11.1. Finally, the Valle Fértil granite has identical εNd(t) and εHf(t) of −5.3 (Dahlquist et al., 2013). The Ordovician detrital zircons in the Rio do Rasto Formation have variable characteristics with a group of negative εHf(t) values between −12.8 and −1.3 (samples PLA-01, PLA-18 and PLA-18); only sample PLA-09 yielded positive εHf(t) between +34.6 and + 8.3. According to Ramos et al. (2013), the paleogeography of southwest Gondwana during the Silurian was characterized by higher mountains in the westward Famatinian Belt with partially eroded Pampean belts surrounding cratonic areas. The similar provenance patterns between the Lolén (Ventania System) and Balcarce (Tandilia System) formations lead Ramos et al. (2013) to attest that the Ordovician Famatinian Belt of Western Sierras Pampeanas was the main source area for both units. Indeed, this is the only region that records plutonic and volcanic rocks of Famatinian age at these latitudes (Ramos et al., 2010). The Ordovician-age detrital zircons from the Rio do Rasto Formation sandstones matches the U-Pb age peaks of the Lolén, Balcarce, Cerrezuelo and La Paloma formations from southwestern Gondwana basins. Once again, the consistent sediment-routing system from south to north points in favor to southward rather than westward source areas. Thus, these evidences reinforce the hypothesis that the

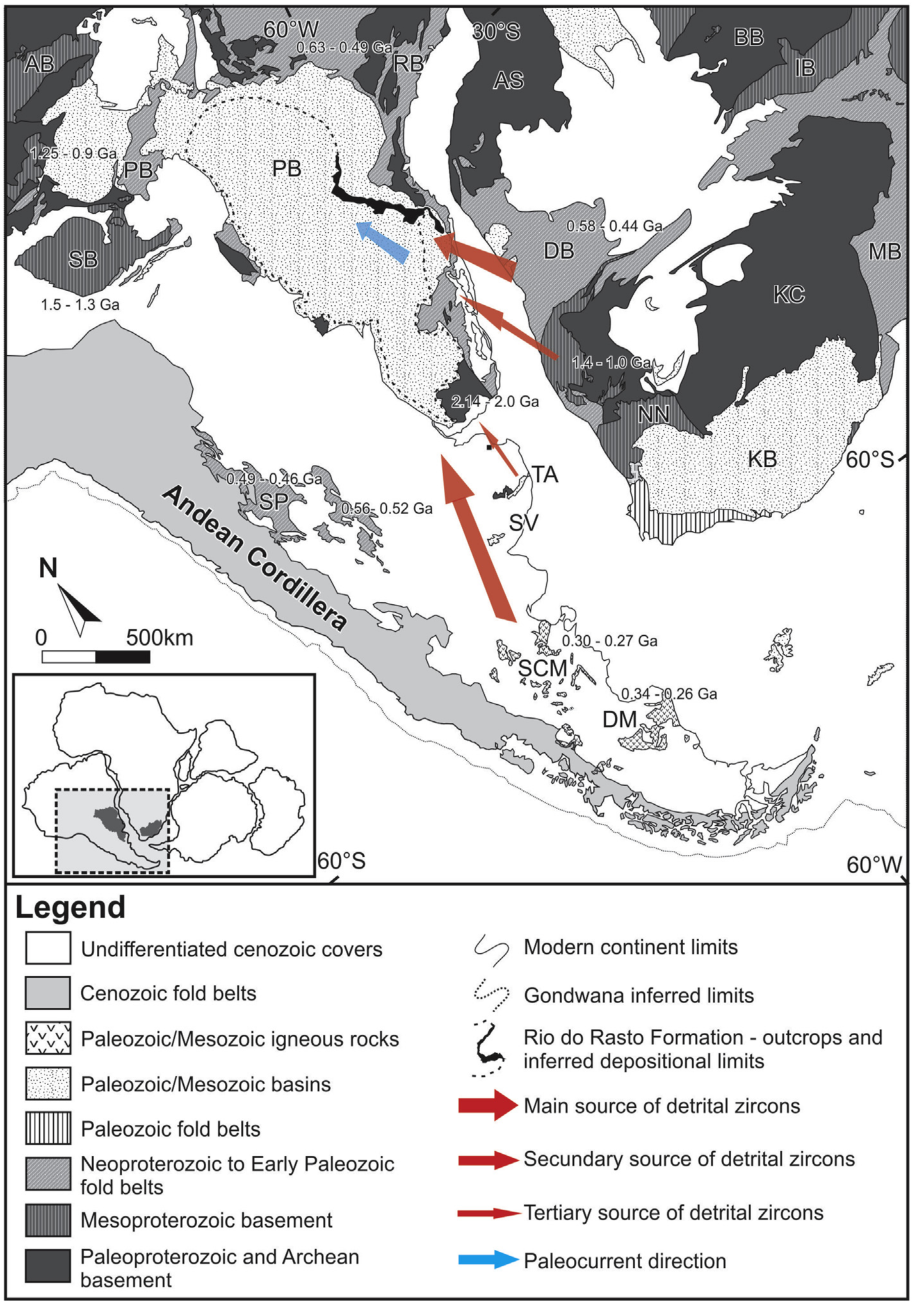

Fig. 6. Provenance of the Rio do Rasto Formation based on paleocurrents, Hf isotopes and detrital zircon ages. With data from Hawkesworth et al. (1986), Unrug (IGCP Project 288) (1996a), Unrug (1996b), DeWitt et al. (1988), Englington (2006), López-Gamundí (2006), Ramos (2008), Warren et al. (2008), Teixeira et al. (2010), Basei et al. (2010), Ramos et al. (2013). PBA – Paraguay-Araguaia Belt; SB – Sunsás Belt; AB – Aguapeí Belt; RB – Ribeira Belt; DB – Damara Belt; NN – Namaqua-Natal Belt; MB – Moçambique Belt; IB – Irumide Belt; BB – Bangweulu Belt; AS – Angolan Shield; KC – Kaapvaal Craton; PB – Paraná Basin; KB – Karoo Basin; SP – Sirreas Pampeanas; SCM – Somuncurá massif; SV – Sierra de la Ventania; DM – Deseado Massif.

sedimentary recycling of the Ventania Fold Belt and siliciclastic rocks of the Tandilia System and Durazno Group were responsible for supplying zircons to the Paraná Basin at Late Permian times. Another possible Ordovician source area are the granitoids from the basement of Patagonia, with crystallization ages of 475 ± 6 Ma and 476 ± 4 Ma (Pankhurst et al., 2006), that can be supplied terrigenous material into the sediment-routing system flowing towards the Paraná Basin. The distance of approximately 1500 km between this region and the Paraná Basin also implies long distance of sedimentary transport (Fig. 6).

The presence of Ordovician, Silurian, Devonian, Carboniferous and Permian-aged detrital zircon grains found in the Late Permian of the Paraná Basin must be carefully interpreted in terms of sedimentary dispersal patterns and its paleogeographic significance for southwestern Gondwana. The morphologies of the Ordovician to Devonian zircons suggest that these grains can be associated with an older sedimentary cycle (see zircon grain morphologies in the Supplementary material), probably product of a Late Paleozoic reworking of the Upper Cambrian-Devonian metasedimentary succession of the Ventania Fold Belt in Argentina and Devonian sedimentary rocks of the Durazno Group in Uruguay. Both units have detrital zircon grains with Ordovician and

Devonian ages. Such argument is strongly corroborated by the absence of paleocurrents indicative of a fluvial sediment-routing system flowing from the west to the Paraná Basin. The old passive margin of Gondwana (Ramos, 2008), preserved in the Ventania Fold Belt, received great volume of sediments derived from Famatina, Cuyania and Pampean terranes during its depositional interval. After the Patagonian collision against the southwestern margin of Gondwana (Ramos et al., 2013), the entire sedimentary succession was deformed and metamorphosed. Tectonic erosion (thrusts) was responsible to remove sediments and re-insert them to the sedimentary cycle. The Permian-Carboniferous ages observed as detrital zircons are in concordance with their derivation from the northern Late Paleozoic magmatic arc proposed by Ramos (2008) in northern Patagonia along the Somún Cura Massif. These grains were most probably carried to the Paraná Basin by antecedent sediment-routing systems flowing northwards.

5.2. Proterozoic sources: South American and African mobile belts and old cratonic terranes

The exhumation of Neoproterozoic-Early Paleozoic igneous and metamorphic rocks of the Damara (southern Africa), Ribeira and Dom Feliciano (central-south Brazil) and Lavalleja (Uruguay) belts may have contributed substantially to the sediment supply of the Rio do Rasto Formation, representing relatively close local sources of detrital zircons with ages ranging between 520 and 650 Ma. Nonetheless, if we consider the reworking of older sedimentary/metasedimentary successions bearing Pampean (520–580 Ma) zircons derived from Sierras Pampeanas, as the Claromecó and Chaco-Paraná basins and the Ventania Fold Belt, it is necessary to consider the possibility that recycling played a key role from the source regions to final sink. The regular sedimentary transport from southern to northern areas recorded in fluvio-deltaic paleocurrents of the Rio do Rasto Formation reinforce that Sierras Pampeanas was not a primarily source area during Permian times of the Paraná Basin.

The Grenville-age zircons around 1.0–1.2 Ga found in the Rio do Rasto Formation (Fig. 5) suggest different potential source areas, both in southern Africa and South America. The lack of paleocurrent data indicative of fluvial and/or deltaic sediment-routing systems flowing from north to southern areas of the Paraná Basin, lead us to discard some possible northward Grenville-age source areas such like as: (i) the <1.21 Ga mafic-ultramafic rocks of the Nova Brasilândia Belt (Teixeira et al., 2010) in Mato Grosso and Rondonia states (Brazil), (ii) the 1110–1112 Ma Rincón de Tigre-Huanchaca Large Igneous Province of the eastern Bolivian SW Amazonian Craton (Teixeira et al., 2015), and (iii) the 1.20–0.95 Ga Sunsás-Aguapeí Province of eastern Bolivia (Teixeira et al., 2010). They are somewhat younger than those derived from the Namaqua-Natal Belt of western Kalahari craton, where juvenile crust formation occurred during two principal periods at ca. 1.4 and 2.2 Ga (Eglington, 2006). For the Ventana Group of the Ventania Fold Belt, Ramos et al. (2013) reported the appearance of Grenville-age zircons in the pattern of provenance and suggested that the Mesoproterozoic basement of Cuyania and/or Pampia was exhumed and supplying zircons to the area during the Silurian-Devonian. For the Rio do Rasto Formation, paleocurrent data obtained by Schemiko et al. (2014) for different regions of the Santa Catarina state reveals fluvial paleodrainages flowing towards east, with divergence to northeast and southeast. However, most of the data presented by the aforementioned authors were acquired along the distal portions of the Rio do Rasto fluvio-deltaic system, situation in which where expected a strong variation in the sedimentary dispersal patterns. Thus, the most potential source areas from such zircon population are the Silurian-Devonian sedimentary recycled sequences of the Ventania Fold Belt, which bears Grenville-age zircons derived from the Western Sierras Pampeanas in NW Argentina, where ages from 1.0 to 1.2 Ga are common (Escayola et al., 2007).

The Mesoproterozoic zircons grains with ages around 1.2–1.4 Ga, indicates possible transport of sediment from the Gordonia and Natal sub-provinces, where juvenile mafic to intermediate igneous rocks with ages from 1300 to 1200 Ma are common (Eglinton et al., 2006). The Rio do Rasto Formation also show uncommon Paleoproterozoic zircons probably coming from the Tijucas Terrane in Uruguay and southernmost Brazil and the Tandilia Belt (2.0–2.2 Ga) in central eastern Argentina (Rapela et al., 2007).

Finally, our data support a scenario of multiple sedimentary origins for the Upper Permian succession of the Paraná Basin, indicating that the sources correspond to Paleozoic terranes docked at the southern Gondwana margin, recycled old sedimentary/metasedimentary successions and Proterozoic basement with adjacent fold belts related to the Brasiliano/Pan-African Orogeny. The geochronologic and paleocurrent information confirm the importance of the African and South American sources and pointing to an existence of transcontinental sediment-routing systems responsible for the detritus transport over long distances. In this way, the alluvial/deltaic system of the Rio do Rasto Formation can represent the end of the sediment saga through the ancient southwestern Gondwana lands.

6. Regional implications and final remarks

The new U-Pb ages and Hf isotopic compositions reveal that the detrital zircons of the Rio do Rasto Formation have similar frequency peaks those obtained by Ramos et al. (2013) for several units in the Paleozoic Ventania Fold Belt and Claromecó Basin of central-eastern Argentina, the Silurian-Devonian successions of the southern Paraná Basin in central-northern Uruguay (Uriz et al., 2016) and Argentinean North Patagonian Massif (Pankhurst et al., 2006; Uriz et al., 2011). These data associated with large number of alluvial paleocurrent measures indicate a consistent sediment-routing system from the south to north, with source areas located to the south and southeast of the Paraná Basin depositional site. All samples evaluated contain zircons grains with equivalent crystallization ages of Permian-Carboniferous igneous rocks from the North Patagonian Massif, indicating rapid exhumation and transport of the immature detritus from the source to the intracratonic basin. It suggests that the existence of an antecedent drainage network active prior to the uplift of the Gondwanides Orogen and the Ventania Fold Belt. This antecedent alluvial system probably run through the rising peripheral bulge located to the north of the orogen (Zerfass et al., 2003) and was the responsible for transport the sediment into the intraplate setting. This implies that both, Permian granites and Silurian-Devonian deposits of the North Patagonian Massif, Paleozoic quartzites and immature sandstones of the Ventania Fold Belt-Claromecó Basin and Silurian-Devonian sandstones of the southern Paraná Basin, were the original long-distance source areas for the Rio do Rasto Formation. Considering the presence of Ordovician to Carboniferous age peaks in the Rio do Rasto Formation and the paleocurrent data, we propose a non-direct provenance from the Sierras Pampeanas in Argentina. As previously observed, the majority of the Proterozoic zircons found in the Rio do Rasto succession coming from the actual West Africa, as Damara (Neoproterozoic-lower Cambrian) and Namaqua-Natal fold belts (Mesoproterozoic) and the Neoproterozoic Ribeira, Dom Feliciano and Lavalleja belts in South America. Based on the evaluation of eolian paleocurrent indicators from the top of the Morro Pelado Member, is also probable that some zircon grains were transported westwards by winds coming from the African terrain.

Paleoproterozoic zircons possibly came from granitic basement units of the Tandilla System in central-eastern Argentina.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsames.2016.06.007.

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