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ORIGINAL PAPER

A Cambrian mixed carbonate–siliciclastic platform in SW Gondwana: evidence from the Western Sierras Pampeanas (Argentina) and implications for the early Paleozoic paleogeography of the proto-Andean margin

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Abstract

The Western Sierras Pampeanas (WSP) of Argentina record a protracted geological history from the Mesoproterozoic assembly of the Rodinia supercontinent to the early Paleozoic tectonic evolution of SW Gondwana. Two well-known orogenies took place at the proto-Andean margin of Gondwana in the Cambrian and the Ordovician, i.e., the Pampean (545–520 Ma) and Famatinian (490–440 Ma) orogenies, respectively. Between them, an extensive continental platform was developed, where mixed carbonate–siliciclastic sedimentation occurred. This platform was later involved in the Famatinian orogeny when it underwent penetrative deformation and metamorphism. The platform apparently extended from Patagonia to northwestern Argentina and the Eastern Sierras Pampeanas, and has probable equivalents in SW Africa, Peru, and Bolivia. The WSP record the outer (deepest) part of the platform, where carbonates were deposited in addition to siliciclastic sediments. Detrital zircon U–Pb SHRIMP ages from clastic metasedimentary successions and Sr-isotope compositions of marbles from the WSP suggest depositional ages between ca. 525 and 490 Ma. The detrital zircon age patterns further suggest that clastic sedimentation took place in two stages. The first was sourced mainly from re-working of the underlying Neoproterozoic metasedimentary rocks and the uplifted core of the early Cambrian Pampean orogen, without input from the Paleoproterozoic Río de la Plata craton. Sediments of the second stage resulted from the erosion of the still emerged Pampean belt and the Neoproterozoic Brasiliano orogen in the NE with some contribution from the Río de la Plata craton. An important conclusion is that the WSP basement was already part of SW Gondwana in the early Cambrian, and not part of the exotic Precordillera/Cuyania terrane, as was previously thought.

Keywords Cambrian clastic metasedimentary rocks · Sr-isotope dating of marbles · SW Gondwana Cambrian platform · SW Gondwana paleogeography · Sierras Pampeanas · Precordillera/Cuyania terrane

Introduction

Modern convergent ocean-continent plate margins often preserve evidence of a succession of processes such as magmatism, accretion of oceanic or continental terranes, subduction interruption and margin stability, and formation of sedimentary basins in different tectonic settings. This type of long-lived non-collisional orogeny is defined as accretionary and records continental crust growth by means of mantle-derived magmatism or accretion of oceanic crust (Cawood et al. 2009). Recognition of these processes is more complicated in the case of old continental margins that were overprinted by younger orogenic processes. Such is the case of the Paleozoic SW margin of Gondwana, where multiple orogenic events occurred and which is being re-worked by the Andean orogeny along the eastern Pacific Ocean.

The pre-Andean basement of SW South America preserves a continuous record of processes from Rodinia break-up to Gondwana assembly (for a review see Casquet et al.

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2012a). The latter culminated in the early Cambrian and resulted in a string of orogenic belts stretching from Brazil down to South Africa, i.e., the Araguaia, Paraguay, Pampean and Saldanian belts (e.g., Rapela et al. 1998; Rozendaal et al. 1999; Fonseca et al. 2004; Tohver et al. 2006; Vaughan and Pankhurst 2008; D´el-Rey Silva et al. 2016). Contemporaneously with these orogenies the Iapetus ocean opened in the west (present coordinates) and a new continental margin developed that eventually evolved into the present day Andean margin, i.e., the proto-Andean margin of Gondwana. The Paleozoic history of the margin is well preserved in the pre-Mesozoic basement of the Andean foreland in Argentina. Basement outcrops extend from northwestern Argentina and the Puna altiplano southwards to the Sierras Pampeanas and Patagonia (Fig. 1).

The Sierras Pampeanas, between 26° S and 33° S (behind modern flat-slab subduction of the Nazca plate), preserve evidence of an early Cambrian orogeny, i.e., the Pampean orogeny that resulted from continental collision between ca. 545 and 520 Ma; for a recent reviews see Ramos et al. (2015)

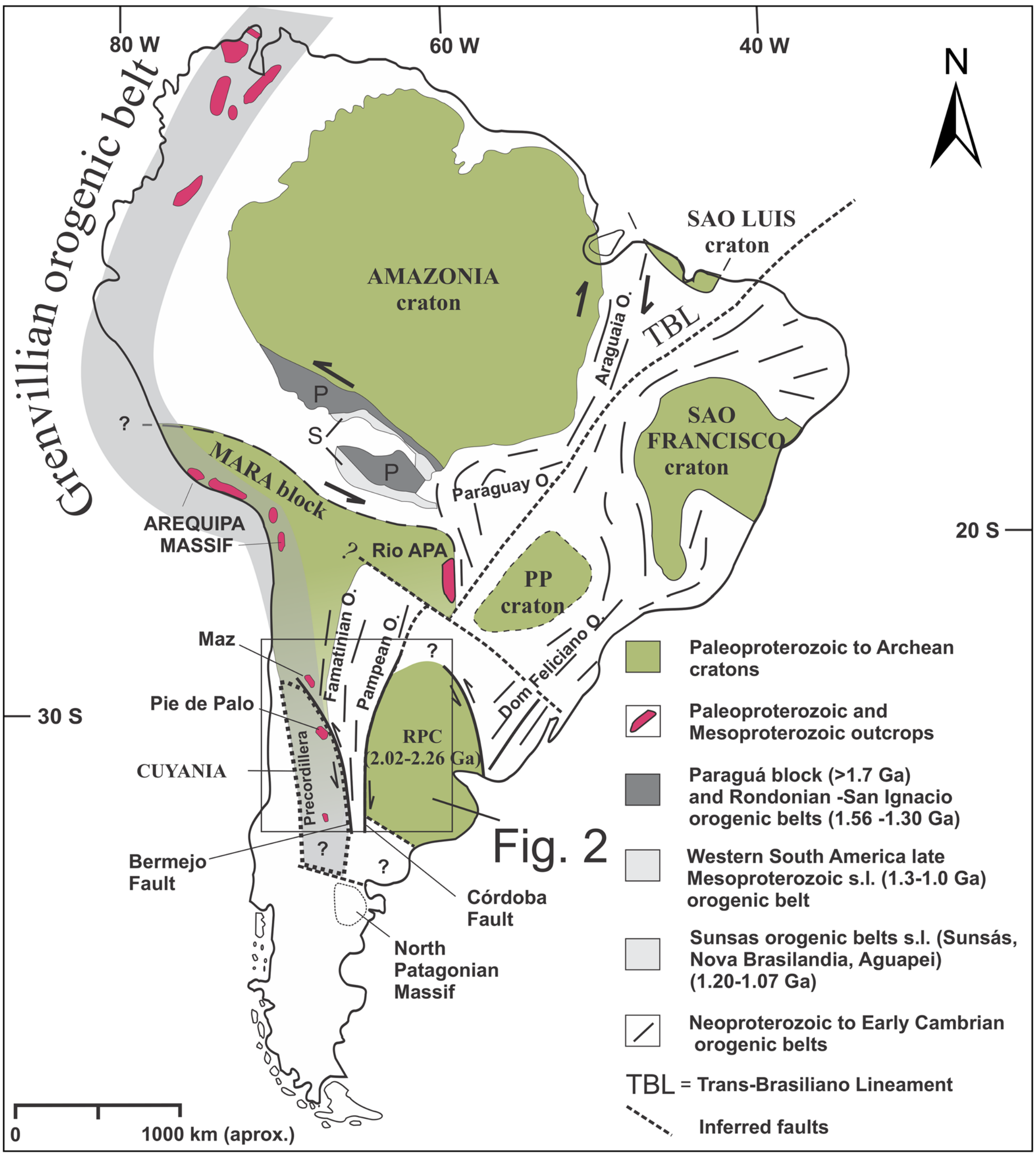

Fig. 1 Map of Precambrian cratons and early Paleozoic terranes of southern South America (modified after Casquet et al. 2012a). MARA: acronym of Maz-Arequipa-Río Apa. PP: Paranapanema craton. RPC: Río de la Plata craton

and Casquet et al. (2018). Subsequent, east-dipping subduction of the Iapetus Ocean started at the proto-Andean margin of Gondwana, resulting in the Ordovician magmatism and metamorphism of the Famatinian orogeny (between ca. 490 and 440 Ma), which is widely recorded from Patagonia to NW Argentina (e.g., Pankhurst et al. 1998, 2000, 2006; Bahlburg et al. 2016). This is part of the approximately 18,000 km long Terra Australis orogen that fringed SW Gondwana from Australia to Venezuela (Cawood 2005). It was followed by a protracted history of orogenic events that still continues at the Andean margin. Between the Pampean and Famatinian orogenies there is a period of time of ca. 30 myrs which is poorly known, because the sedimentary record was strongly involved in penetrative Famatinian (post-490 Ma) deformation and metamorphism and fossils were generally not preserved. Torsvik and Cocks (2011) and Casquet et al. (2012b) proposed that during this period a wide continental platform developed along the SW Gondwana margin. This was coeval with exhumation and erosion of the Pampean orogeny, and with the lateral docking of the Río de la Plata craton along the Córdoba fault (Fig. 1) (Verdecchia et al. 2011).

The Sierras Pampeanas of Argentina offer an excellent opportunity to study the early Paleozoic evolution of SW Gondwana. In this work we provide U–Pb SHRIMP detrital zircon ages from clastic metasedimentary rocks and Sr-isotope composition of marbles from Cambrian sequences of the Western Sierras Pampeanas. Data provided here, combined with those previously published from the Eastern Sierras Pampeanas, Patagonia, and NW Argentina, allow us to better constrain the Cambrian continental platform model, to establish the source areas of sediments and to better define the paleogeographic evolution of this tract of the SW Gondwana margin close to the Cambrian–Ordovician boundary.

Geological setting

The tectonic framework

The Sierras Pampeanas are N–S elongated ranges uplifted by reverse faulting in response to the Cenozoic Andean orogeny (Jordan and Allmendinger 1986) (Fig. 2). The application of robust geochronological methods over the last two decades has permitted recognition that the Eastern Sierras Pampeanas (ESP) and Western Sierras Pampeanas (WSP) (Fig. 2) have quite different geological histories. The ESP comprise mainly Neoproterozoic to late Cambrian clastic metasedimentary rocks (Rapela et al. 2016 and references therein) variably affected by the Pampean and Famatinian orogenies with abundant early Paleozoic magmatism (e.g., Rapela et al. 1998; Pankhurst et al. 1998, 2000; Steenken et al. 2011; von Gosen et al. 2014; Ramos et al. 2015 among many others). In contrast, the WSP consist of a complex igneous and metamorphic basement resulting from late Mesoproterozoic orogenies (Grenville orogeny; ca. 1.3–1.0 Ga; Rapela et al. 2010 and references therein; Varela et al. 2011) and late Neoproterozoic to late Cambrian metasedimentary cover (carbonate and siliciclastic rocks; e.g., Varela et al. 2011; Ramacciotti et al. 2015a; Ramacciotti 2016; Rapela et al. 2016 and references therein), both overprinted by the Famatinian, but not the Pampean, orogeny (Figs. 1, 2).

The Pampean orogeny involved early Cambrian (ca. 545–530 Ma) cordilleran I-type magmatism, mainly intermediate-P/T metamorphism that reached granulite-facies conditions, widespread anatexis and granite formation at ca. 520 Ma (Rapela et al. 1998; Sims et al. 1998; Schwartz et al. 2008; Drobe et al. 2011; Iannizzotto et al. 2013). This orogeny is shown schematically in Fig. 3 based on Casquet et al. (2012a). It involved collision between a Laurentia-derived Paleoproterozoic-to-Mesoproterozoic continental block called MARA and other eastern Gondwana continents such as the Kalahari and the Rio de la Plata cratons. Collision was preceded by consumption of a hypothetical ocean, the Clymene Ocean of Trindade et al. (2006). MARA broke away from Laurentia in the early Cambrian almost coevally with the Pampean orogeny and with the opening of the Iapetus Ocean (Fig. 3).

The trailing edge of MARA became the SW Gondwana margin, which remained passive until the early Ordovician when subduction of the Iapetus oceanic plate initiated the Famatinian orogeny. The latter orogeny involved early-to-middle Ordovician subduction-related I-type and peraluminous magmatism (e.g., Pankhurst et al. 1998, 2000; Dahlquist et al. 2008) and coeval low-to-high-grade low-P/T metamorphism (Murra and Baldo 2006; Gallien et al. 2010; Larrovere et al. 2011; Tibaldi et al. 2013). In some areas, such as the Argentine Puna, magmatism as young as 440 Ma has been ascribed to a late Famatinian stage (e.g., Bahlburg et al. 2016). This orogeny has been explained as resulting from collision against the proto-Andean margin of Gondwana of the Precordillera terrane (e.g., Ramos 1988; Astini et al. 1995; Dalziel 1997; Astini and Dávila 2004). This terrane was first named after the Argentine Precordillera, a morphotectonic block that lies immediately west of the Sierras Pampeanas (Fig. 2a); it consists of an early Cambrian to middle Ordovician carbonate platform with paleontological Laurentian affinity (e.g., Benedetto 2004). There is controversy regarding the provenance of this terrane and time of docking (e.g., Ramos 2004; Finney 2007 and references therein). In the allochthonous (exotic) model, the Precordillera continental block rifted from the Laurentian margin—the Ouachita embayment of the Appalachian margin—in the early Cambrian at ca. 540 Ma (Astini et al. 1995; Thomas et al. 2012). The Sierra de Pie de Palo (WSP) was further

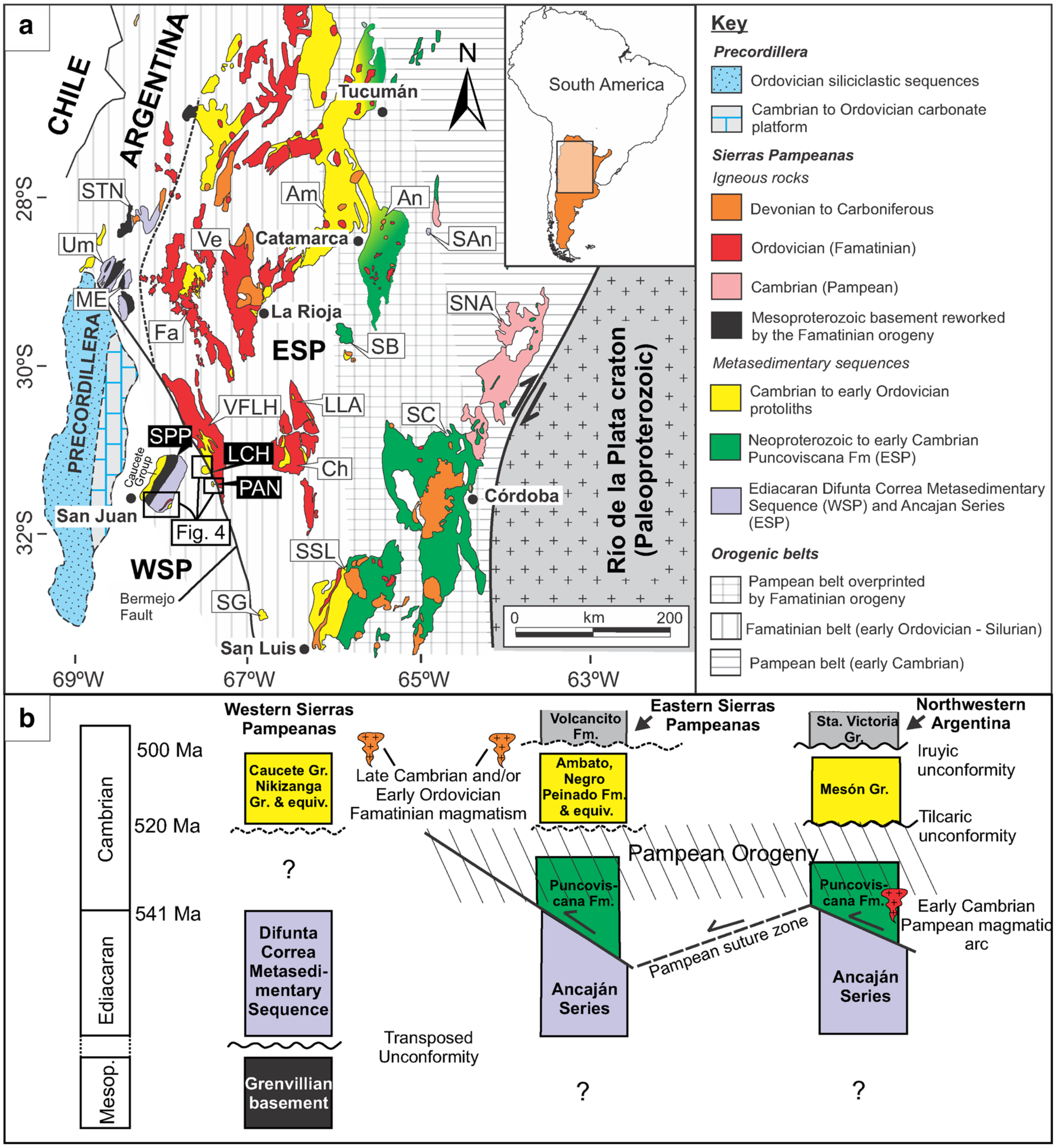

Fig. 2 Geological map of the Sierras Pampeanas and Precordillera (**a**; modified after Rapela et al. 2016) and stratigraphic relationship of the metasedimentary units of northwestern Argentina and the Sierras Pampeanas (**b**). ESP: Eastern Sierras Pampeanas, WSP: Western Sierras Pampeanas. Am: Sierra de Ambato, An: Sierra de Ancasti, Ch: Sierra de Chepes, Fa: Sierra de Famatina, LCH: Loma de Las Chacras, LLA: Sierra de Los Llanos, ME: Sierras de Maz y Espinal, PAN: Pan de Azúcar, SAn: Sierra de Ancaján, SB: Sierra Brava, SC: Sierras de Córdoba, SNA: Sierra Norte de Córdoba-Ambargasta, SPP: Sierra de Pie de Palo, STN: Sierra del Toro Negro, Um: Sierra de Umango, VFLH: Sierra de Valle Fértil-La Huerta

included in the Precordillera terrane as part of a larger composite terrane, Cuyania (for a review see Ramos 2004 and references therein). However, other authors have suggested that the Pie de Palo block was already attached to SW Gondwana in Cambrian times and that it was autochthonous or para-autochthonous and, in consequence, part of the upper plate during Famatinian subduction (Galindo et al. 2004; Finney 2007 and references therein; Mulcahy et al. 2007, 2011).

The metasedimentary rocks

Several Neoproterozoic to early Paleozoic sedimentary successions have been recognized in the Sierras Pampeanas, mainly by means of detrital zircon U–Pb ages, with

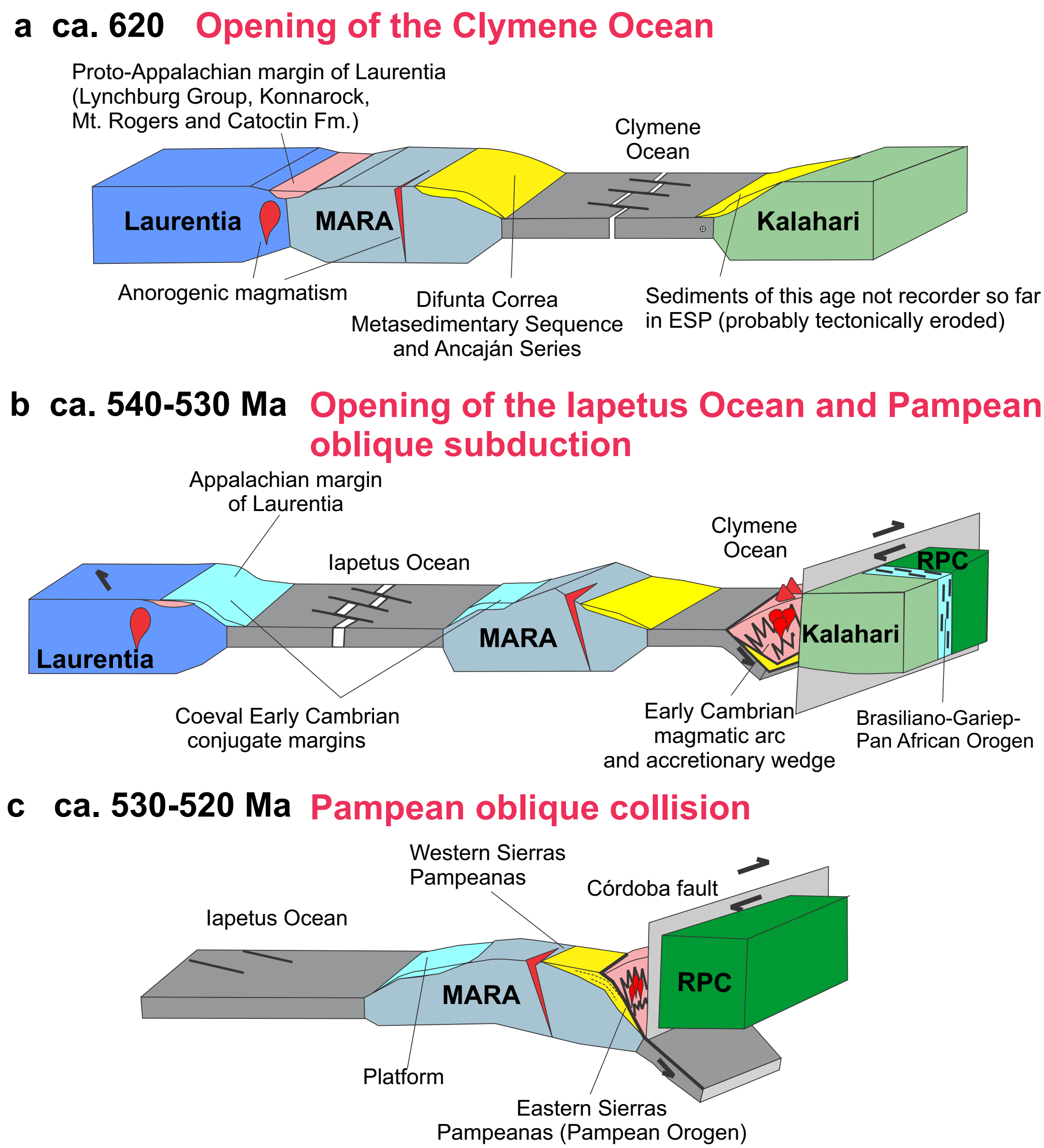

Fig. 3 Geotectonic evolution of southern SW Gondwana between ca. 620 Ma and the end of the Pampean orogeny at ca. 520 Ma preceding eastward extension of the sedimentary platform. Modified after Casquet et al. (2012a). RPC = Río de la Plata craton (ca. 2.02–2.25 Ga)

deposition peaking at various times and in various paleogeographic settings (see Rapela et al. 2016, and references therein). The older succession is Ediacaran (ca. 620 Ma) to early Cambrian and is well exposed in the WSP (Difunta Correa Metasedimentary Sequence) but also extends to the ESP (Ancaján Series) as far as the Sierras de Córdoba, where it was involved in the Pampean orogeny (Murra et al. 2016) (Fig. 2b). This succession consists of metapelites, marbles, para-amphibolites and metaconglomerates with detrital zircon ages peaking mainly at ca. 1.5–1.3 Ga and 1.3–1.0 Ga. This succession is supposed to have been sourced mainly from SE Laurentia (the Granite–Rhyolite and Grenville provinces of North America) but also cannibalistically from the Grenvillian basement of the WSP itself (Ramacciotti et al. 2015a, b; Rapela et al. 2016). These sediments were interpreted as deposited in the hypothetical Clymene Ocean over the eastern margin (present coordinates) of the MARA block (Fig. 3; Casquet et al. 2012a).

Another sedimentary sequence, long-known in the ESP and in NW Argentina, coeval in part with the Difunta Correa sequence, is the Puncoviscana Formation (Fig. 2b). Since metamorphic grade and deformation decreases northwards, this formation is better displayed in NW Argentina; it consists of a rhythmic alternation of slates and sandstones with abundant primary structures and early Cambrian trace fossils, subordinate carbonates, and minor volcanogenic rocks (Aceñolaza and Toselli 2009 and references therein). In the type section its deposition was dated at 537.3 ± 0.3 Ma (age of interbedded felsic tuff; Escayola et al. 2011). In the ESP, i.e., Sierra de Ancasti, Sierras de Córdoba, Sierra Norte de Córdoba, middle-to-high-grade metasedimentary rocks intensely affected by the Pampean orogeny were considered equivalents of the Puncoviscana Formation (Rapela et al. 1998; Escayola et al. 2007; von Gosen and Prozzi 2010). In the Sierras de Córdoba, the depositional age of the Puncoviscana Fm. is constrained by the oldest granite intruding it at ca. 545 Ma (Schwartz et al. 2008). The detrital zircon age pattern of the Puncoviscana Fm. is characterized by two main peaks at ca. 1000–1100 Ma and ca. 680–570 Ma which are typical of Gondwana sources such as Natal-Namaqua belt of South Africa (Kristoffersen et al. 2016) and the Brasiliano–Panafrican belts, respectively (Schwartz and Gromet 2004; Rapela et al. 2007, 2016). Therefore, this formation was probably deposited between ca. 570 and 537 Ma, in a forearc basin or as an accretionary wedge laid down along the eastern margin of the Clymene Ocean when it became active in the late Neopreoterozoic or the early Cambrian (Rapela et al. 2016; Casquet et al. 2018). The contact between the Ancaján Series and the Puncoviscana Formation in the ESP has been interpreted as a cryptic suture (Fig. 2b) (Casquet et al. 2018).

In NW Argentina, where the sedimentary relationships are preserved, middle Cambrian sedimentary rocks of the Mesón Group unconformably overlie the folded Puncoviscana Fm. (Tilcaric unconformity). The upper boundary of the Mesón Group is the Iruyic unconformity, overlain by the Early Ordovician Santa Victoria Group (e.g., Sánchez and Salfity 1999; Aceñolaza 2003). These two unconformities bracket the period of time that is the focus of this paper (i.e., late early Cambrian to the Cambrian–Ordovician boundary). The application of U–Pb detrital zircon geochronology (LA–ICP–MS and SHRIMP) has shown that many metasedimentary rocks in the ESP were in fact deposited within this same period (Collo et al. 2009; Drobe et al. 2011; Verdecchia et al. 2011; Cristofolini et al. 2012; Casquet et al. 2012b; Rapela et al. 2016) and were called "Post-Puncoviscan Series" by Rapela et al. (2016). These sequences underwent penetrative deformation and metamorphism during the Famatinian orogeny. The equivalents to these protoliths in the WSP and elsewhere in Argentina are the focus of this work.

Sampling

Clastic metasedimentary rocks and marbles were collected from three localities in the Western Sierras Pampeanas (WSP): (1) the eastern flank of the Sierra de Pie de Palo, and two small metamorphic outcrops named (2) Loma de Las Chacras and (3) Pan de Azúcar near the western flank of Sierra de Valle Fértil—La Huerta (Figs. 2a, 4; coordinates and mineral composition in Table 1). The Sierra de Pie de Palo is a large metamorphic block with Mesoproterozoic (Grenvillian) rocks and an Ediacaran to Cambrian siliciclastic and carbonate sedimentary cover that underwent strong deformation and low- to medium-grade metamorphism in the Early Ordovician (Fig. 4a, b, e.g., Baldo et al. 1998; Casquet et al. 2001; Vujovich et al. 2004; Rapela et al. 2010; Mulcahy et al. 2011). The upper stratigraphic unit consists of the Caucete and Nikizanga groups that, respectively, crop out on the western and eastern flanks of the range. Both are composed of schists, quartzites and marbles (Naipauer et al. 2010a; Mulcahy et al. 2011; Ramacciotti 2016). One quartzite from the Nikizanga Group was collected for detrital zircon U–Pb geochronology (SPP-22,043; Fig. 4b; Supplementary material). Two samples of graphitic marbles from the Nikizanga Group were collected for Sr-isotope determination (Table 2). Graphitic marble beds are a few-meters thick and show a rhythmic banding of ca. 2–20 mm thick dark grey and light grey bands. The latter are either calcite-rich (mainly calcite and minor muscovite, epidote and phlogopite) or graphite-rich (graphite, dolomite, quartz and plagioclase).

The Loma de Las Chacras is a small outcrop of metamorphic rocks tectonically separated from the Sierra de Valle Fértil-La Huerta by a large Cenozoic fault that obliquely cuts the Paleozoic orogenic grain (Figs. 2, 4c). It consists of a core of granulitic garnet–kyanite migmatites and garnet amphibolites overlain by low-grade garnet schist, quartzites and minor marbles, all affected by the Ordovician Famatinian orogeny (Vujovich 1994; Casquet et al. 2012c; Mulcahy et al. 2014). The depositional age of the low-grade metasedimentary rocks is unknown. Sr, C, and O-isotope composition of these marbles underwent post-depositional changes and are not suitable for isotope stratigraphy (Galindo et al. 2004; Naipauer et al. 2005; Peralta and Castro de Machuca 2010). Detrital zircons were separated from low-grade metasandstone interbedded with garnet schists (LCH-22049; Fig. 4c; Supplementary material).

The Pan de Azúcar is a small poorly known hill (ca. 2 km long) immediately west of the Sierra de Valle Fértil-La Huerta, and south of Loma de Las Chacras (Figs. 2, 4d). It consists of strongly retrogressed low-grade metamorphic rocks: orthogneisses, marbles, phyllites and quartzites. The Pan de Azúcar marbles were correlated with those of the Caucete Group based on lithological similarities (Bastías et al. 1984; Ramos and Vujovich 2000). Just as in the Loma de Las Chacras, the Sr, C, and O-isotope composition was obliterated by alteration processes (Galindo et al. 2004). Detrital zircons were concentrated from a quartzite (PAN-22001; Fig. 4d; Supplementary material).

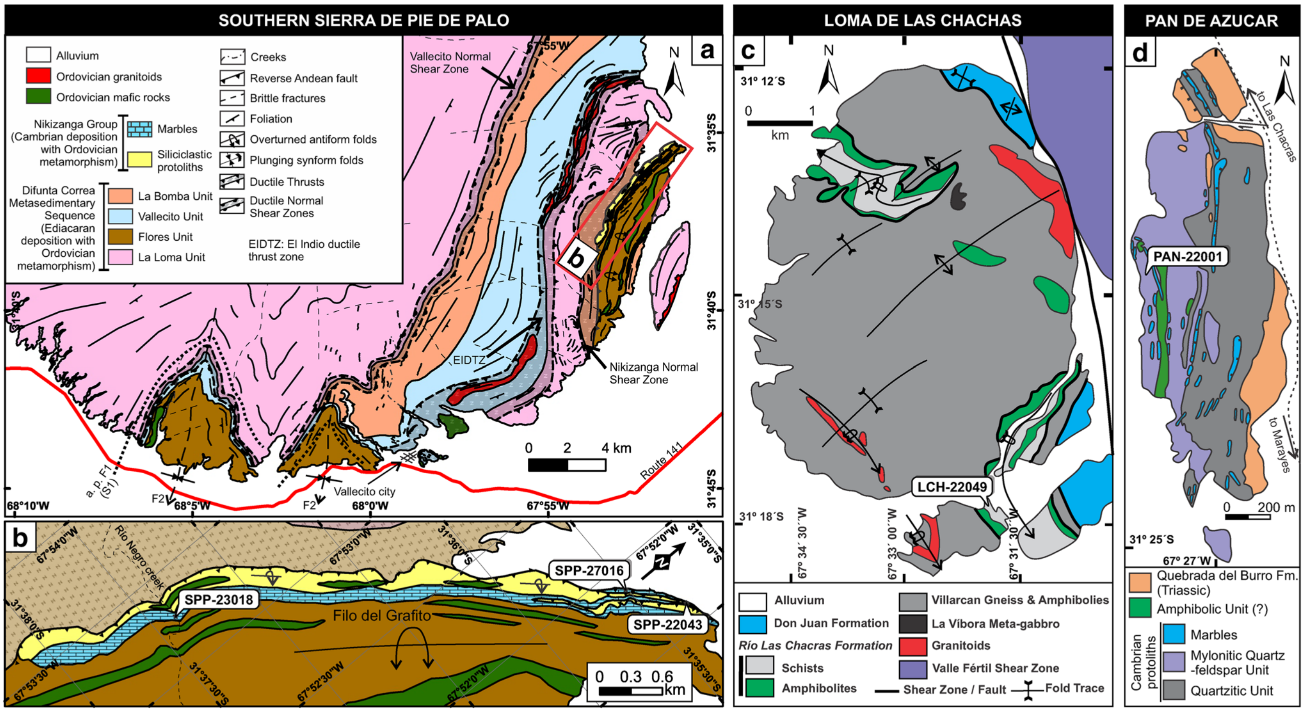

Fig. 4 Geological maps with location of the analysed samples (U–Pb SHRIMP zircon ages and Sr-isotope composition of marbles). **a** Geological map of the southern Sierra de Pie de Palo, **b** Inset of the Sierra de Pie de Palo in the Filo del Grafito area, where the Nikizanga Group crops out. **c** Geological map of Loma de Las Chacras (modified from Mulcahy et al. 2014), **d** Geological map of Pan de Azúcar, after Peralta and Castro de Machuca (2010)

Table 1 Location, rock type and mineral composition of analysed the samples

Sample	Latitude (S)	Longitude (W)	Rock type	Mineral composition
SPP-22043[a]	31° 32′ 15.3″	67° 51′ 26.9″	Quartzite	Qz + Pl + Kfs + Ms + Bt + Chl + Ep + Zrn + Opq
LCH-22049[a]	31° 18′ 05.5″	67° 31′ 36.2″	Metasandstone	Qz + Ms + Bt + Grt + Pl + Zrn
PAN-22001[a]	31° 24′ 31.9″	67° 27′ 40.5″	Quartzite	Qz + Pl + Ms + Chl + Cal + Zrn
SPP-27016[b]	31° 35′ 40.5″	67° 51′ 52.0″	Graphitic marble	Cal ± (Dol,Gr,Opq)
SPP-23018[b]	31° 37′ 22.6″	67° 53′ 14.2″	Graphitic marble	Cal ± (Dol,Gr,Opq)
PPL-46[b]	31° 36′ 04.0″	67° 52′ 23.0″	Graphitic marble	Cal ± (Qz,Ab,Ms,Gr,Opq)

[a]U–Pb SHRIMP detrital zircon geochronology

[b]Sr-isotope composition. Mineral abbreviations after Whitney and Evans (2010)

Analytical methods

Zircon was separated and concentrated using standard crushing, washing (to decant slime), heavy liquids, and paramagnetic separation procedures, as described by Rapela et al. (2007). The zircon-rich heavy mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the Temora reference zircon, sectioned approximately in half, and polished. Cathodoluminescence (CL) images were used to reveal the internal structures of the sectioned grains. The samples were analysed at the Research School of Earth Sciences of the Australian National University (Canberra) with SHRIMP RG in reconnaissance mode and with SHRIMP II for more precise geochronology, following methods as in Williams (1998) (Supplementary material). The reconnaissance mode consisted of four scans through the mass range for each analysis, and reference zircon analysis once every five unknowns, whereas the geochronological mode, used to better constrain the youngest population of zircons, consisted of six scans with full count times on the mass stations, and reference zircon analysis once every three unknowns. Data were reduced using Isoplot/Ex (Ludwig 2003). Common Pb corrections for ages older than

Table 2 Sr-isotope composition of marbles and significant chemical data

Sample	Rb ppm	Sr ppm	Mn/Sr	Mg/Ca	$^{87}Sr/^{86}Sr$	Error 2σ %
SPP-27016	4	713	0.128	0.014	0.709111	0.0004
SPP-23018	8	863	0.060	0.036	0.709027	0.0003
PPL-46*	n.d	941	0.034	0.005	0.709016	0.0004

Chemical analyses by whole-rock XRF (UCM)

*Galindo et al. (2004)

800 Ma were made using ^{204}Pb and, for younger ages, by means of ^{207}Pb (Williams 1998). For ages younger than 800 Ma $^{238}U/^{206}Pb$ ages were used, whereas for the older ones $^{207}Pb/^{206}Pb$ ages were preferred. Analyses with high common Pb ($>2.5\%$ for reconnaissance mode and $>1\%$ for geochron mode), discordance $>10\%$, and error age ($1\sigma>5\%$) were discarded.

Sr-isotope composition was determined from the calcite-rich bands of marbles at the Geochronology and Isotope Geochemistry Center of the Complutense University, Madrid (Table 2). To exclude contamination by other minerals, carbonate samples (ca. 30 mg) were leached in a 10% acetic acid solution and then centrifuged to remove the insoluble residue (Fuenlabrada and Galindo 2001). The solution was subsequently evaporated and then dissolved in 3 ml of 2.5 N HCl. Sr was separated using cation-exchange columns filled with BioRad® 50W X8 (200/400 mesh) resin. The procedural blank was less than 2 ng Sr. Sr-isotope composition was determined on an automated multicollector Phoenix HCT040 (by ISOTOPx, UK) thermal ionization mass spectrometer (TIMS) and $^{87}Sr/^{86}Sr$ values were normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194. The NBS-987 standard was routinely analysed along with our samples and gave an average $^{87}Sr/^{86}Sr$ value of 0.710246 ± 0.000020 (2σ, $n=10$). All the $^{87}Sr/^{86}Sr$ values reported here had within-run statistics that were at or below 3.0×10^{-6} (2σ).

U–Pb SHRIMP detrital zircon ages

Zircon grains from the three analysed samples show similar characteristics and are generally ca. 100 µm in length and have variable shapes, from euhedral prisms with subrounded or broken edges (due to sedimentary transport) to equant forms (Fig. 5). Most grains show internal oscillatory zoning and some have xenocrystic cores. No post-depositional metamorphic rims were recognized. Dating was focused on grains with oscillatory zoning.

Sierra de Pie de Palo (SPP-22043)

Sixty grains were analysed in reconnaissance mode (Supplementary material), seven of which were discarded due to high common Pb or discordance; they were not considered as significant ages nor included in the probability density plot. The remaining analyses range from 462 to 2753 Ma with a main peak at ca. 535 Ma, and subordinate groups of ages at ca. 680, 1040 and 2040 Ma (Fig. 6). The younger group consists of ages from ca. 460 to 560. The sample was then re-run in geochronological mode to better constrain the maximum depositional age. Thirty-two analyses were carried out in this mode, three of which correspond to Mesoproterozoic ages, whereas the younger ones ranged from 437 to 608 Ma

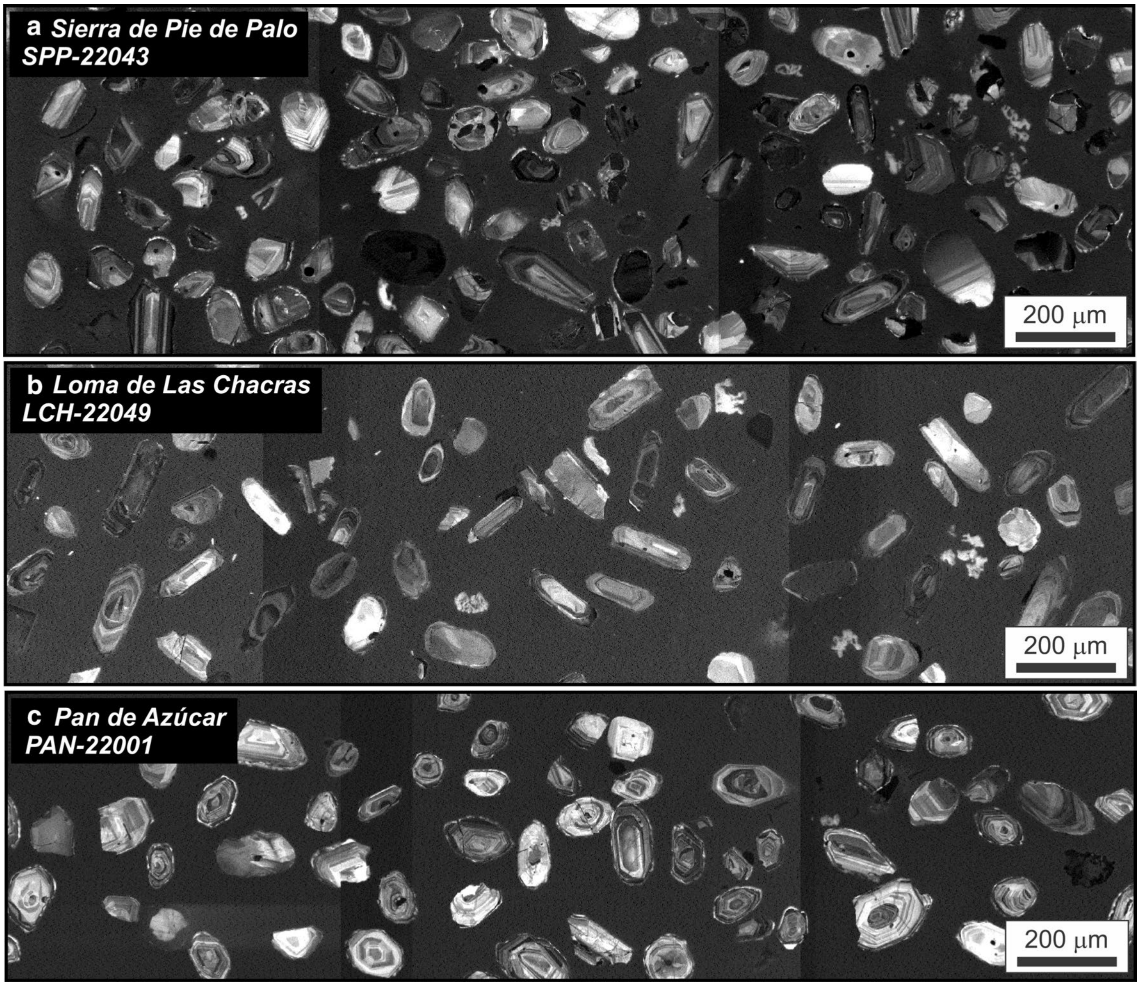

Fig. 5 Cathodoluminiscence images of zircons from the analysed samples showing morphology and internal structures

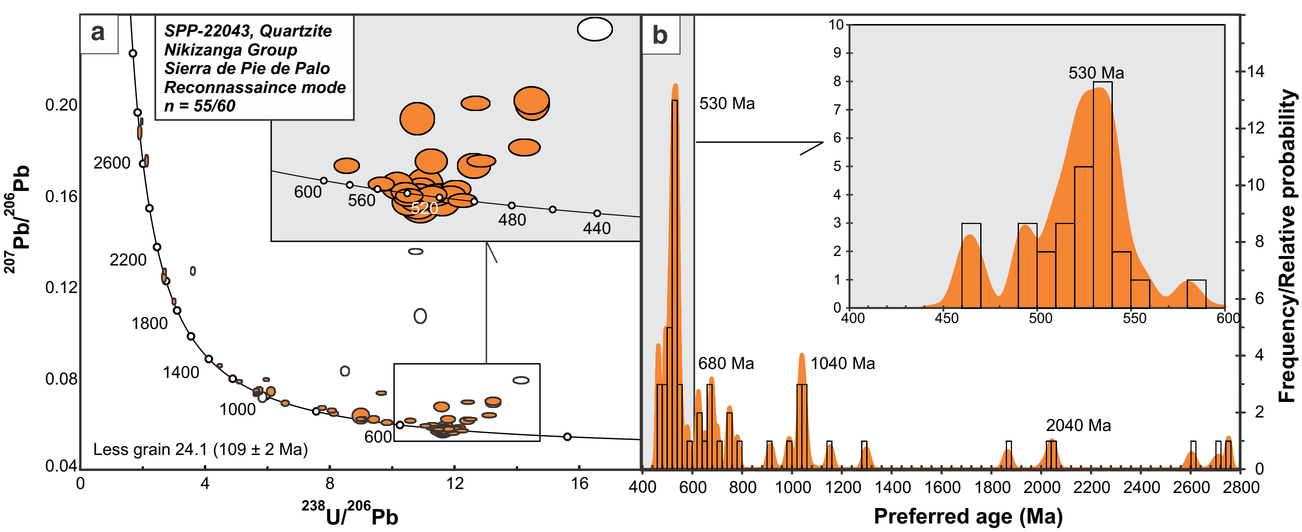

Fig. 6 U–Pb zircon geochronological data from sample SPP-22043 (quartzite; Sierra de Pie de Palo obtained in reconnaissance mode, **a** Tera–Wasserburg diagram showing variable degree of concordance in younger ages. White ellipses were discarded due to high common Pb or discordance, **b** probability density plot showing the main populations of zircons. Note the high variability of concordance of the younger ages

(Fig. 7a, b, c). Seven of the latter ages were discarded due to high common Pb or discordance, and were not included in the probability density plot. Thus, the youngest concordant age is 494 ± 4 Ma, followed by two concordant spots at 496 ± 7 and 506 ± 6 Ma and an age population ($n = 13$) peaking at 525 ± 3 Ma (MSWD = 0.73; $P = 0.72$; Fig. 7d). Zircons from this group are euhedral prisms with variably rounded edges (due to transport) and internal oscillatory zoning. They have U contents between 104 and 583 ppm, Th between 13 and 281 ppm, and Th/U ratios between 0.04 and 0.75, mostly > 0.4. Zircon morphology, internal structures, and Th/U ratios suggest an igneous origin for most of these younger grains. As a general value we consider Th/U > 0.1 as igneous origin and Th/U < 0.1 as metamorphic origin following Rubatto (2002, 2017) although this is not always applicable (e.g., Grant et al. 2009; Marshall et al. 2011). Because of expected but unresolved Pb loss due to Famatinian metamorphic overprint the maximum depositional age of this sample must probably lie between 525 ± 3 Ma (youngest peak) and 494 ± 4 Ma (youngest single age).

Loma de Las Chacras (LCH-22049)

Sixty grains were analysed in reconnaissance mode, six of which were discarded due to high discordance or common Pb and were not included in the probability density plot. Ages range from 501 to 2673 Ma with a main group of dates between 501 and 800 Ma, distributed in peaks

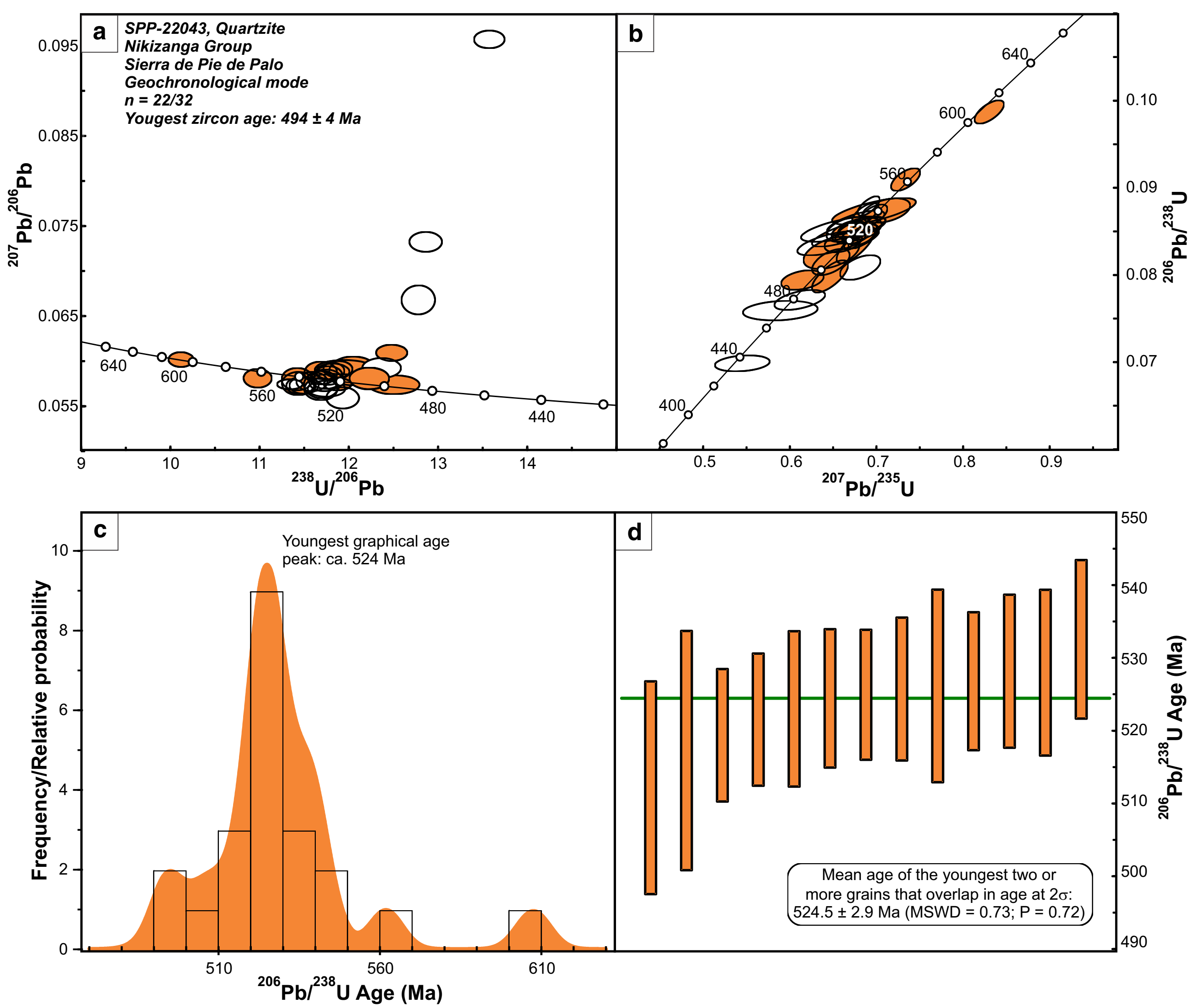

Fig. 7 U–Pb zircon geochronological data obtained in geochron mode from sample SPP-22,043 (quartzite; Sierra de Pie de Palo), **a, b** Tera–Wasserburg (**a**) and Wetherill (**b**) diagrams showing high concordance of the younger ages, except for seven grains (white ellipses) which were discarded due to high common Pb or discordance, **c** Probability density plot of younger zircons, **d** Mean $^{238}U/^{206}Pb$ ages of the youngest peak

at ca. 540, 600 (the main peak) and ca. 800 Ma (Fig. 8a). Paleoproterozoic zircons with $^{207}Pb/^{206}Pb$ ages between 1860 and 2101 Ma define a discordia in the Wetherill diagram with a lower intercept at 1269 ± 69, and an upper intercept at 2167 ± 39 (MSWD = 1.11) suggesting that the source of the older zircons was a Paleoproterozoic crust re-worked in the middle-to-late Mesoproterozoic. The younger zircons range from 501 to 549 Ma and correspond to variably round to prismatic grains with internal structures from oscillatory zoning to unzoned. They have U contents between 85 and 825 ppm, Th = 11–305 ppm and Th/U = 0.10–1.03, i.e., commonly igneous values. The youngest spot yields 501 ± 8 Ma and is followed by two spots at 511 ± 5 and 535 ± 6 Ma. Because some unresolved Pb loss cannot be excluded because of the Famatinian thermal overprint the latter ages are minimum values. If Pb loss was small we can infer a maximum depositional age for this sample between ca. 501 Ma and ca. 535 Ma.

Pan de Azúcar (PAN-22001)

Fifty-two analyses were carried out in this sample in reconnaissance mode, four of which were discarded due to high discordance and one due to a damaged grain tip (spot 31; Supplementary material), and these were not included in the probability density plot. Accepted ages range from 527 to 1877 Ma with a main peak at ca. 1250 Ma and a smaller peak at ca. 1115 Ma. The two youngest zircons yielded 527 ± 6 and 529 ± 6 Ma, and three older spots yield 544, 656 and 805 Ma. Only two grains are Paleoproterozoic, at ca. 1.83 and 1.88 Ga (Fig. 8b). Zircons have U contents between 58 and 799 ppm, Th between 22 and 536 ppm and Th/U ratios between 0.15 and 0.99. The younger spots have

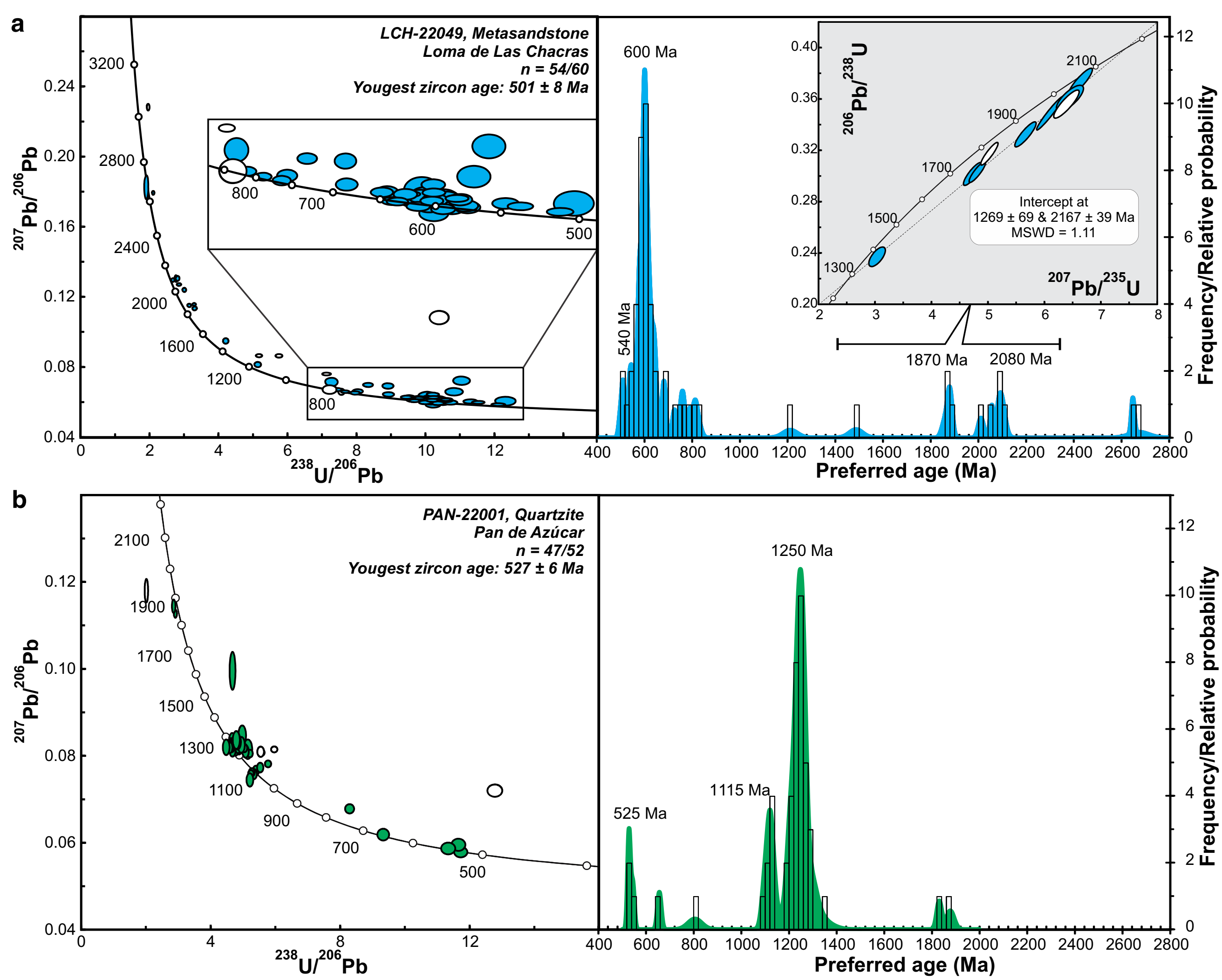

Fig. 8 Tera–Wasserburg and probability density plots from sample LCH-22049 (metasandstone; Loma de Las Chacras) (**a**) and sample PAN-22001 (quartzite; Sierra de Pan de Azúcar) (**b**)

low common Pb contents. Younger grains are prismatic and rounded because of sedimentary transport. They show internal oscillatory zoning and have Th/U ratios between 0.22 and 0.63 suggesting an igneous origin. Since we could expect some unresolved Pb loss we infer that the maximum depositional age of the quartzite is 527 ± 6 Ma or perhaps somewhat older.

Sr-isotope composition of marbles

Two samples of graphitic marbles from the Nikizanga Group (SPP-27016 and SPP-27,018) examined under XRD and microscope consist mainly of calcite with accessory amounts of dolomite, quartz and graphite. They yielded $^{87}Sr/^{86}Sr$ values of 0.70903 and 0.70911, similar to that of sample from the same stratigraphic group PPL-46 ($^{87}Sr/^{86}Sr$ = 0.70902; Galindo et al. 2004) (Table 2). The three values are coincident within errors and all passed the chemical screening criteria (e.g., Melezhik et al. 2001) suggesting that carbonates underwent minor post-depositional modification. Moreover, the two samples show high Sr and very low Rb contents (Table 2) implying that post-deposition radiogenic contribution of ^{87}Rb to the Sr-isotope composition is small.

The Sr-isotope composition of marbles from Pan de Azúcar and Loma de Las Chacras was modified by alteration processes and cannot be used to constrain the depositional age (Galindo et al. 2004; Naipauer et al. 2005). However, the Sr-isotope composition of the Nikizanga Group marbles ($^{87}Sr/^{86}Sr$ between 0.70903 and 0.70911) fits the compiled seawater Sr-isotope compositions (Veizer et al. 1999; Halverson et al. 2010; McArthur et al. 2012) between 510 and 480 Ma on both sides of the maximum $^{87}Sr/^{86}Sr$ value of ca. 0.709200 that was reached at ca. 500 Ma (Fig. 9). This range (510 − 480 Ma) is compatible with the maximum U–Pb zircon depositional ages yielded by sample SPP-22043 from the same unit and the other two samples analysed in this work.

Discussion

Age of deposition and regional correlation of the WSP Cambrian sequences

Detrital zircon geochronology constrains the maximum age of sedimentation of the WSP clastic metasedimentary rocks studied here to between ca. 535 ± 6 Ma and 494 ± 4 Ma, i.e., the minimum and maximum age estimates recovered from the three samples. The range can be best bracketed between a peak value at 525 ± 3 and 494 ± 4 Ma based on sample SPP-22,043. Sr-isotope dating of Nikizanga Group marbles (between ca. 510 and 480 Ma) is compatible with the younger ages yielded by zircons. Sedimentation most probably took place between the late early Cambrian (ca. 525 Ma; late Terreneuvian) and the late Cambrian (ca. 490 Ma; Furongian) (International Chronostratigraphic Chart, 2017; Cohen et al. 2013). This interpretation is compatible with the absence in all the successions of zircons that can be reliably ascribed to derivation from Famatinian granitoids (≤ 490 Ma; Pankhurst et al. 2000) and with the end of the Pampean orogeny and related collisional magmatism at ca. 520 Ma (Casquet et al. 2018). Detrital zircon age patterns and maximum depositional ages similar to those of the WSP sequences described here have been recognized in other metasedimentary successions in Argentina. They are shown in Fig. 11 separated into two groups, according to whether they contain or not detrital grains with Paleoproterozoic Rio de la Plata craton ages. Overall the samples show three main groups of detrital zircon ages: early Cambrian (Pampean orogeny), Neoproterozoic (Brasiliano orogeny) and Mesoproterozoic (Grenville orogeny). A group of samples further show grains with Paleoproterozoic ages assigned to the Rio de la Plata craton (between ca. 2.0 and 2.2 Ga; Rapela et al. 2007; see Fig. 11).

Marbles similar to those of the Nikizanga Group, Pan de Azúcar and Loma de Las Chacras were also recognized in the thick carbonate succession of the upper Caucete Group (El Desecho and Angacos formations; Naipauer et al. 2010b) in the western flank of the Sierra de Pie de Palo. In fact, the Caucete Group marbles were correlated on the basis of their Sr-isotope composition with the Nikizanga Group marbles by Galindo et al. (2004). U–Pb LA–ICP–MS detrital zircon ages obtained by Naipauer et al. (2010b) in the lower siliciclastic layers of the Caucete Group (El Quemado and La Paz formations) record two main groups of ages between ca. 1000 and 1450 Ma, and a minor group between ca. 550 and 530 Ma. Naipauer et al. (2010b) suggested a minimum $^{207}Pb/^{206}Pb$ age of ca. 550 Ma for the El Quemado Fm. (sample QLPcz2), which was interpreted as the maximum depositional age of the Caucete Group. However, a weighted average $^{238}U/^{206}Pb$ age of 517 ± 10 Ma (n = 12) was recalculated for the youngest zircons of sample QLPcz2 by Amato and Mack (2012). Thus, the maximum depositional age of the El Quemado Fm. could be much younger and within the range of ages argued above for the Nikizanga Group quartzite. Moreover, the youngest detrital zircons from sample QLPcz2 have morphology and internal texture features similar to those of our samples. Such a correlation has important paleogeographic consequences (see below). Cambrian marbles have been found in other areas of the WSP, e.g., Sierra de El Gigante and Sierra de Umango (Fig. 2); (Galindo et al. 2004; Varela et al. 2001) as well as in Patagonia (Mina Gonzalito complex; Varela et al. 2014) indicating that coeval carbonate sedimentation took place over a wide area in the late early to the late Cambrian times (triangles in Fig. 10).

Provenance of siliciclastic units and paleogeographic implications

Comparison of the detrital zircon age patterns of the WSP studied in this contribution with those of Patagonia, the ESP, NW Argentina, and the Tandilia and Ventania systems suggest that a continuous sedimentary basin with similar sedimentary sources probably existed over a very large area of SW Gondwana between the end of the Pampean orogeny (ca. 520 Ma) and the beginning of Famatinian subduction (ca. 490 Ma). The source areas of the correlated sequences mentioned above can be attributed to the Pampean belt (520–545 Ma), the Brasiliano/Panafrican orogen (SE Brazil; 570–700 Ma), the Natal-Namaqua belt (southern Kalahari craton; 1.0–1.2 Ga) and the Río de la Plata craton (Paleoproterozoic ages; 2.05–2.2 Ga) (Fig. 12). Cannibalization of both the Puncoviscana Formation and the Difunta Correa Metasedimentary Sequence may also have played a role providing Mesoproterozoic zircons between 1.0 and 1.45 Ga (Ramacciotti et al. 2015a; Rapela et al. 2016 and references therein). Both formations were thoroughly involved in the Pampean orogeny.

Torsvik and Cocks (2011, 2013) suggested that an extensive shelf existed along the SW Gondwana margin in the middle Cambrian. This model was used by Casquet et al. (2012b) to explain similarities in the detrital zircon age patterns of the post-Pampean metaasedimentary successions of the ESP and the Tandilia–Ventania. We hypothesize here that the shelf also extended to the WSP, Patagonia and NW Argentina (Fig. 12a, b). In this hypothesis, the WSP probably constituted the outer (deepest) part of the basin. The scarcity or absence of marble or calc-silicate rocks of late early-to-late Cambrian age in the ESP and NW Argentina (Mesón Group) probably resulted from an inner position in the platform, i.e., closer to the coast line, where siliciclastic sedimentation prevailed (Augustsson et al. 2011). Further west (i.e., seaward) carbonate sedimentation took over, as is common in the outer part of mixed carbonate–siliciclastic shelves (e.g., Yancey 1991). Greco et al. (2017) hypothesized that the late early Cambrian metasedimentary rocks of the North Patagonian Massif (e.g., the Nahuel Niyeu basin), which we interpret here as part of the SW Gondwana shelf, were laid down in a subduction-related extensional forearc basin. However, no evidence whatsoever of a subduction-related magmatic arc or of deformation and metamorphism of late early Cambrian age is recognized in the extensive Sierras Pampeanas or NW Argentina regions. Moreover, in the late early-to-middle Cambrian (520 – 500 Ma), anorogenic rift-related magmatism was widespread in the Sierra de la Ventana and its South African pre-Atlantic counterpart, the Saldania belt (Rozeendal et al. 1999; Da Silva et al. 2000; Rapela et al. 2003).

Verdecchia et al. (2011) divided the Cambrian ESP metasedimentary successions according to whether or not they contained zircons with ages typical of the Río de la Plata craton (Paleoproterozoic; 2.05–2.2 Ga). This craton reached its present position east of the Sierras Pampeanas by large-scale right-lateral displacement along the Córdoba fault between 520 and 510 Ma (Rapela et al. 2007) (Fig. 12a, b). The rising Pampean orogenic belt probably hindered the access of detritus from the Río de la Plata craton to the shelf in the early stage. Later, sometime between 520 and 510 Ma, the orographic barrier disappeared, at least part of it, and zircons from the craton could reach the sedimentary basin in the west (Verdecchia et al. 2011) (Fig. 12c, d). The first group (older) has abundant Mesoproterozoic zircons and a lack of Río de la Plata craton ages; it is represented by the Caucete Group, the Pan de Azúcar, three units from the ESP (Negro Peinado Fm., Sierra de Ambato, and Sierra de Valle Fértil) and the North Patagonian Massif succession (Fig. 11). The second group is characterized by the presence of zircons with Río de la Plata craton ages (2.05–2.2 Ga), dominant Pampean and Brasiliano ages, and a subordinate Mesoproterozoic component. Sequences of this group are represented by the Nikizanga Group, the Ventania and Tandilia sediments, the Mesón Group, two ESP units (Sierra de Los Llanos and Achavil Fm.) and Loma de Las Chacras (Fig. 11). We propose that after final docking of the Río de la Plata craton the shelf sediments were mainly sourced from exposed Pampean orogenic belt and that a Brasiliano component gradually increased in importance as the Pampean belt was eroded and eventually covered by sediments (Fig. 12c, d).

The Cambrian continental platform recognized in Argentina probably extended northwards to Peru and Bolivia and south westwards to SW Africa (Chew et al. 2007; Barnett et al. 1997). The Old Marañon complex of Peru contains migmatites of ca. 478 Ma (leucosome igneous zircons) whose sedimentary protoliths were deposited at ca. 530 Ma (Chew et al. 2007). Although detrital zircon ages were not determined in these migmatites, Ordovician granitoids and the Young Marañon complex contain abundant zircons of ca. 520–500 Ma, ca. 600–650 Ma and 900–1300 Ma (Chew et al. 2007, 2008; Cardona et al. 2009). These ages are similar to those of the Argentinian late early-to-late Cambrian metasedimentary rocks described in this work. Cardona et al. (2009) invoked a Pampean age basement hidden below the Peruvian Andes to explain the detrital zircon ages, although that basement has not yet been found. An alternative explanation is that the sediments were transported from the south (Pampean orogenic belt), along the western margin of the Amazonia craton. Similar detrital zircon age patterns to those of the Marañon complex were also recognized in

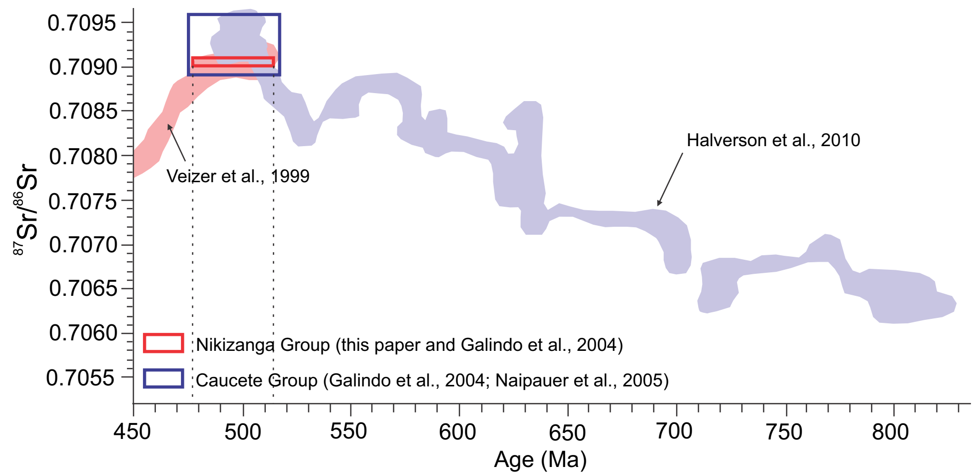

Fig. 9 $^{87}Sr/^{86}Sr$ ratios of Neoproterozoic to early Paleozoic seawater carbonates after compilation of Veizer et al. (1999) and Halverson et al. (2010). The Nikizanga Group marbles with $^{87}Sr/^{86}Sr$ ratios of 0.70903–0.70911 suggest a deposition between ca. 510 and 480 Ma, coeval with the Caucete Group

the Ordovician sedimentary rocks of the Arequipa Massif of southern Peru and Bolivia (Reimann et al. 2010).

In the Saldania belt (South Africa) (Fig. 12), the Kango Group comprises a lower carbonate–turbiditic association (Goegamma Subgroup) and an upper clastic succession (Kansa Subgroup). The latter is represented by immature sandstones and conglomerates which were interpreted as beach, fluvial and alluvial fans deposits (Le Roux and Gresse 1983). They have detrital zircon ages of ca. 520 Ma and were probably deposited in the early Cambrian (Barnett et al. 1997). Moreover, the Upper Nama Group (Fish River Subgroup) in Namibia corresponds to shallow marine and fluvial sediments (Germs 1974, 1983; Geyer 2005) with a maximum depositional age of ca. 530 Ma (detrital zircon ages; Blanco et al. 2011). All these African sediments may correspond to the internal part, i.e., near to the shoreline, of the shelf inferred here (Fig. 12a, b).

Implications for the Precordillera/Cuyania terrane

As previously explained, there are two contrasting hypotheses for the origin of the Precordillera terrane and of its greater version, the Cuyania composite terrane of Ramos et al. (2004 and references therein). Either it was an allochthonous terrane in relation to Gondwana or an autochthonous part of the proto-Andean margin of Gondwana during the early Paleozoic (see Finney 2007 and references therein). With the evidence provided in this contribution we can now better constrain the extent of the Cuyania terrane in the WSP. In the allochthonous model, at the time of deposition of the WSP sequences (probably mainly between ca. 525 and 490 Ma), the hypothetical Cuyania terrane was an isolated block drifting across the Iapetus Ocean. Its source was allegedly the Ouachita embayment in the Appalachian margin of Laurentia from which it rifted at ca. 540 Ma to further collide with Gondwana in the Ordovician (e.g., Astini et al. 1995; Keller 1999; Thomas et al. 2012). A source of

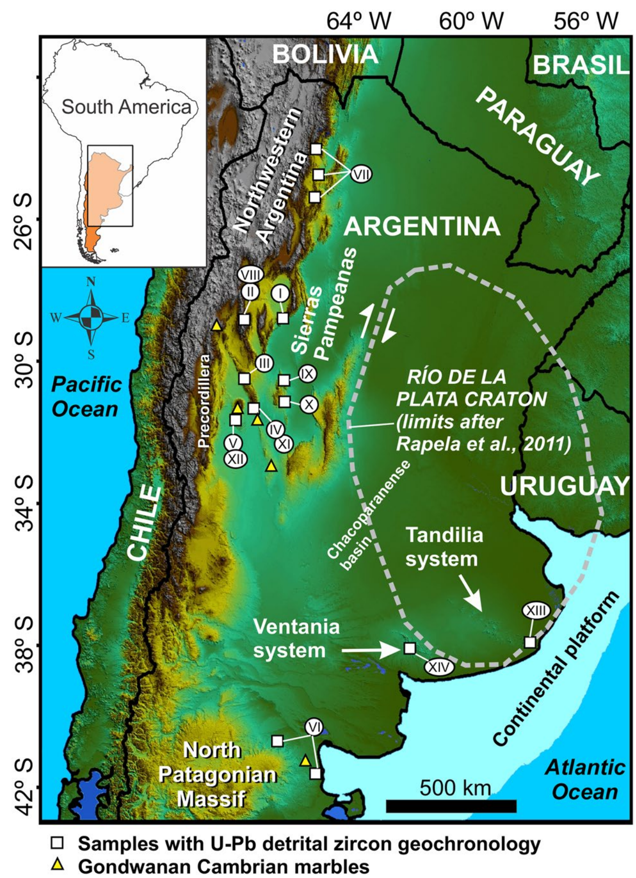

Fig. 10 Location of the late early-to-late Cambrian clastic metasedimentary successions from Patagonia to northwestern Argentina. Roman numerals refer to samples with detrital zircon ages shown in Figs. 11 and 12. Boundary of the Rio de la Plata craton is according to Rapela et al. (2011)

Cambrian zircons might be found in the igneous rocks of the Oklahoma fault system, i.e., the northern boundary of the Ouachita embayment, where igneous rocks between 540 and 530 Ma are found (Thomas et al. 2012 and references

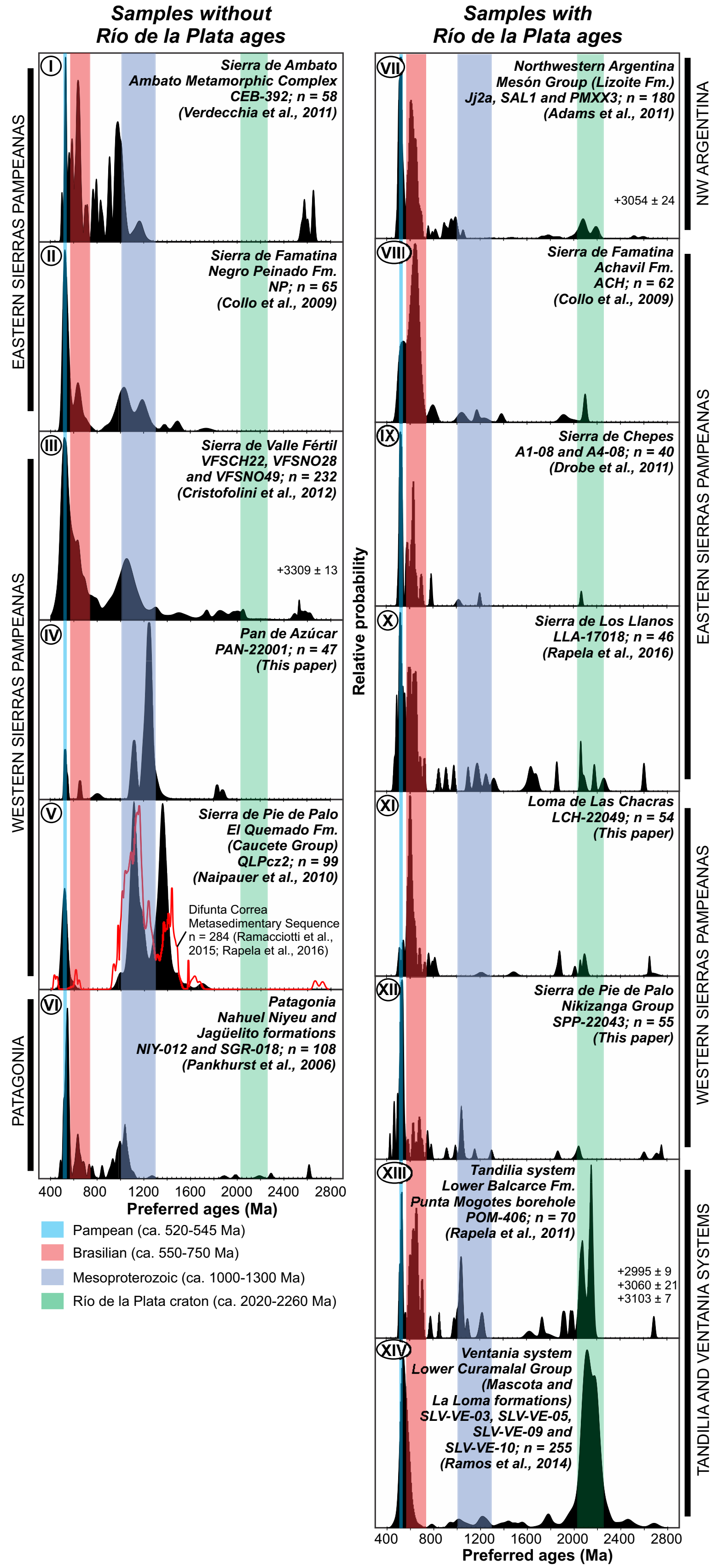

Fig. 11 Probability density plots of U–Pb detrital zircon ages from the late early to the late Cambrian clastic metasedimentary rocks (Roman numerals correspond to samples location in Fig. 10). Left-hand column: samples with no zircons with Río de la Plata craton ages; right-hand column: samples with Río de la Plata age zircons

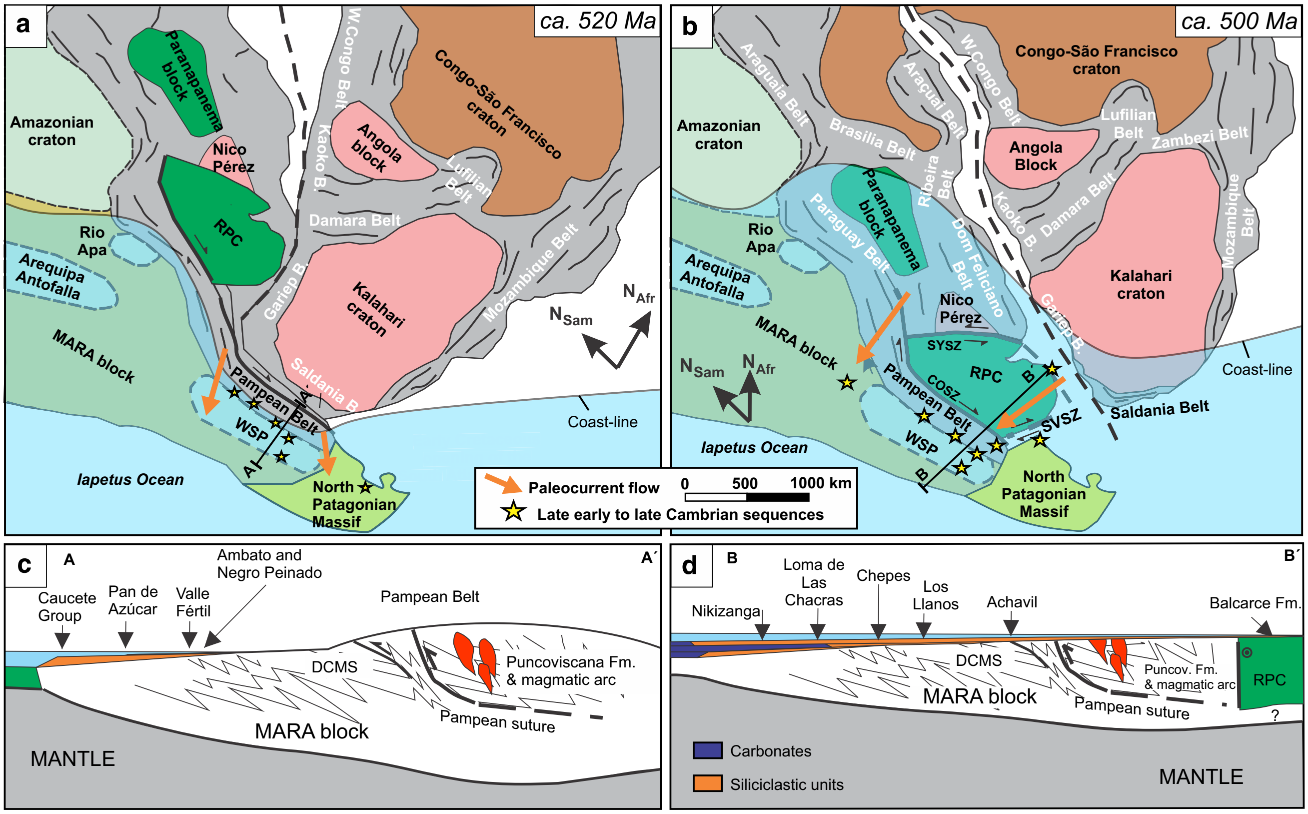

Fig. 12 **a, b** Paleogeographic reconstruction of the main cratonic blocks and orogenic belts involved in SW Gondwana in the late early (ca. 520 Ma) to the middle/late Cambrian (500 Ma) based on Trindade et al. (2006), Rapela et al. (2007) and Frimmel et al. (2011). The Río de la Plata craton was displaced right-laterally to a position close to present becoming a source for zircons to the continental platform on the west. Arrows: detrital zircon sources. Coast line of the continental platform according to Torsvik and Cocks (2013). **c, d** Schematic cross sections (A–A´ and B–B´ in **a** and **b**, respectively) through the continental margin corresponding to current Sierras Pampeanas. DCMS: Difunta Correa Metasedimentary Sequence; WSP: Western Sierras Pampeanas; RPC: Río de la Plata cratón

therein). However, the latter ages are older than the well-defined group of grains of ca. 525 Ma found in our samples. This argument can be extended to the 517 ± 10 Ma group of detrital zircon grains that constrain the maximum sedimentation age of the Caucete Group—allegedly part of the composite Cuyania terrane (review in Ramos 2004). By this time the Precordillera/Cuyania terrane had already drifted away from Laurentia. In consequence in the allochthonous hypothesis the source of Cambrian zircons found in our samples (and in the Caucete Group) had to be in the Precordillera/Cuyania basement itself: such a source has not so far been identified. In the other model, which postulates that the WSP basement was part of the SW Gondwana margin in the early Cambrian, the source of Cambrian zircons contained in the Caucete Groups and in the clastic metasedimentary units on the east can be easily found in the Pampean orogenic belt, where ages between 520 and 545 Ma are widely recorded (e.g., Rapela et al. 1998; Schwartz et al. 2008; Iannizzotto et al. 2013; von Gosen et al. 2014; Casquet et al. 2018). Thus, the Caucete Group and the Cambrian clastic metasedimentary rocks studied here can be correlated. Mesoproterozoic zircons of the Caucete Group (Sierra de Pie de Palo) between ca. 1.0 and 1.45 Ga attributed to Laurentian sources by Naipauer et al. (2010b) are interpreted here as derived from the re-working of the underlying Difunta Correa Metasedimentary Sequence—and/or its Grenvillian basement in the WSP-, where such ages comprise the main zircon populations (Ramacciotti et al. 2015a; Rapela et al. 2005, 2016).

Conclusions

The post-Pampean (≤ 525 Ma) clastic metasedimentary rocks and marbles of the WSP were variably overprinted by the Ordovician Famatinian orogeny (metamorphism and magmatism) at ≤ 490 Ma. Detrital zircon ages together with the Sr-isotope composition of marbles suggest that deposition took place mainly between ca. 525 and 490 Ma.

Between the end of the Pampean orogeny at ca. 520 Ma and the beginning of the Famatinian subduction (ca.

490 Ma) an extensive mixed carbonate–siliciclastic platform existed on the SW Gondwanan margin of the Iapetus Ocean extending at least from Patagonia to NW Argentina. The continental margin was thus passive for approximately 30 myrs. This platform formed in part on the formerly accreted MARA block and probably extended as far east as the Rio de la Plata craton.

Detrital zircons were variably sourced from the erosion of the uplifted early Cambrian Pampean orogenic belt, from the Neoproterozoic Brasiliano orogen and from re-working of the Ediacaran to early Cambrian Difunta Correa Metasedimentary Sequence and the WSP Grenvillian basement. Final denudation of the Pampean orogen eventually allowed input to the basin of detritus from the Paleoproterozoic Río de la Plata craton.

Detrital zircon ages and Sr-isotope compositions of the WSP successions support the hypothesis that the WSP were already attached to SW Gondwana in early Cambrian times as part of the MARA block. Therefore, the WSP were part of the upper plate during Famatinian subduction, and not part of the allegedly allochthonous Cuyania/Precordillera terrane (lower plate) as previously thought.

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