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Identifying Laurentian and SW Gondwana sources in the Neoproterozoic to Early Paleozoic metasedimentary rocks of the Sierras Pampeanas: Paleogeographic and tectonic implications

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ABSTRACT

The provenance of Neoproterozoic to Early Paleozoic sedimentary rocks in the Sierras Pampeanas has been established using U–Pb SHRIMP age determination of detrital zircons in twelve metasedimentary samples, with supplementary Hf and O isotope analyses of selected samples. The detrital zircon age patterns show that the western and eastern sectors of the Sierras Pampeanas are derived from different sources, and were juxtaposed during the Early Cambrian 'Pampean' collision orogeny, thus defining initiation of the supercontinent stage of southwestern Gondwana. The Western Sierras Pampeanas (WSP), which extend northwards to the southern Puna (Antofalla) and the Arequipa Massif (Peru), constitute a single large continental basement of Paleoproterozoic age — the MARA block — that was reworked during the Grenvillian orogeny. The MARA block probably extends eastwards to include the Río Apa block (southern Brazil), but in this case without a Mesoproterozoic overprint. Detrital zircons from the WSP and Antofalla yield age peaks between 1330 and 1030 Ma, remarkably similar to the range of ages in the Grenville province of eastern Laurentia. The WSP Neoproterozoic sedimentary cover to this basement shows the same 1330–1030 component, but also includes important 1430–1380 Ma zircons whose juvenile Hf and O isotopic signatures strongly suggest derivation from the Grenville and the Southern Granite–Rhyolite provinces of eastern Laurentia. In contrast the Eastern Sierras Pampeanas metasedimentary rocks have a typically bimodal detrital zircon pattern with peaks at ca. 1000 and 600 Ma, which respectively indicate sources in the Natal–Namaqua belt and the East African orogen and/or the Dom Feliciano belt of SE Brazil and Uruguay. Sedimentary rocks in the Eastern Sierras Pampeanas and Patagonia deposited during the Late Early Cambrian–Early Ordovician interval, after the Pampean orogeny, have detrital patterns common to many sectors along the Terra Australis orogen, reflecting increasingly dominant input to the Paleozoic basins from the Neoproterozoic to Early Cambrian orogenic belts of the Gondwana margin.
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1. Introduction

The origin, size and accretion time of the different continental blocks of southwest Gondwana are still subject to debate, largely due to the sparse and scattered exposure of pre-Mesozoic basement. Nevertheless, it can be shown that a very large sector of the central and southern Andes is built on Paleoproterozoic basement overprinted by Mesoproterozoic (Grenville-age) events. This includes the Arequipa massif of Peru and the Western Sierras Pampeanas (Loewy et al., 2004; Casquet et al., 2012a, Fig. 1). The apparently similar Paleoproterozoic age and isotope composition of these two blocks, together with the Río Apa sector to the west in Brazil, led to the hypothesis that they formed a common continental mass before the onset of the Mesoproterozoic orogenies — the MARA block (after Sierra de Maz, Arequipa, and Río Apa; Casquet et al., 2009, 2012a). Part of this super-block was amalgamated with Amazonia at ca. 1.3 Ga or earlier, and then with eastern Laurentia between 1.3 and 1.0 Ga during the Grenville orogeny (we use the term Grenvillian to include tectono-magmatic processes in this interval, as in the Grenville province of Laurentia; Goodge et al., 2004, 2008 and references therein). Note that the continental block relationships depicted in Fig. 1 differ in several respects from those proposed by other authors (e.g., Ramos et al., 2010) who consider the northwestern Sierras Pampeanas to be separated from the southern sector of the Arequipa–Antofalla block by

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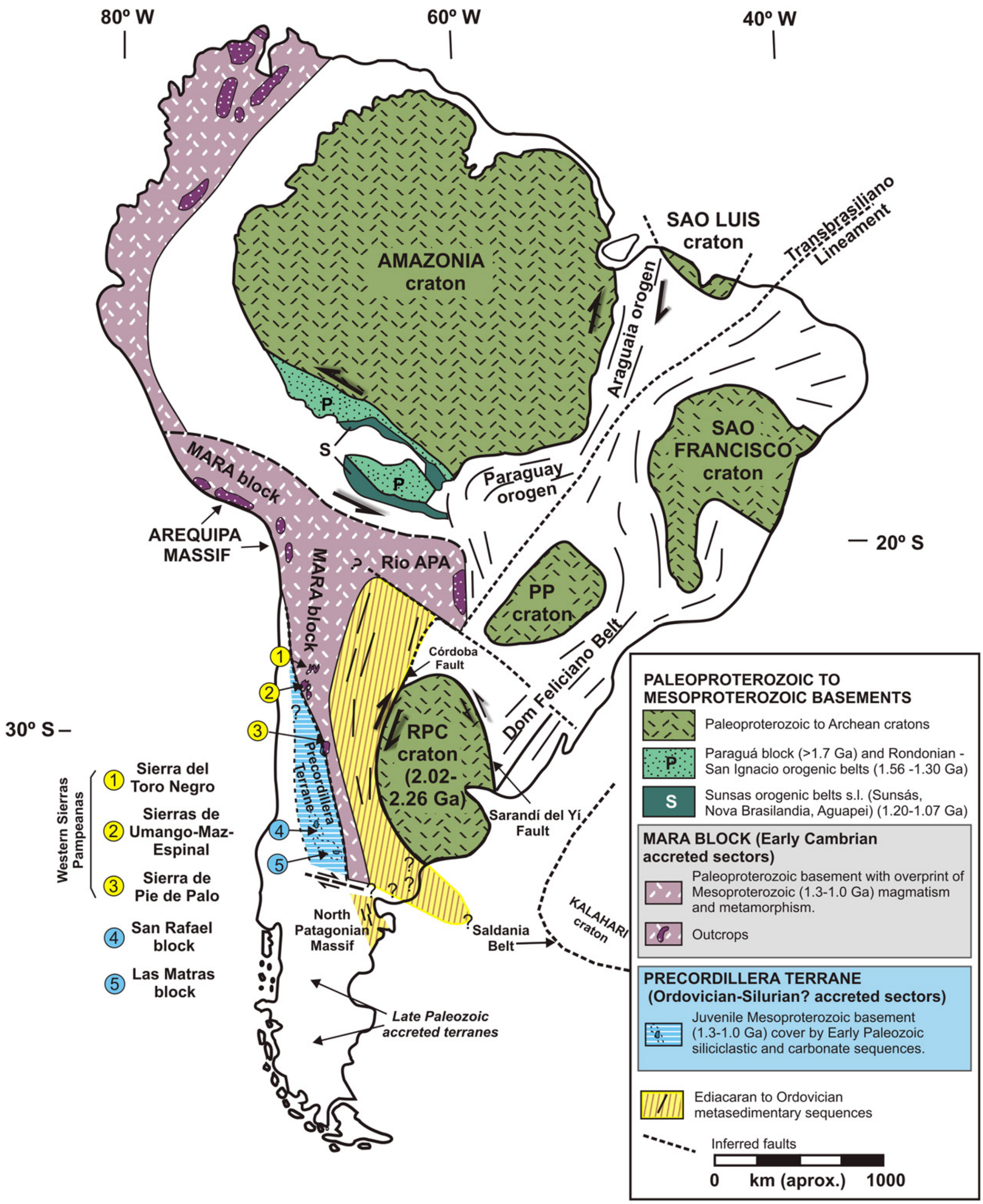


Fig. 1. General map of Precambrian cratons and Early Paleozoic accreted blocks and terranes of southern South America (modified from Casquet et al., 2012a, and references therein). The main localities of Mesoproterozoic basement outcrops in the Western Sierras Pampeanas and other southern provinces are indicated. PP: Paranapanema craton; RPC: Río de la Plata craton.

ophiolite remnants. However, recent geochronological and geochemical studies of these mafic and ultramafic rocks demonstrate that they are not oceanic rocks but Early Paleozoic subduction-related suites (Zimmermann et al., 2014).

The Sierras Pampeanas (Fig. 2), exposed by uplift in the modern 26°–33° S flat-slab segment of the Nazca plate up to 900 km away from the trench, gives a unique opportunity to test models of lateral accretion of the continent. Possibly equivalent basement complexes located south of the flat slab segment (including some in Patagonia) and in the Paraguay belt in central Brazil are largely covered by younger sedimentary and igneous units (see Tohver et al., 2006, 2012; McGee et al., 2014; Pankhurst et al., 2014). Several contrasting geodynamic models have been proposed for the evolution of this large sector, but there is a general consensus that crustal accretion mainly took place during two Early Paleozoic orogenic events, the Pampean (Ediacaran–Early Cambrian) and Famatinian (Ordovician–Silurian) orogenies (e.g., Aceñolaza and Toselli, 1976, 1981; Aceñolaza and Miller, 1982; Pankhurst and Rapela, 1998; Rapela, 2000; Dahlquist et al., 2008; Schwartz et al., 2008; Escayola et al., 2011; Mulcahy et al., 2011, 2014).

Our aim is to start unravelling the provenance (protolith ages) of the different Neoproterozoic to Early Paleozoic sedimentary rocks of the Sierras Pampeanas along this 26°–33° S transect. This is approached by the analysis of samples of the main metasedimentary units using U–Pb SHRIMP age determination of detrital zircons, supplemented by determination of Hf and O isotope compositions in three samples. Our main focus is on the Ediacaran–Cambrian episode of continental accretion, as this is the key interval in which the final assembly of southwestern Gondwana took place. A detailed comparison of the new detrital zircon data with those previously published from the region by our own group and others (recalculated where necessary using the same strict filtering criteria defined below) reveal consistent variations in the detrital patterns for the Sierras Pampeanas basin fills. These characteristics allow us to refine depositional ages and changes of provenance with time and location, as well as to define sediment dispersal patterns and paleogeographical links with eastern Laurentia and southern Africa.

2. Geology

2.1. The Grenvillian basement of the Western Sierras Pampeanas

Based on lithological differences, Caminos (1979) was the first to recognise an eastern group of sierras dominated by abundant Paleozoic granites and metasedimentary rocks (the Eastern Sierras Pampeanas — ESP), and a western group characterised by abundant meta-basic, ultrabasic and calc-silicate rocks (the Western Sierras Pampeanas — WSP). Modern geochronological studies have demonstrated that the WSP have a different geological history to the ESP, involving an exposed Mesoproterozoic (1330–1030 Ma) crystalline basement with a Neoproterozoic to Early Paleozoic sedimentary cover (McDonough et al., 1993; Pankhurst and Rapela, 1998; Casquet et al., 2001; Varela et al., 2003; Casquet et al., 2004; Sato et al., 2004; Vujovich et al., 2004; Casquet et al., 2008a; Rapela et al., 2010; Mulcahy et al., 2011; Varela et al., 2011). The whole basement complex was penetratively deformed during the Ordovician–Silurian Famatinian orogeny (Casquet et al., 2006, 2008a; Mulcahy et al., 2011, 2014 and references therein).

Two 'Grenvillian' domains can be distinguished in the WSP (Rapela et al., 2010). The first domain consists of a Grenville-age oceanic mafic–ultramafic complex that is considered representative of the unexposed basement of the Cuyania/Precordillera terrane, an alleged exotic terrane of Laurentia provenance accreted to Gondwana in the Ordovician–Silurian (Ramos, 2004; Naipauer et al., 2010) (Fig. 1). This complex crops out in the western part of the Sierra de Pie de Palo and minor outcrops in the San Rafael and Las Matras blocks (Fig. 1). In the Sierra de Pie de Palo, the complex is dominated by meta-mafic and meta-ultramafic rocks composed of serpentinite and metaserpentinite bodies, massive metagabbros, metadiorites, mafic schists, amphibolites and garnet-amphibolies, metatonalite, intermediate orthogneisses and metaquarzites (Vujovich and Kay, 1998; Mulcahy et al., 2011). U–Pb ages from ca. 1200 to 1030 Ma have been obtained for this complex (Rapela et al., 2010 and references therein). A first order thrust in the Sierra de Pie de Palo (Pirquitas thrust) separates the mafic–ultramafic complex from the underlying metasedimentary Caucete Group of alleged Early Cambrian age. The Caucete Group is considered the sedimentary cover to the Pie de Palo complex (e.g., Naipauer et al., 2010 and references therein, Van Staal et al., 2011) and the metamorphic and strongly deformed equivalent of the enigmatic, globally recognised, Early Cambrian to Middle Ordovician carbonate platform that crops out in the Argentine Precordillera to the west of the WSP (Fig. 1). There is no exposed underlying basement to the Cambrian and Early Ordovician sedimentary sequence of the Argentine Precordillera, immediately to the west of Sierra de Pie de Palo (Fig. 2), but indirect evidence of its age and composition comes from xenoliths in late igneous rocks and olistoliths in the western slope facies. The xenoliths (in Miocene dacites and andesites) include juvenile mafic pyroxene and pyroxene–garnet granulites, deformed mafic amphibolitic schists and biotite-bearing acid gneisses; these have U–Pb crystallisation ages of 1165–1100 Ma, and metamorphic ages of 1080–1060 Ma (Abruzzi et al., 1993; Kay et al., 1996; Rapela et al., 2010). The terrane (consisting of both the Palaeozoic strata and the inferred Grenville-age juvenile basement) has been considered an exotic terrane derived from Laurentia during the Cambrian and accreted to Gondwana in the Early Ordovician (Astini et al., 1995; Thomas and Astini, 1996). Alternative parautochthonous strike-slip models for the Precordillera terrane have also been proposed (e.g., Aceñolaza and Toselli, 2000; Finney et al., 2005; Finney, 2007 and references therein).

The second 'Grenvillian' domain consists of a Paleoproterozoic continental crust reworked by the Grenville orogeny and with a Neoproterozoic sedimentary cover. It was named the Maz suspect terrane by Casquet et al. (2008a) and is recognised in the sierras of Maz, Espinal and Toro Negro as well as in the central and eastern part of the Sierra de Pie de Palo (Fig. 1). This domain is considered part of the MARA block. In this terrane, low- to high-grade metasedimentary rocks include quartzites, metasandstones, metapelites, marbles and calc-silicate rocks. U–Pb age determinations and geochemical studies in associated igneous rocks show a protracted 1330–1070 Ma evolution that includes initial 'Andean-type' magmatism emplaced in Paleoproterozoic basement, lithospheric thickening, arc–continent collision, lithospheric extension and emplacement of anorthosite–mangerite–charnockite–granite (AMCG) complexes (Casquet et al., 2008a; Rapela et al., 2010). Grenville-age metamorphism has been recognised in some of these rocks (e.g., Sierra de Maz, Casquet et al., 2006). This older basement was intruded by Neoproterozoic igneous bodies, including juvenile 842–846 Ma and 774 $\pm$ 6 Ma A-type granites (Baldo et al., 2006; Colombo et al., 2009; Rapela et al., 2011) as well as a ca. 570 Ma carbonatite complexes (Casquet et al., 2008b).

The present paper deals only with the MAZ terrane and its extension to the basement of the southern Puna, all considered part of the MARA block.

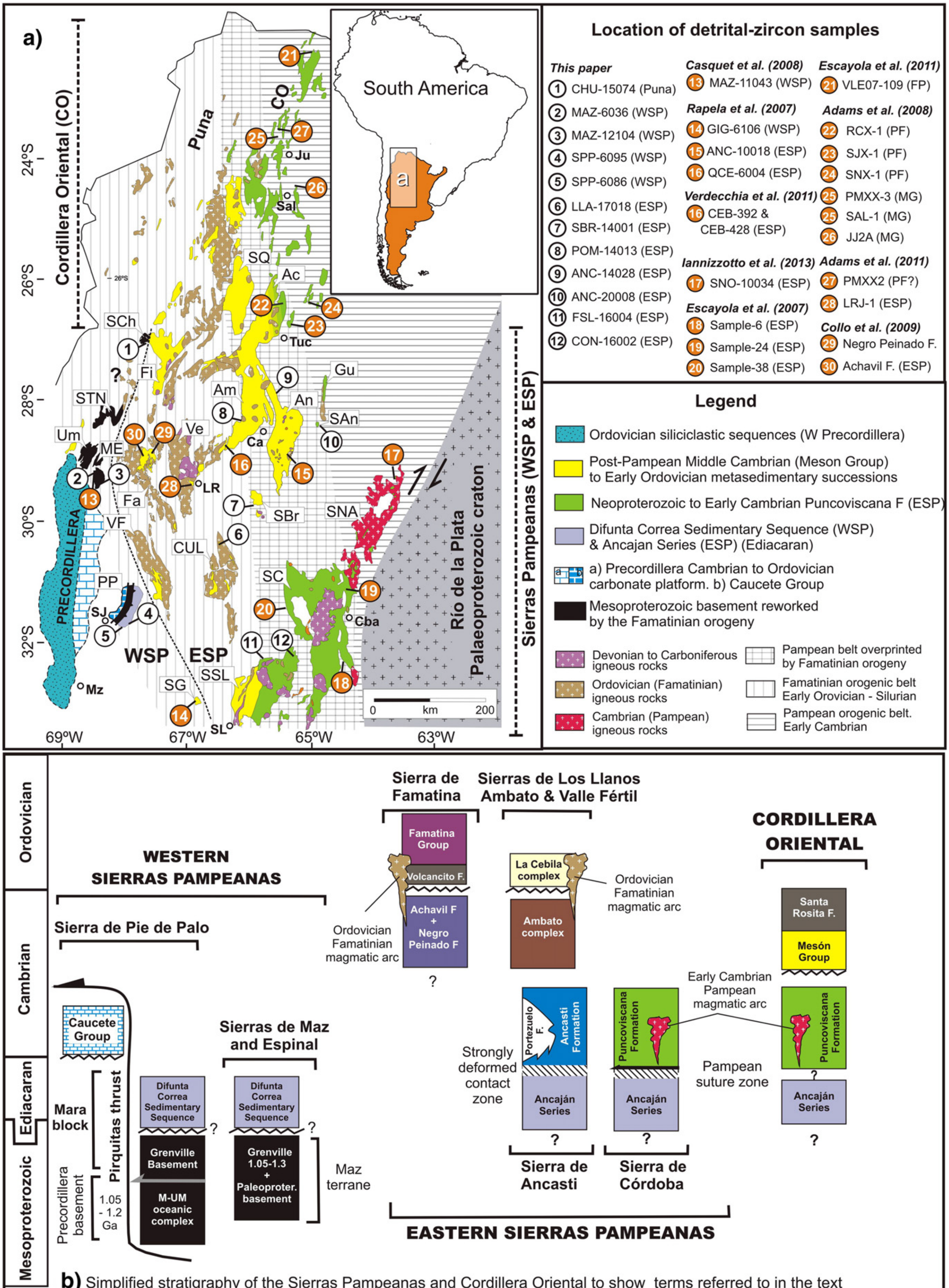
2.2. The post-Grenvillian sedimentary cover in the WSP

A Neoproterozoic metasedimentary cover has been recognised in several Western Sierras Pampeanas, e.g., Sierra de Umango (Varela et al., 2001), Sierra de Maz (Casquet et al., 2008a) and in the central and eastern sector of the Sierra de Pie de Palo (Galindo et al., 2004; Rapela et al., 2005) where it was termed the Difunta Correa Sedimentary Sequence (DCSS). The latter is a key succession composed of metaconglomerates, metaquartzites, meta-arkoses, Ca-pelitic schists, para-amphibolites and marbles (Baldo et al., 1998); it is considered to be of Neoproterozoic age based on $^{87}Sr/^{86}Sr$ isotope composition of the marbles (0.70732–0.70742) and detrital zircons in para-amphibolites, thought to represent an isotopically juvenile siliciclastic fraction with a marine carbonate component (Galindo et al., 2004; Rapela et al., 2005). The DCSS was intruded by Early Ordovician granites (Pankhurst and Rapela, 1998; Mulcahy et al., 2011; Baldo et al., 2012).

In the Sierra de Pie de Palo, the mafic–ultramafic complex is interpreted — as explained above — as the basement of the Precordillera Lower Paleozoic platform succession, of which the Caucete Group is the metamorphic equivalent.

2.3. The metasedimentary successions of the Eastern Sierras Pampeanas

The ESP are located between the Paleoproterozoic Río de la Plata craton (2.26–2.05 Ga, Rapela et al., 2007, 2011, and references therein) and the Mesoproterozoic WSP (Fig. 2). The ESP are composed of (a) low-to-high grade metasedimentary rocks of Late Ediacaran to Early Ordovician age and (b) extensive Paleozoic granites of Cambrian


a)
Cordillera Oriental (CO)
Puna
CO
South America
a
24ºS
26ºS
28ºS
30ºS
32ºS
69ºW
67ºW
65ºW
63ºW
Ju
Sal
SQ
Ac
Tuc
SCh
Fi
STN
Um
ME
Gu
Am
An
SAn
Ca
Ve
LR
Fa
VF
SBr
SNA
CUL
PP
SJ
SC
Cba
PRECORDILLERA
WSP
ESP
SG
SSL
SL
Mz
Río de la Plata Palaeoproterozoic craton
Sierras Pampeanas (WSP & ESP)
0 km 200
Location of detrital-zircon samples
This paper
1 CHU-15074 (Puna)
2 MAZ-6036 (WSP)
3 MAZ-12104 (WSP)
4 SPP-6095 (WSP)
5 SPP-6086 (WSP)
6 LLA-17018 (ESP)
7 SBR-14001 (ESP)
8 POM-14013 (ESP)
9 ANC-14028 (ESP)
10 ANC-20008 (ESP)
11 FSL-16004 (ESP)
12 CON-16002 (ESP)
Casquet et al. (2008)
13 MAZ-11043 (WSP)
Rapela et al. (2007)
14 GIG-6106 (WSP)
15 ANC-10018 (ESP)
16 QCE-6004 (ESP)
Verdecchia et al. (2011)
16 CEB-392 & CEB-428 (ESP)
Iannizzotto et al. (2013)
17 SNO-10034 (ESP)
Escayola et al. (2007)
18 Sample-6 (ESP)
19 Sample-24 (ESP)
20 Sample-38 (ESP)
Escayola et al. (2011)
21 VLE07-109 (FP)
Adams et al. (2008)
22 RCX-1 (PF)
23 SJX-1 (PF)
24 SNX-1 (PF)
25 PMXX-3 (MG)
25 SAL-1 (MG)
26 JJ2A (MG)
Adams et al. (2011)
27 PMXX2 (PF?)
28 LRJ-1 (ESP)
Collo et al. (2009)
29 Negro Peinado F.
30 Achavil F. (ESP)
Legend
Ordovician siliciclastic sequences (W Precordillera)
Post-Pampean Middle Cambrian (Meson Group) to Early Ordovician metasedimentary successions
Neoproterozoic to Early Cambrian Puncoviscana F (ESP)
Difunta Correa Sedimentary Sequence (WSP) & Ancajan Series (ESP) (Ediacaran)
a) Precordillera Cambrian to Ordovician carbonate platform. b) Caucete Group
Mesoproterozoic basement reworked by the Famatinian orogeny
Devonian to Carboniferous igneous rocks
Ordovician (Famatinian) igneous rocks
Cambrian (Pampean) igneous rocks
Pampean belt overprinted by Famatinian orogeny
Famatinian orogenic belt Early Orovician - Silurian
Pampean orogenic belt. Early Cambrian
Ordovician
Cambrian
Ediacaran
Mesoproterozoic
WESTERN SIERRAS PAMPEANAS
Sierra de Pie de Palo
Caucete Group
Pirquitas thrust
Mara block
Precordillera basement
1.05 - 1.2 Ga
Difunta Correa Sedimentary Sequence
Grenville Basement
M-UM oceanic complex
Sierras de Maz and Espinal
Grenville 1.05-1.3 + Paleoproter. basement
Maz terrane
Sierra de Famatina
Famatina Group
Volcancito F.
Achavil F + Negro Peinado F
Ordovician Famatinian magmatic arc
Sierras de Los Llanos Ambato & Valle Fértil
La Cebila complex
Ambato complex
Ordovician Famatinian magmatic arc
Portezuelo F.
Ancasti Formation
Strongly deformed contact zone
Ancaján Series
Puncoviscana Formation
Early Cambrian Pampean magmatic arc
Pampean suture zone
CORDILLERA ORIENTAL
Santa Rosita F.
Mesón Group
Sierra de Ancasti
Sierra de Córdoba
EASTERN SIERRAS PAMPEANAS
b) Simplified stratigraphy of the Sierras Pampeanas and Cordillera Oriental to show terms referred to in the text

(Pampean), Early Ordovician (Famatinian) and Devonian to Carboniferous age.

The Pampean orogeny has been associated with a continent–continent collision (Rapela et al., 1998; Escayola et al., 2011). Schwartz et al. (2008) proposed a model of the Pampean orogeny based on oceanic-ridge subduction alone. Evidence against this model has been discussed by Escayola et al. (2011) and Ramos et al. (2014) and our conclusions (see the Discussion section) also favour the continental collisional interpretation.

The climax of the Pampean orogeny in the Sierras de Córdoba occurred between 525 and 520 Ma, during the isothermal decompression of the thickened Pampean orogen, with development of large migmatitic massifs, emplacement of cordierite granites and associated cordieritite complexes (Rapela et al., 1998, 2002). All these events are considered indicative of mid-crustal levels of the Pampean orogeny.

It is convenient to subdivide the metasedimentary rocks of the ESP into those deposited before, or simultaneously with, the Pampean orogeny, i.e., during the Late Precambrian–Early Cambrian interval (Puncovisca Formation and Ancaján Series) and those deposited after the Pampean orogeny in Late Early Cambrian to Early Ordovician times ("Post-Puncoviscan Series").

2.4. Late Ediacaran–Early Cambrian metasedimentary units

2.4.1. The Puncoviscan series

The high-to-medium metamorphic grade of the ESP basement decreases northwards in NW Argentina, where extensive NNE–SSW trending, very low grade, metasedimentary successions known as the Puncoviscana Formation, unconformably covered by the Middle Cambrian Mesón Group, has been considered as representing the same protolith material (Aceñolaza and Miller, 1982; Willner et al., 1987) (Fig. 2b). This observation is very important, as the low grade of the high level exposures allows recognition of geological relationships and unconformities usually obscured in the high-grade rocks in the deeper structural levels of the ESP. The Puncoviscana Formation in the north is composed of grey and greenish slates and sandstones, with abundant primary structures and Cambrian trace fossils in some sectors, subordinate carbonates and minor volcanogenic rocks (Aceñolaza and Toselli, 2009 and references therein). In the type section, folded turbidites of the Puncoviscana Formation were deposited at 537.3 $\pm$ 0.9 Ma (the Early Cambrian age of interbedded felsic tuffs), with deformation inferred to have occurred in the interval 537–524 Ma (Escayola et al., 2011). In this sector all very low- to low-grade metasedimentary rocks are often included in the Puncoviscana Formation on the basis of their petrographical, structural and geochemical characteristics (e.g., Zimmermann, 2005), but not all have the same depositional age, and they probably include Late Ediacaran successions (Escayola et al., 2011).

In the southern part of ESP, e.g., Sierras de Córdoba, Sierra Norte de Córdoba and Ancasti, widespread greenschist, amphibolite and granulite facies metasedimentary rocks are considered higher-grade equivalents of the lower part of the Puncoviscana Formation, more intensely affected by the Pampean orogeny (Rapela et al., 1998; Escayola et al., 2007; von Gosen and Prozzi, 2010; Casquet et al., 2012a) (Fig. 2b). All along the strike of this tightly folded NNE–SSE belt, the low-to-high grade metasedimentary successions were intruded by Early Cambrian subalkaline arc granites (Rapela et al., 1998; Schwartz et al., 2008; Hongn et al., 2010; Siegesmund et al., 2010; Escayola et al., 2011; Iannizzotto et al., 2013; von Gosen et al., 2014). In the Sierra Norte de Córdoba, deposition of the sediments is inferred to have started in the Neoproterozoic–Early Cambrian interval (>541 Ma, the age of the oldest granites, Schwartz et al., 2008); the compressive D1 event here was active during emplacement of 537 $\pm$ 4 Ma mylonitized granites, and was completed before that of post-orogenic granites at 530 $\pm$ 4 Ma (Iannizzotto et al., 2013). Some Early Ordovician granites, notably a tonalite–trondhjemite suite, also intrude the Cambrian basement of the Sierras de Córdoba (Pankhurst et al., 2000).

2.4.2. The Ancaján Series

The Ancaján Series is a new informal name that we give to an assemblage of medium- to high-grade metasedimentary rocks in the eastern part of the Sierra de Ancasti and in the small, nearby Sierra de Ancaján (Fig. 2). Is consists of strongly folded marbles, quartzite, schists and gneisses formerly known as the Sierra Brava complex (Aceñolaza et al., 1983). The new name is to avoid confusion with the Sierra Brava basement outcrop south of Ancasti where rocks of the Ancaján Series are not found. The central and western parts of the Sierra the Ancasti consist of banded schists of the Ancasti Formation (Willner et al., 1983) and the equivalent migmatite gneisses of El Portezuelo Formation (Aceñolaza et al., 1983). Rapela et al. (2007) constrained the sedimentation age of the Ancasti Formation to a maximum of 570 Ma and correlated it with the Puncoviscana Formation on the basis of the detrital zircon U–Pb age-pattern. Ca- and Ca–Mg marbles are abundant in the Ancaján Series and were dated as Ediacaran by means of the Sr-isotope composition and correlated for the first time with those of the DCSS in the WSP (Murra et al., 2011). U–Pb detrital zircon ages of the Sierra Brava complex first published by Miller et al. (2010) showed striking differences from the Ancasti Formation and more similarities with the DCSS, although the location of the sample and analytical data were not given. The Ancasti Formation and the Ancaján Series are separated by a zone where foliations are strongly transposed to parallelism, probably resulting from Famatinian deformation and metamorphism. Pre-Famatinian relationships are thus obscured. Recent work in the Sierras de Córdoba has shown that the Ancaján Series probably continues southwest of Ancasti. Sr-isotope composition of marbles (0.7073–0.7077) and preliminary SHRIMP detrital zircon U–Pb ages of gneisses interbedded with marbles are compatible with those of the Ancaján Series (Casquet et al., 2014; Murra et al., 2014), implying that the latter rocks were involved in the Pampean orogeny.

2.5. "Post-Puncoviscan Series": Middle Cambrian–Lower Ordovician metasedimentary successions

In northwestern Argentina the Puncoviscana Formation is unconformably overlain by shallow-water siliciclastic deposits of the Middle Cambrian Meson Group (e.g., Sánchez and Salfity, 1999) and the siliciclastic basal deposits of the Santa Rosita Formation (Santa Victoria Group) assigned a Late Cambrian age (500–488 Ma) on the basis of fossil content (see Waisfeld and Vaccari, 2008, and references therein) (Fig. 2). Inherited U–Pb detrital zircon age patterns of the Meson Group imply a relative short sedimentary history with an imprecise maximum depositional age of ca. 500 Ma (Adams et al., 2008, 2011) or more probably 515–520 Ma (Augustsson et al., 2011; Fig. 4). The Meson Group has been ascribed to either a passive margin (e.g., Bahlburg and Hervé, 1997) or a retro-arc foreland basin (Astini, 2008).

Fig. 2. (a) Map of the Sierras Pampeanas (Western Sierras Pampeanas and Eastern Sierras Pampeanas, WSP & ESP) and Northwestern Argentina, with location of detrital-zircon samples. Abbreviations: San Salvador del Jujuy (Ju), Salta (Sal), Tucumán (Tuc), La Rioja (LR), San Juan (SJ), Mendoza (Mz), San Luis (SL), Catamarca (Ca) and Córdoba (Cba). Main ranges: Sierra de Quilmes (SQ), Sierra de Aconquija (Ac), Sierra de Chuquisaca (SCh), Sierra de Fiambala (Fi), Sierra de Ambato (Am), Sierra de Ancasti (An), Sierra de Guasayan (Gu), Sierra de Ancaján (SAn), Sierra del Toro Negro (STN), Sierra de Umango (Um), Sierras de Maz-Espinal (ME), Sierra de Velasco (Ve), Sierra de Famatina (Fa), Sierra Brava (SBr), Sierra Norte-Ambargasta (SNA), Sierra de Valle Fértil (VF), Sierra de Pie de Palo (PP), Sierra de Córdoba (SC) and Sierra de San Luis (SSL). PF: Puncoviscana Formation; MG: Mesón Group. (b) Simplified stratigraphic column of representative areas.

However, in the medium- to high-grade rocks of the ESP it is not easy to differentiate Puncoviscana-equivalent protoliths from younger ones without detailed geochronological evidence (see Hausser et al., 2011; Verdecchia et al., 2011) or very rare significant fossil finds (Verdecchia et al., 2007). Middle Cambrian (post-Pampean orogeny) to Early Ordovician (partly overlapping with the Famatinian arc) sedimentary protoliths have been identified in the metasedimentary complexes of the ESP (see Fig. 1), constrained from geochronological data, stratigraphic relations and/or the age of subsequent metamorphic or igneous episodes. The minimum depositional age of the folded, low-grade metapelite, successions of Sierra de Famatina (Negro Peinado and Achavil formations) (Fig. 2; Fa) is limited by the unconformably overlying Late Cambrian to Early Ordovician volcaniclastic sediments of the Volcancito Formation (Collo et al., 2009). The younger limit for the depositional age of metasedimentary complexes in the Sierra de Ambato (Fig. 2; Am), is constrained by an Ordovician metamorphic event (480–470 Ma; see De los Hoyos et al., 2011; Larrovere et al., 2011; Verdecchia et al., 2011), whereas in the metamorphic succession of Sierra de Los Llanos–Ulapes (CUL in Fig. 2) this limit is marked by the widespread intrusion of Lower Ordovician subalkaline granites (ca. 480 Ma, Stuart-Smith et al., 1999; Pankhurst et al., 2000). An exceptional Early Ordovician depositional age for sedimentary protoliths of the La Cébila metamorphic complex in the southern sector of the Sierra de Ambato is inferred from the preservation of a brachiopod record in high-grade quartzites (Verdecchia et al., 2007). Furthermore, a Late Cambrian to Early Ordovician depositional age of protoliths in Sierra del Valle Fértil, Sierra de San Luis and Sierra de Las Chacras are constrained by Early Ordovician magmatism and metamorphism (e.g., Steenken et al., 2006; Ducea et al., 2010; Drobe et al., 2011; Casquet et al., 2012b). All these post-Puncoviscan metasediments are considered equivalents of the Ambato and La Cébila metamorphic complexes (see Fig. 2b).

3. U–Pb ages of detrital zircons

3.1. Analytical methods

We have determined SHRIMP U–Pb ages for detrital zircons in 12 samples of metasedimentary rocks from the WSP, the southern Puna and the ESP. Sample locations are shown in Fig. 2 and Table 1, where their lithology and mineralogy are summarised.

U–Th–Pb analyses of zircon were made using SHRIMP RG and SHRIMP I at the Research School of Earth Sciences (RSES), The Australian National University, Canberra, Australia, following the methods of Williams (1998, and references therein) as in our previous work (e.g., Rapela et al., 2011). Data were reduced using the SQUID macro of Ludwig (2001). Probability density plots with stacked histograms, Tera–Wasserburg and Wetherill concordia plots were carried out using ISOPLOT/Ex (Ludwig, 2003). The data are presented in the Supplementary Appendix, Table 2. Where the ^{207}Pb-corrected ^{238}U/^{206}Pb age was greater than 1.1 Ga, the ^{204}Pb-corrected ^{207}Pb/^{206}Pb age was plotted, after discounting any that were >10% discordant (as in Table 2). For ages less than 1.1 Ga ^{207}Pb-correction of the ^{238}U/^{206}Pb was preferred, but analyses were filtered out where they had high common Pb (>2.5% of total ^{206}Pb) or uncertainties greater than 5%, as well as a few that were clearly anomalous (e.g., younger than feasible sedimentation age, or probably reflecting Pb-loss during metamorphism). For ^{207}Pb-corrected data, no test of concordance is possible. Data are presented in the Supplementary Appendix, Table 2.

Lu–Hf and oxygen isotopic analyses of selected dated zircons were also performed at the RSES. After selecting zircon populations of known age, and re-polishing the epoxy mounts, oxygen analyses were carried out using SHRIMP II, while Lu–Hf analyses were performed on a Neptune MC-ICPMS coupled with a HelEx 193 μm ArF Excimer laser ablation system, following procedures described in Fu et al. (2014). Full analytical results are presented in Table 3 of the Supplementary Appendix of this paper.

3.2. Western Sierras Pampeanas–southern Puna

CHU-15074 (Sierra de Chuquisaca, southern Puna). A sequence of biotite-spotted mica schists alternating with massive metasandstones occurs here. The sample is from a 40 cm thick quartz-rich metasandstone, with a mineral association of Qz–Pl–Bt–Kfs [Zrn–Ap–Ilm–Ms] (abbreviations after Whitney and Evans, 2010), which indicates medium-grade metamorphism. The metasandstone has a medium-grained (0.5–1 mm) granoblastic fabric, mostly composed of polygonal quartz, K-feldspar and plagioclase. In this sample 90% of the detrital zircons are Mesoproterozoic, mostly in the range 1020–1320 Ma, with a main peak at 1190 Ma, and lesser peaks at 1015, 1070 and 1300 Ma; the remaining 10% are Paleoproterozoic, with a peak at ca. 1890 Ma (Fig. 3a).

MAZ-12104 (Sierra de Maz, western domain; Casquet et al., 2008a). The sample is from a low-grade sequence (biotite zone) of quartzites and metapelites, and is a quartz–biotite phyllite composed of Qz–Bt–Pl–Cal [Tur–Ap–Zrn–Opq–Chl]. Texturally it shows a lepidoblastic and

Table 1
Metasedimentary samples from the Western and Eastern Sierras Pampeanas for U-Pb zircon detrital age provenance.[a]

Sample	Location	Latitude	Longitude	Rock type/geological unit	Mineralogy [b]
Western Sierras Pampeanas					
SPP-6095	Sierra de Pie de Palo	31° 43′57.8″	67° 58′ 34.4″	Para-amphibolite. Difunta Correa calc-silicate succession	Hbl–Cpx–Pl–Qtz [Ttn–Ilm–Zrn–Ap]
SPP-6086	Sierra de Pie de Palo	31° 43′ 00.8″	68° 05′ 48.5″	Meta-conglomerate. Difunta Correa calc-silicate succession	Qz–Pl–Bt–Hbl–Grt–Ms [Opq–Zrn–Ap]
MAZ-6036	Sierra de Maz	29° 11′ 20.1″	68° 28′ 49.6″	Metaquartzite. Central domain of Sierra de Maz.	Qz–Pl–Bt Ms [Ep–Tur–Ilm–Zrn]
MAZ-12104	Sierra de Maz	29° 24′12.4″	68°2 4′ 52.8″	Phyllite. Southeastern domain of Sierra de Maz	Qz–Pl–Bt–Cal [Tur–Ap–Zrn–Opq–Chl]
South Puna (Antofalla)					
CHU-15074	Sierra de Chuquisaca	27° 03′ 26.1″	67° 40′ 43.9″	Quartz-rich metasandstone.	Qz–Pl–Bt–Kfs [Zrn–Ap–Ilm–Ms]
Eastern Sierras Pampeanas: pre- and syn-Early Cambrian Pampean deformation					
ANC-14028	Sierra Ancasti	28° 06′ 08.4″	65° 36′50.6″	Metatexite from Portezuelo Formation	Qz–Pl–Grt–Bt [Zrn–Ilm–Ap]
ANC-20008-2	Sierra de Ancaján	28° 26′ 26.2″	64° 55′ 53.7″	Quartz-rich metasandstone, Ancajan metamorphic complex	Qz–Bt–Kfs–Pl [Rt–Ilm–Grt–Zrn–Ap]
SBR-14001	Sierra Brava	29° 43′ 03.1″	65° 56′ 55.7″	Schist. Sierra Brava metamorphic complex	Qz–Bt–Pl–[Zrn–Ap–Opq]
CON-16002	Sierra San Luis	32°16′ 26.2″	65°13′22.4″	Banded schist. Conlara Formation	Qz–Bt–Pl–Ms [Ap–Zrn–Rt–Ilm]
FSL-16004	Sierra de San Luis	32°14′ 17.2″	65° 41′ 01.5″	Low-grade metasandstone. San Luis Formation	Qz–Bt–Ms–Pl [Ttn–Ep–Zrn–Opq]
Eastern Sierras Pampeanas: post-Early Cambrian Pampean deformation					
LLA-17018	Sierra de Los Llanos	30° 20′ 37.5″	66° 32′ 10.8″	Quartz-rich metasandstone.	Qz–Crd–And–Bt [Zrn–Ap]
POM-14013	Sierra de Ambato	28° 24′ 24.0″	66° 11′ 55.3″	Large metasedimentary septum (banded gneiss) in the Pomán Granite	Qz–Hbl–Bt–Pl–Kfs [Ttn–Ep–Zrn]

[a] See geographical distribution in Fig. 2.
[b] Minerals abbreviations from Whitney and Evans (2010). Accessory minerals in brackets.

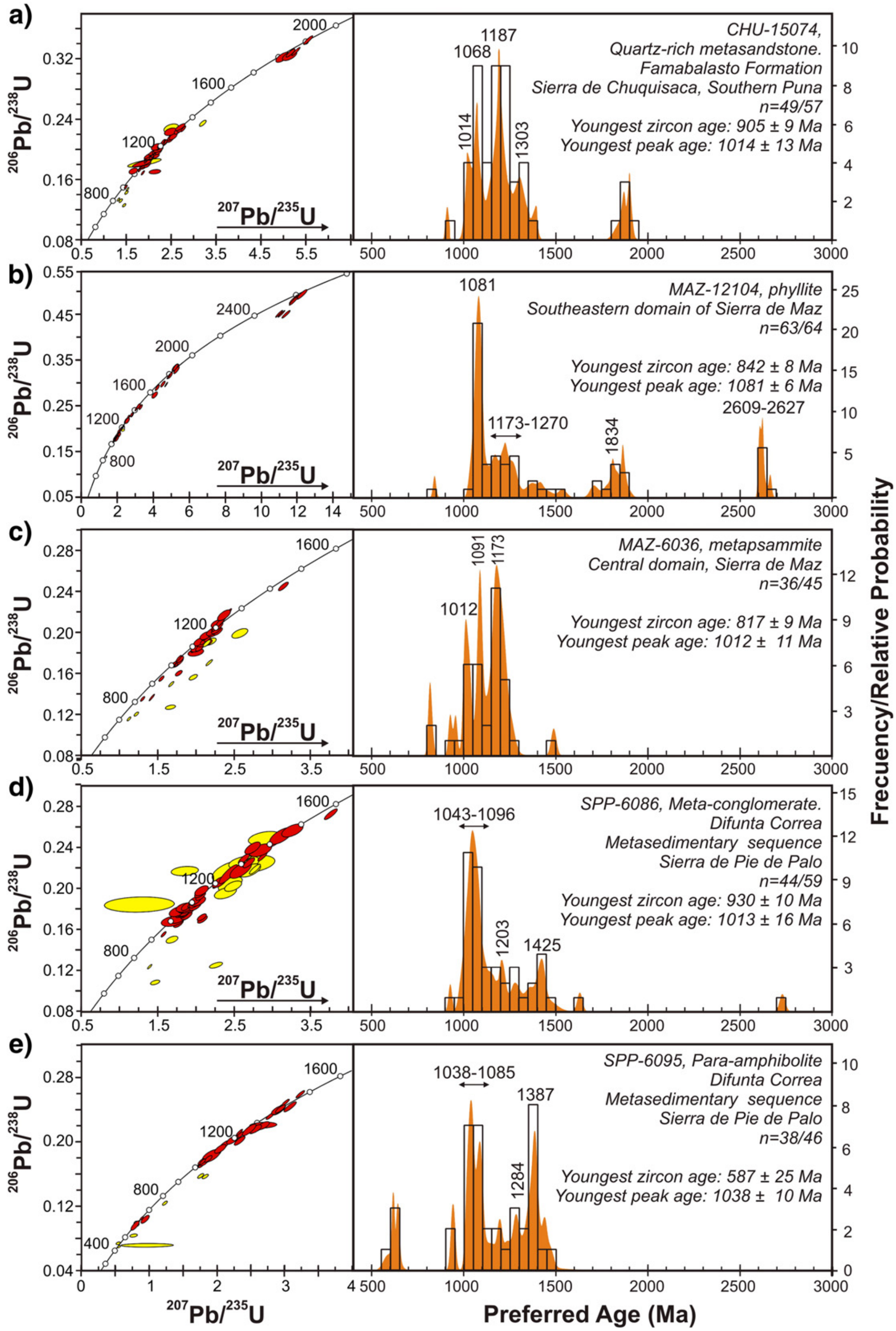


Fig. 3. Wetherill-type plots and ages patterns for detrital zircon U–Pb SHRIMP data of samples from Western Sierras Pampeanas. Selected and rejected analyses are indicated respectively as red and yellow filled error ellipses in the Wetherill-type plot. n = number of selected analysis/total analysis. See text for more explanation.

anastomosed fabric, with plagioclase grains larger than the average size of the quartz–mica matrix. 70% of the detrital zircon ages are Mesoproterozoic. The dominant and youngest peak is at 1080 Ma, with lesser peaks at 1175 and ca. 1240 Ma. The sample also contains significant (ca. 10%) Paleoproterozoic (1800–1870 Ma) and Archaean (ca. 2620 Ma) zircons, the latter being quite abundant.

MAZ-6036 (Sierra de Maz, central domain; Casquet et al., 2008a). The sample comes from a sequence of quartzites, metasandstones, staurolitic schists and amphibolites. It is a medium-grained, quartz–feldspar metasandstone composed of Qz–Pl–Bt–Ms [Ep–Tur–Ilm–Zrn]. The texture is medium-grained decussate, inequigranular, dominated by plagioclase and quartz, with minor biotite and muscovite. Only 36 acceptable zircon ages were obtained from this sample due to marked discordance. The overall pattern suggests Neoproterozoic or Phanerozoic Pb-loss from the main concordant grouping (Fig. 3). For this reason the apparent minor peak at 820 Ma is not considered to indicate a source age. The most concordant of the remaining data yield ages in the range 930–1260 Ma, with discernable peaks at 1010, 1090 and 1175 Ma.

SPP-6086 (Sierra de Pie de Palo, DCSS, Quebrada de Las Flores). The local sequence contains metaconglomerate levels, associated with mica schists, quartz-mica schists and marbles, intruded by dioritic dykes. The sample is a metaconglomerate with clasts 1–2 cm in size and a medium-grade metamorphic mineral association of Qz–Pl–Bt–Hbl–Grt–Ms– [Opq–Zrn–Ap]. The clastic fraction is composed of plagioclase and elongated quartz grains with recrystallized rims, surrounded by a biotite-muscovite lepidoblastic matrix and amphibole and garnet porphyroblasts. Zircon inclusions in biotite and amphibole are conspicuous. SPP-6086 is dominated by detrital zircons of Mesoproterozoic age (Fig. 3d). There is a single major peak at 1050 Ma (with the youngest component of this population at 1000 Ma) and it is possible that this could be resolved into the two youngest peaks of SPP-6095 (see below). There are minor peaks at 1205, 1280 and 1425 Ma, and single zircon grains with ages of ca. 1640 and ca. 2740 Ma indicate the presence of older, recycled material.

Hf isotope compositions of the 1340–1480 Ma zircon detrital component (Table 3) are mostly rather juvenile (εHf_t from +7.1 to +11.2), while most of their oxygen isotopes values are crustal ($\delta^{18}O‰$ from +5.5 to +7.9), with only one grain within the typical mantle range. The corresponding εHf_t and $\delta^{18}O‰$ values for the Grenville-age zircons are scattered (+1.2 to +11.2 and +5.5 to +11.0, respectively); these are not considered further here as the purpose of the Hf–O analyses was specifically to fingerprint the early Mesozoic zircons, since they are more critical in assessing provenance.

SPP-6095 (Sierra de Pie de Palo, DCSS). The sample is a fine-grained para-amphibolite interbedded with metaquartzites, mica schists and marbles. The mineral association of Hbl–Cpx–Qz–Pl– [Ttn–Ilm–Zrn–Ap] indicates medium-grade metamorphism. The petrography is characterised by a thin banded fabric, with nematoblastic, orientated amphibole alternating with lenticular aggregates of polycrystalline quartz. Small, sub-spherical zircons appear as inclusions in the hornblende and euhedral crystals in the quartz–plagioclase domains. In constructing the provenance pattern of this sample (Fig. 3e), an unusually high proportion (25%) were rejected for discordance, high common Pb or imprecision, but the essential pattern is unaffected. As in SPP-6086, the detrital zircons are mostly Mesoproterozoic, with discrete major peaks in the age distribution at 1040, 1085 and 1385 Ma. The youngest zircon ages form a small but significant peak at 620–640 Ma; other minor peaks occur at 1200, 1285 and 1440 Ma.

Detrital zircons in the 1340–1480 Ma interval of this sample also have juvenile Hf isotopic composition (εHf_t from +5.3 to +10.3) and crustal oxygen isotope values ($\delta^{18}O‰$ from +5.9 to +7.9) (Table 3). Grenville-age zircons in this sample have comparable compositions, with εHf_t from +4.9 to +9.2 and $\delta^{18}O‰$ from +6.1 to +9.4.

3.3. The Eastern Sierras Pampeanas

3.3.1. Pre and syn-Early Cambrian Pampean deformation metasedimentary rocks

ANC-14028 (Sierra de Ancasti, western side, Portezuelo Formation; Aceñolaza et al., 1983). This is a sequence of gneisses, metatexitic migmatites and concordant leucocratic granites. The sample is a metatexitic migmatite with quartz–feldspar leucosomes and biotite-rich melanosomes containing abundant zircon. Both mineral association (Qz–Pl–Grt–Bt [Zrn–Ilm–Ap]) and fabric indicate high-grade metamorphic conditions. More than half of the zircons in this sample are Neoproterozoic, with peaks at ca. 545 and 615 Ma and some scattered older ages among which ca. 740 Ma may be significant (Fig. 4a). About 40% of the population is Mesoproterozoic, 920–1170 Ma: the sharpest peak is at ca. 1025 Ma, but with a notable shoulder at ca. 1140 Ma. There are also two concordant Archaean zircons with a mean age of 2670 Ma and a single grain with an age of ca. 1860 Ma.

SBR-14001 (Sierra Brava, southern sector, Sierra Brava complex; Aceñolaza et al., 1983). This outcrop displays a sequence of biotite paragneisses alternating with grey metasandstones. The sample is a quartz-rich metasandstone, with a medium-grade mineral association of Qz–Bt–Pl– [Zrn–Ap–Opq]. It has a medium-grained (1–2 mm) lepido-granoblastic texture. Ignoring three scattered Paleozoic apparent ages, 60% of the zircons are Neoproterozoic (with peaks at 555 and 625 Ma) and 40% are Mesoproterozoic (essentially 1025 Ma but with some spread to younger ages) (Fig. 4b). There is a single age at 1965 Ma.

FSL-16004 (Sierra de San Luis, San Luis Formation; Steenken et al., 2006). The San Luis Formation consists of a monotonous sequence of phyllites and metasandstones. The sample is from a metasandstone level with a metamorphic mineral association of Qz–Bt–Ms–Pl [Ttn–Ep–Zrn–Opq]. It shows a thin-banded, decussate texture in biotite-rich domains, intergrown with fine-grained (0.5–1 mm) granoblastic domains of Qtz–Pl. Unorientated porphyroblasts of muscovite and local concentrations of Ep–Ttn–Zrn are common. The sample has an essentially bimodal age distribution (Fig. 4c). One main peak is at 595 Ma, with slightly younger individual grains down to 485 Ma, possible input from sources at 780/820 Ma, but the main population is at 920–1060 Ma, within which peaks at 1000 and 1055 Ma can be resolved. Once again single grain ages occur back to ca. 2700 Ma.

CON-16002 (Sierra de San Luis, eastern side, Conlara Formation; Steenken et al., 2006). The Conlara Formation is monotonous sequence of banded schists intruded by muscovite–biotite leucogranites and tourmaline pegmatites. The sample was taken from a metasandstone level of the banded schist sequence that shows a medium-grade mineral association of Qz–Bt–Pl–Ms [Ap–Zrn–Rt–Ilm]. The banded fabric consists of lepido-granoblastic domains of Bt–Qz–Zrn–Ap and granoblastic domains of polygonal quartz. Discordant 1–2 cm veins of quartz-plagioclase are common. The zircon age distribution pattern is essentially bimodal (Fig. 4d). There is a range of younger ages from 550 to 700 Ma, with peaks at 570, 600 (the most significant), 660, 695 and 755 Ma, but also a notable small Ordovician peak at ca. 490 Ma. The greater part of the pattern lies between 900 and 1100 Ma, with a sharp peak at 1000 Ma, but with significant spread. There are isolated single ages as old as 2620 Ma.

ANC-20008-2 (Sierra de Ancaján, Ancaján Series). The sample was taken from a series of mica schists, marbles, amphibolites, graphitic schists and ultrabasic rocks, and is a metasandstone with a medium-grade mineral association of Qz–Bt–Kfs–Pl [Rt–Ilm–Grt–Zrn–Ap]. The fabric is defined by a banded texture, composed of granoblastic domains of polygonal quartz and lepido-granoblastic domains of Bt–Kfs–Qz–Pl, with local concentration of accessory minerals (Ap–Zrn–Rt–Ilm). The detrital zircon distribution pattern shows a small group of Neoproterozoic ages, with a peak at 795 Ma, a complex spectrum throughout the Mesoproterozoic, and a significant Paleoproterozoic group at 1820 and 1860 Ma (Fig. 5a). The Mesoproterozoic spectrum shows well-defined age peaks at 935, 990, and 1045 Ma (the latter representing more than 20% of the total population), a broader peak at 1210 Ma with a tail to older ages, and small peaks at 1340, 1450 and 1530 Ma. Detrital zircons in the 1330–1490 Ma interval of this sample have relatively juvenile Hf isotopic composition (εHf_t from +1.9 to +7.3) but mostly crustal oxygen isotope values ($\delta^{18}O‰$ from +4.7 to +9.6) (Table 3).

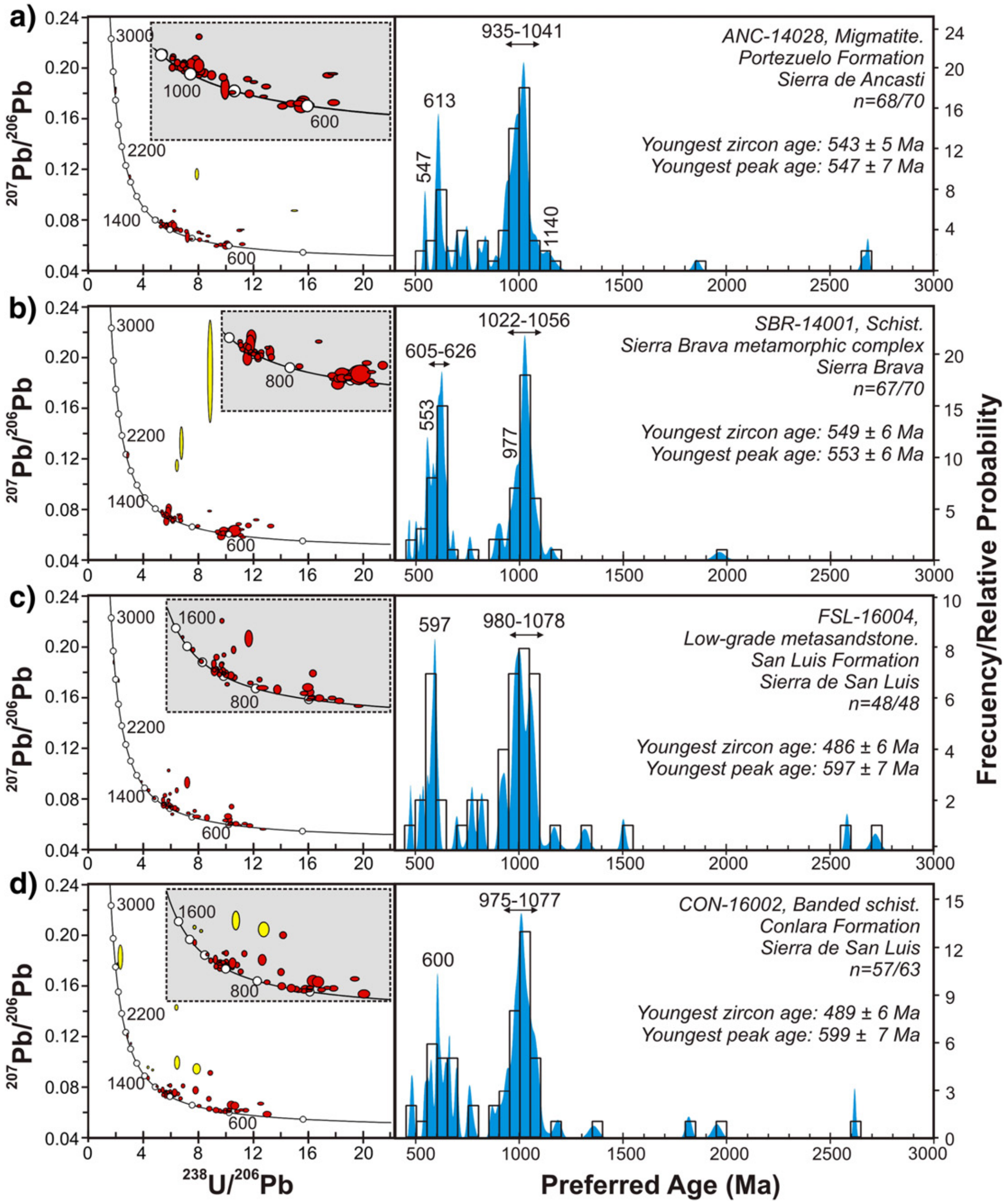


Fig. 4. Tera–Wasserburg plots and ages patterns for detrital zircon U–Pb SHRIMP data of samples of pre- and syn-Early Cambrian Pampean deformation units from Eastern Sierras Pampeanas. Selected and rejected analyses are indicated respectively as red and yellow filled error ellipses in the Tera–Wasserburg plot (see text for more explanation). n = number of selected analysis/total analysis.

3.3.2. Post-Pampean deformation: Early Paleozoic sediments and metamorphic rocks

POM-14013 (Sierra de Ambato, western side). Taken from a 70 × 50 m calc-silicate septum in the Ordovician Pomán granite, the sample is a banded schist with Kfs–Hbl [Bt–Ttn–Ep–Zrn] rich levels alternating with Qz–Bt–Pl and Bt–Kfs rich levels. More than 50% of the zircons in this sample are late Neoproterozoic (Fig. 6a), with age peaks at 575, 620, and 680 Ma; but there is a marked small peak at 495 Ma (Ordovician). Late Mesoproterozoic provenance at 1020 Ma is present but not very abundant, and the ages spread down to about 840 Ma. Scattered ages as old as 2640 Ma complete this pattern.

LLA-17018 (Sierra de Los Llanos, southwestern sector). Large metasedimentary xenoliths occur within the Ordovician granodiorite and gabbro complex of Sierra de Los Llanos (Pankhurst et al., 1998). The sample is from a massive, grey, metaquartzite level, associated with metapelitic hornfels in contact with hornblende gabbros. A granoblastic texture is defined by fine-grained polygonal quartz (Qz–Bt–Pl [Zrn–Ap]), whereas metapelitic levels also contain andalucite and cordierite formed by low-pressure contact metamorphism. There is a wide spread of apparent ages among the detrital zircons in this sample (Fig. 6b). The majority are relatively young (<800 Ma), with a main peak at ca. 515 Ma as well as a strong suspicion of an Early Ordovician age of ca. 490 Ma given by three grains. Peaks are also identified at 600 and 630–650 Ma. Ages older than this (back to Archaean) are difficult to interpret confidently since the discordance pattern suggests that most were affected by Pb-loss at ca. 1000 Ma, although the absence of significant 1000–1200 Ma zircons is curious.

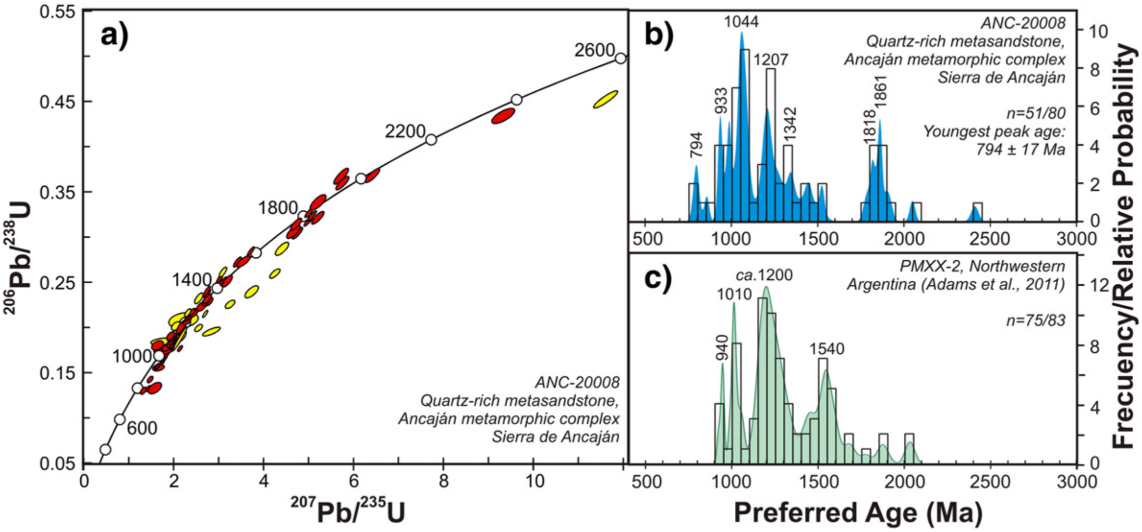


Fig. 5. (a) Wetherill-type plot and age pattern for detrital zircon U–Pb SHRIMP data of the Ancaján Series from Eastern Sierras Pampeanas. Selected and rejected analyses are indicated respectively as red and yellow filled error ellipses in the Tera–Wasserburg plot (see text for more explanation). (b) Comparative age pattern for detrital zircon U–Pb data of a sample (PMXX-2) from Northwestern Argentina (Adams et al., 2011). n = number of selected analysis/total analysis.

4. Discussion

4.1. Sedimentary provenance and paleogeography of the WSP

A composite pattern of metasedimentary rocks from the WSP and southern Puna is shown in Fig. 7a. Most of the detrital zircons seem to be derived from the igneous and metamorphic basement of the WSP, showing conspicuous Grenville-age events between 1330 and 1030 Ma (Rapela et al., 2010), which is precisely the range of Elzevirian and Ottawan orogenic events in the Grenville province of eastern Laurentia (1350–1000 Ma, e.g., McLelland et al., 1996). There are also minor Archaean, Late Paleoproterozoic and Early Mesoproterozoic peaks that are derived from other sources not identified in the WSP. The alternative to Eastern Laurentia as the source for the Grenvillian-age and older detrital zircons is the Rondonia–San Ignacio province in southern Amazonia some 1200 km to the North of the WSP. Here a protracted orogenic history is recorded between the Late Paleoproterozoic and the Late Mesoproterozoic, i.e., between 1.85 and 0.95 Ga (for a review see: Bettencourt et al., 2010; Teixeira et al., 2010). Several of these orogenic events could match the observed zircon age pattern in the WSP. This possibility was however rejected by Naipauer et al. (2010) in their work on the Caucete Group zircons, i.e., the alleged cover sequence to the Precordillera terrane in Sierra de Pie de Palo. Typical southern Amazonia detrital zircon age patterns are well displayed at Puga Hill and Bodoquena outcrops along the margin of the Paraguay belt (Babinski et al., 2013; Figs. 6 & 7); although ages

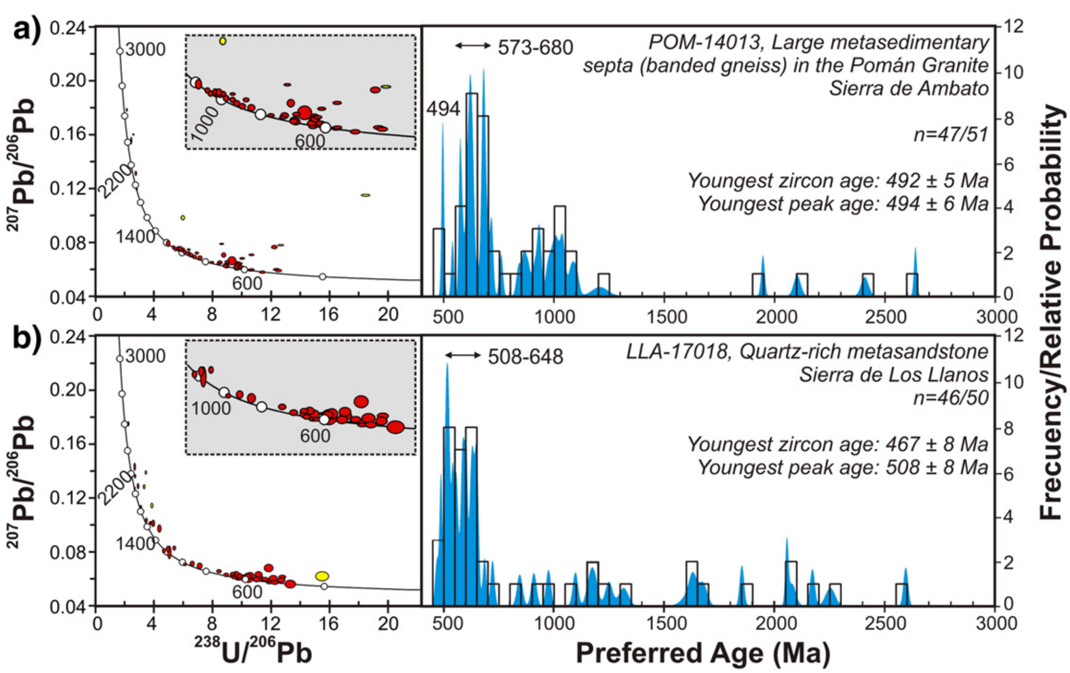
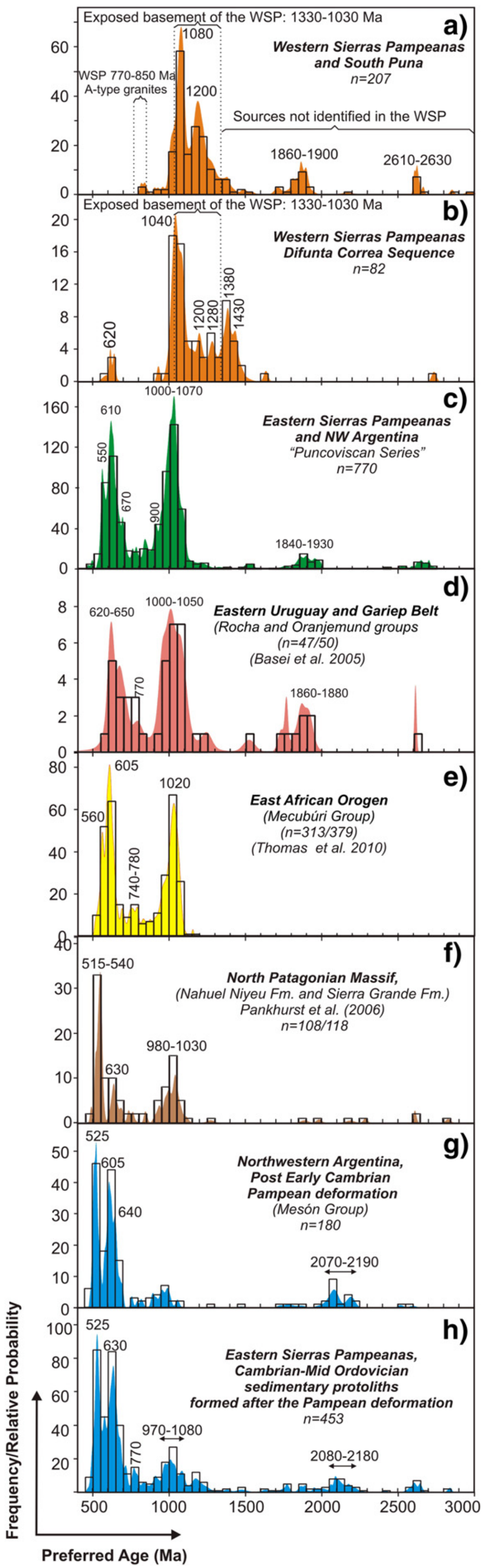


Fig. 6. Tera-Wasserburg plots and age patterns for detrital zircon U–Pb SHRIMP data of samples of post-Early Cambrian Pampean deformation units from the Eastern Sierras Pampeanas. Selected and rejected analyses are indicated respectively as red and yellow filled error ellipses in the Tera–Wasserburg plot (see text for more explanation). n = number of selected analysis/total analysis.



between 1.0 and 1.6 Ga are common, all patterns show dominant peaks at ca. 1.75 Ga and ca. 1.84 Ga which are notably absent from the WSP patterns, particularly for the DCSS rocks. The Ancaján sample shows a minor peak at ca. 1.85 Ga but also lacks the 1.75 Ga peak. We thus consider southern Amazonia provenance to be unlikely for detrital zircons of the DCSS/Ancaján Series protoliths.

The youngest detrital zircon ages of ca. 800–850 Ma observed in the central and western domains of Sierra de Maz (Fig. 3b, c) indicate that at least some metasedimentary rocks were formed in the Neoproterozoic (collectively termed here the DCSS), while others are probably Late Mesoproterozoic. A possible source for the younger detrital zircons is in the isotopically primitive A-type orthogneisses of ca. 845 Ma (Sierra de Maz), which have been related to aborted rifting affecting the basement of the WSP and, on a larger scale, to Rodinia break-up (Colombo et al., 2009; Rapela et al., 2011). As a consequence of the strong Ordovician–Silurian deformation and metamorphic overprint (420–430 Ma, Casquet et al., 2008b; Colombo et al., 2009), the extensional basins associated with these events are now part of the basement of the WSP.

The detrital pattern of the DCSS (Fig. 7b) shows some similarities with the inferred underlying basement of the WSP, but also some notable differences. Apart from an important component in the 1330–1030 Ma range of the in situ igneous-metamorphic basement of the WSP, Early Mesoproterozoic (1430–1380 Ma) and younger Neoproterozoic (620–640 Ma) peaks are distinctive: the latter provides a maximum age for the sedimentary protolith and is coeval with the 620–645 Ma range inferred from the Sr isotope composition of the marine carbonates of the DCSS (Fig. 8).

The peak observed at 1430–1380 Ma in Fig. 7b, for which there are no nearby exposed igneous or metamorphic sources, seems to be particularly significant. Evidence for the Late Neoproterozoic juxtaposition of Laurentia and East Antarctica is based on the presence of ca. 1.4 Ga A-type granites in the Grenville province of Laurentia and equivalent glacial clasts in the Ross Sea margin of East Antarctica (Goodge et al., 2008, 2010). In Laurentia the initial εHf_t values in these ca. 1.4 Ga granites vary according to the nature of the 2.0–1.5 Ga crust that they intrude: $+0.2 \pm 0.8$ in the 1.9–1.7 Ga Penokean and Mojave crustal provinces, $+5.4 \pm 0.9$ in central Yavapai, and $+7.0 \pm 0.9$ in the 1.5–1.3 Ga Southern Granite–Rhyolite Province (Goodge and Vervoort, 2006). The 1345 to 1470 Ma detrital zircon grains from samples of the DCSS have εHf_t in the range $+5.3$ to $+11.2$ (Fig. 9), and such a relatively juvenile isotope composition can only be compared with the ca. 1370 Ma granites of the Southern Granite–Rhyolite Province of Laurentia (Fig. 9a), the most primitive of the 1.4 Ga Laurentian A-type granites. Oxygen isotope determinations carried out on the same grains ($+5$ to $+8$‰, including errors; Fig. 9b) show that most

Fig. 7. Comparison of integrated detrital zircon U–Pb age pattern diagrams constructed from new analyses of this paper and previously published analyses of other authors: (a) Western Sierras Pampeanas and southern Puna: CHU-15074, MAZ-6036, MAZ-12104 (this paper), GIG-6106 (El Gigante complex, Rapela et al., 2007) and MAZ-11043 (Sierra de Maz, Casquet et al., 2008a); (b) Difunta Correa Sequence of Western Sierras Pampeanas from SPP-6095 and SPP-6086 samples (this paper); (c) Eastern Sierras Pampeanas and Northwestern Argentina, "Puncoviscanan Series": ANC-14028, CON-16002, FSL-16004 and SBR-14001 in (this paper), ANC-10018 (Sierra de Ancasti, Rapela et al., 2007), SNO-10034 (Sierra Norte–Ambargasta, Iannizzotto et al., 2013), 24, 38 and 6 (Sierra de Córdoba, Escayola et al., 2007), RCX1, SJX1 and SNX1 (Puncoviscana Formation; Adams et al., 2008), VLEO7-109 (Puncoviscana Formation; Escayola et al., 2011); (d) Rocha and Oranjemund groups of Eastern Uruguay and Gariep Belt: JM-001 and 32710 samples (Basei et al., 2005); (e) East African Orogen (Mecubúri Group, Thomas et al., 2010) (f) North Patagonian Massif (Nahuel Niyeu and Sierra Grande Formations, samples NIY-012 and SGR-018, Pankhurst et al., 2006); (g) Samples of post-Early Cambrian Pampean deformation: Mesón Group, Northwestern Argentina: (samples SAL1, PMXX3 and JJ2A, Adams et al., 2011); (h) Samples of Cambrian–Mid Ordovician sedimentary protoliths formed after the Pampean deformation from Eastern Sierras Pampeanas: LLA-17018 and POM-14013 (this paper), Achavil and Negro Peinado formations (Collo et al., 2009), CEB-392 (Ambato metamorphic complex, Verdecchia et al., 2011) and QCE-6004, LRJ1 and CEB-428 (La Cébila metamorphic complex, Rapela et al., 2007; Adams et al., 2011; Verdecchia et al., 2011, respectively).

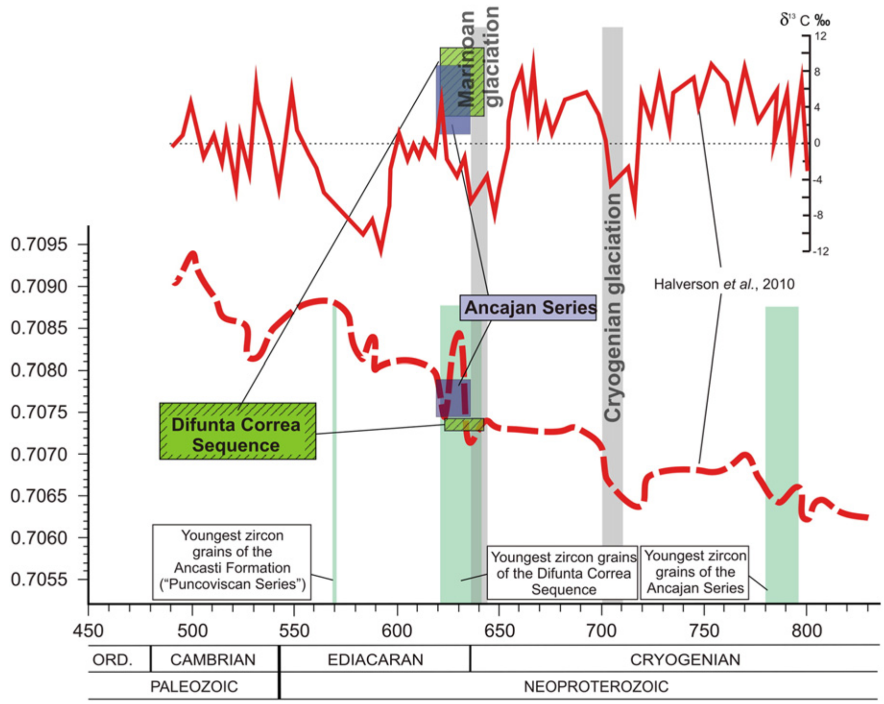


Fig. 8. Temporal variation of $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ PDB in seawater for the Neoproterozoic to Early Paleozoic period after Halverson et al. (2010). The references for the different periods are indicated in the figure. Data: Ancaján Series (Murra et al., 2011); Difunta Correa Sequence (Galindo et al., 2004). Younger zircon ages of the Ancasti Formation and the Ancaján Series are after Rapela et al. (2007) and this paper, respectively.

plot outside the mantle δ^{18} O field, suggesting that, despite the primitive εHf_t signatures, zircon crystallised from melts with mainly crustal O isotope compositions. These data accord with an origin by widespread melting of the lower crust for the Laurentian 1.4 Ga A-type granites (Goodge and Vervoort, 2006). Moreover, as well as a similar zircon age range, similar lithologies to those of NE Laurentia, including anorthosite complexes, have been found in the WSP in the basement of the modern Andean chain (Casquet et al., 2004; Rapela et al., 2010 and references therein). The minor Paleoproterozoic (1.8–1.9 Ga) and Archean (2.6 Ga) peaks in the detrital zircon age patterns of the WSP (Fig. 7a) imply more distant sources and/or reworking from pre-Grenvillian metasedimentary rocks that also form part of the reworked basement (Casquet et al., 2006). Distant sources with these ages are also available in Laurentia, such as the Yavapai and Superior provinces (see Goodge et al., 2004).

The same conclusion has been reached in studies of the Early Cambrian sequences of the Precordillera terrane: the Cerro Totora Formation (Thomas et al., 2004), the Caucete Group in the Sierra de Pie de Palo (Naipauer et al., 2010) and olistolith clasts of 1370 ± 2 Ma and 1367 ± 5 in the Ordovician Los Sombreros Formation (Thomas et al., 2012). These Precordillera sedimentary rocks are equally thought to have been derived from the Granite–Rhyolite Province on the basis of their ca. 1.4 Ga detrital zircon age peaks (Thomas et al., 2012), consistent with the evidence and interpretation reported above. More specifically, the source is identified as the northwest sector of the Granite–Rhyolite Province segment, between the Alabama–Oklahoma and Texas transforms of the Laurentia rift (Thomas et al., 2000; Naipauer et al., 2010; Thomas et al., 2012).

Metasedimentary igneous rocks with the typical DCSS pattern are found in the basement of the southern Puna, as in the Sierra de Chuquisaca at 27° S (Fig. 3a). If terranes with Laurentian affinity are found to the north of the Precordillera, and probably to the south in the North Patagonian Massif, the hypothesis of the Precordillera as a 'lonely traveller' microcontinent crossing Iapetus and originating in the 800 km Ouachita embayment (e.g., Thomas and Astini, 1996) will need to be dramatically expanded.

4.2. Sedimentary provenance of the Eastern Sierras Pampeanas

4.2.1. Sources of the Puncoviscana and post-Puncoviscana detrital patterns

As noted in Section 2, the composite detrital patterns of the ESP metasedimentary units as well as those of NW Argentina, can be subdivided into those deposited before or during the Early Cambrian Pampean orogeny (Fig. 7c, "Puncoviscan and Ancaján Series") and those deposited after the orogeny (Post-Puncoviscan Series, Fig. 7g, h).

The patterns of pre- and syn-Pampean metasedimentary rocks from the southern ESP (Fig. 4) are indistinguishable from those of the tract of the Puncoviscana Formation of NW Argentina that was involved in the Pampean orogeny (e.g., Adams et al., 2008, 2011; Escayola et al., 2011, see sample locations in Fig. 2). An integrated pattern of all these samples is shown in Fig. 7c. Correspondingly, the integrated patterns of the ESP metasedimentary rocks deposited after the Pampean deformation (Fig. 7h) are similar to those of the Late Cambrian Mesón Group (Fig. 7g). This strongly supports the idea that the southern ESP rocks are stratigraphically equivalent to those located at higher structural levels in NW Argentina, as noted above.

The main zircon age pattern of the "Puncoviscan Series" (Fig. 7c) is strongly bimodal, with peaks at ca. 600 and ca. 1000 Ma. The youngest detrital zircons are 555–570 Ma, but the interbedded felsic tuffs of 537.3 ± 0.9 Ma in the type section of the Puncoviscana Formation indicate Early Cambrian sedimentation, ca. 30 Ma after the youngest detrital zircon of their turbiditic host rocks (569 Ma, Escayola et al., 2011). This depositional age is consistent with one of 535 ± 5 Ma recently reported for a deformed meta-rhyolite layer interbedded in meta-clastic rocks in Sierra Norte de Córdoba (von Gosen et al., 2014). As the number of analysed detrital zircons is large (>700), this 570–535 Ma gap seems to be real and suggests that the large 570–680 Ma detrital peak represents derivation from a different Neoproterozoic source that was not part of the Pampean arc, which started in the Early Cambrian at ca. 538–540 Ma.

There are no obvious nearby sources for the bimodal ca. 570–670 and ca. 1000 Ma peaks of the "Puncoviscan Series", which are overwhelmingly dominant and remarkably consistent in the ESP and low-grade

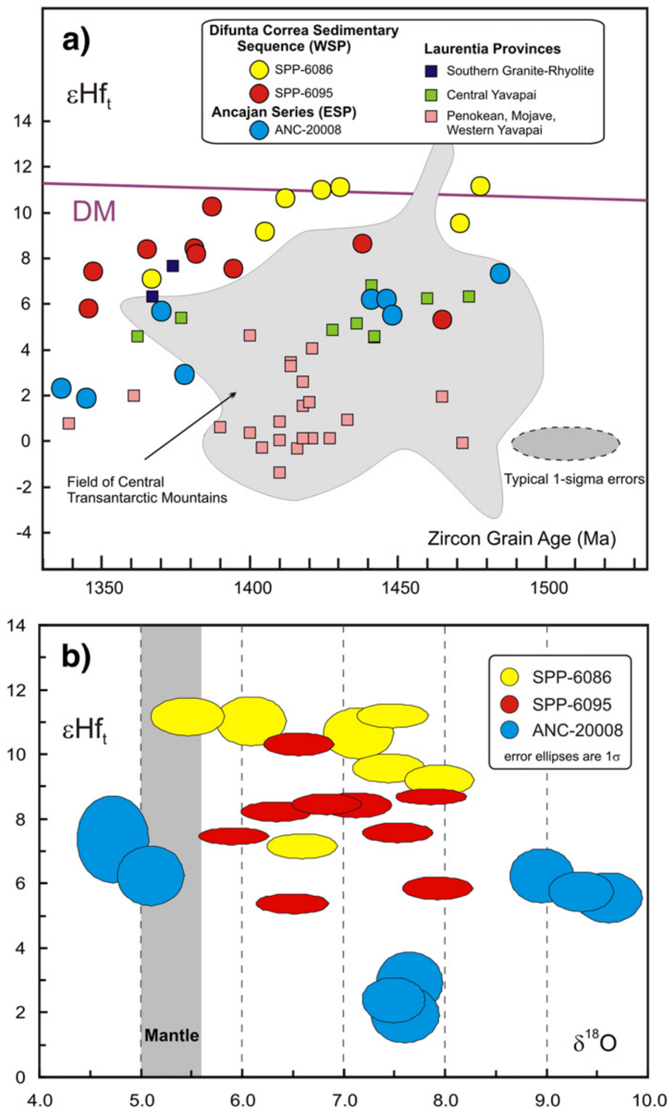


Fig. 9. (a) Age versus εHf_t for detrital zircons from the Difunta Correa Sedimentary Sequence of the WSP and the Ancaján Series of the ESP. Data for Mesoproterozoic A-type granites of basement provinces in Laurentia are from Goodge and Vervoort (2006), while the field of εHf_t for Neoproterozoic and Early Paleozoic detrital zircons from the Transantarctic Mountains is from Goodge et al. (2008). (b) $\delta^{18}O$ versus εHf_t for detrital zircons of the Difunta Correa Sedimentary Sequence and the Ancaján Series. Most of the data indicate that the ca. 1.4 Ga zircons are derived from older crustal protoliths.

equivalents in NW Argentina (Fig. 7c). As noted above, there are 1000 Ma rocks in the WSP and there is a peak with this age in the WSP metasedimentary rocks, but the latter also have conspicuous older Mesoproterozoic peaks of 1200 to 1450 Ma that are largely absent from the "Puncoviscan Series" (Fig. 7a, b). Therefore the Mesoproterozoic rocks of the WSP are not a likely source for the ca. 1000 Ma detrital zircons of the "Puncoviscan Series". The now adjacent 2.26–2.02 Ga Río de la Plata craton (Figs. 1, 2) is also eliminated as a possible source for the "Puncoviscan Series" as the latter contains no zircons with ages in this range (nor are there Mesoproterozoic and Neoproterozoic components in the craton, Rapela et al., 2007). According to paleocurrent records in the clastic sequences of the Puncoviscana Formation (Jezek, 1990), the "Puncoviscan Series" was mainly derived from the east and southeast of the Pampean orogen. Thus the most likely potential sources are (i) the Mesoproterozoic rocks of the Natal–Namaqua belt, southern Kalahari craton and (ii) the Brasiliano–Panafrican granites of southern Africa and SE Brazil and Uruguay (Schwartz and Gromet, 2004; Rapela et al., 2007). In SE Africa, the huge East African orogen (Jacobs and Thomas, 2004; Fig. 7e), exhibits similar bimodal patterns along strike as far as the Pensacola Mountains in East Antarctica (e.g., Goodge et al., 2004; Thomas et al., 2010). There are conspicuous 640–590 Ma granites in the Dom Feliciano Belt of SE Brazil and Uruguay but no 1.0 Ga basement (Basei et al., 2005). However, detrital zircons in the Rocha Group of SE Uruguay and the Oranjemund Group of the Gariep Belt of SW Africa show similar bimodal patterns with a 1.0 Ga component (Basei et al., 2005), suggesting extensive off-shore source-rocks of these ages. The detrital pattern of the "Puncoviscan Series" is compared with that of the Rocha Group in eastern Uruguay and the Gariep Belt (Fig. 7d) and the Mecubùri Group of the East African orogen (Fig. 7e). The resemblance to the Eastern Uruguay–Gariep belt is remarkable: not only are the major peaks and their relative abundance the same, but the most conspicuous secondary peaks of Paleoproterozoic and Archaean age are also similar. Major peaks at 560–605 Ma and 910–1020 Ma are also observed in the East African orogen (Thomas et al., 2010), but in this case the secondary peaks have not been recorded. In both potential sources, the ca. 1000 Ma component is ascribed to the Natal–Namaqua belt of the southern Kalahari, so that they cannot be distinguished on the basis of the Mesoproterozoic detrital zircons.

Another possible explanation for the 570–670 Ma component, proposed by Escayola et al. (2007) and Ramos et al. (2014), involves the collision of a juvenile Neoproterozoic island arc against the Río de la Plata craton. However, there is no current geological evidence for such a juvenile terrane in the Sierras Pampeanas and no deformation of the basement has been identified that could be associated with such a collision. More simply, the evidence described above suggests that either the southwestern or the southeastern Kalahari Mesoproterozoic basements are suitable and available sources for the "Puncoviscan Series" of the ESP, and mixing of sediments from both these sources is possible (Rapela et al., 2007).

Detrital zircon patterns of sediments deposited after Pampean deformation (Fig. 7g, h) generally show the following characteristics compared to those of the "Puncoviscan Series": (i) the abundance of the Mesoproterozoic group (970–1080 Ma) decreases markedly to less than 20%; (ii) the largest peak is Early Cambrian, ca. 525 Ma, which together with a 600–680 Ma Neoproterozoic component dominates the pattern; and (iii) there is a 2170–2190 Ma minor peak, in the age range of the Río de la Plata craton rather than the 1800–1950 Paleoproterozoic peak of the Puncoviscanan Series. These characteristics indicate that both the Pampean belt and the Río de la Plata craton were already exposed in Late Cambrian times (Verdecchia et al., 2011), and imply derivation from local or eastern sources. Sedimentation also involved reworking of the "Puncoviscan Series", which is the probable source of the less conspicuous Mesoproterozoic group (Fig. 7g, h). The post-Pampean provenance pattern is indistinguishable from those of the Byrd Group of the Central Transantarctic Mountains and the Pensacola Mountains in Antarctica (Goodge et al., 2004), and the Kansa Group from southern South Africa (Naidoo et al., 2013), and is probably common all along the Terra Australis orogen of SW Gondwana (Cawood, 2005).

4.2.2. The Ancaján Series

Although volumetrically very scarce compared with "Puncoviscan Series", significantly different detrital zircon patterns have been reported from both the ESP (e.g., eastern Sierra de Ancasti, Miller et al., 2010; no analytical data supplied) and NW Argentina (Quebrada de Humahuaca, Adams et al., 2011). The detrital zircon age pattern of our sample ANC-20008 taken at Ancaján, near the eastern slope of Sierra de Ancasti (Fig. 2), is equivalent to that reported by Miller et al. (2010) and has some similarities to that of Adams et al. (2011) (Fig. 5b, c). The Late Neoproterozoic major peak, so important in the pattern of the "Puncoviscan Series" (Fig. 7c), is absent from these samples (Fig. 5). The abundance of Early Mesoproterozoic zircons in the range 1200–1500 Ma in the Ancaján sample is conspicuous, whereas they are absent from the Puncoviscan pattern. The Quebrada de

Humahuaca sample comes from an area with Ediacaran rather than Phanerozoic fossils, suggesting a sedimentary age older than the typical Puncoviscana Formation (Adams et al., 2011, Fig. 5b), but the Ancaján sample contains a minor group at ca. 800 Ma, indicating that the series cannot be older than Early Neoproterozoic. The patterns of the Ancaján and Humahuaca samples (Fig. 5) have several characteristics in common with the metasedimentary rocks and Neoproterozoic cover of the WSP (Fig. 7a, b), including important Early Mesoproterozoic components (1200–1500 Ma), significant Late Paleoproterozoic peaks (ca. 1800–1900 Ma), and absent or very minor Late Neoproterozoic ("Brasiliano") peaks.

The Ancaján marbles interbedded with the metasandstones, have $^{87}Sr/^{86}Sr$ ratios of 0.70749–0.70787 (Murra et al., 2011). Using the updated isotopic evolution of Sr and C in sea water of Halverson et al. (2010), an Early Ediacaran sedimentation age of 620–635 Ma can be suggested for the Ancaján sequence (Fig. 8) (Murra et al., 2014) — almost the same as that for the DCSS in the WSP (Fig. 8). The Halverson et al. (2010) curve for the Sr-isotope composition of ocean water (Fig. 8) shows that a significant isotopic variability can be expected between 620 and 640 Ma. The almost consecutive Sr-composition range of the DCSS marbles (0.709732–0.70742) and the Ancaján marbles (0.70749–0.70787) suggests that they were slightly diachronous, as could be expected in a wide long-lived platform sequence. Remarkably, marbles from Sierras de Córdoba show Sr-isotope values (0.7073–0.7077) that almost embrace the other two ranges strengthening the idea that the platform was extensive and of Early Ediacaran age. The age can be even better constrained with the youngest detrital zircon age and the C isotope composition to ca. 630 Ma (see Fig. 8).

Hf isotope compositions of the 1370–1450 Ma zircons from the Ancaján Series are not as juvenile as those of the DCSS, whereas they are very similar to those of the A-type granites intruded in the 1.8–1.7 Central Yavapai province of Laurentia (Fig. 9a). The conspicuous 1818–1860 detrital zircon peak of the Ancaján Series (Fig. 5b) is taken to indicate distinct provenance locations in the Laurentian margin for the DCSS and the Ancaján Series. A possible explanation is discussed below in the geodynamics section.

4.3. The relationships between Eastern and Western metasedimentary series in the Sierras Pampeanas: hypothesis and geological constraints

The data presented in this paper show that two distinct series of metasedimentary rocks can be distinguished on the basis of U–Pb SHRIMP zircon detrital ages. On one hand there are rocks that share a Laurentian provenance (from the 1.0–1.3 Ga Grenville province, the 1.3–1.5 Ga Granite–Rhyolite Province and the ~1.37 and 1.45 Ga trans-Laurentian A-type granite province): these crop out extensively in the WSP but can also be found farther east in the ESP associated with Ediacaran marbles (the Ancaján Series, Figs. 5, 7a, b). On the other hand, the pre-535 Ma "Puncoviscan Series" in the ESP contains zircons sourced from southern Africa and eastern South America, i.e., the Grenville-age Natal–Namaqua orogenic belt and Brasiliano–Panafrican granitoids. Two alternative interpretations of these two contrasting types of provenance may be considered:

1) The two metasedimentary series were formerly sourced from quite different continental masses on opposite margins of an open sea or ocean. The two continents eventually collided to produce the Pampean orogeny (e.g., Rapela et al., 2007; Casquet et al., 2012a). We ascribe these to a large continent embracing Laurentia on one side and Kalahari–Adamastoria (see Rapela et al., 2011) and the East African orogen on the other.
2) The two series were sourced from the same continent, i.e., they were laid down along the southern Gondwana margin but at very different locations, implying major and long-protracted transcurrent displacement of the sedimentary basin along the margin in Ediacaran to Early Cambrian times (e.g., Finney et al., 2005).

In the second scenario, the most likely source for the DCSS/Ancaján Series would be East Antarctica, and the Ediacaran DCSS/Ancaján Series basin would have been located somewhere along the Transantarctic margin. A good record of detrital zircons from Eastern Antarctica for this period of time is found in the Neoproterozoic Beardmore Group (<580 Ma) and the basal Early Cambrian Shackleton Limestone (Goodge et al., 2004; Fig. 5). Because East Antarctica was attached to western Laurentia until ca. 720–660 Ma (Goodge et al., 2008) (Fig. 10), Laurentian sources are to be expected for both hypotheses. Comparison of the WSP detrital zircon age patterns (Fig. 7a, b) with those of the Beardmore Group and Lower Shackleton Formation shows that neither contain Brasiliano–Panafrican (Neoproterozoic) zircons. The Transantarctic Mountains patterns are dominated by ages between 1.4 and 1.8 Ga, with a significant minor contributions of Grenvillian (1.0–1.2 Ga), Paleoproterozoic (2.5 Ga) and older (ca. 2.9 Ga) ages. In the WSP, however, zircon ages between 1.0 and 1.4 Ga are dominant, followed by minor peaks at 1.8–1.9 Ga and ca. 2.6 Ga (Fig. 7a, b). These discrepancies would seem rather to favour the proximity of WSP basins to eastern Laurentia, with the relatively smaller 1.4 Ga peak, and minor Paleoproterozoic (1.8–1.9 Ga) and Archean (2.6 Ga) peaks, implying more distant sources in that continent (Fig. 10). Such a paleogeographic scenario (Goodge et al., 2004, 2008) also shows that Transantarctic sedimentary basins were probably more distant from Grenvillian sources than those of WSP sediments, so that Grenville-age detritus would be much less abundant there. Finally, the 1340–1480 Ma detrital zircons of the WSP and the Ancaján Series show Hf and O isotopic signatures similar to those of the A-type granites intruded in the Granite–Rhyolite and central Yavapai provinces of eastern Laurentia (e.g., the Ouachita and Blue Ridge rifts, Fig. 10), whereas they lack the typical crustal signatures of many of the 1340–1480 Ma granites intruded in 2.3–2.9 Early Proterozoic crust in southern Laurentia (Figs. 9, 10). This Hf crustal signature is also shared by a significant fraction of detrital grains in the Neoproterozoic sequences of the Transantarctic Mountains (Figs. 9a, 10).

We thus favour the idea that the Neoproterozoic DCSS and the Ancaján Series were laid down along the margin of one large continent that formerly embraced Laurentia and MARA, separated from SW Gondwana by a sea/ocean (Fig. 10). The MARA terranes drifted away from Laurentia in Late Neoproterozoic–Early Cambrian time to collide with Kalahari and/or Kalahari-detached blocks such as Adamastoria (Rapela et al., 2011) to produce the Pampean orogeny (Casquet et al., 2012a). The structural boundaries between the Neoproterozoic WSP siliciclastic and carbonate sedimentary series, i.e., the DCSS/Ancaján Series and the "Puncoviscan Series" would all be tectonic, resulting from oblique continental collision.

4.4. Geodynamic model for the Pampean orogeny

The evidence provided in this contribution is compatible with the paleogeographic model put forward by Rapela et al. (2007) and Casquet et al. (2012a) in which two continental masses collided obliquely in the early Cambrian. A large part of the Pampean orogen (its eastern part) was subsequently torn off by the first-order Córdoba fault, which was active in early Cambrian times (late- to syn-Pampean orogeny) and dextrally displaced the Rio de la Plata craton to be close to its present position. This fault has been correlated with the Transbrasiliano Mega-Shear Zone (Rapela et al., 2007; Cordani et al., 2013 and references therein). This interpretation is further supported by paleomagnetic evidence (Spagnuolo et al., 2012) that suggests clock-wise rotation of Pampia (the basement of the Puncoviscana Formation) relative to the Rio de la Plata craton in the Cambrian.

The WSP, the Arequipa–Antofalla block and probably other continental blocks such as Rio Apa are considered part of a large Paleoproterozoic block, the MARA block that has a strong Grenville-age overprint along its western side, and was attached to eastern Laurentia in Late Mesoproterozoic times (Casquet et al., 2012a). East Antarctica and the

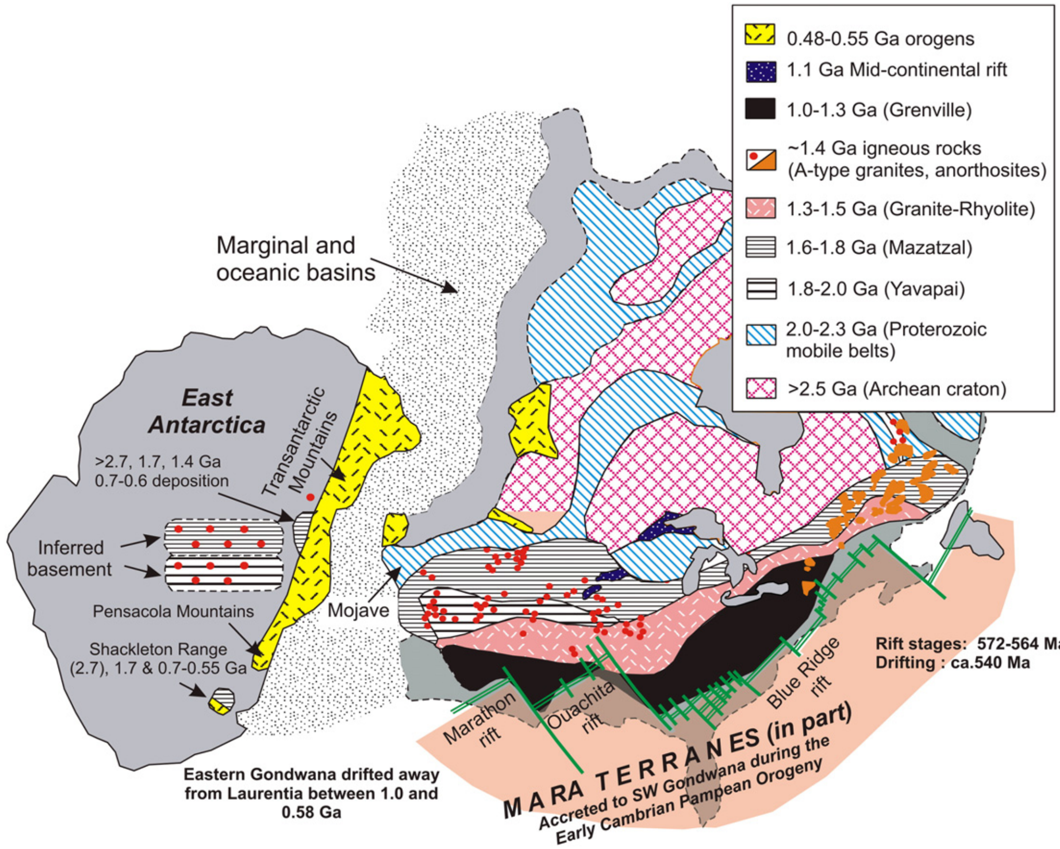


Fig. 10. Late Neoproterozoic paleogeographic reconstruction of Laurentia and East Antarctica with basement provinces, after Goodge and Fanning (2002) and Goodge et al. (2008). The Neoproterozoic to Early Cambrian rift of eastern Laurentia is after Thomas et al. (2012). The inferred location of the MARA terranes along the eastern margin of Laurentia is shown; these are thought to have rifted from Laurentia as a large continental sector which was accreted to southwestern Gondwana during the Early Cambrian.

Natal–Namaqua province of southern Kalahari are also considered to have been connected to southern Laurentia at that time, forming the Rodinia supercontinent (Jacobs, 2009; Goodge et al., 2010).

Protracted rifting of Eastern Laurentia took place throughout the Neoproterozoic (Tollo et al., 2004; Thomas et al., 2012). Two early aborted rifting events, at ca. 840 and 760 Ma, are represented by A-type granitoids in Sierra de Maz and Sierra de Pie de Palo, bearing zircons with juvenile Hf and O isotopic signatures (Baldo et al., 2006; Colombo et al., 2009; Rapela et al., 2011). Further rifting occurred at ca. 570 Ma (Ediacaran), represented by a carbonatite–nepheline syenite complex in the Sierra de Maz (Casquet et al., 2008b), which is consistent with rifting at 572 ± 5 and 564 ± 9 Ma in the Blue Ridge of eastern Laurentia (Aleinikoff et al., 1995). Casquet et al. (2012a) suggest that this latter event probably initiated opening of the Puncoviscan/Clymene ocean (Fig. 11a, after Rapela et al., 1998; Trindade et al., 2006, respectively), which closed in the Pampean orogeny. Further evidence for this comes from the Sr isotope composition of platform carbonates of the Difunta Correa–Ancaján platform sediments, which according to our hypothesis were deposited on the eastern margin of MARA (Figs. 8, 11a). Ediacaran shallow-marine carbonates that were post-glacial with respect to the Marinoan (ca. 635 Ma) and Gaskiers (ca. 580 Ma) events are recorded elsewhere in southern South America (Misi et al., 2007). Hf and O isotopes in 1340–1480 Ma detrital zircons suggest that the source of the DCSS was in the Grenville and Granite–Rhyolite provinces near the Ouachita rift (Fig. 10). The source of the Ancaján Series was probably the Yavapai and Grenville provinces of the Blue Ridge or further north, where anorthosite bodies are abundant (Fig. 10). Extensive 630–580 Ma carbonate platforms would be compatible with the existence of the Puncoviscan/Clymene ocean during Ediacaran time (Tohver et al., 2010), as are recent findings of Ediacaran guide fossils in carbonate sequences in central Brazil (Warren et al., 2014).

During the Early Cambrian the Iapetus ocean opened along a very long rift in eastern Laurentia (Thomas et al., 2012 and references therein) (Fig. 10), separating MARA from Laurentia and developing passive margin sedimentary sequences along the Appalachian margin (Thomas, 2011) (Fig. 11b). Iapetus opening was coeval with the Ediacaran–Early Cambrian (ca. 543–540 Ma) initial deposition of clastic sediments (Puncoviscan Series) and arc magmatism in the Eastern Sierras Pampeanas (Escayola et al., 2011; von Gosen et al., 2014). Widespread ca. 538 Ma Cordilleran I-type granites intruded in a transpressional environment indicate the onset of the Pampean arc (Iannizzotto et al., 2013) (Fig. 11b). There was an interval of ca. 20 Ma between the opening of the Iapetus ocean (ca. 545 Ma) and collision of MARA with Kalahari/Rio de la Plata (530–525 Ma), suggesting an initial separation of, at most, a few thousand kilometres (Dalziel, 1991; Johanson, 2014). Oblique collision of the MARA block against SW Gondwana, which at latitudes 22–33° S is represented by the "Puncoviscan Series", produced strong dextral compression and rapid crustal thickening in the 537–525 Ma interval (Escayola et al., 2011; Iannizzotto et al., 2013; von Gosen et al., 2014) (Fig. 11c). The final episode of the Pampean orogeny was one of widespread uplift, anatexis and formation of large migmatitic massifs, peraluminous granites and cordieritites, mostly in the 525–520 Ma interval (Rapela et al., 1998, 2002). Ophiolite relics of probable Neoproterozoic age in the Sierras de Córdoba (Fig. 11c, Ramos et al., 2000; Escayola et al., 2007) are considered to be remnants of the Puncoviscan ocean obducted during the collision of MARA.

A variation of this model, beyond the scope of this investigation, would be the possibility that the Precordillera terrane (Fig. 1) was also

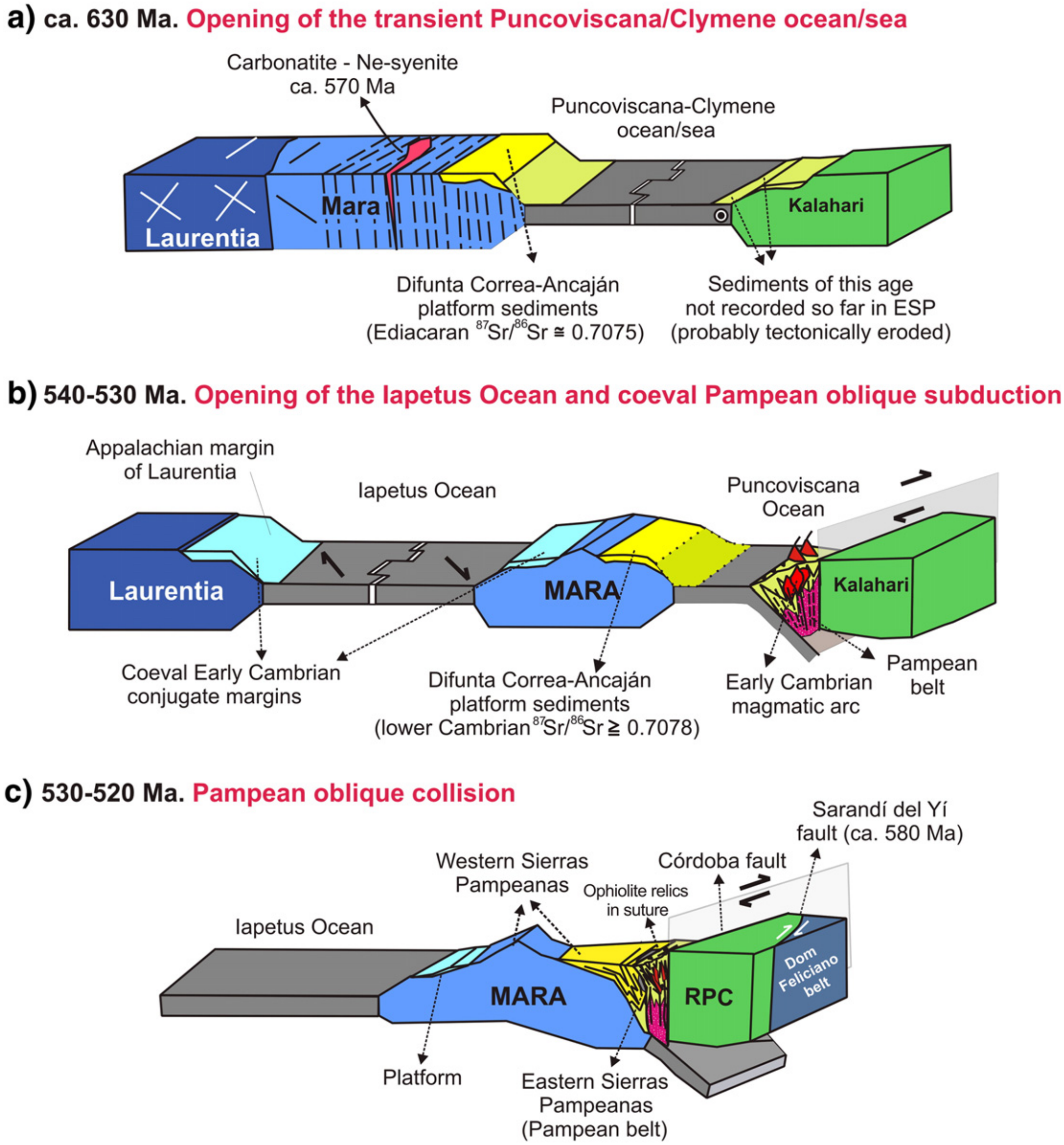


Fig. 11. Diagrams showing geotectonic evolution during the Neoproterozoic and the Early Cambrian that led to the Pampean orogeny and amalgamation of MARA with SW Gondwana. See text for explanation. The figure highlights (a) the role played by the opening of the Puncoviscan/Clymene ocean in the Late Neoproterozoic, (b) the opening of the Iapetus ocean and rifting of the MARA terranes from Eastern Laurentia, coeval with subduction initiation in SW Gondwana (Pampean arc), and (c) the subsequent closure of the Puncoviscan/Clymene ocean as the culmination of the Pampean orogeny.

a relict of the passive margin of Iapetus opposite Laurentia but at a different latitude to MARA and subsequently laterally displaced during the Early Ordovician Famatinian oblique subduction (Mulcahy et al., 2014). Our preferred Neoproterozoic–Early Cambrian scenario is mostly based on geological observations in the modern flat-slab segment of the Andes. However, information recently obtained indicates that the Early Cambrian episode affected other geological provinces to both north and south of this segment. Metasedimentary rocks equivalent to those of the WSP are observed in the southern Puna (Antofalla sector), where alleged Cambrian orthogneisses have also been reported (Escayola et al., 2011). This is consistent with the suggestion that the WSP was part of a single continental crustal block from Mesoproterozoic times (Casquet et al., 2006, 2008a). To the south (Fig. 2b), Cambrian granites (520–530 Ma) have been reported in the basements of the Sierra de la Ventana (Rapela et al., 2003; Tohver et al., 2012), the North Patagonian Massif (Rapalini et al., 2013; Pankhurst et al., 2014) and beneath the Magallanes basin of southernmost Patagonia (Söllner et al., 2000; Pankhurst et al., 2003; Hervé et al., 2010). U–Pb, Hf and O isotopic data of the Cambrian granites of the North Patagonian Massif testify to the presence of continuously recycled older crustal material in the source region of these granites, with largest inherited zircons peaks at 630, 1075 and 1850 Ma (Pankhurst et al., 2014), similar to that of the "Puncoviscan Series" (Fig. 7c).

5. Conclusions

The detrital zircon age patterns of the Sierras Pampeanas metasedimentary rocks show that the Western and Eastern sectors are derived from different sources that were juxtaposed during the Early Cambrian Pampean orogeny. This Early Cambrian accretion defined the outer shape of the continent, and is considered the initiation of the supercontinent stage in southwestern Gondwana. Accretion of Mesoproterozoic terranes is not observed in this time interval along the Transantarctic sector of the proto-Pacific margin of Gondwana.

The metasedimentary rocks of the Difunta Correa Sedimentary Sequence (WSP) and the Ancaján Series of the ESP are considered to have been derived from eastern Laurentia. Their outcrops are not restricted to the latitudes of the Precordillera terrane, but extended further north to the southern Puna. Thus the WSP are only part of a large continental block, the MARA block, once juxtaposed to eastern Laurentia. The continental sector of the WSP shows clear evidence of derivation from local 1330–1030 Ma Mesoproterozoic basements while this was part of the Grenville and the Granite–Rhyolite province of Laurentia. This sector (Sierras of Maz, Umango, Espinal and the central-eastern part of the Sierra de Pie de Palo) is composed of Paleoproterozoic continental basement, reworked during the Grenville orogeny, isotopically (Nd, Pb) similar to the northern sector of the Arequipa block (Casquet et al., 2006, 2008a). The subordinate Ancaján Series of the ESP is also considered to have been derived from eastern Laurentia, but from the Grenville and Yavapai provinces, and was imbricated with the ESP metasedimentary rocks (Puncoviscan series) during the Early Cambrian collision.

The ESP show a very different zircon detrital pattern to that of the WSP — one typified by bimodal peaks at ca. 1000 and 600 Ma. The Mesoproterozoic component is ascribed to sources in the Natal–Namaqua belt, while the Neoproterozoic is considered as derived from either the Dom Feliciano Belt of SE Brazil and Uruguay and/or the East African orogen.

Sedimentary series formed after the Pampean orogeny in the ESP and Patagonia, during the Middle Cambrian–Early Ordovician interval, show detrital patterns common to many areas along the Terra Australis orogen, defined by a large Early Cambrian peak, ca. 525 Ma, which together with a 600–680 Ma Neoproterozoic component dominates the pattern, while the Mesoproterozoic peaks are subordinate. This indicates that contributions from the Neoproterozoic to Early Cambrian orogenic belts that formed during Gondwana assembly started to control sediment input to the Paleozoic basins.

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