Int J Earth Sci (Geol Rundsch)
DOI 10.1007/s00531-010-0559-5

ORIGINAL PAPER

Evolution of exhumation and erosion in western West Gondwanaland as recorded by detrital zircons of late Neoproterozoic and Cambrian sedimentary rocks of NW and Central Argentina

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Received: 9 November 2009 / Accepted: 26 April 2010

Abstract The evolution of the provenance areas for Late Neoproterozoic, Cambrian and Early Ordovician sedimentary and meta-sedimentary rocks of north central and northwest Argentina is discussed using 123 maximum ages of detrital zircons from 42 samples from this and previously published studies. Most detrital zircon ages fall into two groups: 1,200–900 Ma and 670–545 Ma. These ages are essentially identical for the non- to very low grade metamorphic late Neoproterozoic to Early Cambrian Puncoviscana Formation and the low to high grade metamorphic rocks of Eastern Sierras Pampeanas. Hence, both units are related to similar provenance areas at the same time of sedimentation. The time span from zircon crystallization in the Earth's crust to exhumation and erosion may be very long. This is important when determining maximum ages of sedimentary rocks. Variation of zircon maxima may also be influenced by concurrent sedimentary cover of proposed provenance areas. For the late Mesoproterozoic to early Neoproterozoic zircon age group, an active mountain range of the southwest Brazilian Sunsás orogen is the most probable provenance area. The younger, late Neoproterozoic zircons are related to the continuously developing mountains of the Brasiliano orogen of southwest and south central Brazil. Young zircons, up to 514 Ma, from fossil-bearing Puncoviscana and Suncho Formation outcrops are related to late Early Cambrian volcanism contemporaneous with sedimentation. This situation continues through the Late Cambrian to the Early Ordovician, but the Sunsás orogen provenance diminishes as possible Río de la Plata craton origins become important.

Keywords West Gondwanaland · Neoproterozoic · Cambrian · Detrital zircons · Provenance areas

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Introduction

Beginning with the classical work of Schwartz and Gromet (2004), and then during the last 5 years, great emphasis has been placed upon the dating of detrital zircons of sedimentary and metamorphic rocks of northwest and central Argentina. This interest was partly due to the development of rapid and relatively cheap methods of U–Pb zircon dating. The primary aim of these studies was to define the maximum age of sedimentary units like the Puncoviscana Formation in NW Argentina and their metamorphic equivalents. A secondary objective was to shed some light upon the provenance area of these sediments, and consequently, the possible relationship of geological provinces within Gondwanaland. All authors concerned with this topic were citing former studies, without a general synthesis. Furthermore, the principal goal was always to define the maximum ages of these peri-Gondwanan sediments; and consequently the exhumation and erosion history of the provenance areas was rather overlooked. There are now, instead of isolated zircon ages, a great number, and it is possible to consider not only the history of deposition, but also of erosion within the developing Brazilian shield. We consider here the late Neoproterozoic–Early Cambrian period of the Puncoviscana Formation and its strongly metamorphic equivalents, and also the immediately younger Late Cambrian

Mesón Group and Early Ordovician clastic sediments. Younger sediments are only briefly mentioned in the text, because their sedimentary inventory may derive not only from the Brazilian shield rocks themselves but also from recycling of the late Neoproterozoic and Cambrian sedimentary rocks.

Geological setting

Central and northwest Argentina are characterized by the Sierras Pampeanas (Stelzner 1885) (Fig. 1; Sierras Pampeanas: "mountain ranges that rise from the Pampa plains"). To the north, the Sierras Pampeanas pass into the Cordillera Oriental (Eastern Cordillera) which builds the eastern border of the Puna or Altiplano. The classical Sierras Pampeanas are mostly composed of phyllites, schists and gneisses which are intruded by granitoids of varying ages from Cambrian to Carboniferous (see Pankhurst and Rapela (1998) for a compilation). In the northwest, the oldest rocks of the mountain ranges are characterized by the Puncoviscana Formation and some similar rocks with local names. The Puncoviscana Formation is mainly composed of grayish, sometimes reddish and greenish slates, siltstones, sandstones and quartzites. For details, see the summary given by Aceñolaza and Toselli (2009). Volcanic rocks and limestones (marbles) occur in several places. A transition between the non-, or very low grade metamorphic rocks of the Puncoviscana Formation and the low to high grade metamorphic and polyphase deformed basement of the Sierras Pampeanas can be locally observed near Tucumán (Miller and Willner 1981).

The age of the Puncoviscana Formation has been controversial. On the one hand, in many outcrops trace fossils are frequent, which indicate an Early Cambrian age (e.g. Aceñolaza and Durand 1986). On the other hand, granitoids thought to be Precambrian, intrude folded Puncoviscana Formation in many places in the provinces of Jujuy and Salta. It is now generally accepted that most of these granitoids are, in fact, mid-Cambrian or even younger and deposition of the Puncoviscana Formation began in the Late Neoproterozoic and ended in the Early Cambrian.

An immediate relationship between the extended trough of the Puncoviscana Formation and the basement gneisses of the Sierras Pampeanas south of Tucumán, Catamarca and La Rioja, e.g. the Sierra de Ancasti and the Sierras de Córdoba and San Luis was proposed earlier by Aceñolaza and Miller (1982) and later confirmed by e.g. Rapela et al. (1998). Many authors considered the development of the Puncoviscana Formation trough, as well as the metamorphic rocks and granitoids of the Eastern Sierras Pampeanas, as forming part of a great peri-Gondwanan orogenic belt (e.g. Drobe et al. 2009a, b; Söllner et al. 2000c; Vaughan and Pankhurst 2008), defined as the Terra Australis Orogen by Cawood (2005). Detailed geochemical (Steenken et al.

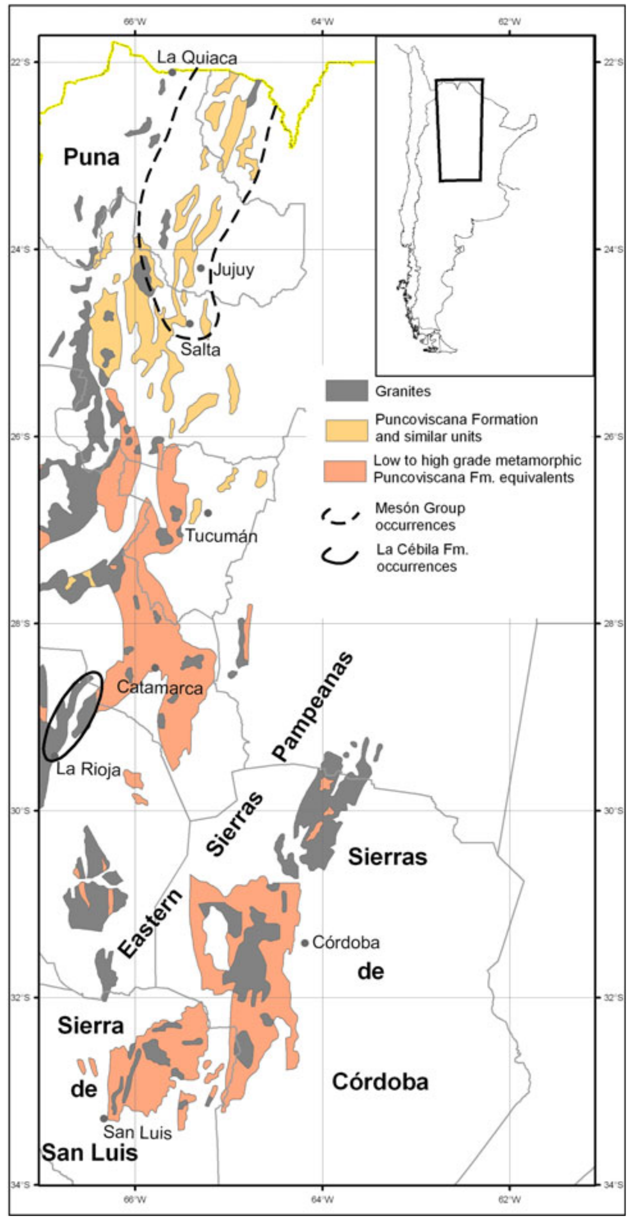

Fig. 1 Distribution of the Puncoviscana Formation, similar units and the metamorphic equivalents of late Neoproterozoic to Early Cambrian sedimentation age in north central and northwest Argentina. Modified after Caminos and González (1996). Occurrences of the Mesón Group in the north (after Adams et al. 2008a) and of the La Cébila Formation in the west (after Toselli et al. 2007) are indicated

2008), geochronological (Drobe et al. 2008; Söllner et al. 2000a) and structural studies (Martino et al. 2009) have confirmed the distinct relationship between the Puncoviscana Formation trough in the far northwest and the metamorphic units to the south, and in the major parts of the Sierras Pampeanas of San Luis and Córdoba. A broad understanding of the temporal history of the Puncoviscana Formation and most of the metamorphic parts of the Eastern Sierras Pampeanas is thus required for a complete consideration of their provenance areas.

The important detrital zircon data (e.g. Finney et al. 2005 and literature therein) of the Cuyania terrane (Western Sierras Pampeanas and Precordillera of Mendoza, San Juan and La Rioja) are not considered in this context. Its provenance as a tectonic sliver of Laurentia, formerly adjacent to the margin of Gondwanaland, or as a later microcontinent drifted from Laurentia, or as a parautochthonous sliver of Gondwanaland itself is debated elsewhere (e.g. Dalziel et al. 1994; Rapalini and Astini 1998; Thomas and Astini 2003; Aceñolaza et al. 2002; Finney et al. 2005; Finney 2007 and literature cited in these articles). All authors agree that this terrane did not form immediate part of the region in consideration here before the Ordovician. Thus, to avoid circular arguments, although their detrital zircon patterns show strong relationships to Gondwanaland (Finney et al. 2005; Finney 2007), we do not integrate them in this present review.

The role of the Pampia terrane

Aceñolaza and Toselli (1976) introduced the concept of a "Pampean Cycle" to define an orogenic cycle active from late Neoproterozoic to Early Cambrian with sedimentation, folding and magmatism occurring in the Sierras Pampeanas and Eastern Cordillera. This definition has subsequently become common in the literature (see e.g. the summary in Pankhurst and Rapela 1998).

Later, the term "Pampeanas terrane" was used by Ramos et al. (1986) referring only to "a magmatic and metamorphic province built on late Precambrian basement at the margin of South America". It was then considered autochthonous, and simply as a synonym for the classical Sierras Pampeanas morphostructural unit of Stelzner (1885). A short time later, Ramos (1988) defined a "Pampean terrane" as a basement unit for the sedimentation of the Puncoviscana basin and the "Eastern Pampeanas" belt. Kraemer et al. (1995) and von Gosen and Prozzi (2009, Fig. 12) called "Terreno Pampia" or "Pampean terrane" a continent situated west of the Río de la Plata craton, separated from this by an ocean of unknown extension and forming the basement of the Puncoviscana Formation. Rapela et al. (1998) explicitly delineated the "Pampia terrane" as a microcontinent temporarily separated from the West Gondwana margin that caused folding of the Puncoviscana Formation when colliding with the Gondwana margin. Steenken et al. (2006) defined the metasedimentary and igneous rocks of the Sierra de San Luis as constituting the "cover of the Pampia craton" or "Pampean Terrane", "which collided with the Río de la Plata craton during the Pampean Orogenic Cycle". On the other hand, Lucassen and Franz (2005), comparing the Pampean Cycle with the young Andean Cycle, concluded that the Pampean orogen is also of continental margin style and no continent–continent collision is necessary for its formation.

Thus, the only important argument for a temporally autonomous Pampia terrane is the strip of mafic and ultramafic rocks at the eastern border of the Sierra de Córdoba (e.g. Bonalumi et al. 1999). Is this a local phenomenon, a short-time intra-continental rift, or is it an indication of a wide-spread ocean at the east that separated the "Pampia terrane" from a more stable Gondwana margin to the east? What was this stable continent, if the Río de la Plata craton was not in the immediate neighborhood when the Sierras Pampeanas ranges were forming (Rapela et al. 2007)? The similarity of lithological (pre-metamorphic) and structural development from the Sierras de Córdoba and the Sierras de San Luis to the more northwesterly Sierras Pampeanas and to the Puncoviscana Formation is distinct, and their common detrital zircon pattern is so related to the Precambrian regions of adjacent Brazil, that we do not believe that a major ocean existed at the east of central Argentina in early Cambrian times. Maybe the small intra-continental rift of the Sierra Chica de Córdoba had been closed rapidly in a very early first phase of deformation as documented in the Sierra de Ancasti by a first deformation age of 554 Ma (Bachmann et al. 1986). If so, a denomination of the Sierras Pampeanas as a particular "terrane" is not needed.

U–Pb geochronology of detrital zircons

General comments

In Table 1, 123 significant data of detrital zircons are presented from the Puncoviscana Formation (late Neoproterozoic-Early Cambrian, NW Argentina), its metamorphic equivalents (NW and central Argentina), Late Cambrian Mesón Group and uppermost Cambrian-Early Ordovician sedimentary rocks (NW Argentina), from 15 sites constituting 42 samples. For technical methods, see the respective articles cited in Table 1.

For most data cited, zircon ages are presented by relative probability diagrams of large ($N > 50$) populations. Age components are usually considered significant only if a component comprises at least 3 or 4 grains per 20 million year interval, and the component itself corresponds to 4 or more percent of total population. In some cases in the literature, the age components are not quoted from relative frequency data but as "from-to" values. These are enclosed in Table 1 unchanged, as they were originally indicated in the publication (for complete information see the respective articles). The ages cited in Table 1 do not refer to isolated single zircon grains. In the literature, the original diagrams often present such isolated zircon data and ascribe them to individual provenance areas. Indicating all these in a single table produces a great list which is hard to

Table 1 Compilation of authors' and previously published data of detrital zircons from the Puncoviscana Formation (late Neoproterozoic–Early Cambrian, NW Argentina), its metamorphic equivalents (NW and central Argentina), Late Cambrian Mesón Group and latest Cambrian–Early Ordovician sedimentary rocks (NW Argentina)

Detrital zircons age group	Very low grade Puncoviscana Fm. and related series	Low to high grade metamorphic Puncoviscana Fm. equivalents	Mesón group and uppermost cambrian and lower ordovician fms	Provenance area
<525 Ma			*522 (13), 521 (13), 520 (6),* 522 (2), 502 (2), 503 (2),	Puncoviscana Fm. and local volcanism
540–515 Ma	534 (1), 530 (1), 523 (1), 519 (2), 514 (2)	530 (8)	538 (2), *530 (7),* 525 (2)	Local magmatism and Puncoviscana Formation
670–540 Ma	668 (1), 656 (1), 650 (1), 636 (2), 635 (1), 628 (1), 627 (2), 626 (1), 624 (1), 618 (1), 612 (1), 612 (1), 596 (1), 576 (2), 555 (2), 555 (1), 552 (2), 551 (1), 545 (2), 541 (2), *650-550 (10)*	668 (3), *640 (15),* 632 (3), *631 (9), 620 (15), 615 (15), 587 (9), 569 (8),* 560 (3), *550 (15), 530 (15) 800-600 (5), 790-620 (5), 700-600 (4), 700-600 (5), 680-570 (7)*	655 (2), *640 (7), 638 (13), 630 (6), 630 (13),* 628 (2), 622 (2), 620 (3), *620 (6),* 615 (2), 606 (2), 597 (2), 595 (3), 581 (2), 576 (2), 547 (3), 544 (2), *790-540 (12), 700-500 (11), 640-580 (14), 580-520 (14),*	Brasiliano orogen of southeast and south central Brazil
1.2–0.9 Ga	1320 (2), 1206 (2), 1162 (2), 1112 (1), 1093 (2), 1061 (1), 1060 (2), 1059 (2), 1056 (1), 1056 (1), 1044 (1), 1038 (1), 1021 (1), 1019 (1), 1014 (1), 1013 (1), 1006 (1), 964 (2), 920 (1), 891 (1), *1100-1000 (10)*	*1050 (4),* 1034 (3) *1000 (15), 962 (9), 950 (15), 1200-1000 (5), 1200-900 (5), 1100-900 (5) 1050-950 (4), 1020-960 (7)*	*1220 (13), 1080(14), 997 (13), 950 (14), 1440-1040 (12), 1200-900 (11)*	Sunsás orogen of southwest and west central Brazil
2.0–1.5 Ga	1893 (1), 1557 (2)	*2,04-1,85* (7)	*1770 (7)*	Ventuari-Tapajós orogen of central Brazil
2.2–2.0 Ga	2114 (1)		2166 (3), 2143 (2), 2125 (2), *2100 (7), 2000 (14),* 2080 (2), *2150-1950 (6), 2120-1890 (12)*	Rio de la Plata Craton of east central Argentina

Numbers in parentheses: Respective publications. Numbers in square brackets: number of analyzed samples. Own analyses are in normal types, analyses taken from literature are in italics. Zircon peaks are mostly only registered if a number of at least 3 or 4 grains per 20 million years exist, and the peak corresponds to 4 or more percent of total grains. In the literature, often not statistically calculated peaks are given but "from-to" values. They were enclosed in the table as they were indicated in the publication. For more information, see the respective papers. (1) Adams et al. 2008b [6], (2) Adams et al. 2009, 2010 [8], (3) Adams (not published data) [2], (4) Schwartz and Gromet 2004 [1], (5) Escayola et al. 2007 [3], (6) Di Cunzolo and Pimentel 2008 [2], (7) Rapela et al. 2007 [2], (8) Drobe et al. 2009b [2], (9) Steenken et al. 2008 [3], (10) Hauser et al. 2009 [1], (11) Reimann et al. 2009 [2], (12) Di Cunzolo and Pimentel 2009 [2], (13) Collo and Astini 2009 [2], (14) Rüsing et al. 2009 [2], (15) Sims et al. 1998 [4] analyze. Consideration of such individual ages results in many hypothetical provenance areas with a wide range of ages. Such ages from single grains may be important for the definition of a maximum age of sedimentation but do not have any rigorous statistical value. Furthermore, most orogens do have older cores or adjacent basement rocks whose zircons may join the sediment load (e.g. Basei et al. 2000; Söllner et al. 2000b; Philipp and Machado 2005 and literature therein), such that isolated grains cannot give unequivocal indications of specific provenance areas. Moecher and Samson (2006) have made critical comments on the detrital zircon records used for provenance analyses. They warn against overestimates as well as underestimates of provenance implications derived from data without careful reflection.

Age distribution of the zircon grain maxima

In Table 1, three regional rock families are shown: (1) non-metamorphic or very Low Grade metamorphic rocks of the Puncoviscana Formation and similar rocks with local names, (2) low to high grade metamorphic rocks that are considered metamorphic equivalents of the Puncoviscana Formation and (3) rocks immediately younger than the Tilcarian (mid-Cambrian) Orogeny: the Mesón Group and Early Ordovician formations. Two large age groups are immediately noticeable: one is concentrated in the range 670–545 Ma, i.e. exactly at the late Neoproterozoic, while an older one ranges from 1200 to 900 Ma, i.e. late Mesoproterozoic to early Neoproterozoic, with a few older or younger exceptions. These are characterized by 2.2–2.0 Ga, 2.0–1.5 Ga and 540–525 Ma and <525 Ma, respectively.

The provenance of the Puncoviscana Formation and metamorphic equivalents

As defined above, we can consider the Puncoviscana Formation and its metamorphic equivalents as one depositional unit (Fig. 1). This is fully confirmed by the detrital zircon ages. All published regional reviews agree that they derive from the Brasiliano Orogen of central and southeast Brazil (e.g. Schwartz and Gromet 2004) or similar orogens of southwest Africa (Fig. 2). There are two exceptions to this general assessment: firstly, in sediments of the Puncoviscana Formation and comparable Early Cambrian fossil-bearing rocks (Suncho Formation), zircons of early Cambrian age occur that form a 540 to 515 Ma group (Adams et al. 2009, 2010). On the one hand, they definitely confirm the Early Cambrian maximum age of part of the Puncoviscana Formation, and on the other hand they document a major local input of volcaniclastic sediments into the Puncoviscana sedimentary basins. Secondly, there is just a single sample (out of a total of 23) from the

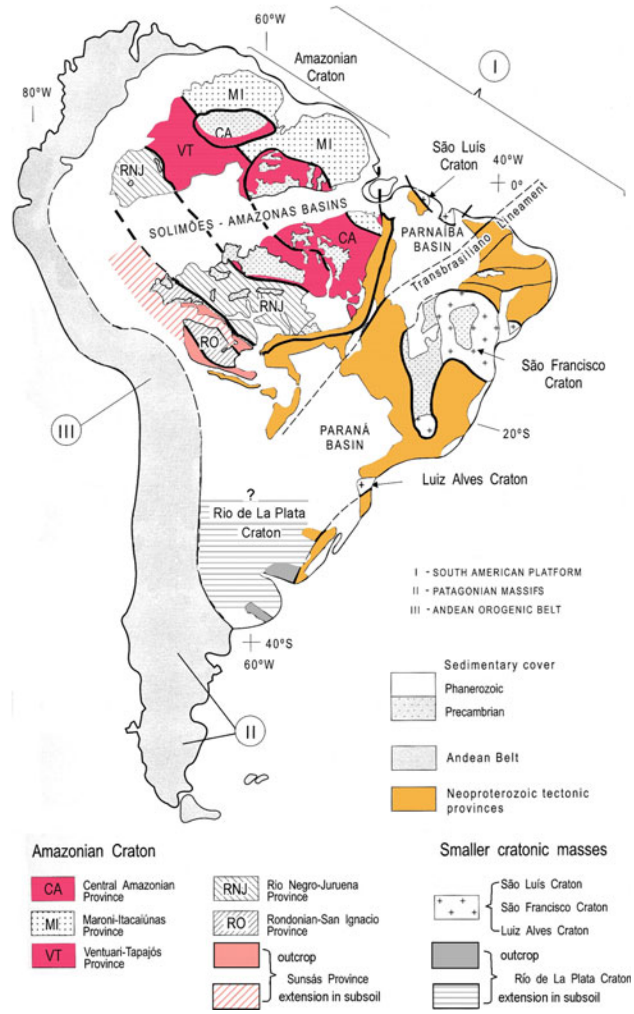

Fig. 2 Geological units of South America. Modified after Cordani et al. (2000). Extension of the Río de la Plata craton ("actual position") after Rapela et al. (2007), former extension of the Sunsás orogen after Santos et al. (2008a, b)

Puncoviscana Formation where this Early Cambrian-late Neoproterozoic zircon age group does not occur, furthermore, in it there is not a single zircon grain younger than 950 Ma (Adams et al. 2010). This is discussed later.

A similar agreement exists on the provenance of the abundant zircons of 1200 (−1400) to 900 Ma. All authors refer them to the Sunsás Orogen in southwest Brazil. Today, the outcrops of the Sunsás Orogen are small, but it is believed that it was formerly much more extensive to the north (Fig. 2; Santos et al. 2008a, b). To the south, it ends at the northern end of the Río de la Plata craton. Recently, a hypothetical orogenic unit of Mesoproterozoic age has been proposed bordering the Río de la Plata craton at its western margin (Aceñolaza and Toselli 2009). Gaucher et al. (2008) suggest that such a Mesoproterozoic belt may be the source for the abundant zircons of this age in the Late Neoproterozoic sedimentary cover of the craton.

The zircon maxima of strata post-dating the Tilcarian (mid-Cambrian) folding

Recently, some zircon geochronology studies have included formations which lie in strong angular unconformity above the rocks of the Puncoviscana Formation. The oldest one is the widespread Mesón Group (Fig. 1), divided into the Lizoite, Campanario and Chalhualmayoc formations (Adams et al. 2008a, 2010; Augustsson et al. 2009). Latest Cambrian and Early Ordovician formations were also studied recently (Reimann et al. 2009; Rüsing et al. 2009; Di Cunzolo and Pimentel 2008, 2009). It is evident (Table 1) that most of the zircon age patterns are similar to those of the Puncoviscana Formation. Late Neoproterozoic grains are widespread. Augustsson et al. (2009), however, showed that the Mesón Group sediments are probably not recycled from the Puncoviscana Formation but have their own provenance area which can be identified within the Brasiliano Orogen. Zircons from the Sunsás Orogen are much scarcer than in the older sediments. It is not surprising that in the post-mid-Cambrian sediments, zircons younger than those in the Puncoviscana Formation are also present. They may derive from simultaneous volcanism (Hauser et al. 2008), and the Early Cambrian zircons may also come from contemporaneous magmatism of the Tilcarian orogenic event (Matteini et al. 2008).

The age of the La Cébila Formation (Fig. 1; Catamarca and La Rioja provinces) is a matter of debate. On the one hand, from one outcrop in the northernmost part of the formation, Early Ordovician fossils have been found (Verdecchia et al. 2007) that demonstrate a post-Tilcarian age. On the other hand, at two outcrops sampled by us and in Rapela et al. (2007), a relationship is seen with the youngest part of the Puncoviscana Formation. For sedimentological and regional reasons, these are included here in the La Cébila Formation. Similarities to the Mesón Group of Jujuy and Salta were noted by Höckenreiner (1998) and Toselli et al. (2007). Analogous sedimentary rocks (Candelaria Formation) from the northeastern–most part of Tucumán province (Aceñolaza and Nieva 2003) may document a continuity of a Cambro-Ordovician molasse basin from the Mesón Group to the La Cébila Formation over a distance of about 900 km.

An important observation is that ages of 2200–2000 Ma, which are mostly lacking in the older rocks, are present in the post-Tilcarian sediments. Our own data that are presented here do not derive from significant age components revealed by relative probability diagrams but are mean values of 6–7 ages from each of the 3 samples. The possible provenance area of these grains has been a matter of discussion in the literature.

Discussion

Firstly, two fundamental problems of detrital zircon geochronology are considered.

It is well known that the youngest detrital zircon ages from sedimentary or meta-sedimentary rock units indicate the maximum age of the sedimentation. This may in fact approximate the time of deposition if the sediments derive from contemporary volcanic rocks. If the zircons originate from metamorphic and magmatic rocks of a distant orogen, it is not as simple. Sedimentary and volcanics rocks deposited either at an active continental margin with respective fore arc and back arc basins or at a passive margin, later transformed into an active one, are subducting to great depths where they are intruded by granitoids during orogenesis. Before they can be eroded to be components of a sediment load, they must be exhumed. This process requires a varying time but might be tens of millions of years, and in case of rejuvenated orogens, hundreds of millions of years. Hence, detrital zircons, if not deriving from synsedimentary volcanism, are carrying a history that includes a considerable time span for exhumation, after the crystallization recorded by the U–Pb ages. Erosion time, transport time and deposition time can be neglected in this context. It may occur that the actual deposition age of the sediments is tens of millions of years younger than the youngest detrital zircons. Thus, sedimentation ages of zircon-bearing rocks of the Puncoviscana Formation could be much younger than the zircons they contain. This reconciles the frequent occurrence in the Puncoviscana Formation of Early Cambrian fossils (Aceñolaza and Durand 1986; Aceñolaza and Aceñolaza 2005 and literature therein) and zircon grains that are mostly late Neoproterozoic (e.g. Adams et al. 2008b; Hauser et al. 2009).

Another important requirement is that a site of sedimentation (fluvial or marine) cannot simultaneously be site of erosion. This is illustrated in two examples.

In the younger samples of the Puncoviscana Formation, zircons of the 1,200–900 Ma group (Sunsás Orogen) become scarce. They are even scarcer in post-Tilcarian sediments such as in the Mesón Group, and in overlying sediments and in the La Cébila Formation. Significantly, the Sunsás Orogen was at least in part a site of *sedimentation* in Late Neoproterozoic-Cambrian times (e.g. Alvarenga et al. 2000; Gaucher et al. 2003; Babinski et al. 2008). Hence, there would then have been a greatly reduced possibility for erosion of such Grenville-age rocks.

A similar reasoning can be applied to the sudden appearance of zircons of 2,200–2,000 Ma in the Mesón Group. They are commonly attributed to the nearby Río de la Plata craton (Dalla Salda 1999). But why do they not appear before this in the zircon age patterns? This might reflect the absence of the Río de la Plata craton before

Cambrian times (Rapela et al. 2007; Gaucher et al. 2008; Blanco et al. 2009), which was only brought into the Mesón Group hinterland along some regional-scale fault in Cambrian times. Furthermore, the early Paleoproterozoic rocks of the Río de la Plata craton are now extensively covered, in angular disconformity, by flat lying Late Neoproterozoic and Early Cambrian sedimentary rocks (e.g. Cingolani and Dalla Salda 2000; Babinski et al. 2008; Iñíguez Rodríguez 1999; Gaucher et al. 2003; 2006). They themselves would have thus prevented or hindered erosion of the underlying rocks of this craton. These latter would have only become accessible for erosion and transport after this sedimentary cycle had ceased, perhaps not until post-Early Cambrian time. This may therefore explain the scarcity of 2.2–2.0 Ga old zircons in the Late Neoproterozoic and Early Cambrian Puncoviscana Formation and its equivalents.

The Brasiliano orogen and local volcanoes as provenance areas for the Puncoviscana Formation and equivalents

We now discuss in more detail the implications of the zircon geochronology (Table 1). In the weakly metamorphic Puncoviscana Formation, in their higher grade equivalents, the Late Cambrian Mesón Group and other latest Cambrian to Early Ordovician sedimentary rocks, the zircon ages are most frequently 670–545 Ma. Thus, the general sediment supply for all should have originated in the same mountain range system. The Brasiliano Orogen of southeast and south central Brazil is a potential provenance site (Adams et al. 2008b and literature there in). There, granitoid intrusions were exhumed continuously in a rising system of orogens which extended from the (present day) Atlantic coast of Uruguay to the Amazon River estuary, and from the South Atlantic coast crossing the younger Paraná basin c. 2,000 km westwards (Cordani et al. 2000). Structurally, this mountain range is highly complicated (e.g. Saalmann et al. 2006; Laux et al. 2005; Campanha et al. 2008; Junges et al. 2008). It was, after the closure of the Proto-Atlantic Ocean, the watershed across the middle of Gondwanaland. The height of these mountains is obviously unknown, but their underlying orogen must have been composed of granitoids of several ages with associated metamorphic complexes (e.g. Basei et al. 2000; Söllner et al. 2000b).

There are two exceptions. A particularly strange one is difficult to interpret. Of the 24 samples studied by us and other authors in the Puncoviscana Formation and equivalents, there is only one which has no zircon ages younger than 950 Ma. The youngest (and very strong) peak in this data set corresponds to a "Grenville" age (Adams et al. 2010). Surprisingly, this sample, with a normal Puncoviscana Formation lithology, comes from an outcrop in the Humahuaca Valley close to Puncoviscana Formation samples with otherwise usual age patterns. However, the trace fossils normally found in this formation are lacking at this locality, which may suggest a pre-Cambrian age. Hence, the best explanation is that the sediments accumulated before the Brasiliano mountain range had formed. This must be before 700 Ma, but not necessarily any closer to the age of the youngest zircon found in this sample.

Also rather exceptional are the samples with principal age components from 534 to 514 Ma, which are mostly from the Puncoviscana and Suncho Formations (Adams et al. 2008b, 2010). Older ages are present but very subordinate. We therefore propose that the primary zircon contribution was from local volcanic sources. The abundant, large (>150 micron) zircons are invariably euhedral, without cores, features which support this conclusion. In these circumstances, the Cambrian age of sedimentation can be inferred not only on the time of zircon crystallization in the Brasiliano mountains and its exhumation and erosion, but also directly from the geological evidence of a local volcanic source. During the transition from a passive margin environment of the Late Neoproterozoic, to a more active margin in the mid-Cambrian (cf. Adams et al. 2008b; Cawood 2005; Schwartz et al. 2008), at a proto-Pacific coast, a chain of volcanoes formed (Coira et al. 1990; Toselli 1992; Omarini et al. 1999). This then vigorously supplied sediment (and zircons) into the Puncoviscana basin. In one of the samples, ages from 2135 to 2058 Ma are frequent, heralding the first contributions from the Río de la Plata craton.

The paleogeography at the Late Cambrian and Early Ordovician

Significantly, during Late Cambrian and Early Ordovician times, the Brasiliano Mountains remained the most conspicuous provenance area for sediments at the Pacific border of Gondwanaland and the Sunsás Orogen gradually declined in importance. The latter feature could be explained by some sort of orogenic barrier (Drobe et al. 2009a, b), an explanation that might also be relevant to the lack of Brasiliano zircons in the Humahuaca Valley outcrop of the Puncoviscana Formation (see above). Alternatively, the reduced sediment supplies from the Sunsás Orogen could also be a consequence of the gradual creation of a sedimentary cover over the greater part of the orogen (Alvarenga et al. 2000; Gaucher et al. 2003; Babinski et al. 2008; Trompette et al. 1998).

Conclusions

1. Most authors agree on the close connection between the non-metamorphic or very weakly metamorphosed Puncoviscana Formation in NW Argentina and its higher grade metamorphic equivalents in the southern Eastern Sierras Pampeanas. They all conclude that both regions form part of a continuous sedimentary cycle of Late Neoproterozoic to Early Cambrian age, which was terminated by folding, metamorphism and plutonism in mid-Cambrian times. The detrital zircon age patterns strongly confirm this. Variable in extent, the provenance areas would have been mountain ranges of (1) the developing Brasiliano orogen and (2) in early times rather than later, those of the Sunsás Orogen developing in the late Mesoproterozoic. Thus, an attribution of the Eastern Sierras Pampeanas to a hypothetical Pampia terrane, originating at a paleo-Pacific ocean margin and colliding with the Río de la Plata craton, is not necessary.
2. In the late Neoproterozoic, Early and Late Cambrian and Early Ordovician a mountain chain persisted in south central and southeast Brazil, continuously delivering sediment detritus to the Pacific margin. Local volcanism in a developing Pampean Orogen partly supplemented the sediment supply to Late Cambrian and Early Ordovician basins.
3. The Río de la Plata craton, which in the late Neoproterozoic–Early Cambrian was not actively supplying sediments to the Pacific border of Gondwanaland, became an important provenance area only in Late Cambrian times. This time delay may have two explanations, firstly as a consequence of the late arrival of the Río de la Plata craton to its Cambrian site along a transcurrent fault, and secondly, and alternatively, the late commencement of erosion of the Paleoproterozoic basement previously hidden beneath the late Neoproterozoic and Early Cambrian sedimentary cover.
4. The continually diminishing contribution of Grenvillian and other Mesoproterozoic detritus to the early Paleozoic sedimentary basins may be due to coverage of the Sunsás Orogen by late Neoproterozoic and early Cambrian sedimentary rocks. Alternatively, the development of mountains at the continental margin may have hindered sediment transport from the orogen.

Acknowledgments The authors gratefully acknowledge the German Research Foundation for granting field and laboratory work (Grant MI 120/45-1,-2). The reviewers Stan Finney and Roberto Martino gave valuable hints for improving the manuscript.

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