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ORIGINAL PAPER

Geodynamic evolution of the Eastern Sierras Pampeanas (Central Argentina) based on geochemical, Sm–Nd, Pb–Pb and SHRIMP data

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Abstract Whole-rock geochemical analyses using major and trace elements in combination with the Sm–Nd and Pb–Pb isotope systems, together with SHRIMP age dating on metasedimentary rocks from the Sierras de Chepes, the Sierras de Córdoba, the Sierra Norte and the San Luis Formation in the Sierra de San Luis, have been carried out to unravel the provenance and the geodynamic history of the Eastern Sierras Pampeanas, Central Argentina. The geochemical and the Sm–Nd data point to a slightly stronger mafic and less-fractionated material in the provenance area of the Sierras de Córdoba when compared to the other units. The T_{DM} model ages from the Sierras de Chepes (~1.82 Ga) and the Sierra Norte (~1.79 Ga) are significantly older than the data from the Sierras de Córdoba (1.67 Ga). The Pb data are homogeneous for the different units. Only the $^{208}Pb/^{204}Pb$ ratios of some samples from the Sierras de Córdoba are higher. A late Pampean detrital zircon peak around 520 Ma from the Sierras de Chepes is in accordance with the new data from the San Luis Formation. This is similar to the literature data from the Famatina Belt located to the northwest of the Sierras de Chepes and also fits the detrital zircon peaks in the Mesón group. These maximum depositional ages were also reported from some locations in the Puncoviscana Formation but are absent in the Sierras de Córdoba. An improved model for the development of the Eastern Sierras Pampeanas in the area between the Sierras de Córdoba and the Puncoviscana Formation is provided. This gives new insights into the late Pampean development of the Sierra de San Luis and the complex development of the Eastern Sierras Pampeanas. This new model explains the younger detrital ages in the Puncoviscana Formation compared with the older ages of the Sierras de Córdoba. Another model of the Sierra de San Luis explains the younger depositional ages of the Pringles Metamorphic Complex and the San Luis Formation when compared to the Nogolí Metamorphic Complex and the Conlara Metamorphic Complex. Additionally, the rather fast change of the high-grade metamorphic conditions in the Pringles Metamorphic Complex and the low-grade metamorphic conditions in the San Luis Formation is explained by extension, the ascent of (ultra) mafic material and later folding and erosion.

Keywords Eastern Sierras Pampeanas · Provenance · Tectonic setting · Gondwana margin · Geodynamic evolution

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Introduction

Metasedimentary rocks, which are a dominant component of the Neoproterozoic–early Palaeozoic metamorphic complexes along the margin of Gondwana, may provide important information about their crustal evolution. Studies about the provenance of (meta-) sediments have been performed by: (1) the statistical analysis of lithoclasts in thin sections (e.g. Dickinson and Suczek 1979; von Eynatten et al. 2003; Zimmermann and Bahlburg 2003), (2) major and trace elements in minerals and whole-rock samples (e.g. Floyd and Leveridge 1987; McLennan et al. 1990, 1993; Zimmermann and Bahlburg 2003) and (3) isotopic whole-rock systems like Pb–Pb or Sm–Nd and single grain studies such as U–Pb dating of detrital zircons (e.g. Rapela et al. 1998; Sims et al. 1998; Bock et al. 2000; Lucassen et al. 2001, 2002; Steenken et al. 2004, 2006).

Different geological settings like passive or active margin, as well as autochthony or allochthoneity of the involved units, were discussed for the Neoproterozoic to early Palaeozoic evolution of the metasedimentary units of the Eastern Sierras Pampeanas and the Cordillera Oriental, (e.g. Ramos 1988; Bahlburg 1990; Astini et al. 1995; Pankhurst and Rapela 1998; Rapela et al. 1998, 2007; Bock et al. 2000; Lucassen et al. 2000; Zimmermann and Bahlburg 2003; López de Luchi et al. 2003; Schwartz and Gromet 2004; Steenken et al. 2004, 2006; Zimmermann 2005; Rapela et al. 2007; Schwartz et al. 2008; Adams et al. 2008; Casquet et al. 2008; Drobe et al. 2009).

The Eastern Sierras Pampeanas constitute a polyphase-deformed morphotectonic unit, which was affected by three main events, the early Cambrian (580–510 Ma) Pampean, the late Cambrian–Ordovician (500–440 Ma) Famatinian and the Devonian (420–350 Ma) Achalian orogenic cycles (Toselli and Aceñolaza 1978; Aceñolaza and Toselli 1981; Omarini 1983; Ramos et al. 1986; Aceñolaza et al. 1988, 1990; Sims et al. 1998; Rapela et al. 1998, 2007; Stuart-Smith et al. 1999; Bock et al. 2000; Siegesmund et al. 2004, 2009; Steenken et al. 2004, 2007; Zimmermann 2005; Drobe et al. 2009). These orogenies are related to the accretion of different terranes integrated into the proto-Andean margin of Gondwana. The Cordillera Oriental comprises a series of deformation belts. The Late Neoproterozoic to Early Cambrian turbiditic sandstones of the Puncoviscana Formation (Turner 1960) were tightly folded and affected by low-grade metamorphism in early Cambrian time (Aceñolaza et al. 2000). The low- to high-grade metasedimentary successions of the Eastern Sierras Pampeanas were considered as an extension of the very low- to low-grade metamorphic conditions in the Puncoviscana Formation (e.g. Schwartz and Gromet 2004; Steenken et al. 2004; Zimmermann 2005; Drobe et al. 2009).

The aim of this study is to present new insights into the Neoproterozoic to Cambrian geodynamic history of the margin of Gondwana by the study of metasedimentary units (Fig. 1) of the Eastern Sierras Pampeanas, i.e. the Sierras de Córdoba, Sierra Norte and the Sierras de Chepes. The data are compared and integrated with our previous results on the Sierra de San Luis, the southernmost morphotectonic units of the Eastern Sierras Pampeanas and the Puncoviscana Formation of the Cordillera Oriental. A combination of major and trace elements, Nd and Pb isotope systematics as well as SHRIMP U–Pb zircon data are used in order to discriminate the provenance and the tectonic setting of the different units. Previously suggested tectonic models for the Cambrian evolution of the margin of Gondwana will be scrutinised by the combination of data presented here and already published results (e.g. Rapela et al. 1998, 2007; Sims et al. 1998; López de Luchi et al. 1999, 2003; Bock et al. 2000; Brogioni 2001; Steenken et al. 2004, 2006; Zimmermann 2005; Escayola et al. 2007; Adams et al. 2008; Drobe et al. 2009; Siegesmund et al. 2009).

Geological setting

The Eastern Sierras Pampeanas (Fig. 1) are composed of uplifted basement blocks, triggered by Miocene to recent flat-slab subduction of the Nazca plate in the area of 27–33° 30′S (Ramos et al. 2002). The eastern sector of this morphostructural unit is mainly affected by the Pampean orogeny, which is characterised by late Neoproterozoic sedimentation and Ediacaran to Cambrian deformation, magmatism and metamorphism (Rapela et al. 2007; Siegesmund et al. 2009). The western sector is dominated by the Famatinian orogeny, which is characterised by upper Cambrian to early Ordovician marine sedimentation and Ordovician and Devonian magmatism (Sims et al. 1998; Rapela 2000; Steenken et al. 2006). In the northern area between 22 and 27°S, the Pampean belt in the Cordillera Oriental is dominated by the Puncoviscana Formation in which very low-grade rocks are associated with medium-grade rocks (Fig. 1).

The *Sierras de Chepes, Malanzán and Los Llanos* (from now on only called *Sierras de Chepes*) are primarily composed of granitoid rocks (Fig. 2). The most important granitoid unit is the 490 ± 5 Ma (U–Pb zircon age) Chepes Granodiorite (Pankhurst et al. 1998). The metasedimentary rocks in the Sierras de Chepes occur as discontinuous outcrops, which are supposed to represent roof pendants of the country rock (Pankhurst et al. 1998). These greenschist- to amphibolite-grade rocks are largely metapelites with intercalations of silt and sandstone beds. Although most of the outcrops are smaller than 1 m, some can reach tens of

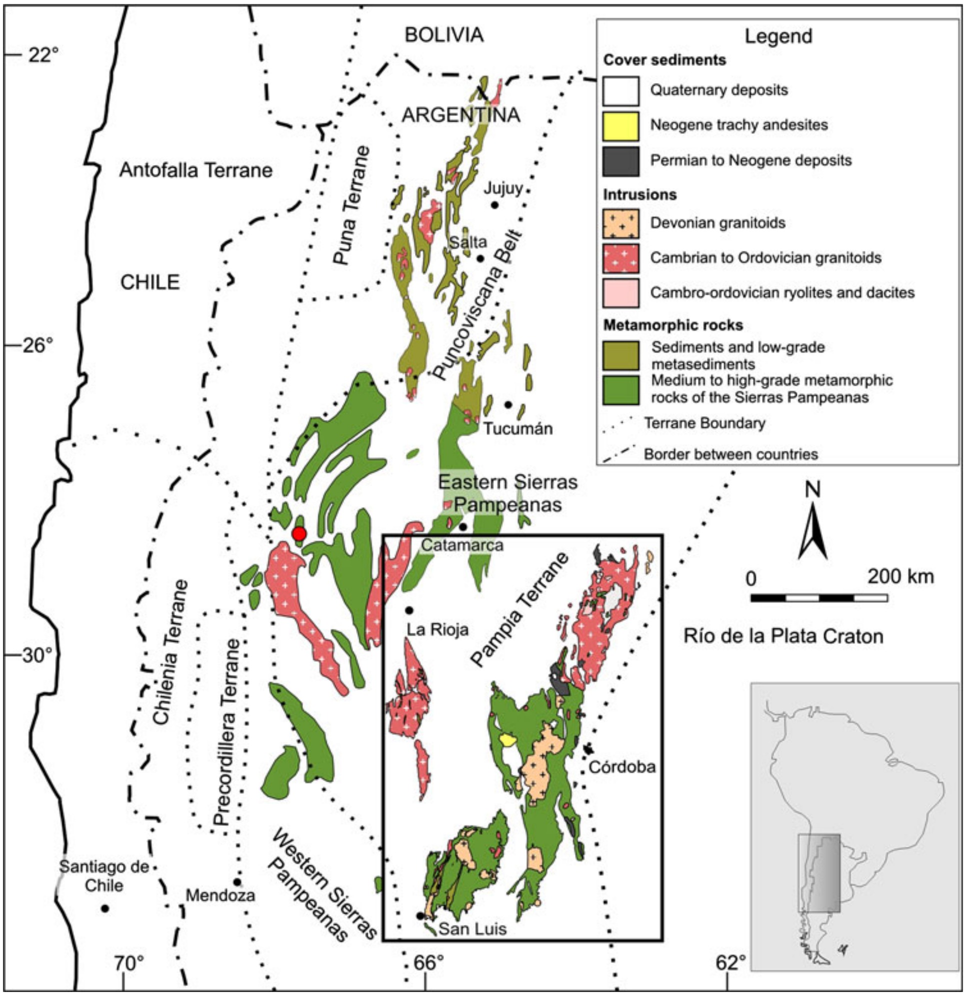

Fig. 1 Geological sketch of the Eastern Sierras Pampeanas, the Puncoviscana Belt and the main terranes west of the Río de la Plata craton (modified after Lucassen et al. 2000; Rapela et al. 2007; Ramos 2008). *Box marks* the study area. The *red spot* indicates the Neigro Peinado Formation and the Achavil Formation (Collo et al. 2009)

metres in size. An early to middle Cambrian metamorphism was proposed by Pankhurst et al. (1998) based on a Rb–Sr errorchron of 513 ± 31 Ma. The T_{DM} model ages for the metasedimentary samples for the Sierras de Chepes are 1.79 and 1.78 Ga, and the $\varepsilon Nd_{(540)}$ values are -6.7 and -6.8. The granitoid rocks give relatively similar values of T_{DM} model ages between 1.79 and 1.59 Ga with $\varepsilon Nd_{(540)}$ ratios between -3.7 and -6.2 (Pankhurst et al. 1998), pointing to a minor or absent mantle contamination of the granitic melt.

The *Sierras de Córdoba* (Fig. 2) are mainly composed of a late Neoproterozoic–early Cambrian marine metasedimentary sequence comprising medium- to high-grade metapelites, metagreywackes, migmatites, marbles and amphibolites, intruded by late Neoproterozoic to Devonian metaluminous to peraluminous granitoid suites (Rapela et al. 1998; Quenardelle and Ramos 1999; López de Luchi et al. 2008; Siegesmund et al. 2009). Granulite facies rocks are located in the south in close proximity to gabbroic intrusions (Otamendi et al. 2004) or in the north (San Carlos Massif) as diatexitic migmatites. Low-grade metamorphic outcrops like the Los Túneles Phyllites are only found in the westernmost sector of the Sierras de Córdoba. The protolith of these rocks were compared with the phyllites of Sierras de Chepes (Rapela et al. 1998). Schwartz and Gromet (2004) analysed single zircons from metasedimentary samples in the northwestern part of the Sierras de Córdoba and got two age maxima. The older is between 1,050 and 950 Ma, and the younger lies between 750 and 550 Ma. These ages represent direct evaporation data of the grains. As the number ($n = 17$) is very low, they do not have a statistical value on their own, but these maxima can also be found in the Puncoviscana Formation (Adams et al. 2008) and in the Conlara Metamorphic Complex in the Sierra de San Luis (Steenken et al. 2006; Drobe et al. 2009).

A series of mafic–ultramafic units can be subdivided into an eastern belt in the Sierra Chica and a western belt in the Sierra Grande and the Sierra de Comechingones (Villar 1985; Kraemer et al. 1995; Escayola et al. 1996, 2004 and references therein). Some of these belts were interpreted as ophiolitic-type associations (Mutti 1987; Martino et al. 1995; Escayola et al. 1996). The early Palaeozoic

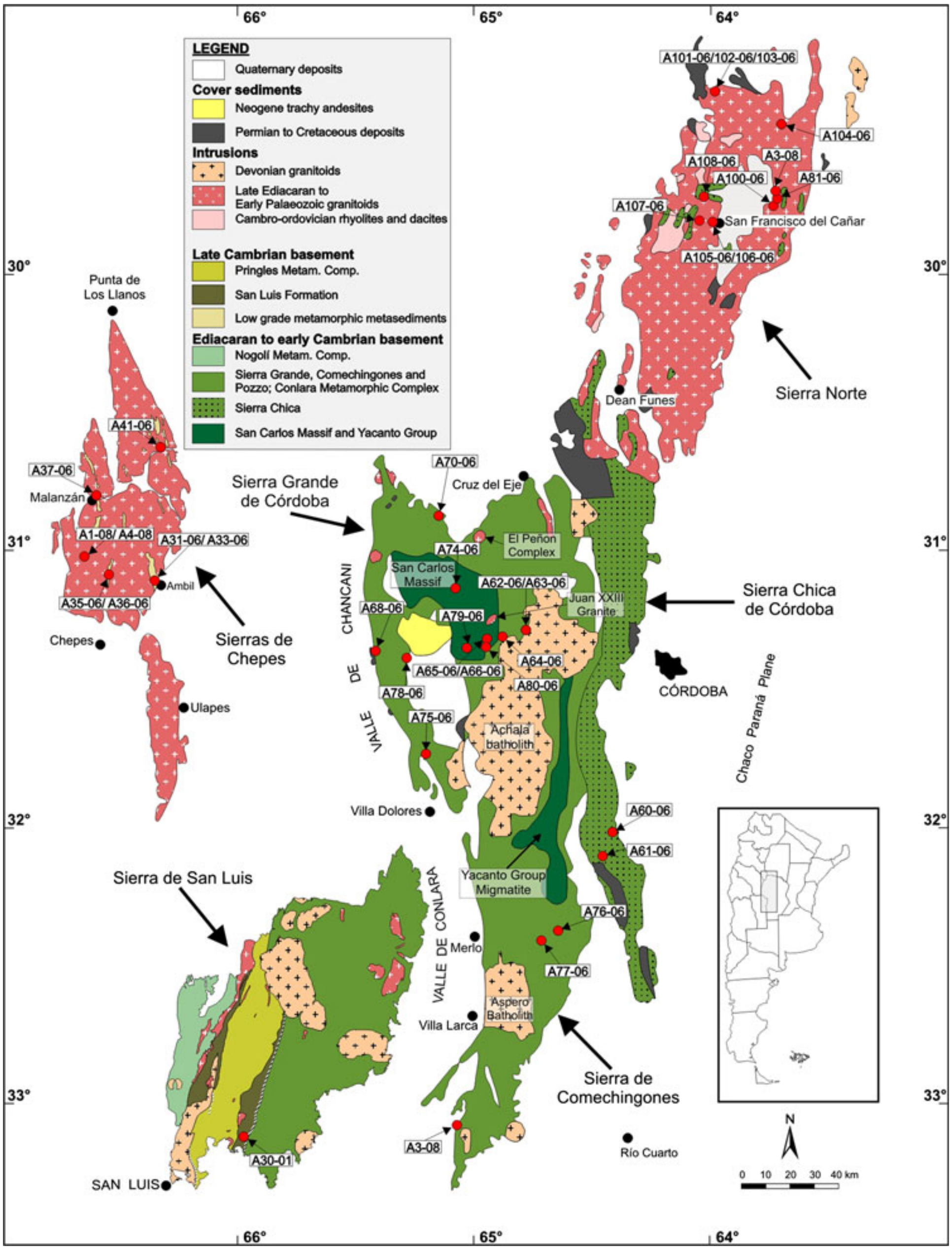

Fig. 2 Geological map of the Sierras de Córdoba, the Sierra Norte, the Sierras de Chepes and the Sierra de San Luis (modified from Martino 2003; Steenken et al. 2006; Siegesmund et al. 2009). The sample locations are indicated with *red circles*

magmatic activity, spatially related to the high-grade migmatitic rocks, is characterised by rounded or elongated S-type plutons with a diameter of a few kilometres in length. U–Pb zircon ages from the highly peraluminous S-type granitoids around 530 Ma and a U–Pb monazite age from a migmatite of 522 ± 8 Ma (Rapela et al. 1998) point to a contemporaneous history. Huge Devonian batholiths like the Cerro Aspero batholith in the south and the Achala batholith (368 Ma U–Pb zircon, Dorais et al. 1997) in the central area of the Sierras de Córdoba are temporally related with the Achalian orogeny.

The *Sierra Norte de Córdoba* (Fig. 2) is the easternmost exposure of the Sierras Pampeanas. The outcrops of the Sierra Norte consist of over 95% of Ediacaran to early Cambrian calk-alkaline granodiorite and monzogranite (Lira et al. 1997; Rapela et al. 1998). U–Pb zircon ages include a 530 Ma age for a hornblende–biotite granodiorite from an unspecified location (Rapela et al. 1998) and upper intercept ages of 557 ± 4 and ca 584 Ma for a rhyodacite and a rhyolitic ignimbrite in the western Sierra Norte (Söllner et al. 2000; Llambías et al. 2003). Concordant to nearly concordant SHRIMP II, U–Pb zircon ages of 531–481 Ma for the Los Burros dacite were interpreted as being variably affected by inheritance and hydrothermal alteration (Leal et al. 2003). Host rocks for the Sierra Norte granitoids are only observed in the central area around San

Francisco del Chañar and in the north. They consist of sparse roof pendants and screens of low- to medium-grade metasedimentary rocks, primarily quartz arenites, quartzo-feldspathic to semipelitic schists and calc-silicates (Lira et al. 1997). Intrusive contacts between magmatic and metasedimentary units were observed.

The *Sierra de San Luis* consists of three principal NNE-trending metamorphic complexes (Fig. 2): the Nogolí, Pringles and Conlara Metamorphic complexes. These amphibolite to granulite facies metamorphic rocks are separated by two narrow low-grade phyllite belts, the phyllites of the San Luis Formation (Prozzi and Ramos 1988). The higher-grade metamorphic units are composed of mainly metasedimentary and metaigneous rocks. Late Cambrian to Ordovician and Devonian intrusives invaded the metamorphic units. Late Cambrian to Early Ordovician (Famatinian) back-arc mafic to ultramafic rocks and island-arc amphibolites are located in the Pringles Metamorphic Complex associated with granulite facies metasedimentary rocks (Sims et al. 1997; Hauzenberger et al. 2001). During the last three decades, a large number of studies have focused on the structural evolution, metamorphism and magmatism of the basement complexes in the Sierra de San Luis (Kilmurray and Dalla Salda 1977; López de Luchi 1986, 1987, 1996; Ortiz Suárez et al. 1992; Llambías et al. 1998; Sims et al. 1998; von Gosen and Prozzi 1998; Delpino et al. 2001, 2007; González et al. 2002; López de Luchi et al. 2003, 2004; Steenken et al. 2004, 2006, 2008).

The geodynamic evolution and temporal relationship of the Conlara Metamorphic Complex and the San Luis Formation with the more western basement complexes, i.e. the Pringles Metamorphic Complex and the Nogolí Metamorphic Complex, are still under discussion. The maximum age for the deposition of the Conlara Metamorphic Complex is provided by a ^{238}U/^{206}Pb SHRIMP detrital zircon age of 587 ± 7 Ma (Steenken et al. 2006). U/Pb zircon data for the Pringles Metamorphic Complex point to a maximum deposition age at ~530 Ma (Sims et al. 1998; Steenken et al. 2006). The minimum sedimentation age is provided by Steenken et al. (2006), who dated metamorphic rims of zircons with 498 Ma (Steenken et al. 2006). A Mesoproterozoic or even older deposition of the Nogolí Metamorphic Complex was assigned on the basis of the presence of banded iron formations and inferred olivine spinifex structures in komatiites (Sato et al. 2001; González et al. 2002). SHRIMP zircon data on the crystallisation of the komatiite shed doubt on this old crystallisation age, as they give a minimum age for the primary crystallisation of 516 Ma and a maximum of 1,200 Ma (Sato et al. 2006). Based on U–Pb dating of zircons, Drobe et al. (2009) only found one Grenvillian age of 1,190 Ma, while the rest of the data from the Nogolí Metamorphic Complex yielded Brasiliano and Pampean ages.

The *Puncoviscana Formation* is about 800 km N-S striking and several thousand metres thick, which comprises very low- to low-grade metasedimentary rocks grading from slates to schists and psammites, and is located between the Bolivian boarder and the City of Tucumán. An Ediacaran to early Cambrian age of the mainly siliciclastic flysch-like turbidites and pelagic clays has been inferred by *Oldhamnia* ichnofossils and other traces (Aceñolaza and Durand 1986; Durand 1996; Aceñolaza and Tortello 2003). LA ICP-MS U–Pb zircon dating of the metasedimentary units revealed two population maxima at 760–580 Ma and 1,100–860 Ma, with minor populations throughout the Meso- and Palaeoproterozoic, but also three samples with dominant younger detrital zircon ages of 550 Ma in two cases and 530–520 Ma in one case (Adams et al. 2008).

Toselli (1990a, b), Willner (1990), Rapela et al. (1998) and Söllner et al. (2000) argued that the San Luis Formation is an equivalent of the Puncoviscana Formation, whereas Steenken et al. (2004, 2006) and Prozzi and Zimmermann (2005) demonstrated isotopic and geochemical similarities between the Conlara Metamorphic Complex and the Puncoviscana Formation. The Eastern Sierras Pampeanas constitute a polyphase-deformed morphotectonic unit, which was affected by three main events the Ediacaran–early Cambrian (580–510 Ma) Pampean, the late Cambrian–Ordovician (500–440 Ma) Famatinian and mostly Devonian (420–350 Ma) Achalian orogenic cycles. Several geological models ranging from collisional to non-collisional were proposed for the Pampean orogen. These models lead to different tectonic settings for the deposition of the protoliths of the metasedimentary units of the Eastern Sierras Pampeanas and the Cordillera Oriental. The Pampean orogenic cycle between 580 and 510 Ma (Ramos 1988; Rapela et al. 1998; Siegesmund et al. 2009) was considered to be the result of collisional events of the Pampean Terrane with the Río de la Plata craton. Geodynamic activity, probably related to ongoing accretion, along the western margin of the present Eastern Sierras Pampeanas in the Famatinian orogenic cycle (Ramos et al. 1986; Sims et al. 1998) was locally associated with late Cambrian sedimentation (Steenken et al. 2006).

Collisional models for the Pampean orogen considered that the metasedimentary units were deposited along a passive margin that later turned into an active margin (Rapela et al. 1998). Rapela et al. (1990) proposed that the metasedimentary units developed along the passive margin of the Río de la Plata craton. An aulacogenic deposition of the sediments with a possible triple junction between the Arequipa–Antofalla, Amazonian and Río Apas cratons due to the distribution of different sedimentary facies was proposed by Rapela et al. (1998) and Ramos (2008). A para-autochthonous continental fragment, the Pampean

Terrane, collided with western margin of Gondwana (Rapela et al. 1998). Pre-collisional east dipping subduction was associated with calc-alkaline magmatism in the Sierra Norte. The prolonged igneous activity with the dominant felsic calc-alkaline granitoids of the Sierra Norte, resulting from post-collisional extension and melting of older I-type source rocks, suggests that the Pampean orogen involved overthrusting of a passive margin basin eastwards over the Río de La Plata craton (Sims et al. 1998; Stuart-Smith et al. 1999). Ramos (2008 and references therein) considered that the Puncoviscana trough was a peripheral foreland basin related to the collision of the Pampia block with the Río de La Plata craton. Schwartz et al. (2008) advocate a ridge-trench collision model, where many of the characteristic features of the Pampean orogen, e.g. local post-magmatic dextral shear zones, can be explained by the change of the plate boundary from convergent to a transform boundary. Rapela et al. (2007) and Casquet et al. (2008) suggested that the Puncoviscana Formation was probably a fore-arc sedimentary sequence that had developed on the southern margins of the Kalahari craton. The collision of the Western Sierras Pampeanas Terrane and the Arequipa craton against the Kalahari craton was followed by the displacement of the Puncoviscana Formation and higher-grade metamorphic equivalents along dextral shear zones (Martino 2003) up to its present position facing the Río de la Plata craton. Escayola et al. (2007) argued for an intra-oceanic island-arc between the Río de La Plata craton and the Pampean Terrane, inhibiting the supply of Palaeoproterozoic material from the craton to the metasedimentary units of the Sierras Pampeanas.

The presence of detrital late Pampean ages around 520 Ma in Cambrian metasedimentary rocks (Steenken et al. 2006; Collo et al. 2009) in the Eastern Sierras Pampeanas denotes that Pampean material must have been exhumed at that time. A decompression and the formation of middle to late Cambrian basins after the peak metamorphic conditions of the Pampean orogeny had been proposed (Baldo et al. 1996; Rapela et al. 1998; Sims et al. 1998). The deformation of the sediments deposited in these basins took place during the early to middle Famatinian orogeny (Sims et al. 1998; Steenken et al. 2004, 2006; Collo et al. 2009).

The provenance of the Puncoviscana Formation was examined on the basis of geochemical and sedimentological studies. A passive margin at the western edge of the Río de la Plata craton with sedimentation from eastern directions was proposed by Aceñolaza et al. (1983), Willner et al. (1985), Ježek and Miller (1986), Rossi de Toselli et al. (1997) and DoCampo and Ribeiro Guevara (2002). Based on the geochemical data of volcanic rocks, Omarini et al. (1999) supported a change from a rift to a back-arc setting. Kraemer et al. (1995) and Keppie and Bahlburg (1999) argued for a foreland basin as the geological setting of the Puncoviscana Formation. Based on the geochemical data, an active continental margin setting for the deposition of the protoliths of the Puncoviscana Formation with sedimentation into a foreland basin was proposed (Zimmermann 2005). A major contribution of volcanic rocks was excluded on the basis of Nd and Pb isotope data (Bock et al. 2000).

Detrital zircon inheritance patterns which do not show a maxima above 2 Ga and Nd model ages between 1.8 and 1.6 Ga for the Puncoviscana Formation and the metasedimentary units of the Eastern Sierras Pampeanas (Bock et al. 2000; Schwartz and Gromet 2004; Steenken et al. 2004, 2006, 2008; Adams et al. 2008; Escayola et al. 2007; Rapela et al. 2007; Drobe et al. 2009) argue against the Río de La Plata craton being a source for the metasediments of the Puncoviscana Formation. T_{DM} model ages from the Río de la Plata craton range between 2.8 and 2.3 Ga (Hartmann et al. 2002; Pankhurst et al. 2003; Rapela et al. 2007). Brito Neves et al. (1999) proposed an origin of the Puncoviscana sediments from the northeast, from Brasiliano-related orogens. Zimmermann (2005) suggested that a magmatic arc blocked the sediments arriving from the Río de la Plata craton. Although there are younger T_{DM} model ages, e.g. in the Cuchilla Dionisio Pelotas Terrane (Oyhancabal et al. this volume), these ages have not been observed in the western part of the Río de la Plata craton.

Sample material

The sample material is shown in the data repository in order to give an overview about the different samples including rock-type mineral assemblage, metamorphic grade and location. The major and trace element concentrations and the most important trace element ratios are provided in the data repository (Tables 1 and 2 data repository).

Whole-rock geochemistry

Major elements

In Sierras de Chepes, three metasedimentary samples (A33-06, A35-06 and A41-06) have SiO_2 values above 72% and Al_2O_3 between 11.0 and 12.8%. The other two samples are shales with SiO_2 concentrations of 60–64% and Al_2O_3 16–19%. The MgO + CaO concentrations are constantly low (2.2–3.6%).

The most abundant rocks in the Sierras de Córdoba have average SiO_2 contents around 69% and Al_2O_3 values about 13.5% independently of their lithology or metamorphic grade. Two metasedimentary rocks (A62-06, A66-06) have distinctively higher SiO_2 values around 75% and Al_2O_3 contents slightly above 11%. The metapelitic samples from the Sierras de Córdoba have comparable SiO_2 and Al_2O_3 concentrations and high Fe_2O_3/K_2O values compared to the metashales from the other units. Although the Fe contents are similar to the metapelites from the other complexes, their K_2O concentration is lower. The MgO + CaO concentration of seven samples is similar to the values for the Sierras de Chepes and the Sierra Norte between 2.6 and 3.8% (A62-06, A66-06, A68-06, A70-06, A74-06, A78-06, A79-06) and slightly elevated for the other nine samples (A60-06, A61-06, A63-06, A64-06, A65-06, A75-06, A76-06, A77-06, A80-06) between 4.5 and 6.6%.

Two samples from the Sierra Norte are metashales (A103-06, A106-06) with typical SiO_2 and Al_2O_3 values (60, 17%). One is an iron-rich shale (A102-06) with a very low concentration of SiO_2 (47%) and high amounts of Fe_2O_3 (9.9%) and MgO + CaO (24.6%). Six samples (A81-06, A100-06, A101-06, A104-06, A105-06, A107-06) have SiO_2 concentrations between 71 and 75% and Al_2O_3 between 11.5 and 13.9% and MgO + CaO contents of 2.2–4.4%. A108-06 has slightly higher amount as of SiO_2 (68.6) and higher concentrations of Al_2O_3 (15.0%), but similar MgO + CaO values (2.4%). The sample A102-06 with its high amounts of Fe_2O_3 and MgO + CaO has an unusual low SiO_2 concentration for a metasedimentary rock of 47% and seems to be affected by contact metamorphism and subsequent major element mobilisation.

Trace elements

The high-field strength elements (HFSE) and certain trace elements have proven to be very useful for provenance and tectonic setting discrimination (Bhatia and Crook 1986; McLennan et al. 1990; Floyd et al. 1991). In this study, the Th/Sc ratio is used as an indicator of the maturity of the source area, taking as a reference the upper continental crust Th/Sc ratio of >0.8. The Zr/Sc ratio is indicative of the zircon concentration, i.e. crustal reworking due to transportation and sorting from the source to the basin (McLennan et al. 1990, 1993). A covariation of Th and Zr was defined by McLennan et al. (1993) for sedimentary rocks from active margins that are least affected by sedimentary sorting and recycling. Zircon accumulation by sorting and recycling during weathering processes would result in Zr enrichment relative to Sc.

In the Th/Sc vs. Zr/Sc diagram (Fig. 3), two separate groups of samples can be distinguished in each of the units. The metasedimentary rocks from the Sierras de Chepes are clustered between Zr/Sc ratios of 10 and 17 except for the banded schist A33-06 with corresponding higher Th/Sc value of 1.7. In the Sierras de Cordoba, the high-grade metasedimentary rocks are bracketed between Zr/Sc 5–10 but they are separated by Th/Sc ratios above or below 0.8. The lower-grade metasedimentary rocks define two clear populations. One is overlapping the higher-grade rocks, i.e. with Zr/Sc < 10, and another with Zr/Sc > 15, which is made up by the quartz phyllite (A68-06), the banded schist A70-06 and the rocks that were taken from or close to the San Carlos Massif.

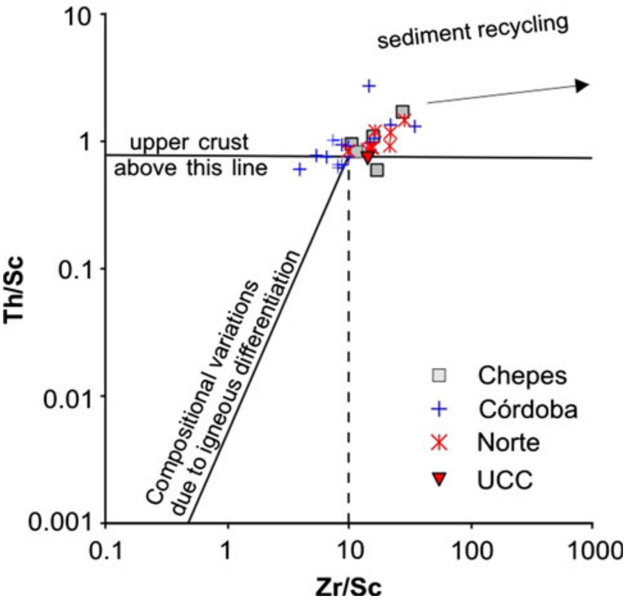

Fig. 3 Provenance and recycling discrimination plot of Th/Sc versus Zr/Sc (McLennan et al. 1990) for samples in the Sierras de Córdoba, the Sierra Norte and the Sierras de Chepes. Th/Sc reflects the input of mafic or acidic material, and Zr/Sc is a proxy for sediment recycling, as Zr mostly comes from zircons that are highly resistant to weathering. There is an overlap in the data of the different domains, but the Sierras de Córdoba seems to show less recycling than the other two domains

The Sierra Norte provides comparable results. Three samples are characterised by ratios between 8 and 10 (A81-06, A102-06, A106-06), of which A81-06 has an extremely low Th/Sc ratio of 0.25 due to a low Th concentration of only 3 ppm. The remaining seven samples (low-grade pelites to gneisses) show values between 14 and 28.

As there is practically no metasediment falling in the high Zr/Sc range typical of zircon accumulation associated with sediment recycling and sorting, a part of the metasedimentary rocks from the Sierra Norte and the lower-grade metasediments of the Sierras de Cordoba delineate a trend of recycling. The Th/Sc ratios, shown by the metasedimentary rocks in reference to the upper continental crust (Th/Sc ratio >0.8), are indicative of sedimentary input from evolved sources. McLennan et al. (1990) suggested that in active margins, Th/Sc ratios of sands can be different to the values in associated muds but no systematic difference between the Zr content of sands and associated muds is found. The scatter towards lower values of Th/Sc mostly for the high-grade rocks of the Sierras de Córdoba could be related with less evolved or magmatic arc sources (McLennan and Taylor 1991).

REE are a robust indicator of provenance and source composition (McLennan et al. 1990). Most of the samples reflect a similar pattern that can be compared to the upper continental crust (McLennan et al. 1990). The samples have similar REE slopes, indicated by La_N/Yb_N ratios of 9.1–9.2 except the phyllite A37-06, which has a distinct lower value of 4.9. These results point, together with the low general concentration of REE, to a loss of LREE. LREE may be mobile if the metasediments contained volcanic glass (Wood et al. 1976; Taylor and McLennan 1985; Utzmann et al. 2002). Therefore, low La abundances and low La_N/Yb_N ratios could be connected to volcanic input. The low amount of REE could also be related to mafic input into this sample, as the Th/Sc ratio is 0.6, the lowest ratio for the Sierras de Chepes. The negative Eu/Eu* anomaly does not show big discrepancies for the samples of this area, ranging between 0.53 and 0.63, but the samples with the lowest anomaly both (A37-06, A41-06) have the lowest values for ΣREE. The lower REE concentration and the smaller Eu/Eu* anomalies both point to a stronger mafic input into these two samples. This is emphasised by the Th/Sc ratios that are also the lowest for these two samples in this area. The scatter of the REE concentrations and the slopes of the REE are bigger in the Sierras de Córdoba (Fig. 4b). The low- to medium-grade metasediments A68-06 and A70-06 have the highest ΣREE of over 300 ppm in the Sierras de Córdoba. These two samples also have high Th/Sc ratios of 1.4 and 1.3., the highest values except sample A80-06 with a ratio of 2.7. Both samples have a La_N/Yb_N ratio of 8.4 and 8.1, typical for the upper continental crust. The samples A60-06 and A79-06 have concentrations of around 250 ppm. These samples are both diatexites with a tonalitic (Qz + Pl + Bt) composition. The La_N/Yb_N values are 7.8 and 8.8, similar to the first group. The third group has ΣREE concentrations between 180 and 220 ppm, including medium-grade gneisses, high-grade stromatites and diatexites. Their slopes, defined by La_N/Yb_N, also vary from 15.5 to 6.4. The fourth group includes the samples with a ΣREE between 120 and 165 ppm. These are a diatexite (A61-06), two host rocks of the Achala batholith (A62-06, 63-06) and a banded schist (A75-06). Samples with low concentrations of REE do not show a lower La_N/Yb_N value. For this reason, element mobilisation can be excluded. This is similar to the Eu/Eu* anomaly that is between 0.43 and 0.67. The only conspicuous value is the lowest of 0.43 that belongs to the sample A80-06, which also has the highest Th/Sc ratio of 2.7 and the highest La_N/Yb_N value of 15.5. The REE slopes from the Sierra Norte (Fig. 4c) can be grouped into La_N/Yb_N values of 8.9–6.9 (A101-06, A102-06, A103-06, A108-06) and another group including the rest of the samples with values of 9.5–11.7. The samples A101-06, A102-06 and A103-06 are all located in one big outcrop, and some of them show contact metamorphism caused by a

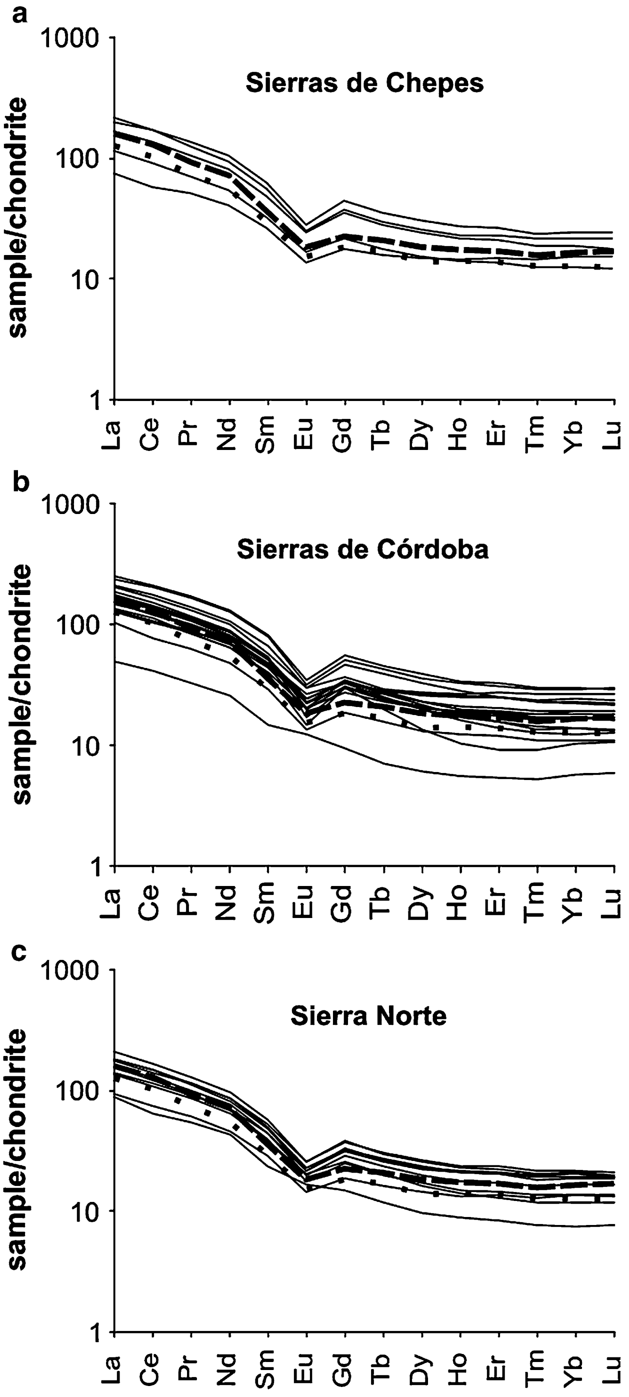

Fig. 4 Chondrite normalised REE patterns (Taylor and McLennan 1985) for samples of the metamorphic complexes of the Sierras de Chepes, the Sierras de Córdoba and the Sierra Norte. The *dashed lines* represent the post-Archaean average Australian shale (PAAS) and the *dotted line* symbolises the upper continental crust (UCC) as defined by McLennan (1989)

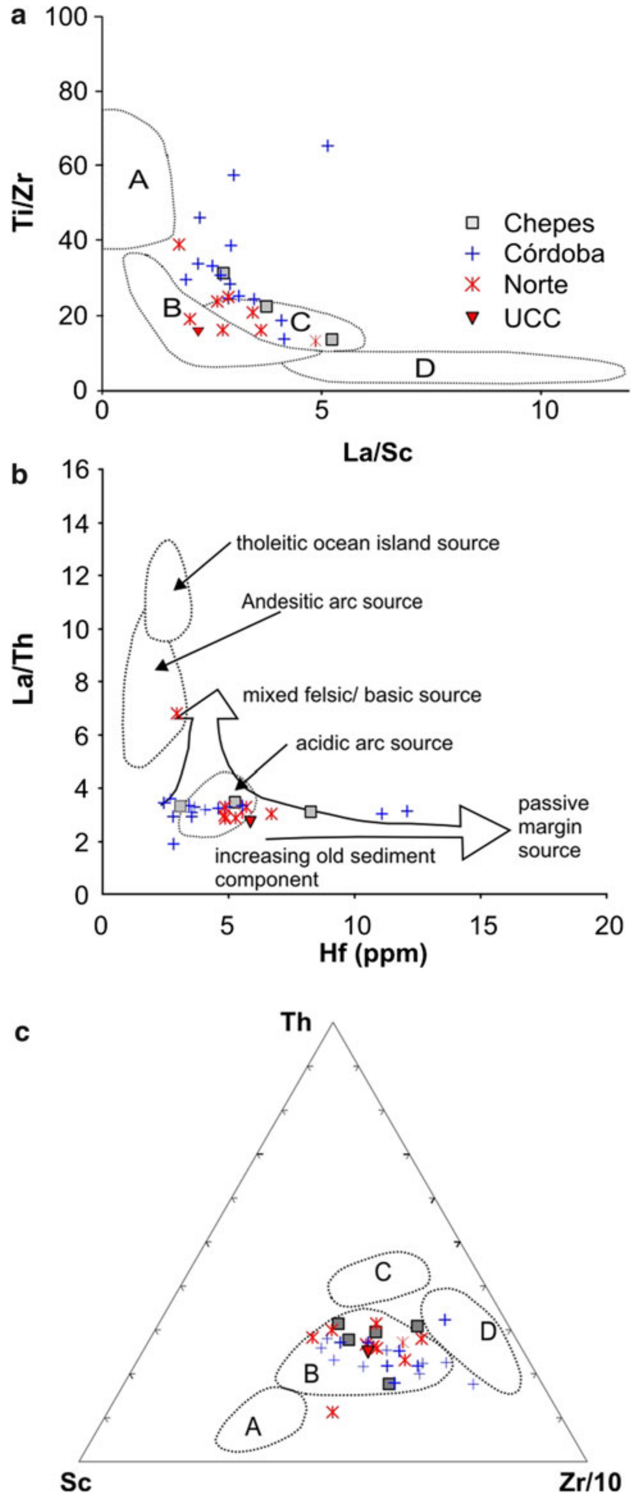

Fig. 5 Tectonic setting discrimination plot based on **a** Ti/Zr versus La/Sc (Bhatia and Crook 1986), **b** La/Th versus Hf (Floyd and Leveridge 1987), **c** Sc-Zr/10-Th (Bhatia and Crook 1986) for samples in the complexes of the Sierras de Córdoba, the Sierra Norte and the Sierras de Chepes. For **a–c**, the samples that plotted as shale in the diagram of Herron (1988) were excluded as Fig. 7a–c were made of sandstones only. *A* oceanic island arc, *B* continental island arc, *C* active continental margin, *D* passive margin. See text for comments

nearby granite. As the REE slopes are steeper for the rest of this unit, the granite could have influenced and, in this case, lowered the REE slope by low LREE concentrations due to mantle input into the melt. Sample A81-06 has a completely different shape of the normalised REE plot, as it hardly shows an Eu/Eu* anomaly. The other samples show values of 0.54–0.64, but A81-06 has a ratio of 0.88. This fits the Th/Sc ratio of 0.25. Both ratios point to a strong mafic influence on this sample.

Tectonic setting

High-field strength elements and certain trace elements such as La, Ti, Zr, Hf, Sc and Th are hardly soluble under surface conditions, and thus very robust provenance indicators of metasedimentary rocks (Bhatia and Crook 1986; McLennan et al. 1990, 1993; Bahlburg 1998) The TiO_2/Zr versus La/Sc ratios, suitable for sandstones, have been shown to discriminate between tectonic settings (Bhatia and Crook 1986). The Ti/Zr vs. La/Sc ratios reflect the amount of magmatic material compared to the input of recycled sources. In this diagram, TiO_2 and Sc reflect the input of mafic derived and/or volcanic material. In contrast, Zr and La display the amount of recycled or silicic sources (Bhatia and Crook 1986). The metapsammites in Fig. 5 plot outside the defined fields. La/Sc values correspond to the ranges for arc-related rocks but TiO_2/Zr corresponds to the ranges for continental and oceanic island arcs.

The La/Th vs. Hf plot (Floyd and Leveridge 1987) provides an indication of the composition of the source material. The element Hf behaves similarly to Zr and therefore also reflects the degree of recycling. The La/Th ratio depends on the degree of differentiation of the magma. The ratio decreases in more evolved magmas as Th behaves incompatible and is enriched in the partial melts. The La/Th ratio of the entire sample collection is bracketed between 3 and 4 and clusters around the average composition of the upper continental crust (Fig. 5b), which would indicate felsic sources. Mixing of old sediment components is indicated by the metasedimentary rocks of Sierras de Chepes and the Sierra Norte. The samples of the banded schist from the Tuclame Formation (A70-06) and the phyllite of Los Túneles (A68-06) show the highest Hf contents, which would suggest higher amounts of recycled components. These two samples also show the highest REE and lower La_N/Yb_N, which suggests a zircon concentration.

In this study, the Th–Sc-Zr/10 (Bhatia and Crook 1986) is used for the discrimination of the tectonic setting. High Zr/Th ratios along with low Sc concentrations point to a passive margin, whereas low Th/Sc ratios in combination with high Sc/Zr values lead to an oceanic island arc setting with low or

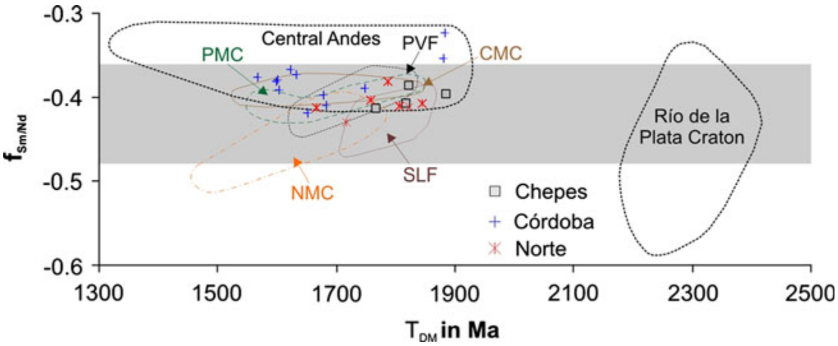

Fig. 6 Plot of $f_{Sm/Nd}$ versus T_{DM} model ages for samples from the complexes of the Sierras de Córdoba, the Sierra Norte and the Sierras de Chepes. The samples and calculation are the same as in Fig. 9, including the *horizontal grey field*. Data for the Río de la Plata from Iacumín et al. (2001) and Pankhurst et al. (2003). The T_{DM} model ages are far apart from those of the Río de la Plata craton. See text for comments. The raw data are shown in Table 3

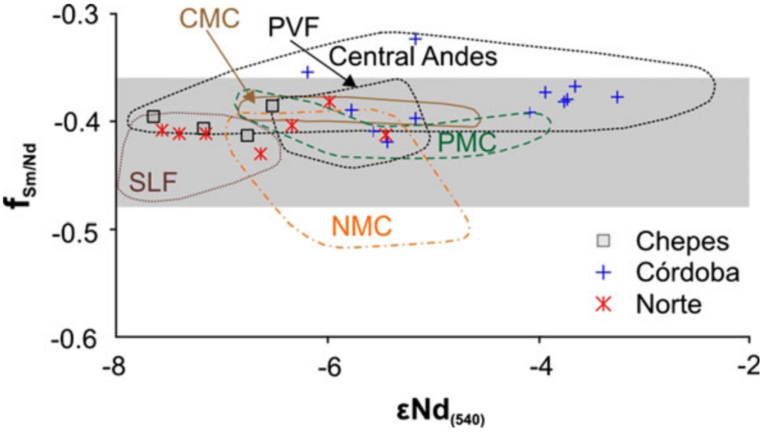

Fig. 7 Plot of $f_{Sm/Nd}$ versus $\varepsilon Nd_{(540\ Ma)}$ for samples of the Sierras de Córdoba, the Sierra Norte and the Sierras de Chepes. Fields for NMC (Nogolí Metamorphic Complex), PMC (Pringles Metamorphic Complex), CMC (Conlara Metamorphic Complex), SLF (San Luis Formation) and PVF (Puncoviscana Formation) are added for comparison. The samples from the Sierras de Chepes scatter in areas of lower $\varepsilon Nd_{(540)}$ values, whereas most of the samples from the Sierras de Córdoba are located in higher $\varepsilon Nd_{(540)}$ ranges. The *grey field* represents the $f_{Sm/Nd}$ limits for the continental crust (Goldstein et al. 1984). The raw data are shown in Table 3

absent recycling and only very low evolved magmas. In Fig. 5c, samples of both metapsammites and slates fall into the field for continental island arc, near the side of the field for continental margin or passive margin, but only the diatexite A80-06 is within the passive margin area in this plot.

Nd-isotope geochemistry

Nd isotopes are of significance for sedimentary rocks in constraining a mean average crustal residence time of their source by the calculation of model ages (T_{DM}), which allows a characterisation of crustal domains of different age and geological history. Sediments derived from old continental crust have highly negative εNd values, whereas juvenile, arc-derived detritus shows less negative or even positive εNd data. The T_{DM} model ages (Table 3 data repository, Fig. 6) were calculated based on the model of Goldstein et al. (1984) that assumes a linear mantle evolution of the isotopic composition. Previously published data are recalculated with this model. The εNd (Table 3 data repository, Fig. 7) data of all analysed samples were back-calculated to 540 Ma, which is the best approximation on the timing of their deposition (Sims et al. 1998; Söllner et al. 2000; Steenken et al. 2006; Adams et al. 2008; Siegesmund et al. 2009). All the samples have $^{147}Sm/^{144}Nd$ values ranging from 0.114 to 0.133 (Table 3 data repository). These values are low (i.e. <0.165) and relatively consistent and thus should yield meaningful model ages as indicated by the steep La_N/Yb_N slopes of the sample isotopic evolution lines of the REE.

The data from Sierras de Chepes show T_{DM} model ages between 1.89 and 1.77 Ga and $\varepsilon Nd_{(540Ma)}$ values between −6.6 and −7.7. The samples A37-06, a shale of the western sector of the Sierras, and A35-06, a litharenite of the southern central sector, exhibit the oldest T_{DM} model ages and more negative $\varepsilon Nd_{(540Ma)}$ data, which agrees with the higher Zr/Sc ratios.

The Sierras de Córdoba have an $\varepsilon Nd_{(540Ma)}$ range between −3.2 and −6.2 ($n = 12$) and T_{DM} model ages between 1.88 and 1.60 Ga. Among the high-grade rocks, samples A80-06 from the Juan XXIII diatexite, located in the San Carlos migmatite, and A61-06 from the southeastern sector of the Sierras de Córdoba (both diatexites), show the highest T_{DM} model ages of 1.88 Ga and the lowest $\varepsilon Nd_{(540Ma)}$ data between −5.2 and −6.2. Although the average crustal residence time is similar to Sierra Norte or the Sierras de Chepes, the $\varepsilon Nd_{(540)}$ is slightly less negative.

The rest of the high-grade rocks are characterised by T_{DM} model ages between 1.7 and 1.6 Ga and $\varepsilon Nd_{(540Ma)}$ values from −3.7 to −5.6. The rocks with younger model ages are the Tala Cruz stromatite (A77-06) and two migmatites from the San Carlos Massif (A74-06 and A79-06).

In the low- to medium-grade rocks, a gneissic resister within a migmatite (A66-06) gives a T_{DM} model ages of 1.75 Ga and εNd data of −5.8, similar to the rocks of Sierra Norte. The remaining three samples (A62-06, A68-06, A70-06) yielded T_{DM} model ages between 1.62 and 1.57 Ga and $\varepsilon Nd_{(540Ma)}$ significantly higher between −3.2 and −4.1. The last two show the highest Zr/Sc ratios and the highest amount of REE, which could imply Zr accumulation.

Six samples from the Sierra Norte show T_{DM} model ages between 1.85 and 1.72 Ga and $\varepsilon Nd_{(540Ma)}$ between −6.0 and −7.6. The youngest T_{DM} model ages of 1.67 Ga and the highest $\varepsilon Nd_{(540Ma)}$ −5.4 were calculated for A102-06, which contains 47% SiO_2. This casts doubt on this sample being a metasedimentary rock without element mobilisation. The rest of the samples show similar T_{DM} model ages and εNd data, including A81-06 with a T_{DM} model ages of 1.82 and an $\varepsilon Nd_{(540Ma)}$ value of -7.4, although the Th/Sc ratio is only 0.25, pointing to significant volcanic input.

Whole-rock Pb–Pb results

Provenance analyses have also been done with the Pb isotopic system in order to discriminate different geological units (e.g. Aitcheson et al. 1995; Kay et al. 1996; Tosdal 1996; Bock et al. 2000; Loewy et al. 2004; Schwartz and Gromet 2004; Drobe et al. 2009). A linear trend should be observed if one unit was supplied by only one homogeneous source or from several well-mixed reservoirs. The Pb ratios represent the average Pb isotopic composition of the metasedimentary source rocks. Pb isotopic compositions can be used to determine sources and the post-depositional history of sedimentary rocks. The advantage of this system is its lack of dependence on present-day closed system behaviour of the parents (^{238}U, ^{235}U, ^{232}Th) or the daughters (^{206}Pb, ^{207}Pb, ^{208}Pb) of the three radiogenic decay systems (Krogstad et al. 2004).

The present-day Pb values for $^{207}Pb/^{204}Pb$ (Fig. 8) are between 15.65 and 15.78, for the $^{206}Pb/^{204}Pb$ between 18.53 and 20.66 and for the ratio of $^{208}Pb/^{204}Pb$ (Fig. 9) between 38.69 and 40.69. The complete Pb data are shown in Table 4.

The samples from the Sierras de Chepes define a linear trend in the uranogenic Pb plot ($^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$) and also in the thorogenic-uranogenic plot ($^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$). The variance is minor. The phyllite A37-06 also defines the trend of the other samples of this unit but exhibits higher ratios of both $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than the other three samples. The metasediments from the

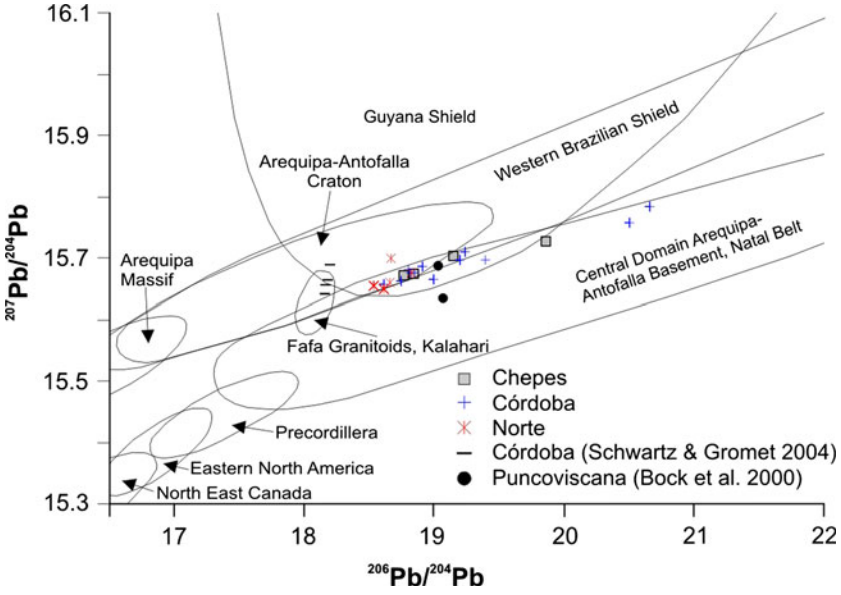

Fig. 8 $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ isotopic correlation diagram (present-day Pb) for the studied areas. The fields for the different basement domains are taken from Tosdal (1996) and Schwartz and Gromet (2004). The data plots in the vicinity of the results from Bock et al. (2000) and Schwartz and Gromet (2004). Both groups used metasedimentary rocks for their analyses. The raw data are shown in Table 4

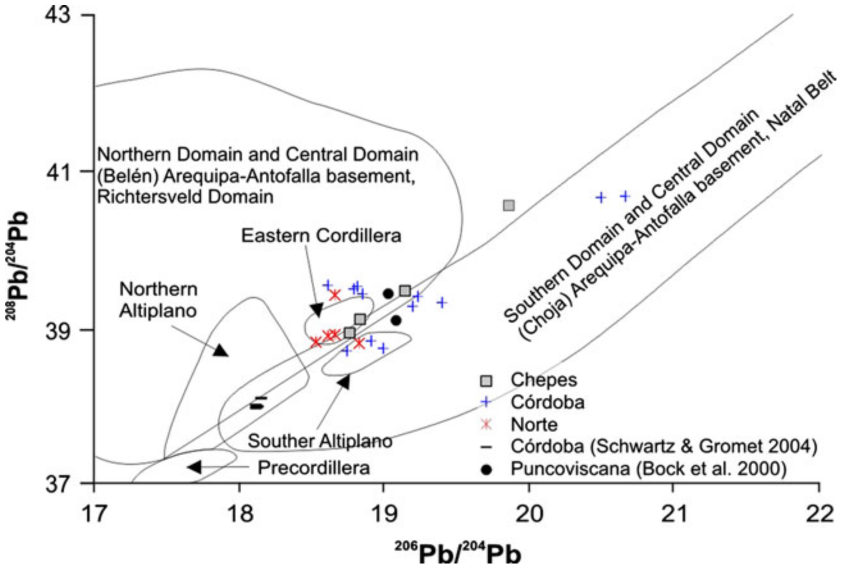

Fig. 9 Isotopic correlation diagram for ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb (present-day Pb) with Pb domains of South America after Aitcheson et al. (1995), Kay et al. (1996), Loewy et al. (2003, 2004 and references therein). The raw data are shown in Table 4

Sierras de Córdoba also define a linear trend in the ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram. Two samples (A68-06, A79-06) are the most radiogenic with by far the highest ^{206}Pb/^{204}Pb ratios, but still on a linear trend of this unit. The data from the ^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram have the highest spread from the whole collection. The rocks A60-06, A76-06, A78-06 and A80-06, all high-grade metamorphic rocks, have elevated thorogenic ^{208}Pb/^{204}Pb ratios. The samples A62-06, A75-06 and A77-06 have low ^{208}Pb/^{204}Pb ratios and seem to be on a trend together with the samples A66-06 and A70-06 who both have higher thorogenic-uranogenic Pb values. The metasediments A68-06 and A79-06 have the highest Pb values and are outside the range of the other samples from this unit (comparable to A37-06 from the Sierras de Chepes).

The data from the Sierra Norte have a very narrow range for the ^{206}Pb/^{204}Pb ratio (18.53–18.82). These values are the smallest and less radiogenic in the collection. Sample A81-06 has an elevated ^{207}Pb/^{204}Pb value of 15.77 compared to the other samples that range from 15.65 to 15.68, slightly outside the range of the other data points from the Sierra. This can also be observed for the ^{208}Pb/^{204}Pb values. Sample A81-06 has a value of 39.42, but the other samples are less radiogenic with values between 38.80 and 38.90. From these four samples, the lowest ratio (38.80) is given by sample A102-06, which has the highest ^{206}Pb/^{204}Pb value of 18.82, shifting it slightly out of the range of the other samples from this unit.

Detrital zircon geochronology: U–Pb SHRIMP dating

In sample A1-08, a banded schist from the Sierras de Chepes, 37 ages were calculated from 36 zircon grains (Figs. 10a, 11a). Three of the four ages (2.2, 13.2, 15.2, 16.2) were not used for the interpretation due to their strongly discordant characteristics (around 20%, Table 5). One age (12.2) was not used due to a common Pb concentration of 1.4%. The youngest age is 465.8 ± 4.7 Ma (all ages are ^{206}Pb/^{238}U ages if not so named) but has a discordance of 8%. The ^{207}Pb/^{206}Pb age of this data points to an age of 506 Ma. The next older age is at 500 Ma, followed by a clear maximum of 14 ages between 511 and 540 Ma. Such maxima were already proposed by Adams et al. (2008) for certain areas in the Puncoviscana Formation, the Negro Peinado Formation and the Achavil Formation (Fig. 1) in which Collo et al. (2009) dated detrital zircons. They yielded one maximum around 520 Ma and a second around 640 Ma. This was similar for two samples they analysed. The next peak for A1-08 is early Pampean at around 570 Ma, followed by two Brasiliano maxima that give ages of 630 and 700 Ma. Afterwards there is a gap until 1,200–1,000 Ma. Only one age is outside this range, giving a ^{207}Pb/^{206}Pb age of 2,100 Ma (Table 5 data repository).

Sample A4-08 is also a banded schist from the Sierras de Chepes. In this case, 19 grains (Figs. 10b, 11a) were analysed. The data points 15.1 and 18.1 were not used due to a common Pb value of above 1.5%. Additionally, the ages from the spots 4.1, 16.1 and 17.1 were not used for interpretation due their discordance (>10%). The age distribution is different in this metasediment compared to A1-08, as no age around 520 Ma was measured (Fig. 12a, b). The youngest grain gives an age of 564 Ma, but it is relatively discordant (10%) and has a ^{207}Pb/^{206}Pb age above 600 Ma. The other samples have ^{206}Pb/^{238}U ages that plot in one group between 580 Ma and 650 Ma, two ages can be found around 780 Ma, one sample is slightly older than 1200 Ma, and one plots around 2,000 Ma.

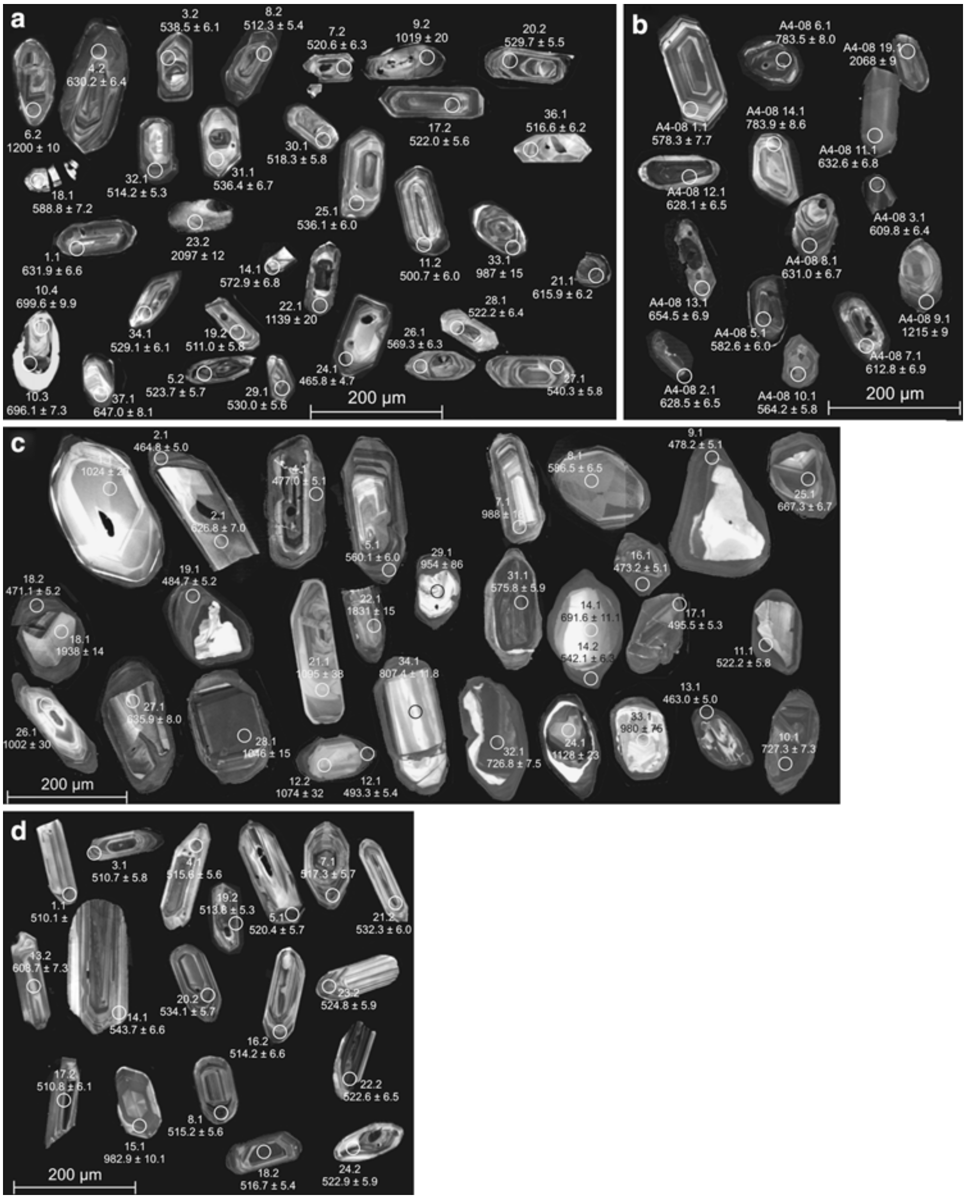

Fig. 10 Cathodoluminescence images of the analysed zircons including measurement spots, ages and errors calculated for the $^{206}Pb/^{238}U$ ratios up to an age of 900 Ma. Older ages are calculated for $^{207}Pb/^{206}Pb$. Samples: **a** A1-08, and **b** A4-08 from the Sierras de Chepes, **c** A3-08 from the Monte Guazú Complex in the southernmost Sierras de Córdoba, **d** A30-01 from the San Luis Formation

Forty ages were calculated for the orthogneiss A3-08 from the Monte Guazú Complex, the southernmost part of the Sierras de Comechingones (Fig. 10c). Four analyses show common Pb amounts of 2% or more (3.1, 5.2, 6.1, 30.1) and/or are highly discordant (6.1, 9.2, 20.1, 30.1) and were not taken into consideration. The 34 remaining ages have their youngest maximum in the Famatinian (Fig. 11b, 12c), resulting in a concordant age of 471.1 Ma ± 2.1 Ma (MSWD = 0.027, 1σ), calculated from six data points (2.1, 4.1, 9.1 13.1, 16.1 18.2). These data were measured on zircon rims. The spots yielded very low Th/U ratios of 0.003–0.013, pointing to a metamorphic overprint. Older grains directly fade into Pampean ages at around 540 Ma. The Th/U ratio is still low between 0.01 and 0.08 but significantly higher compared to the Famatinian ages. These data points are followed by Brasiliano ages up to 730 Ma. Two grains give 800 Ma, before there is a gap up to 920 Ma. Ten grains can be found between 1,120 and 920 Ma. Only two analyses yield older ages. One is a slightly discordant zircon with a $^{207}Pb/^{206}Pb$ age of 1,830 Ma and one concordant age of 1,960 Ma. All but one Th/U ratio between 0.19 and 1.97 from the data points yield ages over 600 Ma, pointing to magmatic growth (Fig. 10c).

Sample A30-01 is a low-grade phyllitic rock from the San Luis Formation. From the 26 ages (Fig. 10d), seven could not be used because of extremely high common Pb values up to 26% and/or discordant behaviour (2.1, 9.1, 10.1, 11.2, 12.1, 25.4, 26.2). From the remaining 19 data points, 16 range between 510 and 544 Ma (Fig. 11d, 12c).

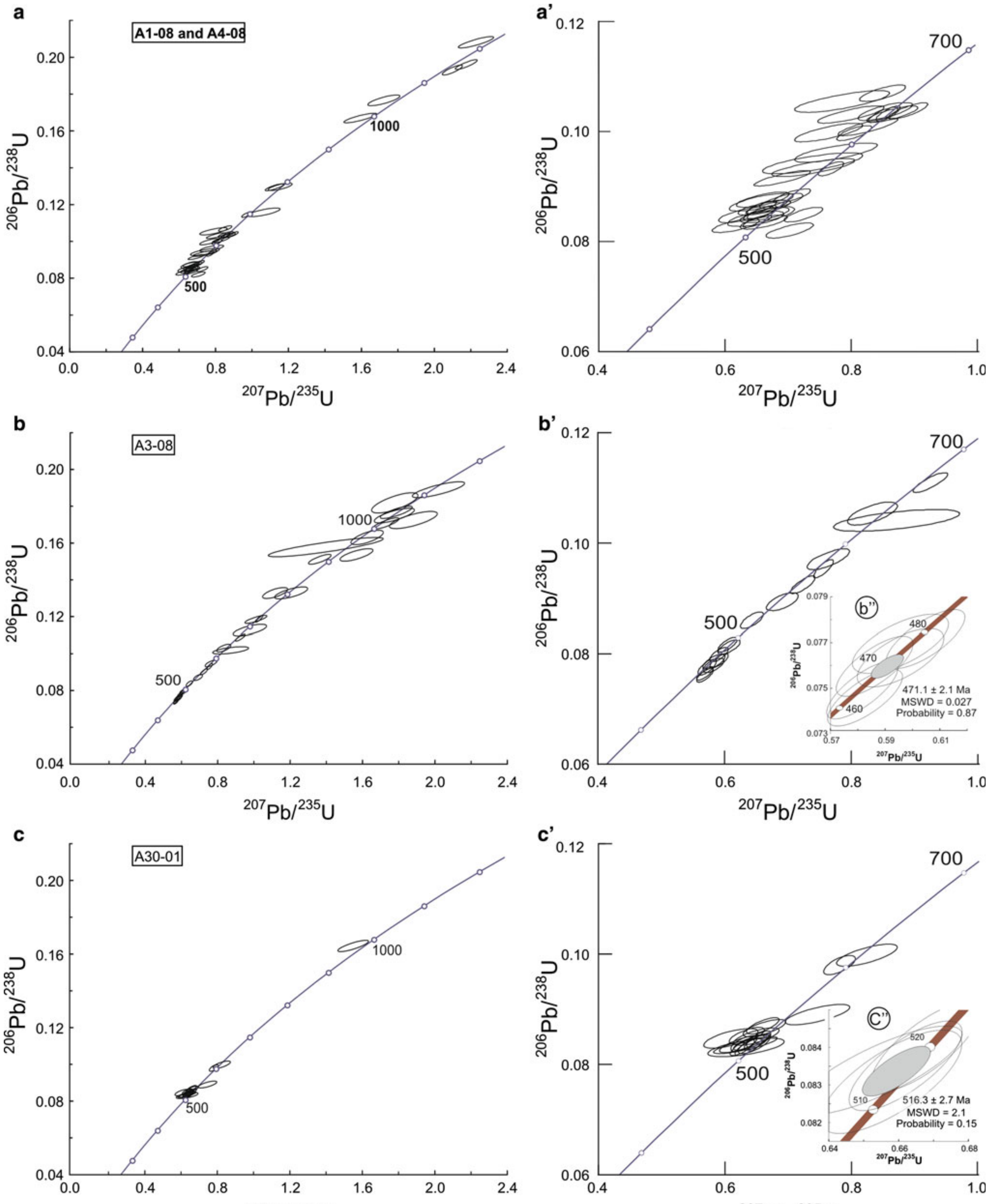

Fig. 11 Wetherill concordia diagrams for the samples are shown in **a–c** for a range up to 1,200 Ma. The Palaeoprotorezoic ages are not shown. An enlargement of the Brasiliano to Famatinian ages can be seen in **a′–c′**. The raw data are shown in Table 5

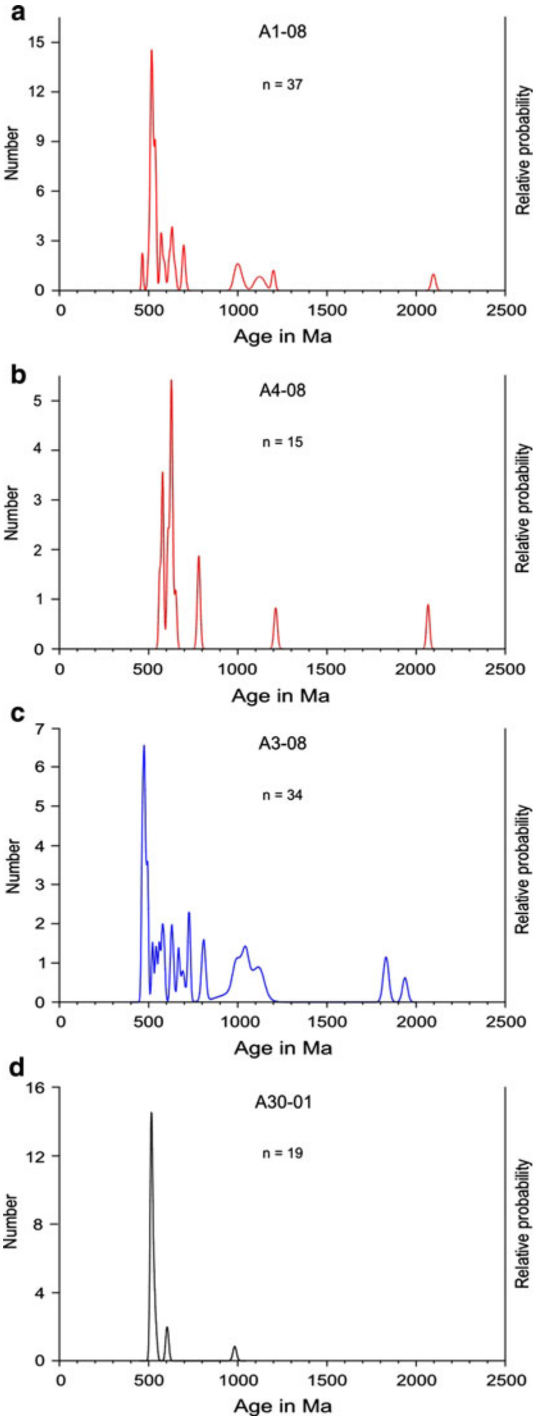

Fig. 12 Probability density plot for the samples **a** A1-08, **b** A4-08 from the Sierras de Chepes, **c** for the orthogneiss A3-08 from the Monte Guazú Complex in the southernmost Sierras de Córdoba and **d** for the sample A30-01 from the San Luis Formation. The ages are ^{206}Pb/^{238}U ages up to 900 Ma. Older ages are ^{207}Pb/^{206}Pb ages. The raw data are shown in Table 5

Only three data points show older ages, pointing to two subordinate Brasiliano (600 and 609 Ma) sources. One zircon spot has a Grenvillian age of 982 Ma.

Provenance analysis

Trace elements implications

The limit for Th/Sc ratios representing the UCC was set at 0.8 (McLennan 2001). Lower values would point to a more primitive, volcanic influence. The Th/Sc ratios of the Sierras de Chepes vary depending on the rock type. The banded schists A33-06 and A35-06 have values of 1.7 and 1.1, whereas the other metasediments have values between 0.9 and 0.6. This points to a more mature source area of the litharenites compared to the other three samples from this area. This is also reflected in the Th/Sc vs. Zr/Sc diagram (Fig. 3) in which the degree of recycling (higher Zr/Sc ratios) is plotted against compositional differences (Th/Sc). There is a general trend towards higher Th/Sc ratios and higher Zr/Sc ratios, pointing to a sediment recycling (maturity) except for A37-06 with the lowest Th/Sc ratio, but relatively high Zr/Sc ratios. This sample is also noticeable by very low amounts of LREE (Fig. 7a) and a very small La_N/Yb_N ratio of only 5 compared to the four other samples that all have ratios slightly above 9. This could point to a mobilisation of the REE. In the Sierras de Córdoba, seven samples plot below the limit of 0.8. Although the mean value is similar to the Sierras de Chepes and the Sierra Norte, only one sample from each of these units plots below 0.8 (except A81-06). These samples are three medium-grade (A63-06, A64-06, A65-06) and four high-grade metamorphic rocks (A61-06, A76-06, A77-06 and A79-06). All these samples have low Zr/Sc ratios below 10, which can only be seen for the high-grade metasedimentary rocks (A60-06 and A78-06 with Zr/Sc ratios of 7.5 and 8.8). Three medium-grade samples (A62-06, A66-06, 75-06) have slightly higher values around 15 together with Th/Sc values between 0.9 and 1.1. The metasediments which seem to be most evolved in the Sierras de Córdoba are the phyllite A68-06 and the banded schist A70-06. They both have the highest Th/Sc values of 1.3 and 1.4 and the highest Zr/Sc ratios of 22 and 35 and seem to be the samples with highest maturity. An absolute exception in terms of the Th/Sc ratio is the diatexite A80-06 with a ratio of 2.7 and a relatively high Zr/Sc ratio of 14. In the Th/Sc vs. Zr/Sc diagram (Fig. 3), there is a trend towards higher recycling at higher Th/Sc ratios. A80-06 is not included in this trend as the Th/Sc ratio is much higher for this sample at comparable Zr/Sc ratios. Such a trend also exists for the samples of the Sierra Norte, but the values are higher compared to the Sierras de Córdoba, in the range of the Sierras de Chepes. The sample A81-06 from the Sierra Norte has to be excluded from the interpretation concerning the maturity, as it seems to have a strong volcanic influence, which can be seen in magmatically zoned plagioclase crystals in the thin sections and in the extremely low Th/Sc ratio of 0.25. This is also supported by the REE (Fig. 4c). Sample A81-06 has a very weak Eu/Eu* anomaly of 0.88 compared to 0.55–0.64 of the other samples from this unit. Additionally, the chondrite-normalised ratios for HREE are very low, around 8. The second sample with a Th/Sc ratio below 0.8 is A102-06. In the description of the major elements, it was already mentioned that contact metamorphic reactions including fluids or volcanic detritus during the sedimentation have affected this rock. For this reason, the value of 0.7 is not typical for the Sierra Norte. Three samples with the highest amount of SiO_2 and the lowest concentration of Al_2O_3 (A100-06, A104-06, A105-06) have the highest Th/Sc ratios of 1.2–1.5. The remaining five samples (A101-06, A103-06, A106-06, A107-06, A108-06) have significantly lower Th/Sc ratios around 0.9, but the Zr/Sc ratios of both groups from the Sierra Norte have an overlap, making a distinction of the maturity more difficult. There is also a tendency towards a higher degree of recycling for samples with higher Th/Sc ratios, as in the samples before. The difference of the three units is that the samples from the Sierras de Córdoba generally have lower Th/Sc ratios and lower Zr/Sc ratios, pointing to less recycling and a more mafic input. The reason could be a shorter distance to the basin in which the metasediments of the Sierras de Córdoba were transported and a stronger volcanic input. Both could be related to a volcanic arc in close vicinity compared to the units of the Sierras de Chepes and the Sierra Norte. Comparing these data to the metamorphic units of the Sierra de San Luis and the Puncoviscana Formation (Sims et al. 1997; Brogioni 2001; López de Luchi et al. 2003; Zimmermann 2005; Drobe et al. 2009), only the samples from the Conlara Metamorphic Complex (López de Luchi et al. 2003; Steenken et al. 2004) and parts from the San Luis Formation (Sims et al. 1997; López de Luchi et al. 2003; Drobe et al. 2009) plot similarly to the samples from the Sierras de Córdoba, indicating a comparable volcanic influence in these three units. Diagrams to decipher the provenance and tectonic setting of the source rocks, using trace element data (Fig. 5a–c), point to a continental island arc for most of the samples, but there are differences between the three domains. The samples from the Sierras de Córdoba plot closer to the oceanic island arc field or point to a less recycled source in all three diagrams (Fig. 5a–c), whereas the samples from the Sierra Norte show a less pronounced volcanic influence and can be found in the continental island arc field and acidic arc source (Fig. 5b), respectively. The samples from the Sierras de Chepes have a bigger spread in general but show more similarities to the Sierra Norte than to the Sierras de Córdoba. Although there is a slight tendency to a stronger mafic input, especially in the Sierras de Córdoba, the difference to the Sierra de San Luis and the Puncoviscana Formation in terms of the geochemistry is not significant (Sims et al. 1997; Brogioni 2001; López de Luchi et al. 2003; Zimmermann 2005; Drobe et al. 2009). Nevertheless, there is a difference in the influence of mafic material in the Sierras de Córdoba compared to all other domains in the Eastern Sierras Pampeanas, similar to the Th/Sc and Zr/Sc data (Figs. 3, 4). Although the provenance of the metasediments in the Sierras de Córdoba is more basic compared to the other units from the Eastern Sierras Pampeanas, there are two samples that point to a stronger reworking (A68-06, A70-06). These two metasediments have the lowest Ti/Zr values combined with the highest La/Sc values in the Sierras de Córdoba (Fig. 5a), a low La/Th ratio and high Hf concentrations (Fig. 5b) pointing to a provenance with high reworking. These samples plot closest to the passive margin field (Fig. 5c) in the Th–Sc–Zr/10 diagram. In this diagram, they are accompanied by sample A80-06 due to its very high Th/Sc ratio. This sample has a very strong negative Eu/Eu* anomaly pointing to a more mature source, which would be a reason for the huge difference to the other samples. These features pointing to a passive margin cast doubt on a uniform development of the Sierras de Córdoba. This is related either to a different provenance or to rapid facies changes within the basin.

Implications for the Nd-isotope geochemistry

The Sierra Norte and the Sierras de Chepes have a scatter for Nd-isotope data similar to the metamorphic complexes from the Sierra de San Luis, except for the San Luis Formation. This unit can be compared with the low-grade rocks of the Mesón Group in NW Argentina (Bock et al. 2000), and the clastic rocks of the Negro Peinado and Achavil Formation of the Famatina Belt in which Collo et al. (2009) reported even older T_{DM} model ages and more negative εNd data. The data from the Sierra Norte are only slightly younger and less evolved when compared to the above-mentioned units. The striking difference from these units in contrast to the Sierras de Córdoba, the Puncoviscana Formation and the domains from the Sierra de San Luis (except the San Luis Formation) is the absence of T_{DM} model ages younger than 1.7 Ga and $\varepsilon Nd_{(540\ Ma)}$ ratios higher than −6.0 (Rapela et al. 1998; Bock et al. 2000; Steenken et al. 2004; Escayola et al. 2007; Drobe et al. 2009). All these authors reported inhomogeneous ages between 1.9 and 1.5 Ga. In the new data, the Sierras de Córdoba exhibit one group of six samples having very low T_{DM} model ages of 1.63–1.57 Ga together with rather high $\varepsilon Nd_{(540\ Ma)}$ values of −4.1 to −3.2 in contrast to high T_{DM} model ages of 1.88 Ga (A61-06, A80-06) and $\varepsilon Nd_{(540\ Ma)}$ ratios of −5.2 and −6.2. Rapela et al. (1998) already published similar, nonhomogeneous data for the Sierras de Córdoba. This can also be traced in the Sierra de San Luis (except the San Luis Formation) when the datasets from Steenken et al. (2004) and Drobe et al. (2009) are combined. The samples that point to a passive margin have rather low T_{DM} model ages of 1.6 Ga. The age of 1.88 Ga for sample A80-06 could also be explained by the high Th/Sc ratio of 2.7 and the strong Eu/Eu* anomaly of 0.43, pointing to a mature sample, but in the case of A61-06 (T_{DM} 1.88 Ga) with a Th/Sc ratio of 0.6 and an Eu/Eu* anomaly of 0.61, this is not that simple. This sample has a low La_N/Yb_N value and the highest $^{147}Sm/^{144}Nd$ value of 0.133 that might be a hint to element mobilisation, similar to A37-06 from the Sierras de Chepes (1.89 Ga). Escayola et al. (2007) proposed a magmatic arc between 760 and 600 Ma in the eastern sector of the Sierras de Córdoba, related to westward subduction in the beginning and later eastward subduction. The eastward subduction was accompanied with the approach of the Grenvillian-aged Pampia Terrane. These authors described a cross section through the Sierras de Córdoba with a continuous decrease in the T_{DM} model ages towards the east due to increasing volcanic activity, lowering the T_{DM} model ages. The new data cannot support a decrease in the T_{DM} model ages towards the east. No tendency towards a direction or a metamorphic grade was visible. Although a cross section with decreasing T_{DM} model ages to the east might be difficult to establish in the Sierras de Córdoba, there is a tendency in the young (<1.7 Ga) T_{DM} model ages from the eastern sector like the Sierras de Córdoba, the Conlara Metamorphic Complex and the Puncoviscana Formation. This was already correlated by Steenken et al. (2006) to the western sector like the San Luis Formation, the Sierras de Chepes and the Negro Peinado and Achavil Formations (Collo et al. 2009). The deposition of these sediments took place after the sedimentation of the Sierras de Córdoba, the Conlara Metamorphic Complex and the Puncoviscana Formation. Thus, the older T_{DM} model ages in the west could result from decreasing volcanic activity and/or a stronger reworking of these sediments, in addition to the greater distance towards the magmatic arc. The T_{DM} model ages of the Mesón group are similar to the data from the Sierras de Chepes, the San Luis Formation and the data from the Famatina Belt (Steenken et al. 2004; Collo et al. 2009; Drobe et al. 2009) but there are only four data points. Three give T_{DM} model ages of 1.82–1.74 Ga and one sample is far younger, yielding 1.46 Ga (Bock et al. 2000). The problematic unit in this discussion is the Sierra Norte, which has comparable Sm–Nd data like the Sierras de Chepes, the San Luis Formation or some areas in the Famatinian ranges (Collo et al. 2009), but is located in the easternmost sector of the Pampian Sierras de Córdoba, where younger T_{DM} model ages are reported.

Possible source rocks for the metasediments of the Eastern Sierras Pampeanas could either be located in the north (Arequipa–Antofalla craton, Sunsas Belt) or from the Kalahari craton and its vicinity. Although the Río de la Plata craton is juxtaposed to the Eastern Sierras Pampeanas, it can be excluded as important source, as typical T_{DM} model ages of this craton (Fig. 6) are between 2.7 and 2.2 Ga (Cingolani et al. 2002; Hartmann et al. 2002; Pankhurst et al. 2003, Rapela et al. 2007). Consequently, the protoliths of the Eastern Sierras Pampeanas must have been deposited in a north–south striking basin. The sediments filling this basin could have come from the north, the south or from both directions. Another possibility is that rocks with a similar Nd isotopic signature and geochemistry of the Eastern Sierras Pampeanas were overlying the Río de la Plata craton and have been completely eroded. A later juxtaposition of the Sierras Pampeanas besides the Río de la Plata craton along shear zones has been discussed by e.g. Rapela et al. (2007), Drobe et al. (2009) and Siegesmund et al. (2009). Different models were discussed in the literature. Rapela et al. (2007) proposed that a major continental mass that included the Western Sierras Pampeanas, the Arequipa–Antofalla basement and the Amazonia craton collided with the Río de la Plata and the Kalahari craton around 540–520 Ma, to produce the Pampean orogeny that caused the main metamorphic overprint of Eastern Sierras Pampeanas (Rapela et al. 2007; Steenken et al. 2007; Drobe et al. 2009; Siegesmund et al. 2009). Due to similar T_{DM} model ages.

Whole-rock Pb–Pb evidence

The Pb evolution of the $^{207}Pb/^{204}Pb$ of the different domains is almost indistinguishable. The meta-arkose A81-06 from the Sierra Norte is the only sample with a slightly elevated $^{207}Pb/^{204}Pb$ ratio (15.70). The reason for this could be the volcanic source of the sample, also visible in the low Th/Sc value of 0.25. The other samples, not only from the Sierra Norte, plot in between the western Brazilian Shield and the Arequipa–Antofalla craton. These have slightly higher $^{207}Pb/^{204}Pb$ ratios than the Natal belt and the Central Domain of the Arequipa–Antofalla craton, which have lower $^{207}Pb/^{204}Pb$ ratios with a slight tendency towards the latter that can be seen in the samples A68-06 and A79-06 that show the highest $^{206}Pb/^{204}Pb$ (Fig. 8) ratios. This is similar to the Pb isotopy for the Sierras de Córdoba (Schwartz and Gromet 2004) and the Puncoviscana Formation (Bock et al. 2000; Drobe et al. 2009) and the different domains in the Sierra de San Luis (Drobe et al. 2009). The $^{208}Pb/^{204}Pb$ ratios (Fig. 9) show a broader distribution, not as cigar-shaped as the $^{207}Pb/^{204}Pb$ (Fig. 8). The values are still difficult to assign to either the Northern, Central (Belén) Domain of the Arequipa–Antofalla basement and the Richtersfeld Domain with elevated $^{208}Pb/^{204}Pb$ ratios or the Southern Domain Central Domain (Choja) of the Arequipa–Antofalla basement and the Natal Belt with lower $^{208}Pb/^{204}Pb$ values. The bigger spread in the Pb data from the Sierras de Córdoba could have its origin in the stronger volcanic influence or, in case of the four high-grade metamorphic samples (A60-06, A76-06, A78-06 and A80-06), in elevated $^{208}Pb/^{204}Pb$ values due to mobilisation of U during melting. Uranium addition would lead to a flatter slope of the Pb evolution in the $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 9). Uranium loss would increase the slope. The concentration of Th should remain relatively constant as it is immobile. Similar features were also observed by Lucassen et al. (2001) from the central Andes between 21 and 27°S. These authors analysed, among other samples, xenoliths from the lower crust. These high-grade metamorphic gneisses displayed elevated $^{208}Pb/^{204}Pb$ ratios and similar $^{206}Pb/^{204}Pb$ ratios compared to the low-grade rocks. This feature was interpreted as U loss in the high-grade metamorphic rocks (Lucassen et al. 2001) and could be connected with some of the high-grade rocks of this collection.

Identifying a certain provenance area for the different domains is not easy, similar to the Pb values from the Puncoviscana Formation and the Sierra de San Luis, discussed by Drobe et al. (2009). These authors could not address a definite area as the source of the metasedimentary rocks, as the Pb data plot in between the available sources (Figs. 8, 9). The data are similar to Schwartz and Gromet (2004), who suggested that the Kalahari craton is the source for the Sierras de Córdoba, and also comparable to the two analyses of Bock et al. (2000) from the Puncoviscana Formation who proposed a homogeneous Pb isotopy. A mixing of different sources could be expected, as the samples were taken in a former active continental margin.

Constrains from the detrital SHRIMP ages

Sample A30-01 from the San Luis Formation shows the lowest spread in the collected dataset. There is a sharp maximum around 517 Ma (Fig. 12d) according to the probability density plot, also represented by a concordant age (Fig. 11c′) of 516.3 ± 2.7 Ma (5 data points, 2σ). A similar narrow range for the San Luis Formation was also reported by Drobe et al. (2009) with the difference that these authors reported a peak around 575 Ma. Both samples have one well-defined peak. The age difference between the peaks could probably be due to the different source rocks, which both had well-defined age maxima, but at different times. One early Pampean age peak around 570 Ma and one late Pampean peaks around 517 Ma. The maximum age of sedimentation for the San Luis Formation should be 510 Ma, as three data points (1.1, 3.1, 17.1) indicate this age. These ages cannot be related to metamorphic overprint as this unit never exceeded lower greenschist metamorphic conditions (Wemmer et al. in review). Thus, the zircon ages have to be detrital. Detrital ages around 520 Ma can also be found in the metasedimentary rocks of the Sierras de Chepes (A1-08). The strongest maximum can be found at 520 Ma, pointing to a similar maximum age of sedimentation as in the San Luis Formation. Additionally, there are early Pampean ages around 570 Ma, Brasiliano ages with the strongest maximum around 630 Ma and also Grenvillian and older ages. The metamorphic conditions in the Sierras de Chepes were not high enough to cause a new growth of metamorphic rims. This may be represented by certain data points (11.2, 24.1), with one age around 501 Ma and one Famatinian spot of 466 Ma. These ages might be underestimated due to their slight discordant behaviour (8 and 3%). The $^{207}Pb/^{206}Pb$ ages of these data points are 506 Ma and 518 Ma (Table 4 data repository), being close to the common age maximum of this sample. If the zircons in the metasedimentary enclaves would have been affected by the intrusion of the granitoids of the Sierra de Chepes, they should have ages around 490 Ma, as Pankhurst et al. (1998) dated the intrusions to this age, based on zircons from the granitoid body itself. Consequently, the zircon ages in the metasedimentary rocks should be detrital. Similar age maxima of 522 Ma can be found in the Negro Peinado Formation and the overlying Achavil Formation (519 Ma) in the Famatina belt (Collo et al. 2009) as well as in the Mesón group (pers. comm. C. Augustsson), which lies discordantly on the folded Puncoviscana Formation. All these units are in the western area of the Eastern Sierras Pampeanas and, with exception of the greenschist- to amphibolite-grade metasedimentary rocks from the Sierras de Chepes, low-grade metasediments. This leads to the conclusion that the ages around 520 Ma are detrital ages, giving an age maximum for the deposition. Consequently, the Pringles Metamorphic Complex and the San Luis Formation from the Sierra de San Luis were deposited after the Pampean orogeny as formerly reported (Steenken et al. 2006; Drobe et al. 2009). The new data are slightly younger than the synsedimentary zircon age of 529 Ma ± 12 Ma from Söllner et al. (2000) for the San Luis Formation. The similarity of the ages further north in the Sierras de Chepes, in the Famatina belt (Collo et al. 2009) and in the Mesón group (pers. comm. C. Augustsson) could point to a connected event for all these units at the western margin of the Eastern Sierras Pampeanas. Steenken et al. (2006) published concordant ages from zircon rims from the Pringles Metamorphic Complex of 498 Ma. This implies that the sedimentation must have taken place between 510 and 500 Ma. Older Pampean, Brasiliano and Grenvillian ages are also present in these samples, except for the San Luis Formation, which seems to have a more restricted provenance area with a dominant age pattern of 520–590 Ma. The age distribution of the other units is similar to the Sierras de Córdoba, the Conlara Metamorphic Complex and the Puncoviscana Formation, which were deformed and intruded during the Pampean orogeny. The older grains show inherited Grenvillian ages and Neoproterozoic Brasiliano ages (800–600 Ma) with a provenance either from the Sunsas Belt or from the collision zone between the Río de la Plata and the Kalahari craton, where similar ages can be found. The similarities between the Sierras de Córdoba and the Conlara Metamorphic Complex in the south and the Puncoviscana Formation in the north based on zircon age dating and Sm–Nd isotopy have already been shown by Schwartz and Gromet (2004), Steenken et al. (2004, 2006), Rapela et al. (2007), Adams et al. (2008) and Drobe et al. (2009). The provenance of the metasedimentary rocks from the Sierras de Chepes and the orthogneiss from the southernmost part of the Sierras de Córdoba (A3-08 in the Monte Guazú Complex) had not been checked in detail with these techniques. The differences are the U–Pb zircon age peak around 520 Ma in the Sierras de Chepes and a Famatinian peak in the Sierras de Córdoba around 475–470 Ma with a concordant age at 471.1 Ma ± 2.1 Ma (five ages, 2σ, Fig. 11b′). The young ages around 470 Ma is not supposed to represent detrital zircons, as the metamorphism in the Sierras de Córdoba started much earlier. Additionally, the Th/U values are extremely low (below 0.015). Such young ages were interpreted as a hydrothermal event in the Sierra Norte (Leal et al. 2003; Siegesmund et al. 2009). These zircon ages are similar to the Famatinian ages in the Pringles Metamorphic Complex (Steenken et al. 2006), and the monazite ages in the Nogolí Metamorphic Complex, but cannot be found in the detrital zircons from the Sierras de Chepes and the Conlara Metamorphic Complex. This young event could be related to magmatic activity also reported from the Sierras de Córdoba, in which Siegesmund et al. (2009) reported concordant ages in the San Carlos migmatite of 496 Ma ± 9 Ma. It can also be traced in the San Miguel gneiss in the Sierra Norte with an age of 492 Ma ± 4 Ma from the same authors. The main magmatic activity in the Sierras de Córdoba and the Sierra Norte took place between 555 and 525 Ma (Rapela et al. 1998: Stuart-Smith et al. 1999; Söllner et al. 2000; Leal et al. 2003; Llambías et al. 2003; Schwartz et al. 2008). Siegesmund et al. (2009) also found older bodies, like the Cañada del Sauces diatexite with a concordant age at 577 Ma ± 11 Ma. If these ages belong to an intrusion that took place in the Sierras de Córdoba, the sedimentation has to be older in contrast to previous models. Ages of 570 Ma can also be found in the Sierras de Chepes ($n = 3$) and the Monte Guazú Complex ($n = 3$) but seem to be detrital, as no earlier high-temperature metamorphism was reported here and the intrusions took place at a later time (Dahlquist et al. 2005). The distribution of the detrital zircon ages in the northern part of the Sierras de Córdoba (Schwartz and Gromet 2004), the southern part, although an orthogneiss was taken in the Monte Guazú Complex, and the Conlara Metamorphic Complex in the Sierra de San Luis (Steenken et al. 2006; Drobe et al. 2009), is very similar. All have age peaks at 580, 630 Ma, around 700 Ma, around 800 Ma, at 1,000 Ma and some ages between 2,100 and 1,800 Ma. Adams et al. (2008) published ages for the Puncoviscana Formation in the same range, with the only difference being that they also observed Late Palaeoproterozoic–Neoarchean ages. Based on this data, the rocks of the Sierras de Córdoba and the Conlara Metamorphic Complex could represent higher-grade metamorphic equivalents of the Puncoviscana Formation. Adams et al. (2008) also showed two samples that have age clusters with distinct age maxima at 530–520 Ma, similar to the Mesón group or proposed southern equivalents like the Famatina belt, the San Luis Formation and the metasediments of the Sierras de Chepes. These young ages are in conflict to U–Pb intrusion ages of 536 ± 7 Ma and 534 ± 9 Ma (U–Pb zircons) syn- to post-orogenic calc-alkaline granites (Bachmann et al. 1987). Another problem is the Santa Rosa de Tastil Batholith to the west of the city of Jujuy (Hongn et al. 2001). These authors give an intrusion age of 525–520 Ma and discussed the contact of the granite with the Mesón Group and the Puncoviscana Formation as intrusive. Although the dating has been done conventionally, this would lead to an age for the Mesón Group that is older than 525 Ma, which is doubtful. The Mesón group is definitely younger than the Puncoviscana Formation due to a discordant contact between each other. These data are contradicting the zircon ages from Adams et al. (2008) who found peaks at 520 Ma, which are very distinct and a strong argument that the Sierras de Córdoba are about 50 Ma older than the Puncoviscana Formation. Nevertheless, there are still possibilities to connect these units by having a closer look on the geodynamic situation.

Geodynamic model

For a general tectonic setting, an overview of the investigated area around 580 Ma is given in Fig. 14a. The discrepancy between the age of the intrusions and the detrital zircons in the Puncoviscana Formation might have its origin in an idea already proposed by Zimmermann (2005) who talked about cannibalistic recycling of the Puncoviscana Formation. Sediments are deposited into a foreland basin during the subduction at the active continental margin of Gondwana. The sediments could become folded due to the ongoing subduction, uplifted and probably already affected by magmatic activity (Fig. 13b, b′). The folded and uplifted sediments, together with the local intrusions, could be deposited into a foreland basin, similar to the basin in which they already were deposited (Fig. 13c, c′). Due to a ridge subduction in the Sierras de Córdoba and the Sierra Nórte (Schwartz et al. 2008; Siegesmund et al. 2009), the heat production was increased (Fig. 13c) and could have caused the high-grade metamorphism in the Sierras de Córdoba and Cambrian granites in the Sierra Norte (Fig. 13d). At the same time, only low-grade metamorphism took place in the Puncoviscana Formation. Local granites were emplaced due to the ongoing subduction (Fig. 13d′). This setting would be similar to the west coast of Sumatra. There is no trench visible (the Java trench starts further in the southeast) due to high sedimentation rates. This leads to the uplift of the accretionary prism above the sea level and erosion in front of the active volcanic arc. Sediments from the Puncoviscana Formation could be elevated similarly and be affected by volcanic activity that could be the source of the zircon ages of 520 Ma (Adams et al. 2008). Alternatively, they also could have been deposited in a peripheral foreland as proposed by Zimmermann (2005). Another source for these zircons could be young Pampean intrusions like the Santa Rosa de Tastil Batholith (to the west of the city of Jujuy) with ages around 525 Ma (Hongn et al. 2001). Intrusions like this could have become uplifted in such a regime and also could have acted as the source for the young zircons (Fig. 13e, e′). While the outcrops of the Puncoviscana Formation as we see them today were affected as described above, the outcrops of the Sierras de Córdoba and the Conlara Metamorphic Complex have their origin in a much deeper level of the crust. Some rocks with a similar metamorphic grade like the Puncoviscana Formation may possibly have been above the outcrops of the Sierras de Córdoba and the Conlara Metamorphic Complex but became eroded. The deeper parts that we see today could not be affected by younger detrital zircons with an age around 520 Ma, as they were already buried in middle crustal depths. Due to the stronger elevation and erosion of the southern part of the Eastern Sierras Pampeanas, we have older metamorphic and also older intrusion ages in the Sierras de Córdoba and in the Conlara Metamorphic Complex when compared to the Puncoviscana Formation.

The setting must have changed afterwards, at least in the northern part, as the Mesón group in NW Argentina not only lies discordantly on the Puncoviscana Formation but is built up by very mature sandstones in contrast to the Puncoviscana Formation or the San Luis Formation that shows similar sedimentation ages of below 520 Ma, like the Mesón Group. Collo et al. (2009) also reported comparable ages from the Famatina belt. These authors assume that the protolith of the San Luis Formation and the Pringles Metamorphic Complex were deposited earlier than the Negro Peinado and Achavil Formation. Due to absolutely similar ages in the San Luis Formation, these units could have been deposited more or less contemporaneously to the Pringles Metamorphic Complex and the San Luis Formation.

The different metamorphic grade of the low-grade San Luis Formation and the amphibolite to granulite facies Pringles Metamorphic Complex remains as an ongoing problem. This problem could be solved by depositing the sediments into a back-arc basin (Fig. 14a), with the Pringles Metamorphic Complex at the bottom and the San Luis Formation above it. The extensional back-arc setting could have lead to mafic intrusions (Fig. 14b) as described by Hauzenberger et al. (2001). These intrusions would be the heat sources that lead to amphibolite and local granulite facies metamorphism in the Pringles Metamorphic Complex. As the San Luis Formation was deposited above, it was less affected by this metamorphism. After the extension phase, the basin was closed and the (meta) sediments became folded (Fig. 14c) and uplifted. The following erosion exposed high-grade rocks in the central part, named the Pringles Metamorphic Complex, beside low-grade rocks at the eastern and western limits, named the San Luis Formation (Fig. 14d). The sedimentation must have taken place between 510 and 498 Ma, as the age of three detrital zircons in the San Luis Formation gives 510 Ma and the oldest metamorphic ages in the Pringles Metamorphic Complex are zircon rims with 498 Ma (Steenken et al. 2006).

Conclusion

A distinction between the Sierras de Córdoba pointing to a stronger influence of volcanic/mafic material and the Sierra Norte and the Sierras de Chepes, which seem to have more acidic sources, can be made using trace element geochemistry. The Sierras de Córdoba show less recycling and influence of volcanic/mafic material, which points to a stronger influence of an oceanic island arc as the source for the metasediments, whereas the Sierras de Chepes and the Sierra Norte point to an active continental margin or a continental island arc. The data from the Sierras de Córdoba are comparable to literature data from the Conlara Metamorphic Complex, but the Sierras de Chepes and the Sierra Norte seem to have similarities to the other domains from the Sierra de San Luis and the Puncoviscana Formation.

Similar to the geochemical data, the Sierras de Córdoba generally shows the youngest T_{DM} model ages and the

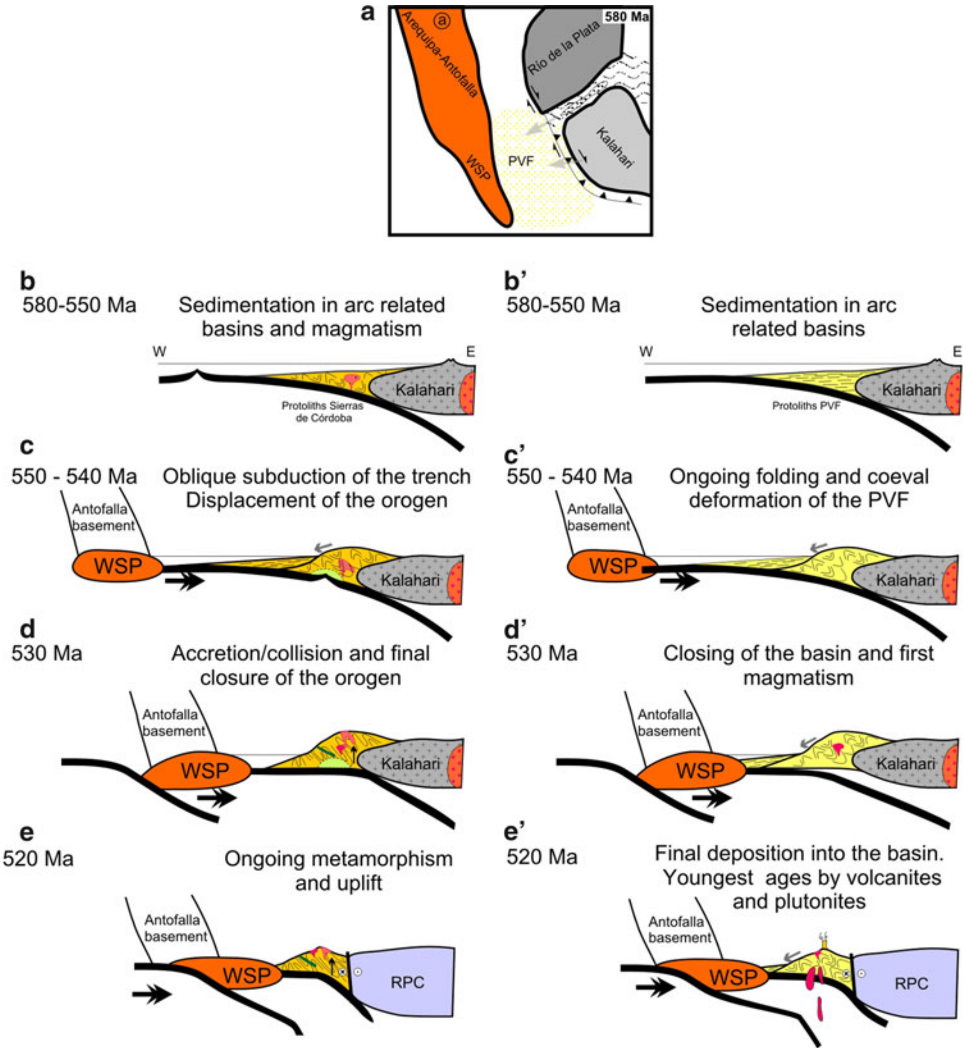

Fig. 13 Model of the formation of western Gondwana between 580 and 520 Ma (modified after Rapela et al. 2007; Siegesmund et al. 2009), with an overview of the palaeogeographic situation at the western margin of Gondwana at 580 Ma (**a**). The figure is divided into a *left hand side* that represents the southern area with the Sierras de Córdoba and the Conlara Metamorphic Complex and a northern area with the Puncoviscana Formation on the *right hand side*. **b**, **b′** While the older protoliths of the Sierras de Córdoba are already intruded by granitoids, there is no indication of folding or metamorphism in the protoliths of the Puncoviscana Formation. **c**, **c′** Ongoing subduction and sedimentation leads to deformation and uplift of the fore-arc sediments and redeposition of the (meta) sediments. **d**, **d′** In the Sierras de Córdoba a ridge subduction (Schwartz et al. 2008) causes a heat input (*light green*). While the ridge subduction causes high-grade metamorphism, migmatisation and the development of (ultra) lenses in the Sierras de Córdoba, the first granitoids invade the Puncoviscana Formation, but resedimentation of the for arc (meta) sediments still takes place. **e**, **e′** At 520 Ma, the basin is closed in the south. The metamorphic Sierras de Córdoba becomes uplifted (**e**) and acts as the source rocks for the San Luis Formation and the Pringles Metamorphic Complex (Fig. 14). In the north, the basin is nearly closed. Volcanic material and/or granites being eroded could act as the source for the youngest zircons of 520 Ma (Adams et al. 2008) in the Puncoviscana Formation (**e′**)

highest ε_{Nd} data, only comparable to some data points of the Conlara Metamorphic Complex and the bimodally fed Pringles Metamorphic Complex. There is a big gap to the Sierras de Chepes and the Sierra Norte, which have older T_{DM} model ages and a more negative εNd isotope characteristic. These older ages and stronger evolved $\varepsilon Nd_{(540)}$ data are similar to the San Luis Formation and the Famatina belt, which were deposited after the Sierras de Córdoba and the Conlara Metamorphic Complex. The Mesón group would also fit into the group of these older T_{DM} model ages, but with one very young exception of 1.46 Ga.

Most T_{DM} model ages in the Sierras de Córdoba are around 1.6 Ga, and the $\varepsilon Nd_{(540)}$ values vary between −4 and −5, but there are also two samples with model ages of 1.9 Ga and lower $\varepsilon Nd_{(540)}$ data of −6 to −5. This is similar to the Conlara Metamorphic Complex, which seems to have inhomogeneities varying from strongly evolved material to relatively primitive. Although there are big

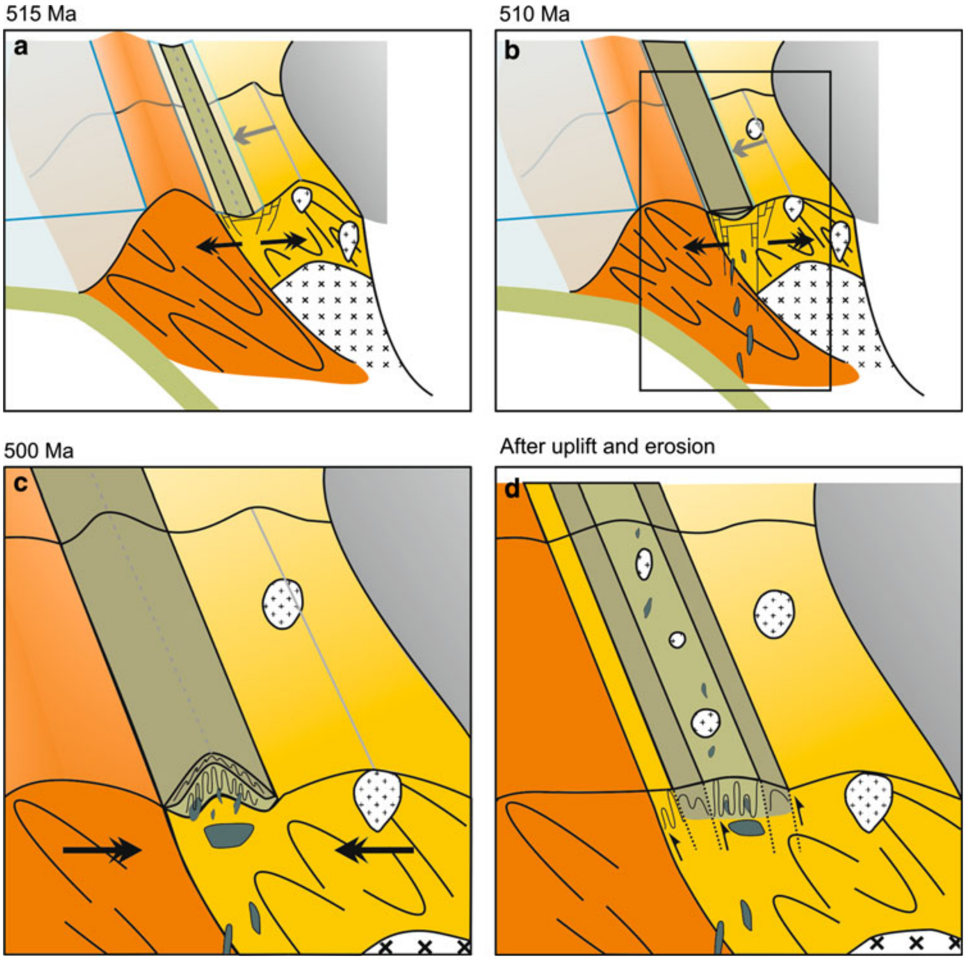

Fig. 14 Due to the approach of the Western Sierras Pampeanas (*orange*), a back-arc basin developed west of the Eastern Sierras Pampeanas (*yellow*), which was fed by sediments of the newly formed orogen (**a**) that later formed the Pringles Metamorphic Complex (*light olive green*). Ongoing subduction and opening of the back-arc basin permitted the ascent of (*ultra*) mafic melt (Hauzenberger et al. 2001), while the sedimentation of the San Luis Formation (*olive*) took place (**b**). Due to the collision the Western Sierras Pampeanas with the Pampean orogen, the basin was closed and folded. The (*ultra*) mafic intrusion caused amphibolite to granulite metamorphism in the Pringles Metamorphic Complex, while the San Luis Formation (*dark olive green*) was less affected as it was located in higher crustal levels (**c**). After uplift and erosion of this area, two belts of the low-grade metamorphic San Luis Formation are in direct contact with the high-grade Pringles Metamorphic Complex

differences between these data, there is no trend to younger ages from north to south or from west to east visible.

The ^{207}Pb/^{204}Pb data of all the units plot in a linear array, similar to formerly published data from the Sierra de San Luis and the Puncoviscana Formation. A distinction of different units is not possible, nor a clear statement regarding the provenance area, as the data points are between all possible sources. The only exclusion that can be done is a provenance from Laurentia, because the Pb isotopic ratios are lower in these areas. The ^{208}Pb/^{204}Pb ratios show a less linear trend, pointing to a stronger variability especially in the Sierras de Córdoba. Nevertheless, it cannot be concluded whether the metasediments were derived from southern Africa, the Arequipa–Antofalla basement or the Brazilian Shield, as the ratios plot in between these domains.

A maximum age of sedimentation for the San Luis Formation and the Sierras de Chepes of around 510 Ma can be proposed by detrital U–Pb SHRIMP ages from these units. Nevertheless, the provenance area of these units has to be different, as the San Luis Formation only has three data points that do not fall in a peak around 520 Ma, whereas the Sierras de Chepes also has a lot of Brasiliano and Grenvillian ages and even two ages that fall into the Palaeoproterozoic. Despite the peak around 520 Ma, the samples from the Sierras de Chepes have similar age patterns like the formerly analysed samples from the Conlara Metamorphic Complex and the Sierras de Córdoba. The sample from the southern part of the Sierras de Córdoba also has similar age distributions like the aforesaid but also was affected by a Famatinian event at around 470 Ma that was metamorphic and has nothing to do with the provenance. The zircons that are relevant for the Provenance analyses are similar to the ages reported from the Conlara Metamorphic Complex and the northern part of the Sierras de Córdoba. We propose a geological model with cannibalistic recycling that makes it possible to correlate the Puncoviscana Formation with the Sierras de Córdoba and the Conlara Metamorphic Complex. The absence of ages around 520 Ma can be seen in outcrops of middle crustal levels in the Sierras de Córdoba and the Conlara Metamorphic Complex, or by the sample locations, as the ages around 520 Ma were not found in all samples analysed in the Puncoviscana Formation. Younger sedimentation took place west of the Sierras de Córdoba, the Conlara Metamorphic Complex and the Puncoviscana Formation. These units are the San Luis Formation, the Pringles Metamorphic Complex, Famatina belt and the Mesón group. These units do not only have detrital zircon age maxima around 520 Ma and some spots as young as 510 Ma, but also higher T_{DM} model ages and lower $\varepsilon Nd_{(540)}$ data than the more eastern units, except the medium- to high-grade Pringles Metamorphic Complex. Although the Sierras de Chepes has all the features just discussed, it cannot be excluded that it is an equivalent of the Puncoviscana Formation and the Conlara Metamorphic Complex, as the banded schists in this unit are absolutely similar to the ones in the Conlara Metamorphic Complex. The San Luis Formation was deposited on the Pringles Metamorphic Complex. Due to a deeper burying and folding during the metamorphism followed by uplift and erosion, there are two low-grade metamorphic belts (the San Luis Formation) east and west of the medium- to high-grade metamorphic Pringles Metamorphic Complex.

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Appendix

Analytical techniques

For geochemical and isotope whole-rock analyses, the sample material was crushed following standard techniques using a jaw crusher and an agate mill. Major elements were analysed at the Geoforschungszentrum (GFZ) in Potsdam using a Panalytical XRF-PW 2400.

Whole-rock geochemistry

Dissolution of the sample material for trace element measurements was performed in two parallel sessions at the Department of Geochemistry and Isotope Geology at the Geoscience Centre of the Georg-August-Universität in Göttingen (GZG). In this laboratory, the samples were dissolved in autoclaves as described in Heinrich and Herrmann (1990). Approximately 100 mg of sample powder was dissolved in 1 ml HF (40%) and 2 ml HNO_3 (65%) at 180°C for at least 12 h. After drying, 1 ml HF (40%) and 1 ml $HClO_4$ (70%) were added, and the samples were reheated up to 180°C for another 12 h. Finally, the disintegrated sample was dissolved in 2 ml HNO_3 (65%) and diluted with H_2O up to 100 ml. In the Department of Isotope Geology, the time-pressure-dissolution gadget (PicotraceTM) was used. Two millilitres HF (40%) and 1 ml HNO_3 (65%) were added to about 100 mg of sample powder and released after a reaction time of 3 h. Afterwards, the sample was dissolved in 2 ml HF (40%), 1 ml HNO_3 (65%) and 1 ml $HClO_4$ (70%) at 130°C for at least 72 h. Subsequently, the acids were evaporated at a fixed temperature of 140°C, and 5 ml 6 N HCl was added at 160°C for at least 48 h. After releasing the HCl, nitrates were gained from the reaction product by adding 200 ml HNO_3 (65%). Finally, the samples were dissolved in 2 ml HNO_3 (65%) and diluted up to 100 ml with H_2O. The same standard of known composition was used in both departments. Differences in the analyses between the two slightly different techniques in both departments could not be observed. This was checked by comparing the data of some samples that were dissolved in both ways. ICP-MS measurements at the Department of Geochemistry were taken using a Plasma Quad II + from VGTM. Analytical accuracy and precision were monitored using the standards JA-2, QC-1 and MA-N. The error is about 10–15% (2σ).

Nd-isotope data

Nd and Sm isotopic analyses were performed on representative samples by the conventional isotope dilution technique. The samples were placed into Teflon vials, weighed and spiked with a suitable amount of ^{150}Nd–^{149}Sm spike solution prior to dissolution in a mixture of 2 ml HF and 1 ml HNO_3 with a PicotraceTM digestion system. The solutions were processed by standard cation exchange techniques for the purification of the Sm and Nd fractions. For the determination of isotopic compositions, Sm and Nd were loaded with 2.5 N HCl on pre-conditioned double Re filaments. Measurements of isotopic ratios were taken on a thermal ionisation mass spectrometer (TIMS) Finnigan Triton measuring in static mode (GZG, Department of Isotope Geology). Repeated measurement of the Nd in-house standard yielded a $^{143}Nd/^{144}Nd$ ratio of 0.511798 ± 0.000077 ($n = 71$, 2σ) over the course of this study. The obtained Nd isotopic ratios of the samples were normalised to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Total procedure blanks were consistently below 150 pg for Sm and Nd. All $^{143}Nd/^{144}Nd$ ratios are reported with their 2σ internal precision plus the uncertainties resulting from the spike correction. The data were calculated according to the model of Goldstein et al. (1984).

Pb isotopic data

Rock powders were pretreated with HBr, dissolved with HF and HNO_3 during addition of HBO_3 (Connelly et al. 2006) and then dried and redissolved in HNO_3. Pb isotope ratios of whole rocks were analysed at the Institute of Geography and Geology, University of Copenhagen, using a VG Sector 54 IT mass spectrometer. Chemical separation of Pb was performed over conventional anion exchange columns with HBr–HCl, followed by purification on 200-ml Teflon columns. Fractionation of Pb during static multi-collection mode mass-spectrometric analysis was monitored by repeated analysis of the NBS 981 standard (Todt et al. 1993) and amounted to 0.105 ± 0.008% per atomic mass unit (amu; $n = 12$, 2σ). Procedural Pb blanks remained below 50 pg; this low blank does not affect the measured Pb-isotopic ratios of the samples significantly.

SHRIMP U–Pb zircon dating

All zircons were mounted in epoxy at the Research School of Earth Sciences (RSES, Canberra), together with the RSES reference zircons FC1. Photomicrographs in transmitted and reflected light were taken of all zircons. These, together with SEM CL images, were used to decipher the internal structures of the sectioned grains and to target specific areas within the accessories (i.e. metamorphic rims or inherited cores) using a 4- to 6-nA primary O_2 ion beam with an c. 25-µm-diameter spot.

For the zircon calibration, the Pb/U ratios were normalised relative to a value of 0.1859 for the ^{206*}Pb/^{238}U ratio of FC1 reference zircons, equivalent to an age of 1.099 Ga (Paces and Miller 1993). U and Th concentrations were determined relative to the SL13 standard. The error in the standard calibration was 0.25% on the SHRIMP II.

Uncertainties given for individual analyses (ratios and ages) are at the 1σ level. However, uncertainties in any calculated weighted mean ages or concordia ages (Ludwig 2000) are reported as 95% confidence limits (unless stated otherwise) and include the uncertainties in the standard calibrations where appropriate. Concordia plots, regressions and weighted mean age calculations were carried out using Isoplot/Ex 3.0 (Ludwig 2003).

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