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Detrital zircon ages of Neoproterozoic sedimentary successions in Uruguay and Argentina: Insights into the geological evolution of the Río de la Plata Craton

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ABSTRACT

Although the Río de la Plata craton is exposed over a relatively large area in Uruguay, eastern Argentina, and southernmost Brazil, its geological evolution is poorly known because of great geological complexity and paucity of data. We report here U–Pb ages of detrital zircons from samples of five Neoproterozoic sandstone units deposited on the Río de la Plata Craton (RPC) in Uruguay and Argentina. The zircon ages provide definitive evidence of a great range of ages of rocks composing the craton—ages that would not have been known without the geochronology of detrital zircons. In turn, these new ages allow for a much fuller understanding of the nature and history of the craton.

Quartz arenites of the Piedras de Afilar Formation show typical Transamazonian ages with peaks at 2.00–2.07, 1.87 and 1.78 Ga. However, the most important zircon population in the sample analyzed is Mesoproterozoic with maxima at 1.49, 1.35, 1.24 and 1.0 Ga. Archean zircons are subordinate. On the other hand, zircons recovered from two sandstone levels in the Arroyo del Soldado Group (Yerbal and Cerros San Francisco formations) are mostly Archean in age with maxima at 3.2 and 2.72–2.78 Ga. Palaeoproterozoic zircons are also prominent in this unit with peaks at 2.45 and 2.19, of which the latter is a typical Transamazonian age. Two samples from the Sierras Bayas Group in Tandilia (Argentina) show different age spectra. Sandstones of the Villa Mónica Formation have a unimodal zircon population of Transamazonian age with a peak at 2.15 Ga. Sandstones of the Cerro Largo Formation are characterized by a dominant Transamazonian zircon population with peaks at 2.15, 2.0 and 1.78, but also display important Archean-earliest Palaeoproterozoic (3.33, 2.99, 2.7, 2.46 Ga) and Mesoproterozoic peaks (1.55, 1.23 and 1.05 Ga).

The abundance of Mesoproterozoic detrital zircons is surprising, given the limited outcrop area of Mesoproterozoic units in the RPC. Thus, the Mesoproterozoic orogenic event responsible for the generation of the dextral Sarandí del Yí megashear is much more important than previously assumed. A proto-Andean, Mesoproterozoic belt is suggested as the source of the Mesoproterozoic detritus. Archean rocks of the RPC crop out only in the Nico Pérez Terrane in Uruguay. The presence of Archean zircons in sandstones of the Sierras Bayas Group in Argentina suggests that the Nico Pérez Terrane was much closer to Tandilia than it is today. This is in accordance with the proposed sinistral reactivation of the Sarandí del Yí Shear Zone in the Cambrian, which resulted from tangential collision of the Cuchilla Dionisio-Pelotas Terrane. Finally, the conspicuous absence of Neoproterozoic zircons confirm other lines of evidence suggesting that the Neoproterozoic strata were deposited on a stable continental margin opening to the east and south. The Neoproterozoic basins had obviously no contribution whatsoever from Brasiliano-Pan African belts, supporting the idea of Cambrian terrane accretion as the mechanism responsible for the present configuration of the Río de la Plata Craton and the final amalgamation of Gondwana.

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1. Introduction

The Río de la Plata Craton is a medium-sized continental block occurring in Uruguay, eastern Argentina and southernmost Brazil (Fig. 1), which interacted with a number of other palaeocontinents during the amalgamation of southwestern Gondwana in the Neoproterozoic-early Palaeozoic. Notwithstanding its importance for understanding the Brasiliano-Pan African orogeny, it has remained rather poorly known because of its complexity and protracted evolution.

As a result of the first radiometric dating of the Precambrian basement of Uruguay (Hart, 1966) the existence of two orogenic cycles was recognized: (1) a western domain characterized by ages of ~2000 Ma and (2) an eastern domain which yielded ages between 700 and 500 Ma (Bossi et al., 1967). Additional Rb–Sr ages (Umpierre and Halpern, 1971) and geological mapping (Bossi et al., 1975) supported this model, and the data were interpreted according to the geosynclinal theory as representing an old craton (Río de la Plata Craton, RPC), essentially of Transamazonian age (2.2–1.8 Ga), and a mobile belt assigned to the Brasiliano Cycle in Uruguay (Almeida et al., 1973).

Applying plate tectonics to explain the structure of the Precambrian basement of Uruguay and southern Brazil, Fragoso Cesar (1980) proposed westward subduction of oceanic crust beneath the Río de la Plata Craton to explain the structure of the Dom Feliciano Belt. Using different data, Ramos (1988) demonstrated that the South American continent underwent a series of collisions in many different directions durng the late Neoproterozoic to early Cambrian. In the case of the Brasiliano Cycle in Uruguay, Ramos (1988) postulated collision with eastward subduction of oceanic crust.

With regard to the geology of Uruguay, the two opposing interpretations reflected insufficient geological information, and stimulated further geologic studies of key areas, especially after the recognition of large transcurrent faults (Bossi and Navarro, 1991). While mapping in detail the Piedra Alta mafic dike swarm, dated at 1790 ± 5 Ma (U–Pb on baddeleyite: Halls et al., 2001), Bossi and Campal (1992) recognized and described a dextral megashear zone with mylonites up to 8 km wide. The dike swarm is clearly affected by this shear zone (Sarandí del Yí shear zone, SYSZ, Fig. 1), and the curvature of the eastern part of the dike swarm is consistent with dextral shear. Furthermore, no dikes occur east of the SYSZ. The age of the Sarandí del Yí shear zone is probably late Mesoproterozoic as shown by post-emplacement thermal overprinting of the Piedra Alta mafic dike swarm (Bossi et al., 1993b) between 1370 and 1170 Ma, reflected in initial release portions of ^{40}Ar–^{39}Ar spectra and Rb–Sr mineral isochrons (Teixeira et al., 1999). Bossi and Navarro (2001) report an ^{40}Ar–^{39}Ar age of 1240 ± 5 Ma for the same event. The SYSZ is a continental-scale megashear (Unrug, 1996) that separates two very different geological terranes: (1) the Nico Pérez Terrane defined by Bossi and Campal (1992) and located east of the SYSZ and (2) the Piedra Alta Terrane defined by Bossi et al. (1993a) and consisting of the mainly Palaeoproterozoic (2000 ± 100 Ma) block located west of the SYSZ (Figs. 1 and 2). Finally, Gaucher et al. (1998) concluded, on the basis of paleontological and geological data, that the Sierra Ballena Shear Zone (SBSZ) represents the eastern boundary of the Nico Pérez Terrane (Figs. 1 and 2).

The application of the terrane concept to the Precambrian basement of Uruguay has led to separate studies elucidating the independent evolution of each tectonostratigraphic unit (Coney et al., 1980; Howell, 1989), thus providing a means for deciphering the long and complicated geological history of the larger region. The Piedra Alta and Nico Pérez Terranes have been accepted and used with minor modifications by most researchers dealing with the Precambrian geology of Uruguay and southern Brazil. Both tectonostratigraphic units compose the RPC, and behaved as a unit with respect to the Cambrian orogenic event that affected the region (Bossi and Gaucher, 2004). More recently, the easternmost Cuchilla Dionisio Terrane (=Punta del Este Terrane), and its northward extension into southern Brazil (Cuchilla Dionisio-Pelotas Terrane), has been interpreted as an allochthonous block of African affinity (Bossi and Gaucher, 2004; Basei et al., 2005) juxtaposed to the RPC along the Sierra Ballena megashear (Figs. 1 and 2). Furthermore, Bossi et al. (2005) and Ribot et al. (2005) recognized and described a significant mylonite band (Colonia shear zone) that they interprerted as a terrane boundary between the northern Piedra Alta Terrane and the southern Tandilia Terrane (Fig. 1), which also crops out in Buenos Aires Province, Argentina (Fig. 3). On the basis of cross-cutting relationships between mylonites and well-dated dike swarms, Bossi et al. (2005) suggested that the age of the Colonia shear zone is between 1790 ± 5 Ma and 1588 ± 11 Ma (Halls et al., 2001; Iacumin et al., 2001). The basement ages of both the Piedra Alta and Tandilia Terranes in Uruguay and Argentina are dominantly Transamazonian, being between 2.2 and 1.8 Ga (Bossi et al., 1998; Cingolani and Dalla Salda, 2000; Peel and Preciozzi, 2006).

Neoproterozoic sedimentary successions crop out extensively in the Nico Pérez Terrane and in the Tandilia Terrane in Uruguay and in Argentina (Fig. 1). These successions are, respectively, the Arroyo del Soldado Group (Gaucher et al., 1996; Gaucher, 2000), the Piedras de Afilar Formation (Bossi, 1966, 1983; Spoturno et al., 2005), and the Sierras Bayas Group and Cerro Negro Formation (Poiré, 1987; Gómez Peral et al., 2007). An Atlantic-type continental shelf was interpreted as the geotectonic setting for their deposition (Poiré, 1987; Gaucher, 2000; Gaucher et al., 2003, 2005), on the bases of sandstone petrography, lateral persistence of lithofacies over hundreds of kilometers, absence of synsedimentary volcanism, and occurrence of thick carbonates and chemical deposits (BIF, chert).

We present here the results of U–Pb LA-ICP MS (*Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry*) dating of 460 detrital zircons from three different Neoproterozoic to Early Cambrian sedimentary covers of the RPC in Uruguay and Argentina: the Arroyo del Soldado Group, the Piedras de Afilar Formation, and the Sierras Bayas Group. Moreover, one granite pluton (Arroyo Mangacha Granite) was dated using the U–Pb SIMS (*Secondary Ions Mass*

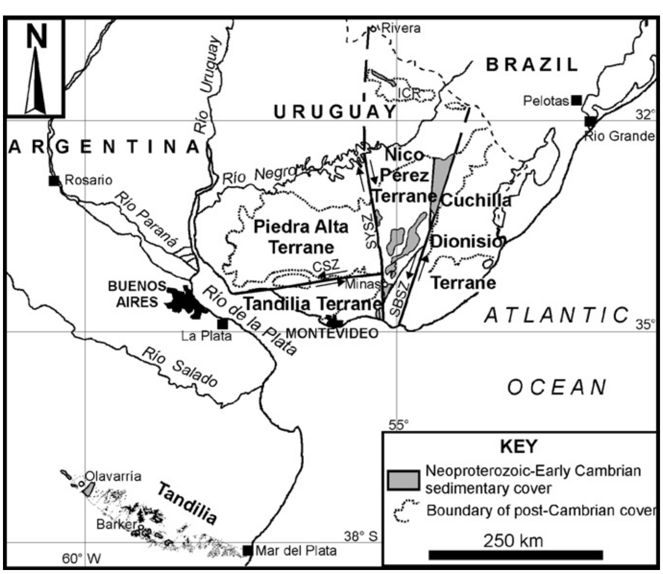

Fig. 1. Map of the eastern Río de la Plata Craton, showing outcrop areas of the Arroyo del Soldado Group, Piedras de Afilar Formation and Sierras Bayas Group (modified from Gaucher et al., 2005). ICR: Isla Cristalina de Rivera; CSZ: Colonia Shear Zone; SYSZ: Sarandí del Yí Shear Zone; SBSZ: Sierra Ballena Shear Zone.

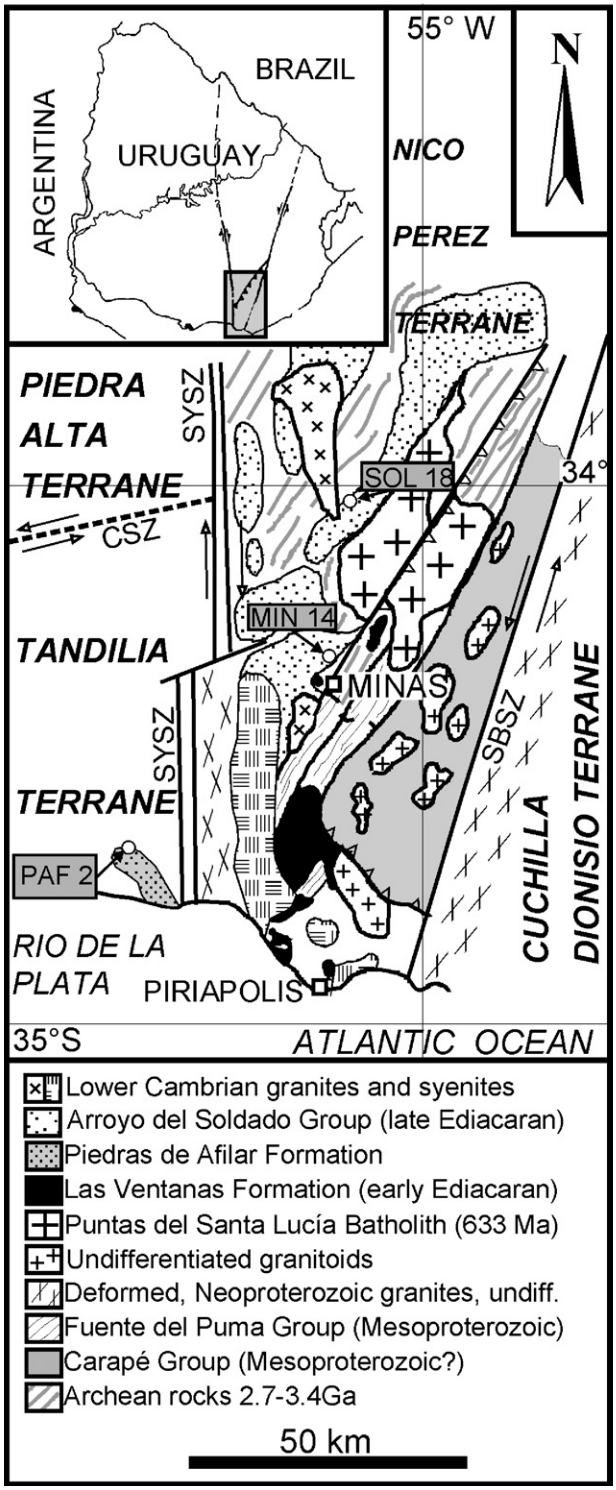

Fig. 2. Geological map of the southern Nico Pérez Terrane and neighbouring areas of the Tandilia, Piedra Alta and Cuchilla Dionisio terranes in Uruguay (modified from Gaucher et al., 2008). CSZ: Colonia Shear Zone; SYSZ: Sarandí del Yí Shear Zone; SBSZ: Sierra Ballena Shear Zone. *Note*: location of the sampled sites SOL 18 (Fig. 9), MIN 14 (Fig. 13) and PAF 2 (Fig. 5).

Spectrometry) method. These data are definitive evidence for source rocks that probably were located within the basement of the RPC and thus provide new insights into the geotectonic setting of the Neoproterozoic basins and surprising results with respect to the basement geology of the RPC.

2. Neoproterozoic-early Cambrian sedimentary covers of the RPC

2.1. Arroyo del Soldado Group

The Arroyo del Soldado Group (ASG) is a 5-km-thick platform succession unconformably overlying a mainly Archean to Neoproterozoic basement in the Nico Pérez Terrane, Uruguay (Gaucher et al., 1996, 1998; Gaucher, 2000; Fig. 2). The group (Fig. 4) is characterized by an alternation of predominantly siliciclastic (Yerbal, Barriga Negra, Cerro Espuelitas and Cerros San Francisco formations) and thick carbonate units (Polanco and Cerro Victoria formations), which extend laterally over hundreds of kilometers. These formations, in ascending order, are characterized as follows (Gaucher, 2000):

(a) The Yerbal Formation is a fining-upward, mainly siliciclastic unit more than 1500-m thick. Sandstones occur at the base; siltstones dominate up section, and BIF and chert intercalations occur at the top (Gaucher et al., 2004).
(b) The Polanco Formation is composed of ~900 m of bluish gray, pure limestones, limestone–dolostone rhythmites and, more rarely, pure dolostone.
(c) The Barriga Negra Formation is composed of 1500 m of conglomerates of differing compositions.
(d) The Cerro Espuelitas Formation is 1200-m thick and composed of intercalated dark shales and chemical sediments, such as oxide-facies BIF and chert.
(e) The ~300-m-thick Cerros San Francisco Formation is composed of quartz arenites and subarkoses.
(f) The Cerro Victoria Formation is 400-m thick and mainly stromatolitic limestones with trace fossils indicative of Cambrian age (Montaña and Sprechmann, 1993; Sprechmann et al., 2004).

Volcanic, volcaniclastic and pyroclastic rocks are completely absent. Carbonates were deposited on pericontinental, storm-dominated carbonate ramps. Siliciclastic units were deposited in a basin with a gentle palaeoslope, resulting in sandstones being texturally and mineralogically mature quartz arenites or subarkoses (Gaucher, 2000). Together, these features indicate a stable, Atlantic-type continental margin as the geotectonic setting of the Arroyo del Soldado basin (Gaucher, 2000). This platform probably was the depositional setting of the correlative Sierras Bayas Group of Argentina (Gaucher et al., 2005) and the Corumbá Group of Brazil (Gaucher et al., 2003).

2.2. Piedras de Afilar Formation

The Piedras de Afilar Formation crops out in a restricted area of the recently recognized Tandilia Terrane (Bossi et al., 2005) in southern Uruguay (Jones, 1956; Bossi et al., 1998; Spoturno et al., 2005; Fig. 2). It is more than 700-m thick and made up of a basal sandstone succession that passes upwards into shales and then carbonates at the top (Fig. 5). The sedimentary succession (Fig. 6), as described by Coronel et al. (1982), is composed of, in ascending order: 350 m of predominantly quartzitic sandstones and shale interbeds with cross-stratification, ripple marks and flute casts common in the sandstones; 350 m of laminated siltstones; and fine-grained, intensively folded limestones. Dolerite sills intrude and significantly alter the stratigraphic succession at many levels.

The basement of the Piedras de Afilar Formation comprises amphibolite-facies metasedimentary rocks of the Montevideo Formation (Pando Belt), as well as the Soca rapakivi granite

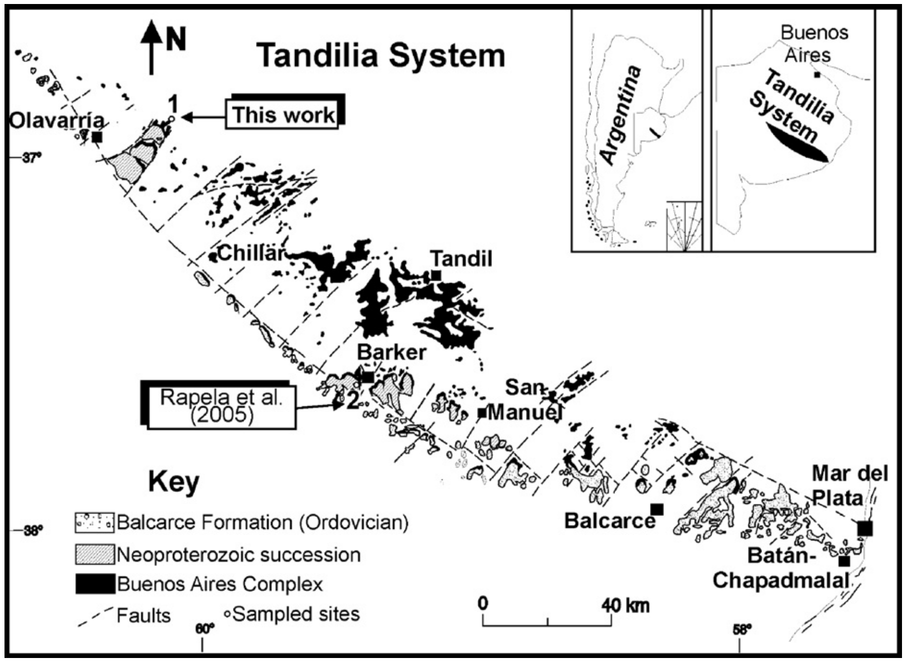

Fig. 3. Geological map of Tandilia, showing outcrops of the Neoproterozoic succession (Sierras Bayas Group/Cerro Negro Formation) and location of sampled outcrops (Villa Mónica Quarry, this work; Barker area, Rapela et al., 2005, 2007). Modified from Poiré et al. (2006).

(Oyhantçabal et al., 1998). The intrusion yielded an U–Pb SHRIMP zircon age of 2056 ± 6 Ma (Santos et al., 2003). The Piedras de Afilar Formation rests with erosional and angular unconformity on these basement units (Fig. 7A), thus representing an unmetamorphosed sedimentary cover of the Río de la Plata Craton.

2.3. Sierras Bayas Group

The Sierras Bayas Group occurs in the Tandilia orographic belt, located in central Buenos Aires Province, Argentina (Fig. 3). It comprises, in ascending order (Poiré et al., 2006; Gómez Peral et al., 2007; Figs. 4 and 8): (a) the 50-m-thick Villa Mónica Formation

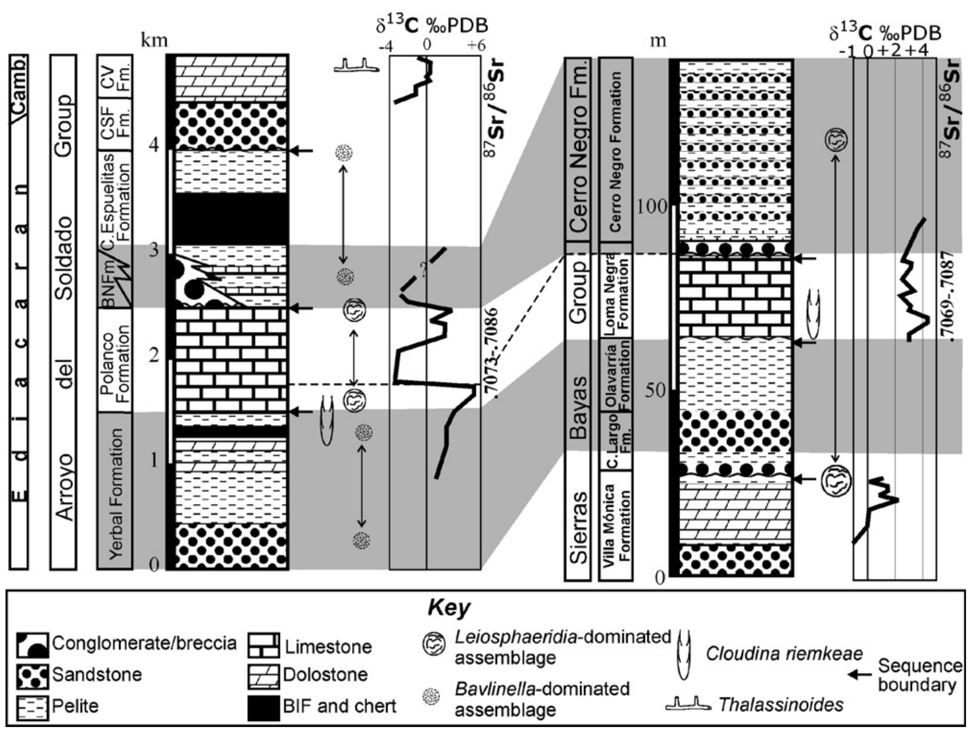

Fig. 4. Composite stratigraphic columns and correlation of the Arroyo del Soldado Group and the Sierras Bayas Group-Cerro Negro Formation (modified from Gaucher et al., 2005). Litho-, bio- and chemostratigraphic data are shown (sources: Gaucher et al., 2003, 2004, 2007 and references therein; Gómez Peral et al., 2007 and references). BNFm: Barriga Negra Formation, CSF Fm.: Cerros San Francisco Formation, CV Fm.: Cerro Victoria Formation.

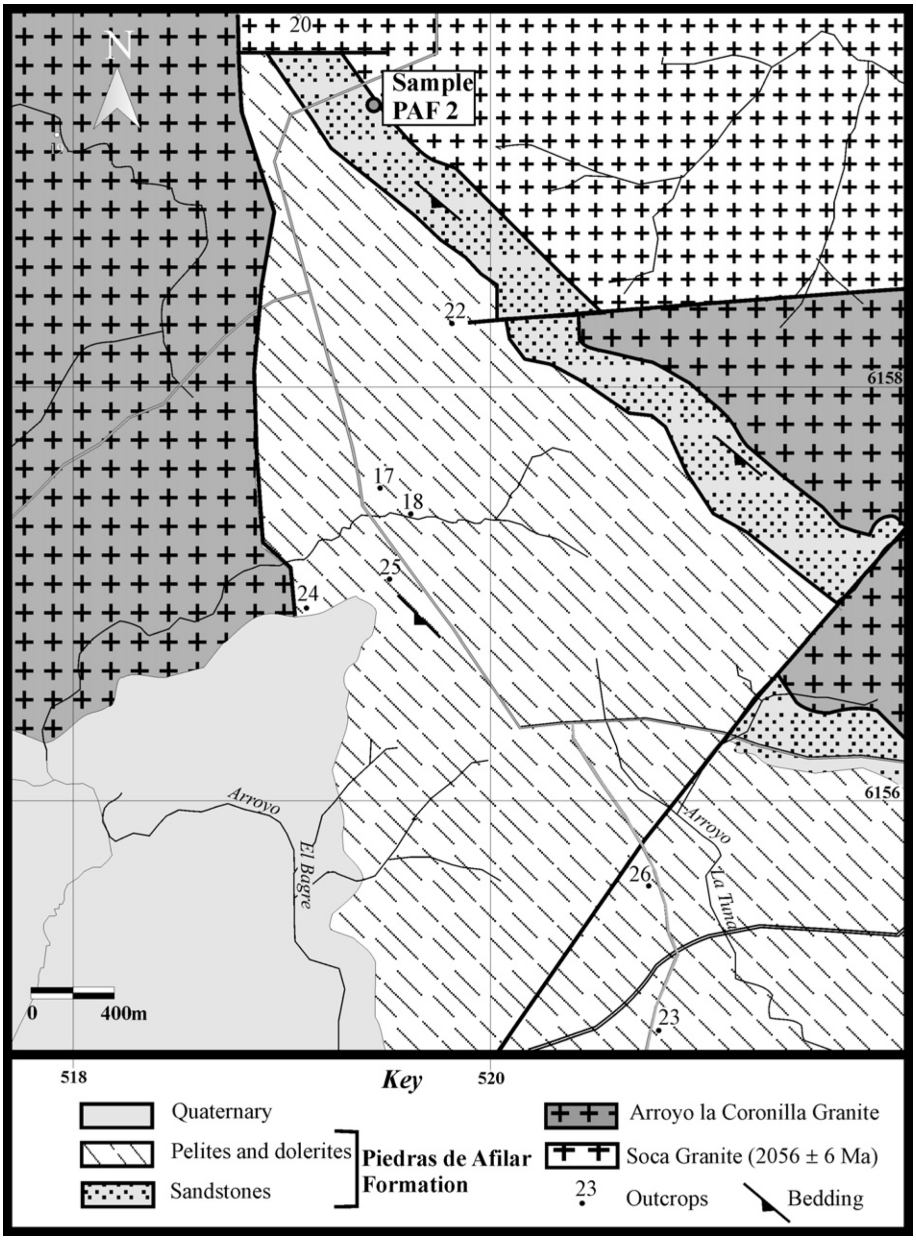

Fig. 5. Geological map of the Piedras de Afilar Formation in its type area (point PAF 2, Fig. 2). Note location of sampled quartz arenites. Age of the Soca Granite according to Santos et al. (2003). Flat coordinates given refer to the Uruguayan Yacaré datum.

composed of quartz arenites at the base (Fig. 7D) and stromatolitic dolostones at the top (Poiré, 1993); (b) the 45-m-thick Cerro Largo Formation characterized by diamictites and pelites at the base and passing upwards into quartz arenites (Fig. 7E; Poiré, 1993); (c) the Olavarría Formation of Andreis et al. (1996), which is 30 m of siltstones, shales and heterolitic siliciclastics, and which correlates with the Las Aguilas Formation in the central Tandilia region (Poiré and Spalletti, 2005); and (d) the 40-m-thick Loma Negra Formation, which is composed of red and black, micritic limestone (Borrello, 1966) and bounded at the top by a regional unconformity that is interpreted as palaeokarst (Barrio et al., 1991).

The Cerro Negro Formation (Iñíguez and Zalba, 1974) overlies with erosonial unconformity the Sierras Bayas Group (Fig. 4). A Lower Palaeozoic sandstone succession, known as the Balcarce Formation (Dalla Salda and Iñíguez, 1979), covers all the Neoproterozoic units with erosional unconformity.

The basement of all the Neoproterozoic succession is the Palaeoproterozoic Buenos Aires Complex (Marchese and Di Paola, 1975), which is composed of granitoids, migmatites, mylonites, amphibolites and basic dikes (Cingolani and Dalla Salda, 2000). Although the main tectonomagmatic event in Tandilia is of typical Transamazonian age (2.2–2.1 Ga) (Hartmann et al., 2002b), a mafic dike swarm representing an extensional event yielded an age of 1588 ± 11 Ma (Iacumin et al., 2001; Teixeira et al., 2002). No Archean units have been recognized in the Tandilia area.

3. Age constraints

3.1. Arroyo del Soldado Group

The age of the ASG is radiochronologically constrained by: (a) a maximum U–Pb SHRIMP age of 633 ± 12 Ma for the Puntas

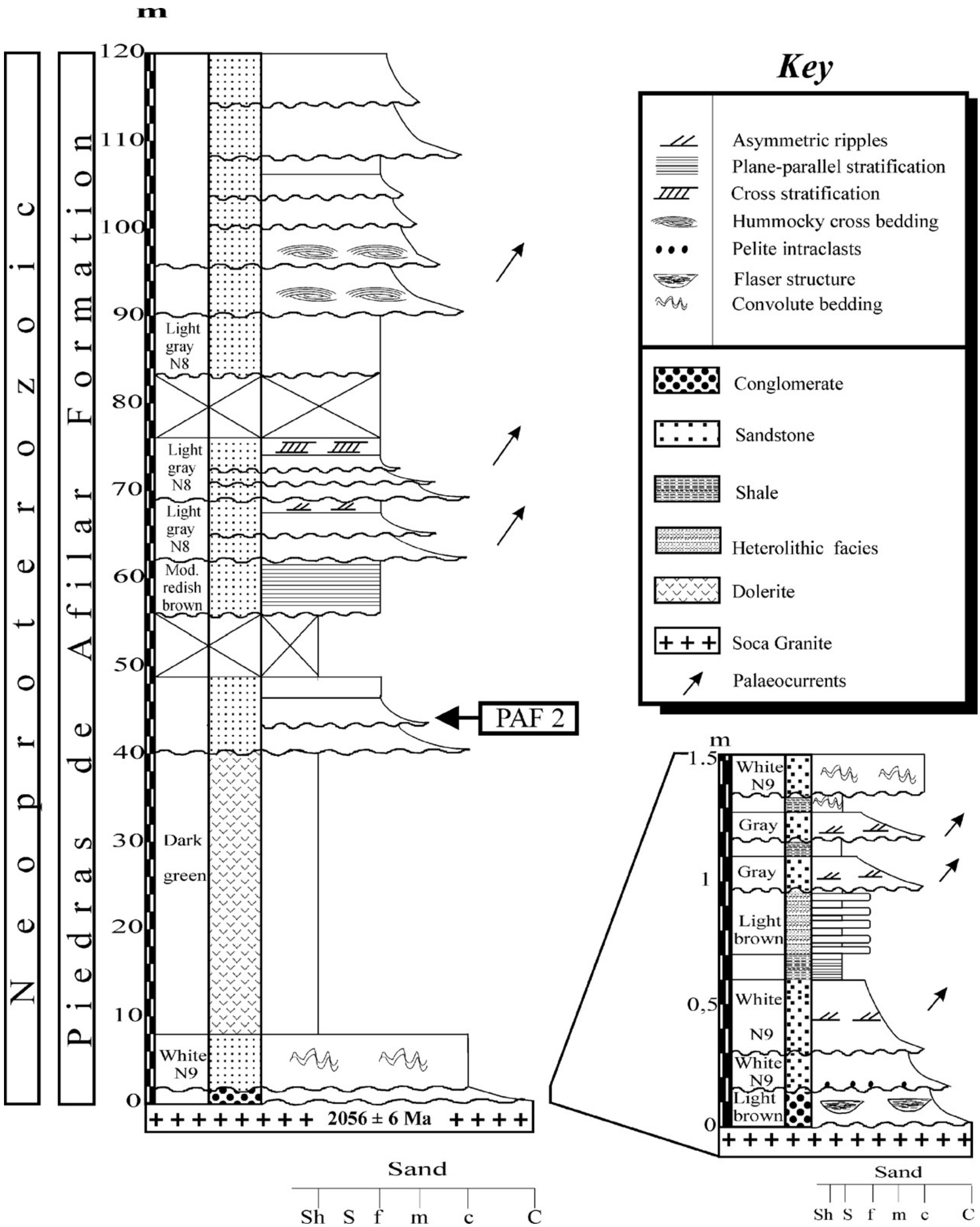

Fig. 6. Stratigraphic column of the Piedras de Afilar Formation at the sampled locality (Fig. 5), and stratigraphic location of sample PAF 2.

del Santa Lucía pluton (Hartmann et al., 2002a), which the ASG unconformably overlies; and (b) a minimum Rb–Sr isochron age of 532 ± 11 Ma for the Guazunambí Granite (Kawashita et al., 1999a), which intrudes the ASG. In addition, K–Ar ages ranging between 532 ± 16 and 492 ± 14 Ma have been reported for the recrystallization of pelites within the group (Cingolani et al., 1990; Gaucher, 2000).

Biostratigraphic data also point to an upper Ediacaran age for the lower and middle ASG, and a lowermost Cambrian age for the Cerro Victoria Formation (Fig. 4). An assemblage of skeletal fossils that includes *Cloudina riemkeae* Germs (1972), *Titanotheca coimbrae* Gaucher and Sprechmann (1999) and at least five other genera and species occurs in the uppermost Yerbal Formation (Gaucher and Sprechmann, 1999; Gaucher, 2000; Fig. 4). *Cloudina* is rec-

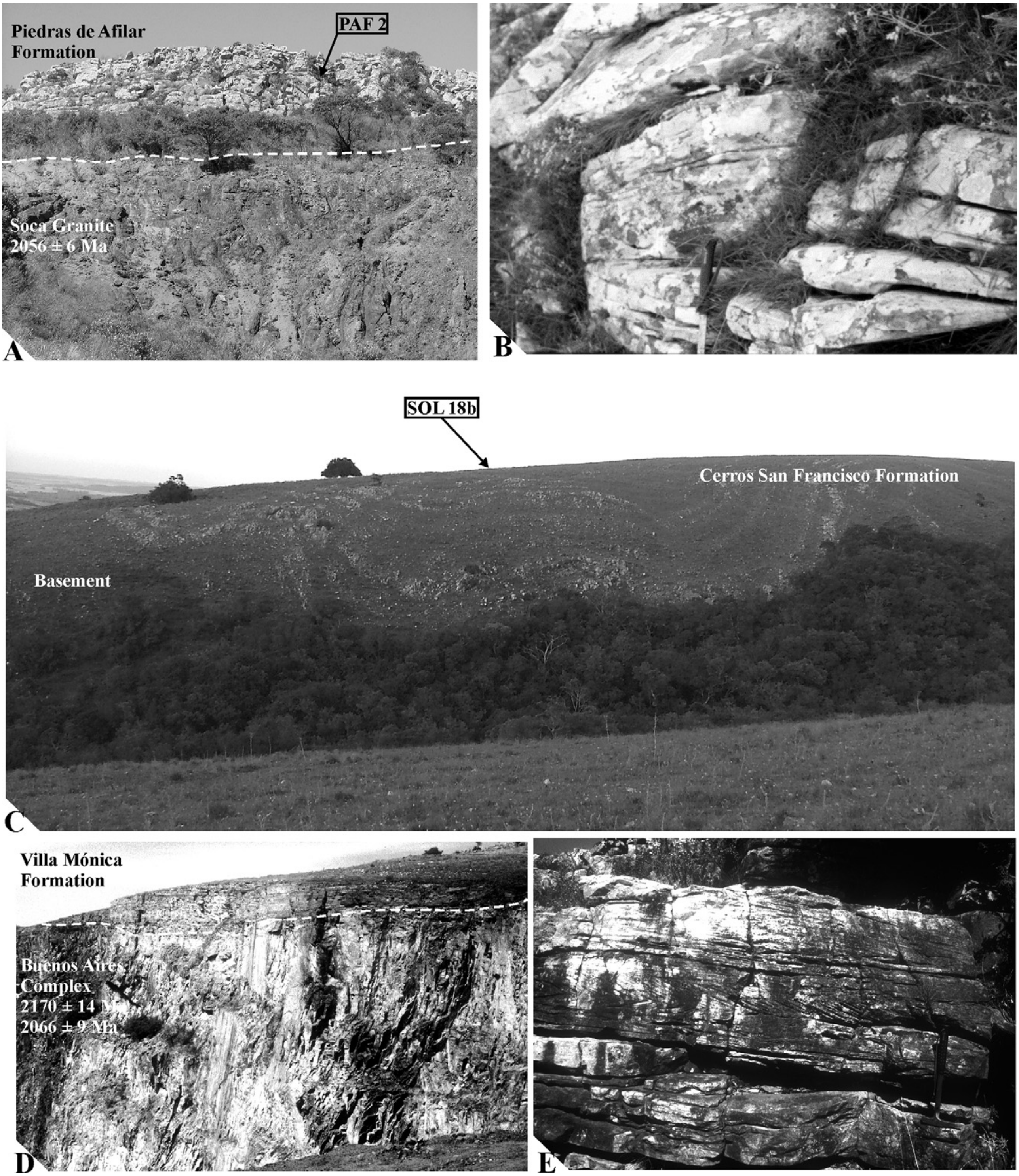

Fig. 7. Outcrop photographs of the sampled localities. (A) Erosional unconformity between the Piedras de Afilar Formation and its Palaeoproterozoic basement at sample localiity PAF 2 (shown), cliff is ~25-m high. (B) Megahummocky cross-bedding (λ = 5 m) in quartz arenites of the Cerros San Francisco Formation at Cerro de la Sepultura; length of hammer (bottom-center) is 0.4 m. (C) Cross-sectional view of section of the Cerros San Francisco Formation, taken from the west, showing location of sample SOL 18b; note synclinal structure and contact with underlying metasedimentary basement; the tree on top of the hill is 5 m high. (D) Sandstones of the Villa Mónica Formation overlying with erosional unconformity Buenos Aires Complex granitoids at Villa Mónica Quarry, the site of sample 06-SF-07; ages of basement rocks taken from Hartmann et al. (2002b); height of cliff ~50 m. (E) Quartz arenites of the Cerro Largo Formation at its stratotype (point 1, Fig. 3); note herringbone cross-stratification near the middle part and megaripples at the base; hammer is 0.4-m long.

ognized as an index fossil of the upper Ediacaran (Grant, 1990; Amthor et al., 2003), and has a global distribution in rocks of that age (Gaucher et al., 2003 and references therein). A low-diversity, high-abundance assemblage of organic-walled microfossils is preserved in the ASG as well (Gaucher et al., 1996, 1998; Gaucher, 2000). *Bavlinella faveolata*, *Soldadophycus bossii* and *S. major* are abundant in the siliciclastic units, and a slightly more diverse assemblage (*Leiosphaeridia-Lophosphaeridium* assemblage) occurs

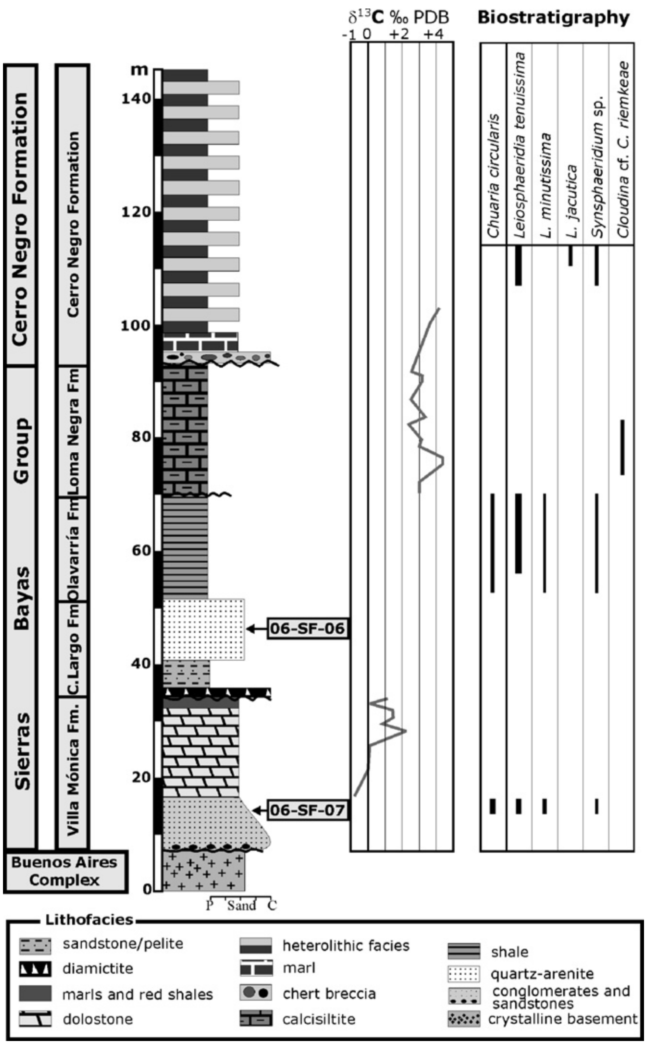

Fig. 8. Stratigraphic column of the Sierras Bayas Group and Cerro Negro Formation in the Olavarría area (Fig. 3), modified from Gómez Peral et al. (2007). Note the stratigraphic position of the sampled sandstones (06-SF-06 and 06-SF-07). Biostratigraphic data from Gaucher et al. (2005).

in the carbonates of the Polanco Formation (Gaucher, 2000; Fig. 4). These fossil distributions are consistent with an upper Ediacaran correlation for the lower and middle ASG, especially considering the absence of large sphaeromorphs and acantomorphs (Vidal and Moczydlowska-Vidal, 1997; Knoll, 2000; Grey et al., 2003).

Substantial evidence supports a Lower Cambrian correlation for the Cerro Victoria Formation (Montaña and Sprechmann, 1993). Large ichnofossils representing complex infaunal burrow systems, classified by Sprechmann et al. (2004) as *Thalassinoides* isp., are common in the formation. They represent a behavioural pattern that is unknown in the Proterozoic (Crimes, 1992), and they are associated with other ichnofossils (*Planolites*, *Gyrolithes*) that are characteristic of lowermost Cambrian patterns (Droser et al., 2002). *Thalassinoides* with almost identical preservation and size occurs in the upper La Flecha Formation of the Argentine Precordillera at Quebrada La Angostura, and the La Flecha Formation has been correlated with the Upper Cambrian (Peralta, 2000; Buggisch et al., 2003). Carbon-isotopic curves for the Cerro Victoria Formation (Gaucher et al., 2007) closely resemble $\delta^{13}C$ global curves for the Lower Cambrian (Derry et al., 1994; Montañez et al., 2000), which show low-amplitude secular variations between −3.5 and +0.64‰ PDB (Fig. 4). Finally, a granitic mylonite from a shear zone cutting the Cerros San Francisco and Cerro Victoria formations yielded a Rb–Sr age of 540 ± 25 Ma (Umpierre and Halpern, in Bossi and Campal, 1992).

The Arroyo Mangacha Granite is a small (2.2 km^2), undeformed pluton, elongated north to south, and covered by strata of the Arroyo del Soldado Group (Figs. 9 and 10). It is typically porphyritic with zoned orthoclase phenocrysts ~1 cm in maximum dimension (Fig. 12A and B). The original cumular texture is well preserved, and enclaves are common. The granite is made up of 40% quartz, 38% orthoclase, 17% oligoclase and 5% biotite; microcline, sphene and iron oxides (magnetite?) are accessory minerals. We report here an U–Pb SIMS zircon age for the Arroyo Mangacha Granite (sample SOL 3: Fig. 9), yielding a concordant age of 583 ± 7 Ma (Fig. 11; Table 1). This represents the best maximum age constraint available for the Arroyo del Soldado Group because sandstones of the Cerros San Francisco Formation are in sedimentological contact with this pluton along an erosional unconformity (Figs. 9 and 10). A gritty, poorly sorted sandstone at the base of the Cerros San Francisco

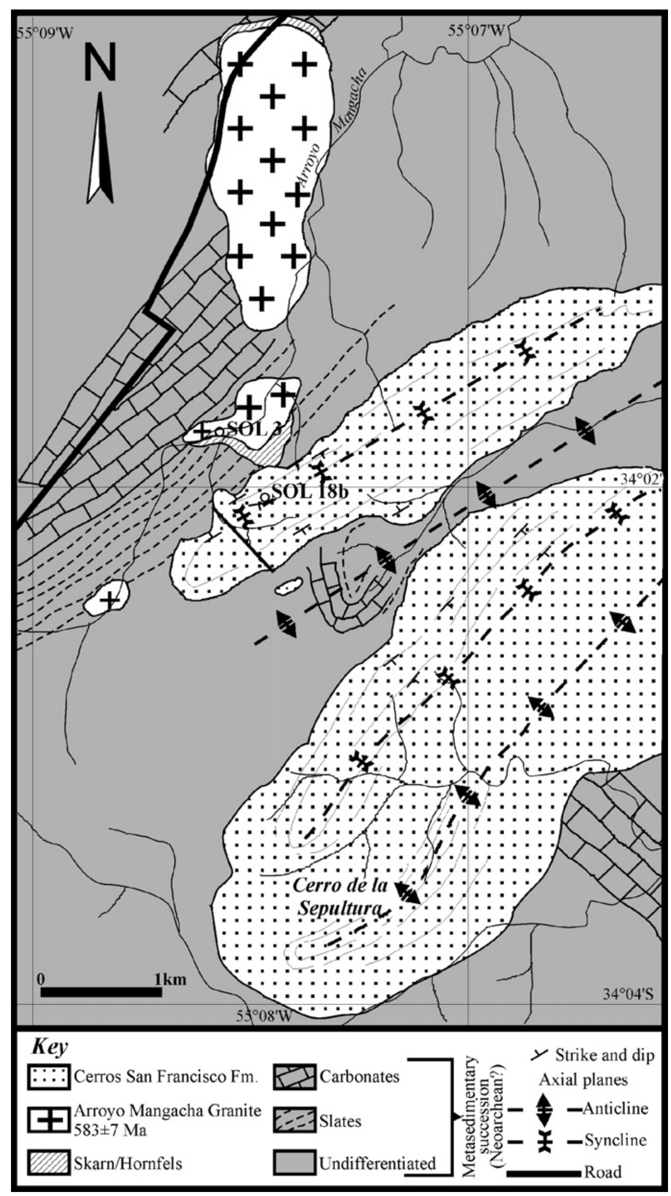

Fig. 9. Geological map of the Arroyo del Soldado Group at Cerro de la Sepultura. Note location of sampled quartz arenites of the Cerros San Francisco Formation (SOL 18b) and the dated Arroyo Mangacha Granite (SOL 3).

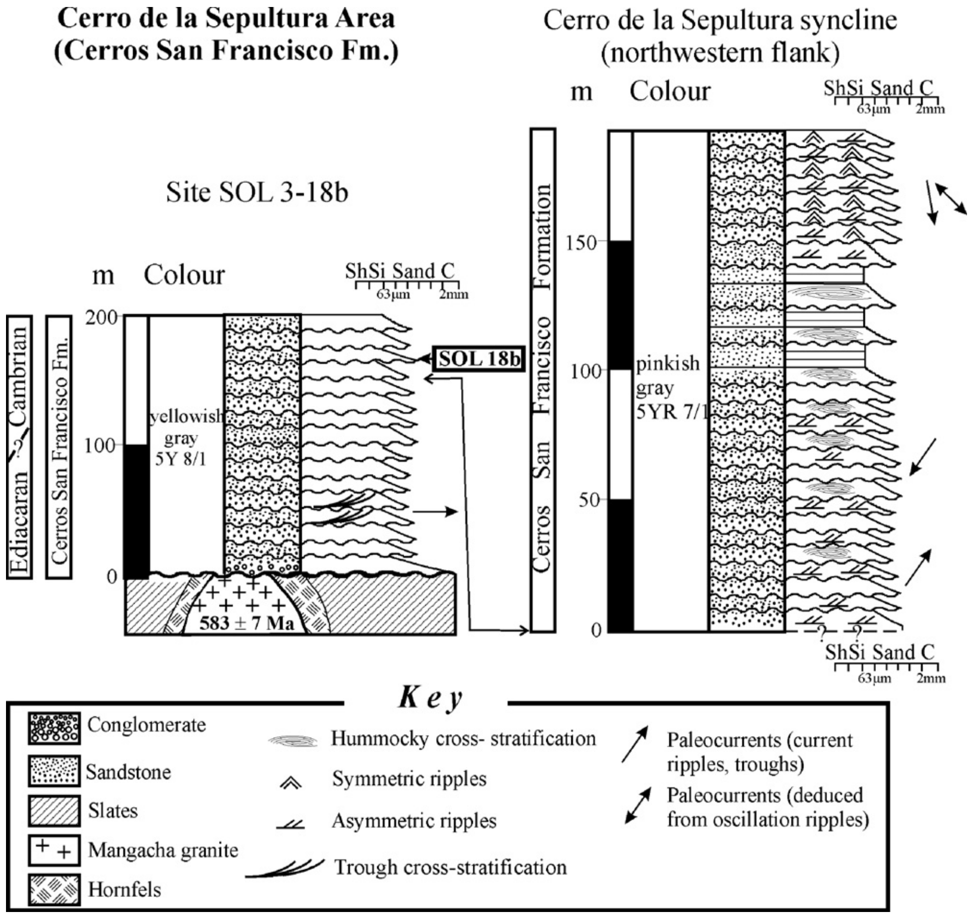

Fig. 10. Stratigraphic column of the Cerros San Francisco Formation at the sampled site and at Cerro de la Sepultura (Fig. 9), and stratigraphic location of sample SOL 18b. Modified from Gaucher (2000).

Formation contains abundant, subangular to subrounded feldspar clasts (mainly orthoclase and subordinate microcline) and granite lithoclasts directly derived from the Arroyo Mangacha Granite (Fig. 12C and D).

3.2. Piedras de Afilar Formation

Little information is available to determine the age of the Piedras de Afilar Formation. Shales in the formation give K–Ar ages of 382 ± 11 Ma (Cingolani et al., 1990). These are difficult to reconcile with the geology, and may reflect thermal overprinting by dolerites that intrude the succession. Micropalaeontological sampling of black, pyritic siltstones has been unsuccessful (Gaucher, 2000).

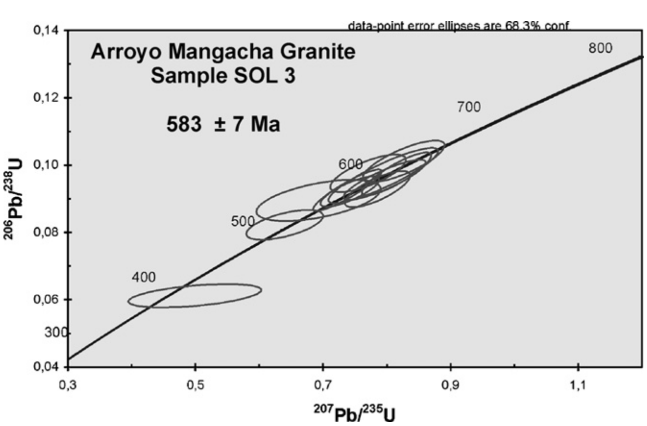

Fig. 11. U–Pb concordia plot of zircon data of the Arroyo Mangacha Granite (Fig. 9).

Pamoukaghlian et al. (2006) reported δ^{13}C values of +5.05 and +5.80‰ PDB for carbonates in the upper Piedras de Afilar Formation. δ^{13}C values between +5 and +6 ‰ PDB are more often encountered in Neoproterozoic carbonate successions, especially in the Cryogenian and Ediacaran (Halverson et al., 2005). Mesoproterozoic carbonates show values mostly between 0 and +3.5‰ V-PDB (Kah et al., 1999). Cambrian carbonates, on the other hand, are characterized by δ^{13}C values between −4 and +2.5‰ V-PDB (Montañez et al., 2000). Therefore, the data reported by Pamoukaghlian et al. (2006) suggests a Cryogenian or Ediacaran age for the Piedras de Afilar Formation. A younger age is unlikely because the unit is intruded by the La Tuna Granite (Spoturno et al., 2005), the age of which cannot be younger than Early Cambrian.

Pecoits et al. (2007) suggest correlation of the Piedras de Afilar and Cerros San Francisco formations on lithostratigraphic grounds alone. Three independent lines of evidence militate against this correlation: (1) δ^{13}C values of carbonates of the upper Piedras de Afilar Formation (Pamoukaghlian et al., 2006) are much higher than δ^{13}C of carbonates overlying the Cerros San Francisco Formation (Cerro Victoria Formation), which are always lower than +1‰ V-PDB (Gaucher et al., 2007); (2) as will be shown below, source areas of both units were very different; and (3) the poorly preserved acritarchs reported by Pecoits et al. (2007) for the Piedras de Afilar Formation actually favor correlation with the Yerbal Formation

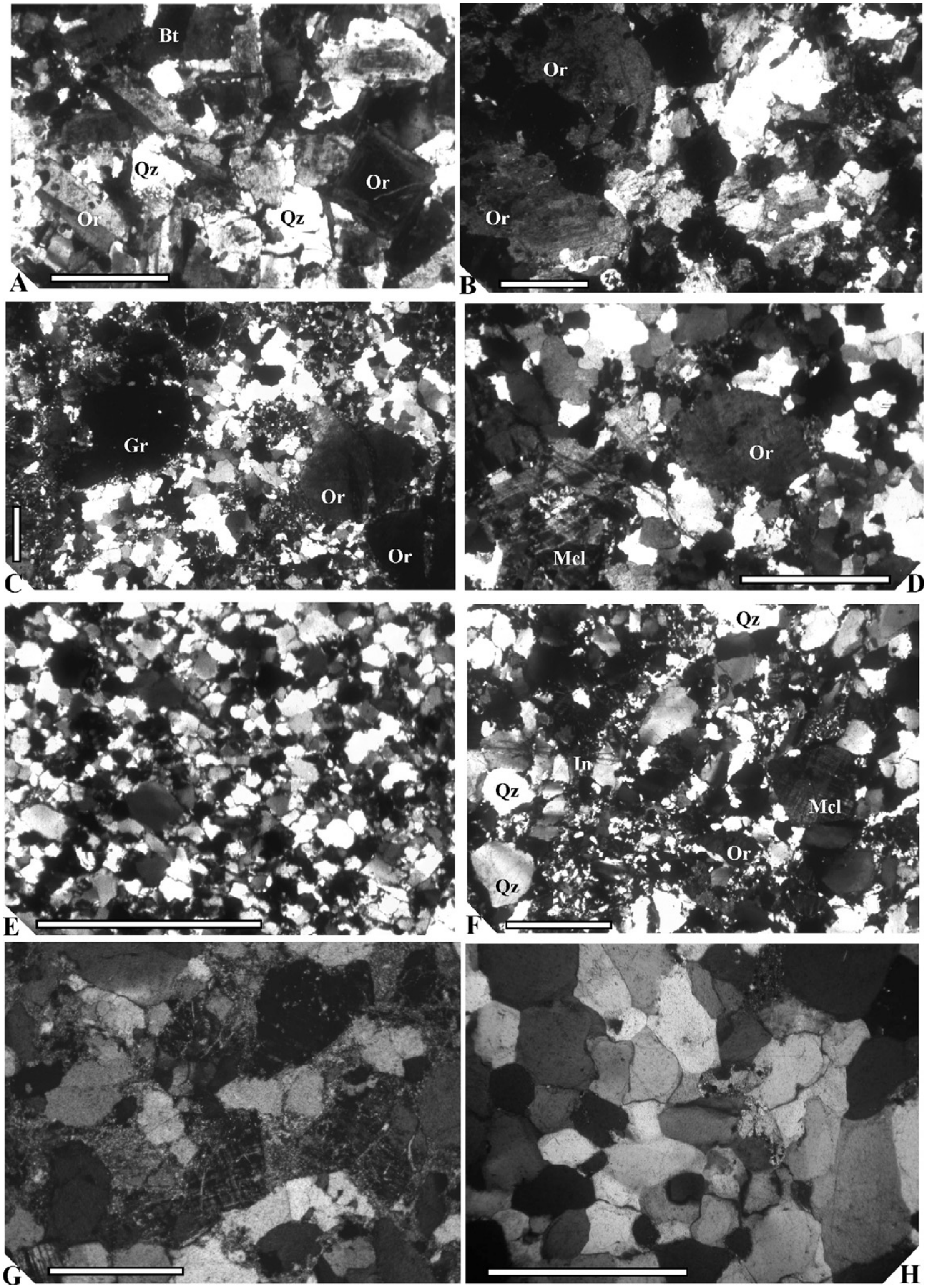

Fig. 12. Microphotographs of thin sections of sampled sandstones and granite. (A) Arroyo Mangacha Granite. Note subhedral orthoclase phenocrysts (Or), interstitial quartz (Qz) and accesory biotite (Bt). (B) The same thin section as (A) showing a large, zoned, orthoclase phenocryst (Or). (C) Very coarse, gritty sandstone of the basal Cerros San Francisco Formation between sites SOL 3 and 18b. *Note*: subrounded granite lithoclast (Gr), orthoclase (Or) and sutured quartz clasts. (D) The same thin section as (C) showing subrounded to subangular orthoclase (Or), microcline (Mcl) and sutured quartz clasts (rest). (E) Quartz arenite of the Cerros San Francisco Formation at locality SOL 18b. (F) Coarse-grained subarkose of the Yerbal Formation at locality MIN 14. Note microcline (Mcl), orthoclase (Or) and quartz (Qz) clasts, as well as a single siltstone intraclast (In). (G) Coarse sandstone of the Villa Mónica Formation, showing microcline clasts and some illite matrix. (H) Quartz-arenite of the Cerro Largo Formation at the sampled locality. All scale bars represent 1 mm.

and not with the Cerros San Francisco Formation, as pointed out by Pamoukaghlian et al. (2006).

3.3. Sierras Bayas Group

The occurrence of *Cloudina* in the Loma Negra Formation, indicates a late Ediacaran age (Gaucher et al., 2005). A low-diversity acritarch assemblage dominated by *Leiosphaeridia*, also consistent with an Ediacaran age, occurs in the Villa Mónica, Cerro Largo and Cerro Negro formations (Fig. 4; Pothe de Baldis et al., 1983; Cingolani et al., 1991; Gaucher et al., 2005). Gómez Peral et al. (2007) reported $\delta^{13}C$ values of −1.3 to +2.2‰ PDB, increasing up section, for dolostones of the Villa Mónica Formation (Figs. 4 and 8), and the Loma Negra Formation has $\delta^{13}C$ values of +2.7 to +4.5‰ PDB and $^{87}Sr/^{86}Sr$ ratios between 0.7069 and 0.7087 (Kawashita et al., 1999b). Together, the biostratigraphic and chemostratigraphic data suggest a late Ediacaran age for the Sierras Bayas Group.

Gaucher et al. (2005) correlated the Sierras Bayas and Arroyo del Soldado groups at a formational level (Fig. 4). The Cerro Largo and Olavarría formations correlate with the Yerbal Formation, and limestones of the Loma Negra Formation correlate with the Polanco Formation. The Cerro Negro Formation is correlative with the lower Cerro Espuelitas Formation, but the Villa Mónica Formation does not correlate any known unit in the Arroyo del Soldado Group.

4. Materials and methods

Standard thin sections of sandstones and other lithologies were prepared and carefully analyzed and point-counted under a petrographic microscope Leica DM LP (usually 200–300 points were counted).

Detrital zircons were extracted using standard procedures for mineral separation. Around 500–800 zircons per sample were randomly mounted in epoxy, sanded and polished to expose the interiors of zircon grains. Unknown and standard zircons were mounted in inner half of the mount area in order to reduce fractionation. Around 100 zircons were analyzed from each rock. The grains analyzed were selected randomly from all sizes and morphologies present in the sample mounts. Grains with visible fractures, inclusions, or compositional zoning and those smaller than beam size were avoided. Core of grains were preferred to avoid possible metamorphic overgrowths.

Detrital zircon crystals were analyzed in polished section with a VGI Isoprobe multicollector ICP-MS equipped with nine Faraday collectors, an axial Daly collector, and four ion-counting channels (Gehrels et al., 2006). The Isoprobe is equipped with an ArF Excimer laser ablation system, which has an emission wavelength of 193 nm. The collector configuration allows measurement of ^{204}Pb in an ion-counting channel while ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U are simultaneously measured with Faraday detectors. All analyses were conducted in static mode with a laser beam diameter of 35 μm, operated with an output energy of ∼32 mJ (at 23 kV) and a pulse rate of 8 Hz. Each analysis consisted of one 20-s integration on peaks with no laser firing and twenty 1-s integrations on peaks with the laser firing. The total analysis time per zircon grain was ∼90 s. The depth of each ablation pit was ∼15 μm. Hg contribution to the ^{204}Pb mass position was removed by subtracting on-peak background values. Inter-element fractionation was monitored by analyzing fragments of a large zircon crystal from Sri Lanka, which has a concordant TIMS age of 564 ± 4 Ma (2σ) (Gehrels et al., 2006). This reference zircon was analyzed once for every five unknown grains (Fig. 16; Table 3). Uranium and Th concentrations were monitored by analyzing a NIST 610 Glass. The lead isotopic ratios were corrected for common Pb, using the measured ^{204}Pb, assuming an initial Pb composition according to Stacey and Kramers (1975) and respective uncertainties of 1.0, 0.3 and 2.0 for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$. The calibration correction or systematic error (age of standard, calibration correction from standard, composition of common Pb, decay constant uncertainty) in the session was 0.9–1.3% for $^{206}Pb/^{238}U$ and 0.8–1.0% for $^{206}Pb/^{207}Pb$ (1-sigma errors).

Concordia diagrams and age probability diagrams are presented for each sample using ISOPLOT (Ludwig, 2003). Accordingly, the age probability plots used in this study were constructed using the $^{206}Pb/^{238}U$ age for young (<1.0 Ga) zircons and the $^{206}Pb/^{207}Pb$ age for older (>1.0 Ga) grains. This division at 1000 Ma results from the increasing uncertainty of $^{206}Pb/^{238}U$ ages and the decreasing uncertainty of $^{206}Pb/^{207}Pb$ ages as a function of age. In old grains, ages with >30% discordance or >5% reverse discordance are considered unreliable and were not used.

Zircon crystals from the Arroyo Mangacha Granite were hand-selected from heavy mineral concentrates (ρ > 3.30) obtained from the <250 μm size fraction. Zircon grains mounted on double-sided tape were potted in epoxy, sectioned with 4000 grit SiC paper, and polished to 0.3 μm with polycrystalline diamond. Sample mounts were then ultrasonically cleaned and coated with Au. Uranium–lead ages were obtained using the UCLA Cameca ims 1270 ion microprobe. A mass-filtered 10 nA $^{16}O^-$ beam with 22.5 kV impact energy was focused to a 30-mm spot. Flooding the sample surface with O_2 at a pressure of $\sim 4 \times 10^{-3}$ Pa increased Pb^+ yields by a factor of ∼1.7. Secondary ions were extracted at 10 kV with an energy band-pass of 50 eV. The mass spectrometer was tuned to obtain a mass resolution (∼5000) that was sufficient to resolve the most troublesome molecular interferences (i.e., those adjacent to the Pb peaks). Ten cycles of measurements at $^{94}Zr_2{}^{16}O$, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{238}U, and $^{238}U^{16}O$ were obtained. Characteristics of the energy spectra of Th^+, U^+, and UO^+ (relative to the other ions) lead us to apply small energy offsets so that these species could be measured at their maximum intensities. Anthropogenic common Pb values appropriate to southern California and measured ^{204}Pb were used to perform correct common lead corrections. The relative sensitivities for Pb and U were determined on reference zircon AS-3 (Paces and Miller, 1993) using a modified calibration technique described in Compston et al. (1984).

5. Results

5.1. Arroyo del Soldado Group

Yerbal Formation. The upper Yerbal Formation was sampled at the Arroyo Campanero section near Minas (Gaucher, 2000; Figs. 2 and 13). There, a 50-m-thick sandstone unit is overlain by banded siltstones yielding abundant and well-preserved *Waltheria marburgensis* and *Titanotheca coimbrae* (Gaucher and Sprechmann, 1999; Gaucher, 2000; Figs. 13 and 14). These fossils characterize the upper Yerbal Formation throughout the Arroyo del Soldado basin (Gaucher and Sprechmann, 1999; Gaucher, 2000). The sampled rock (sample MIN 14) is a very coarse-grained sandstone rich in intraclasts derived from underlying dark siltstones (Fig. 12F). Clast composition is as follows: quartz, 68.3% (monocrystalline, 38.2%; polycrystalline, 30.1%); orthoclase, 13.9%; perthitic feldspar, 2.3%; microcline, 2.3%; siltstone intraclasts, 10.8%; granite, 1.4%; opaque minerals, 0.7%; and muscovite, 0.3%. With this modal composition, the sandstone is a subarkose (Pettijohn et al., 1987). Subarkose beds are 1–2-m thick and display normal grading. The presence of pertithic feldspars, microcline (Fig. 12F) and granite lithoclasts is definitive evidence of an immediate granitic source for the sandstone sample.

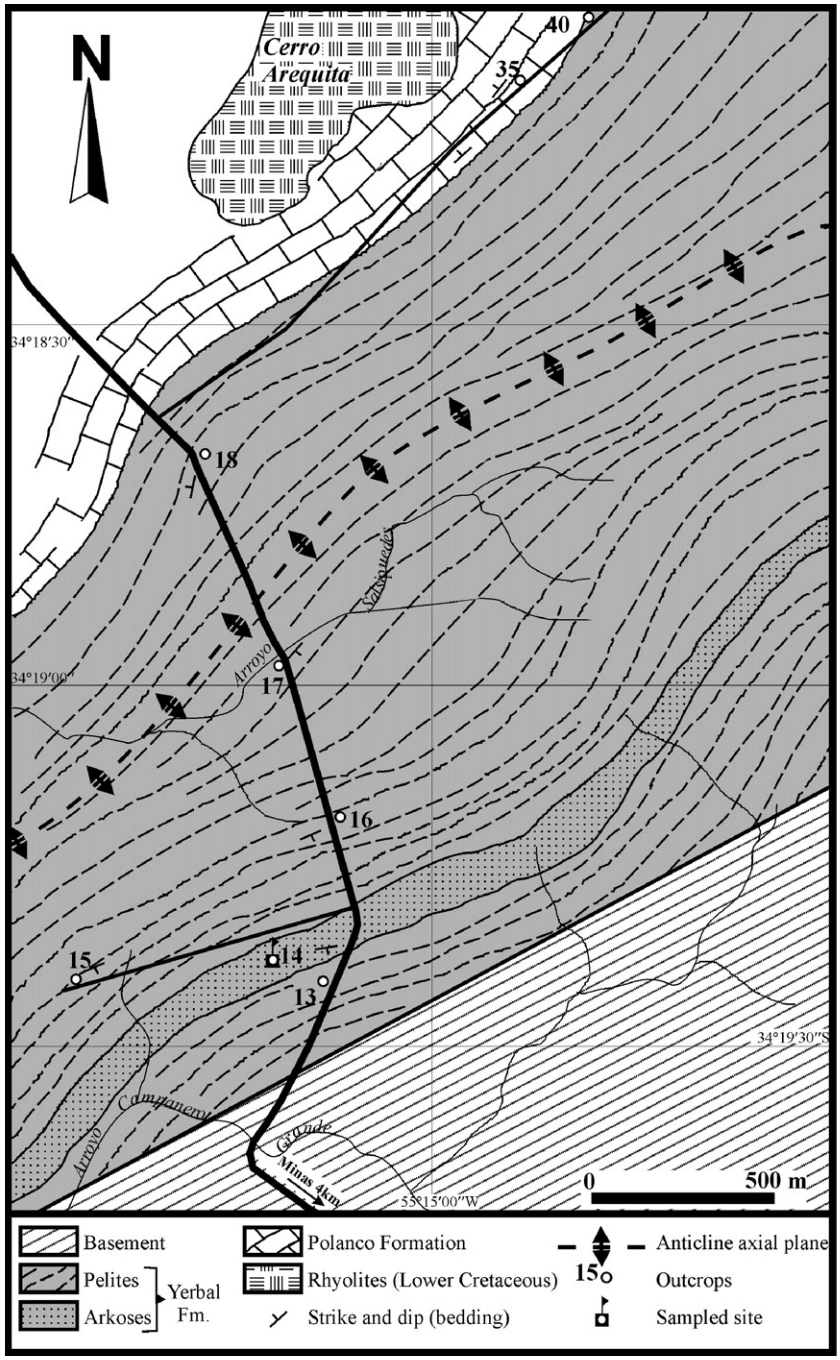

Fig. 13. Geological map of the Arroyo del Soldado Group at the Arroyo Salsipuedes Anticline, near Minas. Note location (point MIN 14, Fig. 2) of sampled subarkoses of the Yerbal Formation.

Ninety-two concordant zircon grains were dated by LA-ICP MS, yielding an essentially unimodal spectrum with a dominant peak centered at 2450 Ma (Figs. 15 and 16). Two grains yielded ages of 2044 Ma and five grains show Archean ages between 2895 and 2662 Ma. Thus, the subarkose is interpreted here as a first-cycle sandstone mainly derived from a granite with an age of 2450 Ma. The possible source rock may be represented by the Arroyo Perdido Granite (Bossi et al., 1998), also named Cerro del Cura Granite, which crops out only 7 km to the west of the sampled site. This granite has a protomylonitic texture; phenocrysts are composed of potassic feldspars; and biotite is the main mafic mineral. According to Gaucher et al. (2006a), it yielded a Rb–Sr age of 2001 ± 117 Ma (Ro = 0.699628), but this age might actually represent a minimum age and not the crystallization age of the Arroyo Perdido Granite.

Blanco et al. (2007) report detrital zircon ages of one sandstone sample from the Yerbal Formation at its type area, 200 km to the NNE of Minas (Fig. 1). The dominant zircon population is Palaeoproterozoic, centered at 2.2 Ga, followed by subordinate peaks at 1.05, 2.0 and 3.0 Ga (in order of importance). The sample analyzed by Blanco et al. (2007), more mature than the one analyzed here, reflects more accurately the entire source area of the Yerbal Formation.

Cerros San Francisco Formation. The Cerros San Francisco Formation was sampled in the Cerro de la Sepultura area (Gaucher, 2000; Fig. 9). There, sandstones of the Cerros San Francisco Formation

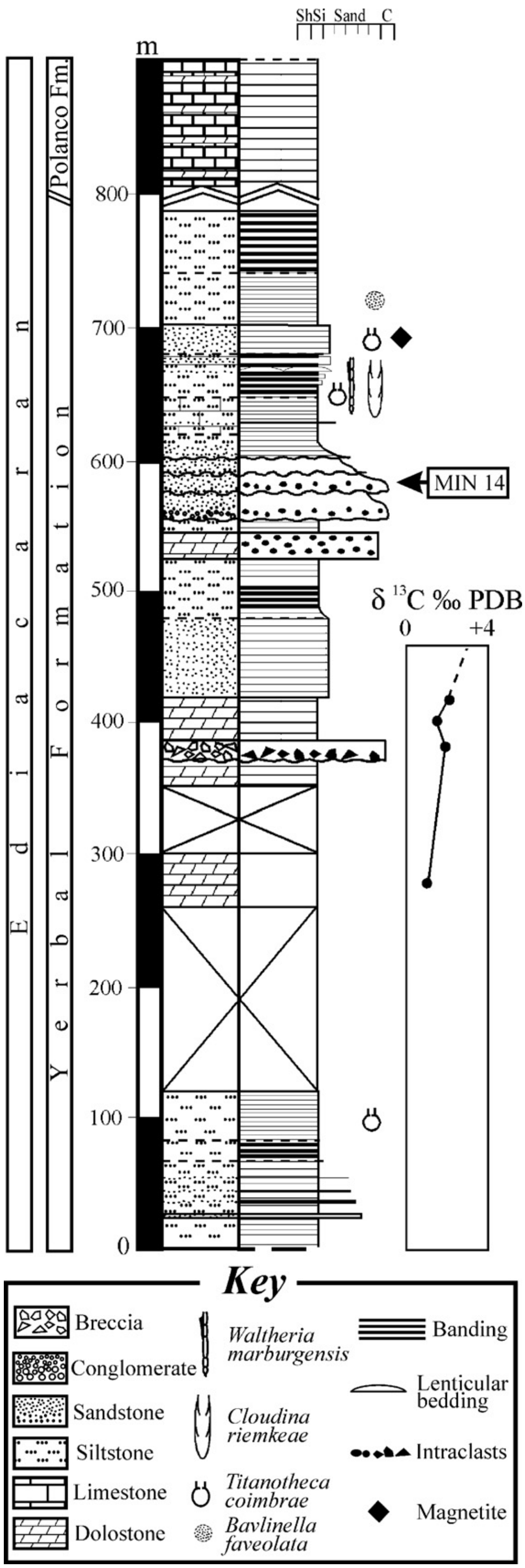

Fig. 14. Stratigraphic column of the Arroyo del Soldado Group at the Arroyo Salsipuedes Anticline (Fig. 13), and stratigraphic location of the sampled sandstones (MIN 14). Range of fossils according to Gaucher (2000); chemostratigraphic data from Gaucher et al. (2004).

overlie with erosional and angular unconformity pre-Ediacaran sedimentary rocks, mainly composed of dolostones, shales and subordinate sandstone (Fig. 9). The Arroyo Mangacha Granite intruded this metasedimentary succession (Fig. 9), producing contact metamorphism in the shales. On the other hand, sandstones of the Cerros San Francisco Formation overlie the granite with erosional unconformity. These sandstones also unconformably overlie the shales at localities away from the intrusion.

The sample analyzed (SOL 18) is a medium- to coarse-grained, reddish, ferruginous quartz arenite occuring between predominantly fine-grained, supermature sandstone beds 150 m stratigraphically above the contact with basement rocks (Figs. 7B and C, 9, 10, and 12E). Associated sedimentary structures include hummocky (Fig. 7B) and swaley cross-stratification, current ripples and planar cross-bedding (Gaucher, 2000; Fig. 10). Palaeocurrents are predominantly to the east.

Eighty-six detrital zircons were dated and show a polymodal distribution with mainly Archean and Palaeoproterozoic populations. Two prominent Archean peaks can be recognized (Fig. 15): one double peak at 2778–2715 Ma and including 53% of all zircons, and a minor one between 3225 and 3045 Ma represented by 9% of the population. Both peaks closely match important tectono-magmatic events that affected the Nico Pérez Terrane at 3100 and 2700 Ma and are represented by La China and Las Tetas complexes (Hartmann et al., 2001). Palaeoproterozoic zircons show essentially one single peak centered at 2188 Ma and comprising 30% of all zircons. They overlap typical Transamazonian ages in the neighbouring Piedra Alta and Tandilia terranes (Bossi et al., 1998, 2005; Hartmann et al., 2002b; Santos et al., 2003; Peel and Preciozzi, 2006; Fig. 1). In the Nico Pérez Terrane, Santos et al. (2003) reported a U–Pb SHRIMP crystallization age of 2140 ± 6 Ma for the Rivera meta-trondhjemite, and a metamorphic event dated by the same method at 2077 ± 6. Gaucher et al. (2006a) obtained a Rb–Sr age of 2001 ± 117 Ma for the Arroyo Perdido Granite. Therefore, the source of these zircons could be located in the Piedra Alta or Tandilia terranes or, less probably, in the Nico Pérez Terrane. It is worth noting that several zircons have ages between 2565 and 2358, representing a poorly defined peak. The youngest zircon in the sample yielded an age of 2060 ± 24 Ma.

Blanco et al. (2007) report detrital zircon ages for one quartz-arenite sample of the Cerros San Francisco Formation at its type area near Illescas, 100 km to the north of Minas (Fig. 1) and 60 km to the NW of sample SOL 18. The age distribution obtained by Blanco et al. (2007) is dominated by Palaeoproterozoic zircons (2.1–2.2 Ga), with subordinate, poorly defined Archean peaks at 2.5, 2.7, 3.1 and 3.5–3.6 Ga). This pattern is similar to that reported above for the Cerros San Francisco Formation. Interesting differences are the higher proportion of Transamazonian zircons in the western outcrop area and a concomitant decrease in the abundance of Archean zircons. This shows that Transamazonian zircons were mostly sourced in the neighbouring Piedra Alta and Tandilia terranes. For reasons that will be presented later (see Section 6), the most probably source of the Transamazonian zircons was the Buenos Aires Complex and other basement units of the Tandilia Terrane.

5.2. Piedras de Afilar Formation

The Piedras de Afilar Formation was sampled at a quarry that exposes extensively the lower part of the formation and its contact with underlying basement rocks (Figs. 5 and 6). There, the Piedras de Afilar Formation rests with erosional unconformity on the Soca Granite, which has a U–Pb SHRIMP age of 2056 ± 6 Ma (Santos et al., 2003; Fig. 7A). The sample is from an interval of fine- to coarse-grained, normally graded sandstone beds with rip-

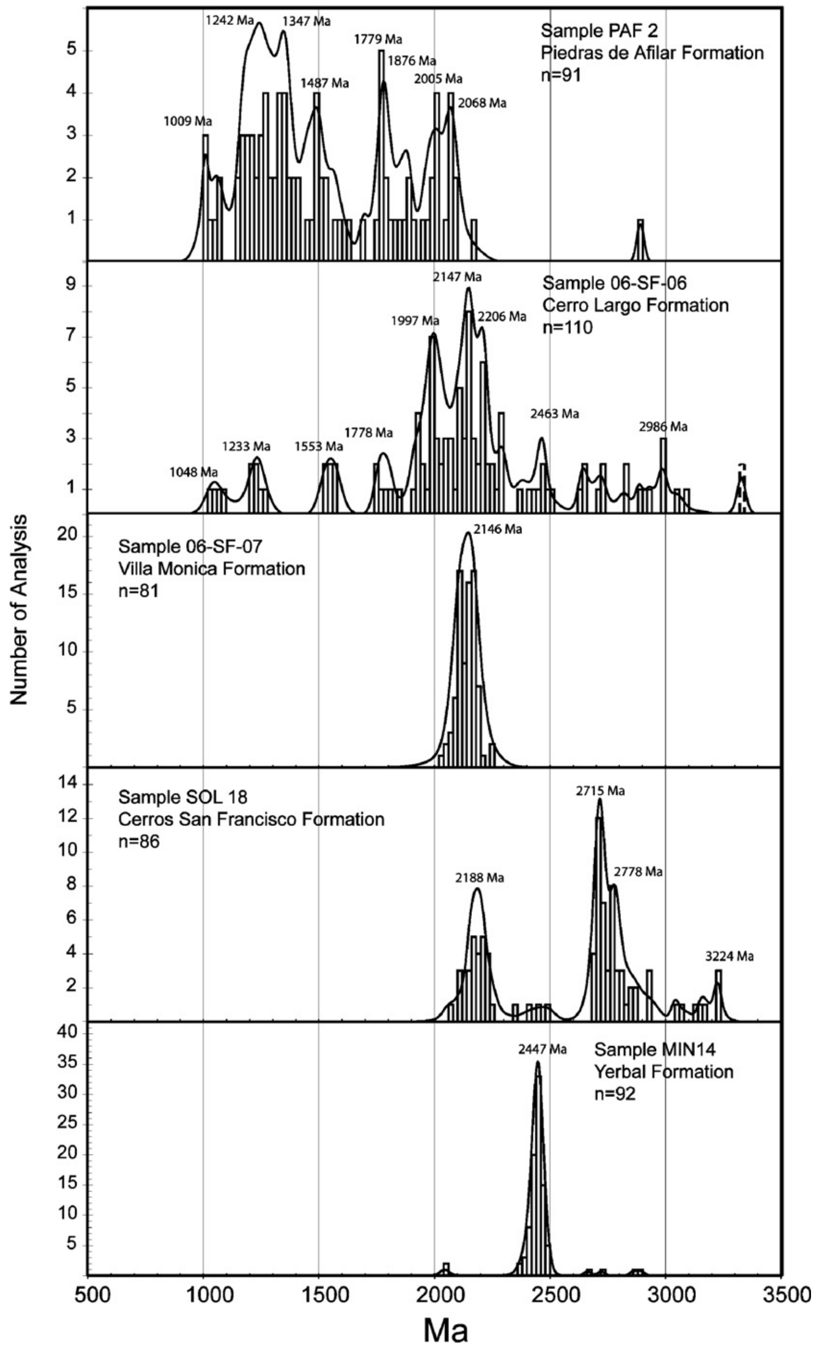

Fig. 15. Detrital zircon age spectra and relative age-probability curves for samples analyzed. Note prominent populations in the Archean, Palaeoproterozoic and Mesoproterozoic and the absence of Neoproterozoic zircons.

ples and cross-bedding and located 45 m stratigraphically above the contact with the basement (Figs. 6 and 7A). The sampled sandstone is a coarse-grained, mineralogically and texturally mature, quartz arenite (Pettijohn et al., 1987) with a clast composition of 92% quartz (75% monocrystalline, 17% polycrystalline), 5% alkali feldspars, 2% lithic fragments and 1% opaque minerals.

Ninety-one dated zircons give a polymodal distribution with mainly Mesoproterozoic and Palaeoproterozoic ages. The following peaks can be recognized (Fig. 15):

(a) a dominant Mesoproterozoic population (62% of total population) with four distinct peaks at 1487 Ma, 1347, 1242 and 1009 Ma,
(b) a Palaeoproterozoic population comprising 37% of the studied zircons with peaks at 2005–2068 Ma and 1779–1876 Ma, and
(c) a single zircon (1%) with an Archean age of 2890 Ma.

The older Palaeoproterozoic peak can be readily ascribed to the Transamazonian Orogeny (Camboriú event of Hartmann et al., 2002b), including zircons in the age range between 2163 and 1954 Ma. These ages are the most widespread in the basement of the neighbouring Piedra Alta Terrane, and also in the Tandilia Terrane (Bossi et al., 1998, 2005; Hartmann et al., 2002b; Santos et al., 2003; Peel and Preciozzi, 2006; Fig. 1). The younger Palaeoproterozoic peak, comprising zircon ages between 1911 and 1620 Ma also matches known basement units, such as the Piedra Alta Mafic

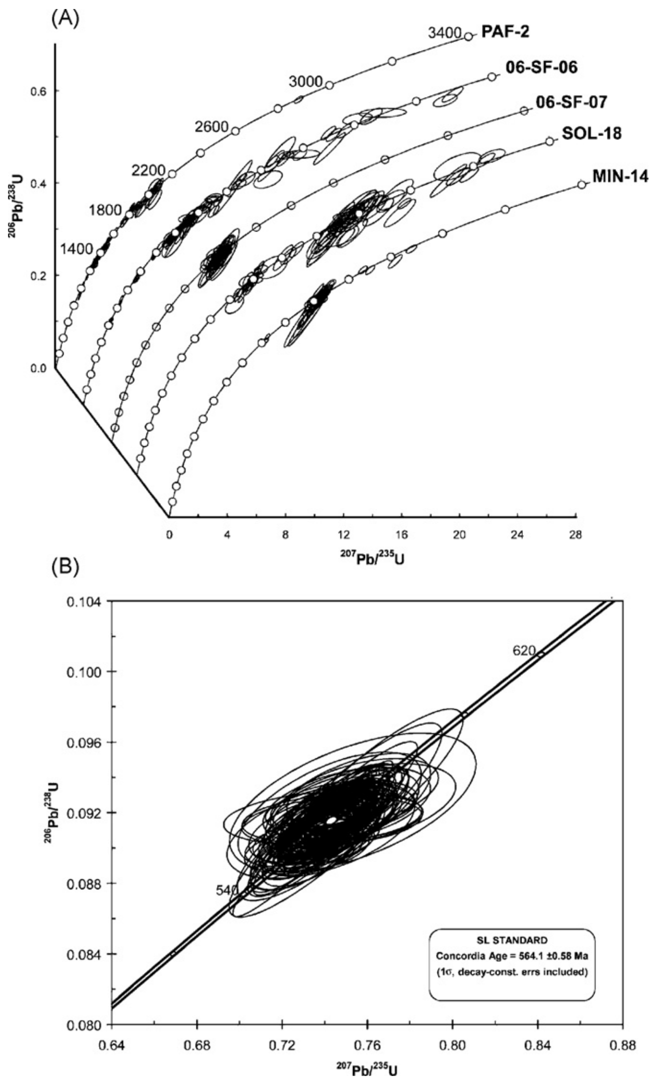

Fig. 16. A: Concordia plots of analyzed detrital zircon grains. B: Concordia plot of analyses of SL2 Standard, measured once every five unknown grains.

Dike Swarm (1790 ± 5 Ma: U–Pb on baddeleyite, Halls et al., 2001; 1725 ± 10 Ma, $^{40}Ar/^{39}Ar$: Teixeira et al., 1999) and acid metatuffs in the Piedra Alta Terrane (1753+6/-4 Ma U–Pb: Peel and Preciozzi, 2006). Extensive anorogenic magmatism occurred in the same age range in the Nico Pérez Terrane with the most important unit being the Illescas Rapakivi Granite (1784 ± 5 Ma, U–Pb: Campal and Schipilov, 1995).

The abundant detrital zircons of Mesoproterozoic age are surprising and reveal fundamental aspects of the Río de la Plata Craton that have been unknown, ignored, or underestimated and that are discussed extensively below.

The youngest detrital zircon grains with ages of 1008 ± 13 and 1006 ± 31 Ma confirm a Neoproterozoic depositional age for the Piedras de Afilar Formation, as suggested by Pamoukaghlian et al. (2006) on the basis of chemostratigraphy.

5.3. Sierras Bayas Group

5.3.1. Villa Mónica Formation

The sample analyzed (06-SF-07, Fig. 12G) was collected at the Villa Mónica Quarry (Figs. 3 and 7D), which is the stratotype of the unit. It comprises coarse-grained quartz wackes with 25% illite matrix, 73% quartz clasts and 2% hematite as cement, and also coarse-grained quartz arenite. The unit rests on top of altered Palaeoproterozoic basement assigned to the Buenos Aires Complex (Poiré, 1987; Fig. 7D).

Eighty-one dated zircons yield a unimodal population centered at 2146 Ma and with typical Transamazonian ages between 2256 and 2022 Ma (Fig. 15). Rapela et al. (2005, 2007) report detrital zircon ages for one sample of the Villa Mónica Formation in the Barker area (Fig. 3). Its zircon population is also predominantly Transamazonian with a peak at 2240 Ma, but it includes a subordinate Mesoproterozoic peak centered at 1135 Ma. Therefore, the source of the Villa Mónica Formation must have been mainly the Palaeoproterozoic Buenos Aires Complex because the sample analyzed in this study and that reported by Rapela et al. (2005, 2007) are 100 km apart (Fig. 3).

5.3.2. Cerro Largo Formation

Sample 06-SF-06 is a medium-grained sandstone cropping out at Cerro Largo (type section), nearby the Villa Mónica quarry (Figs. 3 and 7E). It is composed of 97% quartz and 3% muscovite and clay minerals (mainly kaolinite and illite), thus representing a typical quartz arenite (Pettijohn et al., 1987; Fig. 12H). The unit is characterized by trough and herringbone cross-stratification, wave ripples and asymmetric megaripples (Poiré, 1987; Fig. 7E).

One hundred and ten concordant zircons were dated, yielding a complex, polymodal distribution spanning most of the Archean, the Palaeoproterozoic, and Mesoproterozoic (Fig. 15). Palaeoproterozoic zircons of Transamazonian age (between 1910 ± 18 and 2297 ± 17 Ma) represent the most important population with peaks at 2.21, 2.15 and 2.00 Ga and comprising 58% of all dated grains. These ages are roughly coincident with the Encantadas and Camboriú orogenic events, respectively, recognized in Tandilia by Hartmann et al. (2002b). A younger Palaeoproterozoic peak centered at 1778 Ma (5% of grains), prominent in the sample from the Piedras de Afilar Formation, has the same age as widespread anorogenic magmatism in the Piedra Alta and Nico Pérez Terranes in Uruguay. A number of zircons (6%) yielded earliest Palaeoproterozoic ages with a peak at 2463 Ma, which matches the dominant detrital zircon ages of the Yerbal Formation (Fig. 15). Surprisingly, 16% of the zircon population yielded Archean ages between 3328 and 2640 Ma. These are the oldest zircons reported from Argentina. They define three loose peaks centered at 3.3, 3.0, and ca. 2700 Ma, which correspond approximately to important tectonomagmatic events in the Nico Pérez Terrane at 3400, 3100 and 2700 Ma (Hartmann et al., 2001; Fig. 15). Mesoproterozoic zircons represent 15% of the population and define distinct peaks at 1553, 1233 and 1048 Ma. These sub-populations closely resemble Mesoproterozoic detrital zircon ages in the sample from the Piedras de Afilar Formation, except for the absence of a 1.35 Ga peak in the Cerro Largo Formation. The youngest detrital zircon of sample 06-SF-06 yielded an age of 1032 ± 28 Ma.

6. Discussion

6.1. Source areas and structure of the Río de la Plata Craton (RPC)

The most conspicuous ages of detrital zircons in Neoproterozoic sedimentary units of the RPC are Palaeoproterozoic, mainly between 2.2 and 2.0 Ga, which match the widespread Transamazonian Orogeny (Hartmann et al., 2002b; Santos et al., 2003). Transamazonian age zircons occur in all samples analyzed, and comprise the dominant population in the samples from the Sierras Bayas Group (Fig. 15), the western Cerros San Francisco Formation (Blanco et al., 2007), and the eastern Yerbal Formation (Blanco et al., 2007). Therefore, Transamazonian rocks were important sources

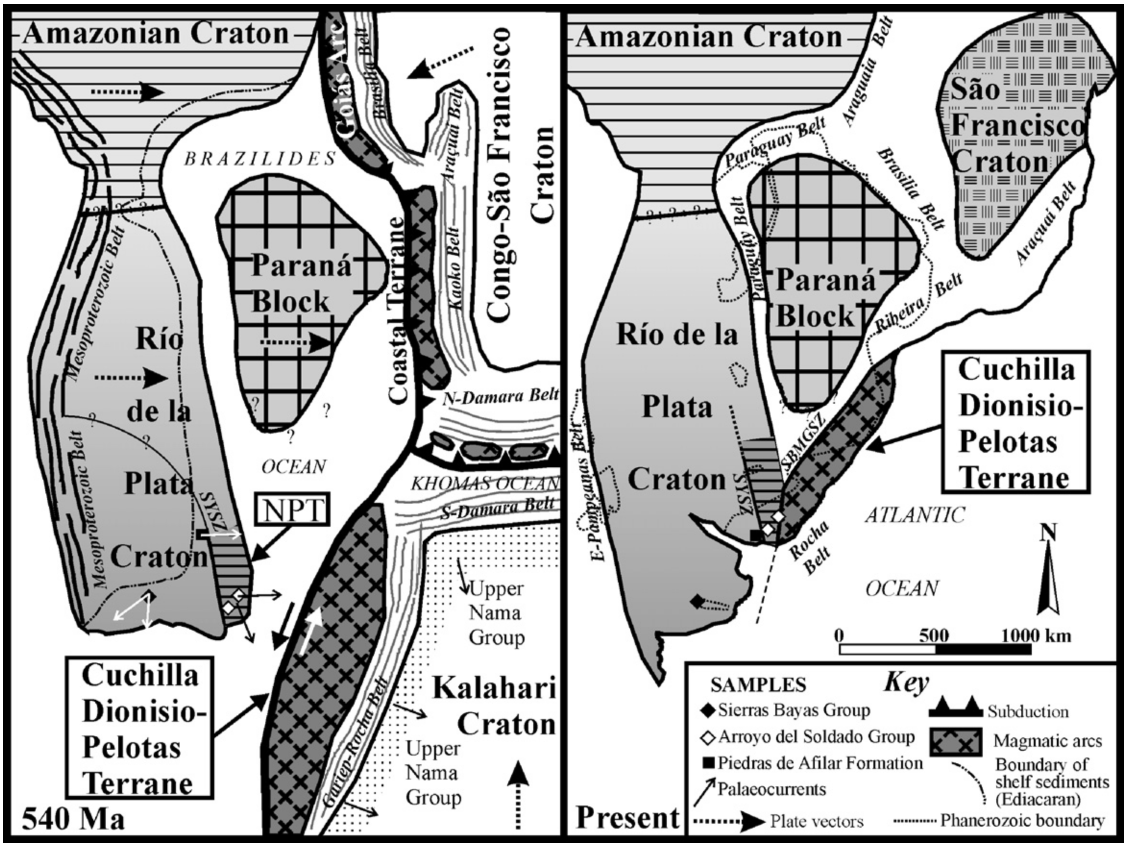

Fig. 17. Palaeogeographic reconstruction of the Río de la Plata Craton near the Neoproterozoic-Cambrian boundary (540 Ma), immediately prior to the accretion of the Cuchilla Dionisio-Pelotas Terrane, and present configuration. NPT: Nico Pérez Terrane, SYSZ: Sarandi del Yí Shear Zone. SBMGSZ: Sierra Ballena-Major Gerçino Shear Zone. The location of sampled units and the inferred boundary of the Sierras Bayas-Arroyo del Soldado-Corumbá shelf sediments is shown. Only a few areas of the Río de la Plata Craton are actually exposed, and none of the Paraná Block is exposed (Paraná-Paranapanema Block of Mantovani and Brito Neves, 2005). The location of magmatic arcs is shown, both active (e.g. Damara Belt) and already accreted (others) by 540 Ma. Note northwards displacement of the Nico Pérez Terrane after the tangential collision with the Cuchilla Dionisio Terrane plus Kalahari Craton. The interaction of the Congo-São Francisco Craton with the Paraná Block is still poorly understood. Location and evolution of the Coastal Terrane according to Goscombe and Gray (2007), and the Goiás Magmatic Arc according to Valeriano et al. (2004). Modified from Gaucher et al. (2003) and Bossi and Gaucher (2004).

for all the units studied, including those in the Nico Pérez Terrane where Transamazonian-age basement rocks are not so widespread. Considering that palaeocurrents in the Arroyo del Soldado Group are predominantly to the east (Gaucher, 2000), the Transamazonian detritus was probably sourced in the Piedra Alta and – most probably – Tandilia terranes (Fig. 17). Palaeoproterozoic (Transamazonian) zircons in the analyzed samples are clearly divided into two distinct peaks (Fig. 15): one at 2200–2150 Ma (Encantadas orogenic event) and another at 2000 Ma (Camboriú orogenic event, Hartmann et al., 2002b). The older Transamazonian peak occurs in the Sierras Bayas and Arroyo del Soldado samples, but, significantly, not in the Piedras de Afilar Formation, where only the younger peak is recorded. According to Santos et al. (2003), basement rocks of the Piedra Alta Terrane mainly record the younger Camboriú event, and the Buenos Aires Complex in Tandilia records both. Therefore, whereas Palaeoproterozoic detritus in the Piedras de Afilar Formation was mainly derived from the Piedra Alta Terrane, in the Arroyo del Soldado and Sierras Bayas groups it was sourced in the Buenos Aires Complex of the Tandilia Terrane.

Our data show that Archean rocks form an integral part of the RPC because Archean zircons occur in all but one of the samples studied, and are the dominant population in one of them (Cerros San Francisco Formation). However, only the Nico Pérez Terrane is known to contain extensive Palaeo- to Neoarchean magmatic and metamorphic rocks (Hartmann et al., 2001). To account for the abundance of Archean zircons in the Cerro Largo Formation (Fig. 15) in Argentina, presently 500 km southwest of the Nico Pérez Terrane, we suggest that the Tandilia region was much closer to the Nico Pérez Terrane in the Neoproterozoic (Fig. 17). The sinistral reactivation of the Sarandí del Yí Shear Zone, which occurred in the Cambrian as a result of the collision of the Cuchilla Dionisio Terrane (530 ± 10 Ma: Bossi and Campal, 1992; Bossi and Gaucher, 2004), was responsible for the northward movement of the Nico Pérez Terrane along the Sarandí del Yí Shear Zone (Fig. 17). The magnitude of this displacement must have been several hundreds of kilometers. Palaeocurrents in the Cerro Largo Formation indicate source areas to the north and east (Teruggi, 1964; Poiré, 1987). It is noteworthy that Archean zircons comprise only 1% of the population occurring in the Piedras de Afilar Formation, which is presently only 60 km away from outcrops of Archean rocks (Bossi and Ferrando, 2001; Fig. 2). If the Nico Pérez Terrane was not in its present position in the Neoproterozoic, the paucity of Archean zircons in the Piedras de Afilar Formation can be easily explained. Conversely, the absence of Mesoproterozoic zircons in the samples from the Arroyo del Soldado Group, less than 100 km to the east (downcurrent) of the Piedras de Afilar Formation, also suggests that the Nico Pérez Terrane was not in its present position in the Ediacaran (Fig. 17). A significant northward displacement of the Nico Pérez Terrane in the Cambrian is also consistent with the Tandilia Terrane – and not the Piedra Alta Terrane (Figs. 1 and 17) – being the main source of the Transamazonian zircons in the Arroyo del Soldado Group.

The abundance of Mesoproterozoic zircons in the samples from the Piedras de Afilar and Cerro Largo formations is surprising. To date, Mesoproterozoic rocks were considered absent in the RPC by most authors (e.g. Cingolani and Dalla Salda, 2000; Almeida, 2004; Rapela et al., 2005, 2007). Bossi et al. (1998) recognized the importance of Mesoproterozoic rocks in the Nico Pérez Terrane for the first time, and Cingolani (in Bossi et al., 1998) reported K–Ar ages of 1253 ± 32 Ma for synkinematic muscovites that crystallized along southwest-vergent thrust planes in the Nico Pérez Terrane. Post-emplacement thermal overprinting of the Piedra Alta mafic dike swarm (Bossi et al., 1993b) between 1370 and 1170 Ma (peak at 1240 ± 5 Ma), reflected in initial release portions of ^{40}Ar–^{39}Ar spectra and Rb–Sr mineral isochrons (Teixeira et al., 1999; Bossi and Navarro, 2001), was interpreted as reflecting the main movement of the Sarandí del Yí Shear Zone (Bossi et al., 1998). Mesoproterozoic ages also were reported for volcanosedimentary units in the southern Nico Pérez Terrane. Gómez Rifas (1995) reported one K–Ar age of 1208 ± 10 Ma for metabasalts of the Fuente del Puma Group (Fig. 2). Garau's (in Bossi and Navarro, 2001) Pb–Pb measurements of galenas from the same unit yield ages between 1500 and 1200 Ma. Whereas rhyolites from the eastern part of the Fuente del Puma Group yielded U–Pb zircon ages of 1429 ± 21 Ma, gabbros intruding the center of the succession yielded U–Pb ages of 1492 ± 4 Ma (Oyhantçabal et al., 2005). Mesoproterozoic anorogenic magmatic activity is recorded by the 1588 ± 11 Ma mafic dike swarm of Tandilia (U–Pb on baddeleyite: Teixeira et al., 2002). Gaucher et al. (2006b) argue for a late Mesoproterozoic age for the Mina Verdún Group in the Nico Pérez Terrane (Poiré et al., 2005) on the basis of chemostratigraphy and stratigraphic relationships. The present configuration of these Mesoproterozoic successions is probably a result of the Cambrian collision of the Cuchilla Dionisio Terrane, with the Mesoproterozoic units being largely fault-bounded packages (Fig. 17).

The above-mentioned Mesoproterozoic ages partially match the detrital zircon ages obtained for the Piedras de Afilar and Cerro Largo formations. A prominent peak at ~1240 Ma in both samples closely compares to the age of tangential terrane collision represented by the Sarandí del Yí Shear Zone (Figs. 2 and 17). An important peak centered at 1487 Ma in the Piedras de Afilar Formation correlates with zircon ages reported for magmatic units of the Fuente del Puma Group. The ~1550 Ma peak could also be associated with anorogenic magmatism represented by tholeiitic dike swarms (Teixeira et al., 2002).

The 1.0 Ga peak of typical Grenvillian-Namaqualan age does not match any known unit in the RPC. Grenvillian ages of 1006 ± 37 Ma (U–Pb: Preciozzi et al., 1999) were reported for orthogneisses of the Cuchilla Dionisio Terrane (=Punta del Este Terrane; Fig. 2). Detrital zircons from Ediacaran sedimentary units (Rocha Formation) sourced in the Cuchilla Dionisio Terrane also have a prominent peak at ~1000 Ma (Basei et al., 2005). However, a number of facts militate against the Cuchilla Dionisio Terrane being the source of Grenvillian detritus. Considerable, varied geologic evidence indicates that the Cuchilla Dionisio Terrane was not accreted until the Cambrian (Bossi and Gaucher, 2004; Basei et al., 2005). If the Grenvillian sediments were sourced in the Cuchilla Dionisio Terrane, then samples yielding them should also include Neoproterozoic zircons between 750 and 600 Ma, typical of the Cuchilla Dionisio Terrane (Basei et al., 2005). However, Neoproterozoic zircons are conspicuously absent in our samples. Also, the easternmost samples (Yerbal and Cerros San Francisco formations) contain no Mesoproterozoic zircons or just a negligible Mesoproterozoic population (Blanco et al., 2007). Thus, the Cuchilla Dionsio Terrane can be confidently ruled out as a source of Mesoproterozoic detritus.

It is unlikely that the limited outcrops of Mesoproterozoic rocks in the Nico Pérez Terrane were the source of the significant zircon populations between 1.5 and 1.0 Ga in the Piedras de Afilar and Cerro Largo formations. Thus, a different source is envisaged for the Grenvillian zircons: a proto-Andean Mesoproterozoic belt in the western RPC, which may represent the southward extension of Mesoproterozoic units of the Amazonian Craton.

Several Mesoproterozoic tectonomagmatic events are recognized in the southwestern Amazonian Craton and its possible southward extension, the Río Apa Block. In the Rondonian-San Ignácio province, three tectonomagmatic events are recognized by Tassinari and Macambira (2004, and references therein): (a) a short-lived magmatic event between 1509 and 1494 Ma, (b) the Santa Helena juvenile magmatic arc between 1481 ± 47 and 1433 ± 6 Ma, and (c) the younger San Ignácio Orogeny (Litherland et al., 1985), characterized by alkaline granitoids and peak metamorphism between 1450 and 1300 Ma. The Sunsás Orogenic Cycle, well represented in the southern tip of the Amazonian Craton and correlative with the Grenvillian Orogeny (Santos, 2003), is characterized by metamorphism and granite intrusions between 1250 and 990 Ma according to Tassinari and Macambira (2004, and references therein). The alternative tectonic scheme of Santos (2003) envisages the subdivision of the Sunsás Orogenic Cycle into three orogenic events between 1456 and 1110 Ma (Santa Helena, Candeias and Nova Brasilândia orogenies), with post-Sunsás, anorogenic granitoids emplaced between 1080 and 974 Ma.

Cordani et al. (2005) reported Ar–Ar ages of 1300 Ma for granitoids in Paraguay, which suggests continuation of the Mesoproterozoic belts southwards into the Río Apa Block. One granitoid in the Río Apa Block yielded an Ar–Ar age of 1060 Ma, which is further evidence of the continuation of this orogen to the south (Cordani et al., 2005).

The coincidence of ages between the detrital zircon ages in our samples and the Mesoproterozoic tectonomagmatic events in Amazonia is noteworthy. Mesoproterozoic detrital zircon populations of Neoproterozoic sandstone units sourced in the Sunsás Province are remarkably similar to those reported here for the RPC. According to Santos (2003), detrital zircon ages of post-Sunsás sandstones (e.g. Palmeiral Formation) in the southern Amazonian Craton are characterized by peaks at 1560, 1450, 1320–1250 and 1150–1050 Ma, which are essentially identical to the peaks identified here at 1553, 1487, 1347–1240 and 1010 Ma for the Piedras de Afilar and Cerro Largo formations.

Gaucher et al. (2003) suggested that the Río de la Plata and Amazonian cratons were already amalgamated in the Ediacaran, based on the continuity of the Arroyo del Soldado shelf at least between Corumbá in Brazil and Tandilia in Argentina (Fig. 17). The Mesoproterozoic zircons found in Neoproterozoic sedimentary covers of the RPC argue in favour of this hypothesis because they suggest that the Mesoproterozoic belts of Amazonia continue into the Río Apa Block and southwards into the RPC (Fig. 17). It is significant that Mesoproterozoic units fringe the Río de la Plata and Amazonian cratons to the west. Chew et al. (2007) suggest that the Arequipa-Antofalla Block accreted to Amazonia during the Grenvillian-Sunsas Orogeny. In the Sierra de Pie de Palo of the Cuyania Terrane (western Argentina), a Grenvillian (1.1–1.0 Ga) metamorphic basement known as Pie de Palo Complex is exposed (Ramos, 2000). It has been regarded by a number of authors as an allochthonous block accreted in the early Palaeozoic to Gondwana (Thomas and Astini, 1996; Thomas et al., 2004). However, if the alternative view of the Cuyania Terrane as a para-authochtonous block of Gondwanan affinity is accepted (Aceñolaza et al., 2002; Finney et al., 2005), these extensive Grenvillian rocks could have acted as the source of Neoproterozoic sedimentary units of the RPC. Recent data on the timing of tectonic events in the Pie de Palo range by Mulcahy et al. (2007) support the idea of the Pie de Palo range being a para-authochtonous block of Gondwanan affinity.

Further evidence supporting a proto-Andean, Mesoproterozoic belt in the RPC comes from the observed trend of increasing relative abundance of Mesoproterozoic detrital zircons in Neoproterozoic sandstones toward the west of the craton. Grenvillian detrital zircons were reported by Schwartz and Gromet (2004) and Rapela et al. (2007) for Neoproterozoic-Cambrian metasedimentary units of the Eastern Sierras Pampeanas in western Argentina, probably a part of the RPC. Parallel to the increasing importance of Mesoproterozoic detrital zircons, a decreasing importance of Transamazonian zircons is observed toward the west. The ratio between Mesoproterozoic and Palaeoproterozoic detrital zircons increases toward the west from near 0 in the Arroyo del Soldado Group through 0.29–0.60 for the Cerro Largo/Piedras de Afilar Formation, to between 0.56 and 4.9 for the Eastern Sierras Pampeanas (La Cébila and Ancasti formations respectively: Rapela et al., 2007). In the Western Sierras Pampeanas, Palaeoproterozoic detrital zircons largely disappear (Finney et al., 2005; Naipauer et al., 2006; Rapela et al., 2007) and Mesoproterozoic zircons dominate. This transition from Palaeoproterozoic-dominated to Mesoproterozoic-dominated detrital zircon populations toward the west is strong evidence of a proto-Andean, Mesoproterozoic belt marking the western boundary of the RPC.

In reconstructing the evolution of the western, proto-Andean margin of the RPC, Rapela et al. (2007) propose a Gondwanan provenance for the sedimentary successions in the Eastern Sierras Pampeanas with the Kalahari Craton and its peripheral belts as the likely sources for the Mesoproterozoic zircons in these successions. However, the data presented here demonstrate that Mesoproterozoic detrital zircons are also widespread in the core of the RPC and identify this crustal block as a most likely source for the Mesoproterozoic zircons in stratigraphic successions of the Eastern Pampeanas. Recognizing this local source simplifies interpretations of the palaeogeographic evolution of the western margin of the RPC.

In summary, the detrital zircon age populations of our samples indicate that, in addition to the typical and widespread Palaeoproterozoic (mainly Transamazonian) rocks, Archean and Mesoproterozoic magmatic and metamorphic rocks are prominent in the basement of the RPC. The main corollary may be that the RPC was involved in the Mesoproterozoic (Grenvillian) collage leading ultimately to the amalgamation of Rodinia, as already suggested by a number of authors (e.g. Meert and Lieberman, 2008), and a logical consequence of recent advances in the tectonic evolution of the Arequipa-Antofalla Block (Chew et al., 2007).

6.2. *Palaeogeography of the Rio de la Plata Craton in the Neoproterozoic*

One of the most striking features of our samples is the absence of Neoproterozoic zircons (Fig. 15). This is easily explained in the case of the Arroyo del Soldado Group and the correlative Sierras Bayas Group by their geotectonic setting, which was an Atlantic-type, passive continental margin far removed from Brasiliano/Pan-African orogenic belts (Gaucher, 2000; Gaucher et al., 2003, 2005). Sm–Nd analyses of sandstones and shales from the Arroyo del Soldado Group yield T_{DM} model ages between 1.6 and 2.9 Ga and ε_{Nd} values of approximately −10 (Blanco et al., 2007; Mallmann et al., 2007), which also support a passive margin setting for the unit.

We analyzed 20 additional zircon grains from samples 06SF06 and 06SF07 (Cerro Largo and Villa Mónica formations) in order to identify any possible magmatic young rims. No young ages were found but many of them gave discordant ages due to lead loss. The absence of Neoproterozoic zircons ranging in age from 750 to 600 Ma is especially interesting. Protracted, collisional granite generation in the Cuchilla Dionisio-Pelotas Terrane (Bossi and Gaucher, 2004) spanned the interval of 650 to 550 Ma (Philipp et al., 2000; Silva et al., 2005). Older Neoproterozoic granitic intrusions include the Rocha Syenogranite (762 ± 8 Ma U–Pb SHRIMP: Hartmann et al., 2002a) and tonalitic xenoliths within the Pelotas Batholith (781 ± 5 Ma U–Pb SHRIMP: Silva et al., 2005). All these ages are reflected in detrital zircon populations of the Rocha Formation, which was sourced in the Cuchilla Dionisio-Pelotas Terrane (Basei et al., 2005). In fact, 31% of all zircons from the Rocha Group dated by Basei et al. (2005) fall within the interval of 764–596 Ma. On the other hand, these ages are absent in all five of our detrital zircon samples from the RPC despite the large number of grains analyzed (460), showing that the Cuchilla Dionisio Terrane was not in its present location to act as a source to the analyzed basins. Therefore, the allochthonous nature of the Cuchilla Dionisio-Pelotas Terrane is confirmed, and its docking to the RPC must have occurred no earlier than the Early Cambrian (Fig. 17), as proposed by Bossi and Gaucher (2004) and Basei et al. (2005), and contrary to the proposal of Oyhantçabal (2005) and Oyhantçabal et al. (2006, 2007).

In contrast to their absence in our samples, Neoproterozoic detrital zircons were recently discovered by Blanco et al. (2007) in samples from the Arroyo del Soldado Group from other localities, along with the other detrital-zircon age populations that we report. One grain from a sandstone sample of the Yerbal Formation yielded an age of 664 ± 14 Ma, another grain from the Cerros San Francisco Formation was dated at 605 ± 53 Ma and 28% of zircons from a sample of the Barriga Negra Formation define an age population of 631 ± 12 to 566 ± 8 Ma. These ages match at least two extensional magmatic events at ∼630 and ∼580 Ma that are represented in the Nico Pérez Terrane by the Puntas del Santa Lucía Batholith (633 ± 8 Ma, U–Pb SHRIMP: Hartmann et al., 2002a), the Arroyo Mangacha Granite (583 ± 7 Ma), the Pan de Azúcar Pluton (579 ± 1.5 Ma, Ar–Ar: Oyhantçabal et al., 2007), the Nico Pérez mafic dike swarm (581 ± 13 Ma, K–Ar: Rivalenti et al., 1995), and bimodal volcanism associated with the Las Ventanas Formation (615 ± 30 Ma K-Ar: Sanchez Bettucci and Linares, 1996; Fig. 2). All these units have been associated with the rifting event that initiated the opening of the Arroyo del Soldado Basin (Blanco and Gaucher, 2005; Gaucher et al., 2008).

Thus, the Arroyo del Soldado and Sierras Bayas groups, were deposited on a passive continental margin postdating at least one important rifting event responsible for the opening of the basin. The combined lithostratigraphic, palaeocurrent, Sm-Nd and detrital zircon data allow to confidently rule out an interpretation as a foreland basin, as suggested by Pecoits et al. (2007). The shelf probably included the Corumbá Group in western Brazil (Boggiani, 1998; Gaucher et al., 2003). These units are not only lithologically and geochronologically correlative (Gaucher et al., 2003, 2005), but they also share the same basin architecture (a ramp deepening to the east and southeast) and a Cambrian deformational history. The minimum length of the shelf was 2,500 km, thus representing a major palaeogeographic feature in southwestern Gondwana (Fig. 17). Early Cambrian tangential collision of the Río de la Plata Craton with the Cuchilla Dionisio-Pelotas Terrane was responsible for the final closure of the basin (Fig. 17).

7. Conclusions

Detrital zircon populations of Neoproterozoic sedimentary covers of the Río de la Plata Craton (Arroyo del Soldado Group, Piedras de Afilar Formation, Sierras Bayas Group) are characterized as follows:

(a) Palaeoproterozoic zircons occur in all samples analyzed. Among the five samples, distinct peaks are at 2.45, 2.21–2.15, 2.0 and 1.8 Ga. Peaks at 2.21–2.15 and 2.0 Ga can be ascribed to the Transamazonian Orogeny (Encantadas and Camboriú events, respectively: Hartmann et al., 2002b). Anorogenic magmatism affecting most of the craton is probably responsible for the 1.78 Ga zircons.

(b) Archean zircons occur in all samples except that from the Villa Mónica Formation. They are the dominant population in the Cerros San Francisco sample. Among the samples, peaks are at 3.4–3.2, 3.0, and 2.7 Ga. The only Archean units known in the Río de la Plata Craton are located in the Nico Pérez Terrane (Hartmann et al., 2001) and the tectonomagmatic events recorded there correspond closely to the Archean peaks in our samples.

(c) Mesoproterozoic zircons occur in the Piedras de Afilar and Cerro Largo formations and are the dominant population in the former. Distinct peaks are at 1.5, 1.35, 1.24, and 1.0 Ga. To account for these Mesoproterozoic detrital zircons, we propose that a Mesoproterozoic belt is located at the western, proto-Andean margin of the Río de la Plata Craton. This belt is possibly the southern extension of the Rondonian-San Ignácio and Sunsás belts of the Amazonian Craton.

(d) There is a conspicuous absence of Neoproterozoic zircons in all of our samples.

The Arroyo Mangacha Granite yielded an U–Pb SIMS (ion microprobe) zircon age of 583 ± 7 Ma, which serves as a maximum age for the Cerros San Francisco Formation and the whole upper Arroyo del Soldado Group.

The detrital-zircon age populations in our samples are consistent with deposition of the Neoproterozoic successions of the Río de la Plata Craton on an Atlantic-type continental margin, as proposed by Gaucher (2000) and Gaucher et al. (2003). Docking of the Cuchilla Dionisio-Pelotas Terrane occurred in the Cambrian by means of tangential tectonics and represents one of the last events of Gondwana amalgamation (Búzios Orogeny: Schmitt et al., 2004).

The tangential collision of the Cuchilla Dionisio Terrane sinistrally reactivated the Sarandí del Yí Shear Zone, displacing the Nico Pérez Terrane northwards several hundreds of kilometers. Evidence of this displacement include: (a) Archean detrital zircons in the Cerro Largo Formation of the Tandilia region; (b) Transamazonian-age detrital zircons in the Arroyo del Soldado Group recording the Encantadas orogenic event, as they do in the Sierras Bayas Group, but those in the Piedras de Afilar Formation recording only the younger Camboriú orogenic event; and (c) absence of Mesoproterozoic zircons in the Arroyo del Soldado Group, although they are abundant in the Piedras de Afilar Formation. Accordingly, the Nico Pérez Terrane can be viewed as a parauthochtonous terrane at the margin of the Río de la Plata Craton, in situation analogous to that of the northern Cordillera of North America (Colpron et al., 2007).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2008.07.006.

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