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The Grenville-age basement of the Andes

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ABSTRACT

The analysis of the basement of the Andes shows the strong Grenville affinities of most of the inliers exposed in the different terranes from Colombia to Patagonia. The terranes have different histories, but most of them participated in the Rodinia supercontinent amalgamation during the Mesoproterozoic between 1200 and 1000 Ma. After Rodinia break-up some terranes were left in the Laurentian side such as Cuyania and Chilenia, while others stayed in the Gondwanan side. Some of the terranes once collided with the Amazon craton remained attached, experiencing diverse rifting episodes all along the Phanerozoic, as the Arequipa and Pampia terranes. Some other basement inliers were detached in the Neoproterozoic and amalgamated again to Gondwana in the Early Cambrian, Middle Ordovician or Permian times. A few basement inliers with Permian metamorphic ages were transferred to Gondwana after Pangea break-up from the Laurentian side. Some of them were part of the present Middle America terrane. An exceptional case is the Oaxaquia terrane that was detached from the Gondwana margin after the Early Ordovician and is now one of the main Mexican terranes that collided with Laurentia. These displacements, detachments, and amalgamations indicate a complex terrane transfer between Laurentia and Gondwana during Paleozoic times, following plate reorganizations and changes in the absolute motion of Gondwana.

RESUMEN

El análisis del basamento de los Andes muestra fuertes afinidades grenvillianas en la mayoría de los asomos expuestos en los diferentes terrenos desde Colombia a Patagonia. Los terrenos tienen diferentes historias, pero la mayoría de ellos participó en el amalgamamiento del supercontinente de Rodinia durante el Mesoproterozoico entre los 1.200 y 1.000 millones de años. Después de la fragmentación de Rodinia, algunos terrenos quedaron del lado de Laurentia tales como Cuyania y Chilenia, mientras que otros quedaron del lado de Gondwana. Algunos de ellos, una vez colisionados con el cratón Amazónico permanecieron unidos, experimentando diversos episodios de rifting todo a lo largo del Fanerozoico, tales como los terrenos de Arequipa y Pampia. Otros fragmentos de basamento fueron despegados en el Neoproterozoico y amalgamados nuevamente a Gondwana en el Cámbrico inferior, Ordovícico medio o Pérmico. Unos pocos fragmentos de basamento con edades metamórficas pérmicas fueron transferidos a Gondwana después de la fragmentación de Pangea procedentes de Laurentia. Algunos de ellos fueron parte de los terrenos mexicanos presentes. Un caso excepcional es el terreno de Oaxaquia que se despegó del margen gondwánico y es ahora uno de los principales terrenos mexicanos que colisionaron con Laurentia. Estos desplazamientos, despegues y amalgamamientos indican una transferencia compleja de terrenos entre Laurentia y Gondwana durante los tiempos paleozoicos, controlados por reorganizaciones de las placas y cambios en el movimiento absoluto de Gondwana.

1. Introduction

The early proposal of Moores (1991) who postulated through his SWEAT hypothesis that the North American Grenville continued in eastern Gondwana, led to one of the first reconstructions of the Rodinia Supercontinent presented by Hoffman (1991). The new paleogeography advanced by Hoffman (1991) displaced Baltica as the conjugate margin of the Appalachians, and located western Gondwana as a counterpart of the present eastern margin of Laurentia. In this reconstruction the Amazon craton, mainly based on the extension of the Mesoproterozoic Sunsas orogen in its western margin, was located as the conjugate margin of the Grenville

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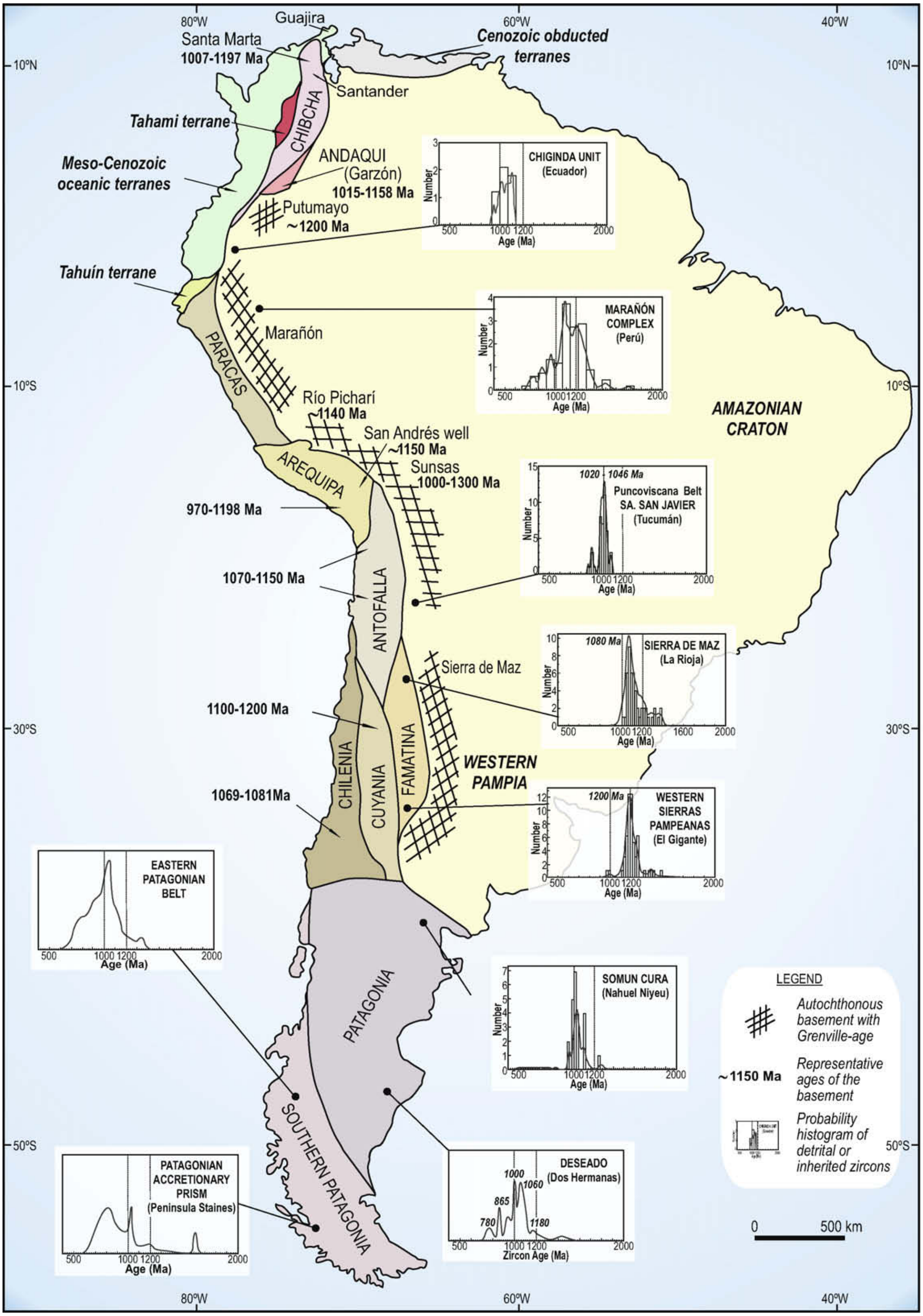

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Fig. 1. Different basement blocks that composed the pre-Andean basement of the Andes with indication of the proposed autochthonous margin of South America, based on Ramos (2009) and different sources discussed in the text.

platform of the Appalachians. This innovative proposal on the Laurentia–Gondwana connection opened almost 20 years of active research in the Andean basement to evaluate the validity of the extension of a Grenville-age basement in western South America.

The purpose of this paper is to review the present status of the Laurentia–Gondwana connection based on the present knowledge on the age and composition of the different terranes that compose the Andean basement. The striking results presented in Fig. 1, not only confirm Hoffman's ideas, but also extend the Grenville-age basement throughout the present western margin of South America.

In order to review the new data, the Laurentia–Gondwana connections are divided in three different stages: (1) Grenvillian terranes left in South America after Pangea break-up; (2) Laurentian derived and para-autochthonous Gondwanian terranes along the Terra Australis orogen accreted during the Paleozoic; and (3) Grenvillian-age terranes left in Gondwana after Rodinia break-up. A brief mention of those terranes that originated in Western Gondwana, mainly in South America, and were finally accreted to Laurentia in Paleozoic times will also be done.

2. Grenvillian terranes left in South America after Pangea break-up

There is some relative consensus on the pre-Andean fitting between Laurentia and Gondwana (Fig. 2) based on reliable paleomagnetic data as depicted by Pindell and Kennan (in press, and cites there in). However, the location of the different independent blocks that formed Mexico and Central America, which constitute a series of terranes between Laurentia and Gondwana are still matter of debate. They have been summarized by Keppie and Ortega-Gutiérrez (1995, 2010), Keppie (2004), Weber et al. (2006, 2008), Keppie et al. (2008a,b), among others.

In order to evaluate the characteristics and composition of the Gondwana conjugate margin preserved in South America prior to the formation of Pangea, it is required to eliminate the different terranes accreted in post-Triassic times. The present tectonic setting of the Northern Andes is illustrated in Fig. 3a. With the aim of reconstructing the original continental margin the following steps must be taken: (1) to eliminate the Middle Miocene accretion of the Panama microplate (Taboada et al., 2000; Cediel et al., 2003) also known as the Choco terrane (Duque-Caro, 1990) which suture runs along the western margin of the Cordillera Occidental and along the San Juan – Atrato valleys; (2) to remove the accretion of the oceanic plateau accreted during latest Cretaceous times represented by the Piñon-Dagua terrane along the Dolores-Romeral fault system of Colombia and Ecuador (see discussion in Jaillard et al., 2005; Vallejo et al., 2006), and finally to remove the island arc accretion occurred in Early Cretaceous times represented by the Amaime, Peltetec, Raspas, and other related terranes (see details in Bosch et al., 2002; Ramos, 2009).

The conjugate margin of Pangea is illustrated in Fig. 3b. This margin has not been palinspastically restored either by the important stretching related to the Triassic–Jurassic rifting during the Pangea break-up as suggested by Pindell et al. (1998), or by the significant shortening associated with the Andean deformation as computed by Restrepo-Pace et al. (2004), Cortés et al. (2006). However, as the magnitude of both effects is within the same order, the depicted margin should be close to the conjugate ancient margin of Gondwana that formed Pangea.

The examination of this margin shows some interesting facts. There is a series of basement blocks constituted by metamorphic rocks of late Paleozoic age, which are situated along the proto-continental margin and west of the early Paleozoic orogens identified by Restrepo and Toussaint (1982). These blocks are preserved in the Cordillera Central of Colombia, in the Cordillera Real of Ecuador and in the Amotape region of northern Peru and southernmost Ecuador.

The northern block in Colombia has been identified as a suspect terrane by Restrepo and Toussaint (1988), and known as the Tahami terrane. The high to medium metamorphic grade rocks of El Retiro have been considered as Precambrian (Restrepo and Toussaint, 1978), until the recent dating of Ordóñez-Carmona and Pimentel (2002) and Ordóñez-Carmona et al. (2006), complemented by the U–Pb dating in zircons of Vinasco et al. (2006) in the Palmitas and Abejorral granitic gneisses, that gave ages ca.

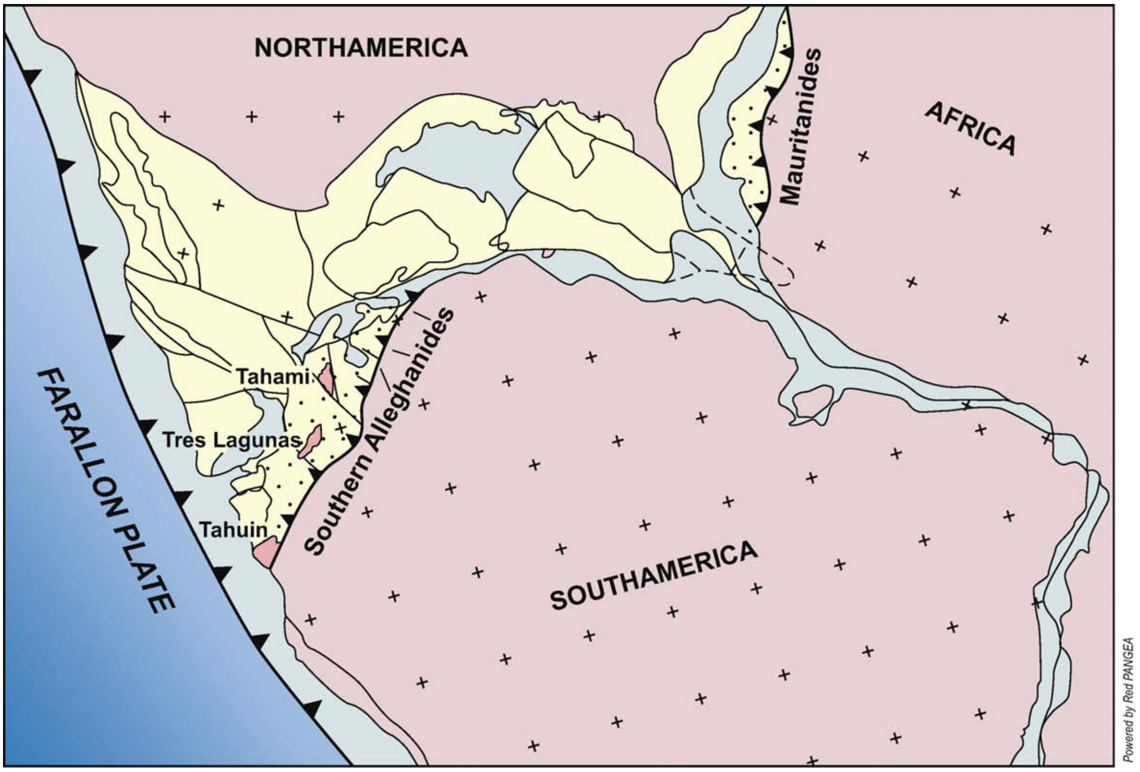

Fig. 2. Pangea reconstruction with indication of late Paleozoic metamorphic rocks of South America (Tahami, Tres Lagunas and Tahuin) involved in the southern Alleghanides deformation (continents fit based on Pindell and Kennan, in press).

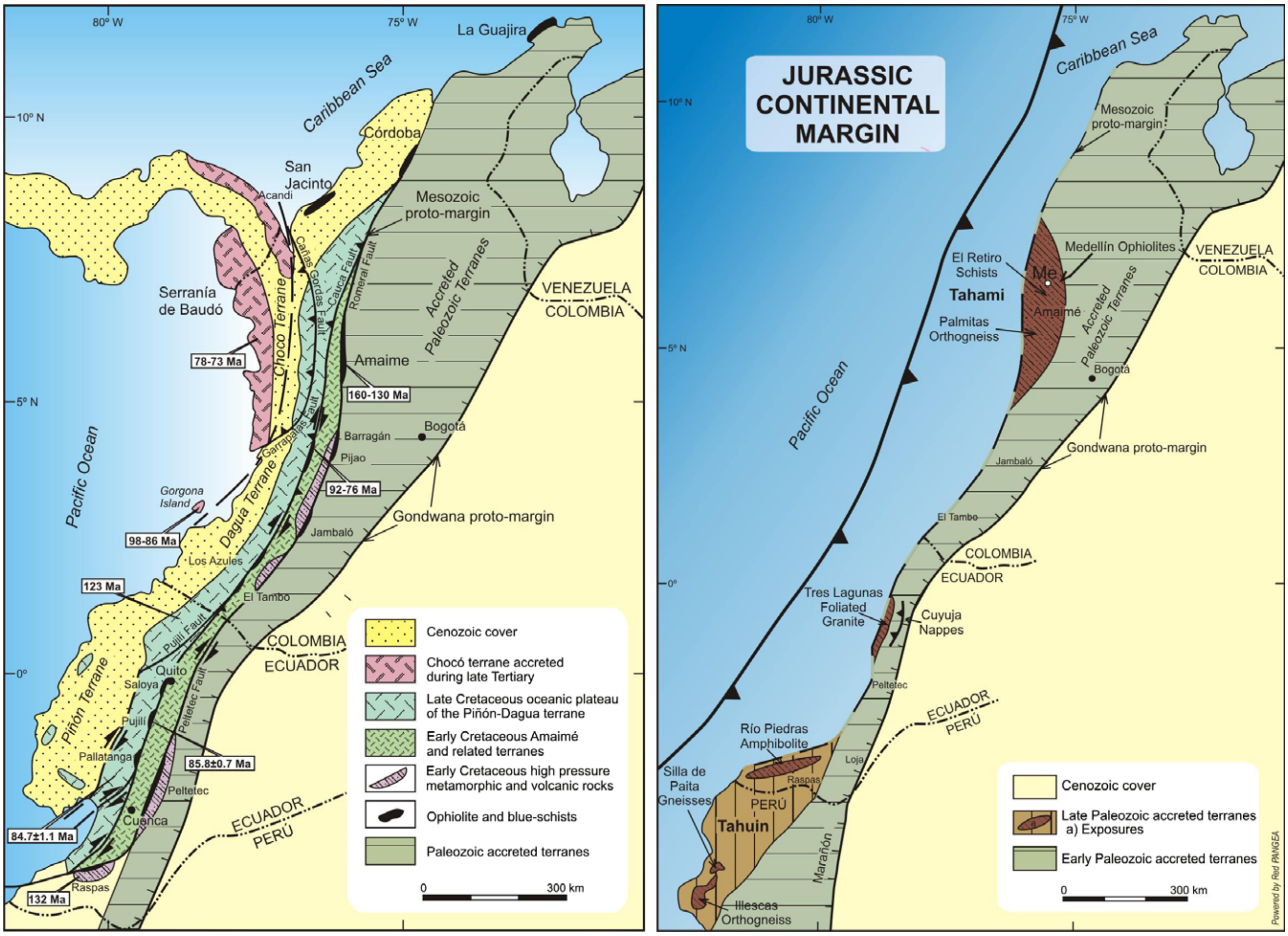

Fig. 3. (a) Present tectonic setting of the northern Andes based on Aleman and Ramos (2000), Vallejo et al. (2006); (b) Post-Pangea continental margin prior to the accretion of the oceanic terranes. Me: Medellín city.

275 Ma and are associated with Ar–Ar ages between 240 and 215 Ma related to the break-up of Pangea.

These Permian orthogneisses and mylonites have a calc-alkaline signature and represent crustal melts, probably produced in an arc setting followed by an important collision and extensional collapse. These rocks are in tectonic contact with a belt of garnet-bearing amphibolites, peridotites, and stratified dunites east of Medellín (see location in Fig. 3b), which represent remnants of an ophiolitic suite of possible Permian age (Restrepo, 2003; Martens and Dunlap, 2003; Restrepo et al., 2009), reworked during the Triassic break-up event (Restrepo et al., 2009). Kinematic indicators of the foliated amphibolites show a vergence to the northeast (Pereira et al., 2006).

The outline of the Tahami terrane was prepared taken in consideration the premises of Restrepo et al. (2008, 2009). It is interpreted as a piece of a Laurentian derived terrane, associated with the magmatic arc developed in some of the Mexican and Central America Terranes, probably with Grenvillian affinities.

High-grade rocks exposed in tectonic inliers south of the Tahami terrane in the Cordillera Real of Ecuador, were interpreted as possible basement fragments of the Precambrian Guyana Shield basement and correlated with the analogous rocks of Cordillera Central of Colombia (Pratt et al., 2005). These gneisses and amphibolites at Papallacta were partially interpreted as either Precambrian or Paleozoic (Herbert, 1977). The metamorphic rocks are intruded by the Tres Lagunas and Jubones foliated granitoids (Litherland et al., 1994; Sánchez et al., 2006), which form a large S-type granitic belt that extends along the western slope of the Cordillera Real. These foliated granites are unconformably intruded by the calc-alkaline Azafran batholith, with U–Pb ages in zircons of 143 ± 1 Ma (Noble et al., 1997). Although many authors have correlated the metamorphosed rocks with the Tahami terrane, geochronological data are still scarce. A U–Pb age of 227.3 ± 2.2 Ma, obtained for the southernmost outcrops of the Tres Lagunas Granite is the only control. These rocks, both the Tres Lagunas Granite and Paleozoic migmatitic gneisses, have 1400–1600 Ma Nd-depleted mantle model ages (TDM) (Noble et al., 1997) similar to some rocks of the Tahami terrane (Vinasco et al., 2006).

These gneissic rocks and foliated granitoids are also exposed in the Tahuín and Amotape region, outlining a block characterized by tectonic contacts, immediately north of the Huancabamba deflection (Fig. 3b), which was interpreted by Feininger (1987), Mourier et al. (1988) as an allochthonous terrane. The Rio Piedras amphibolite identified as a mafic intrusion, together with El Oro metamorphic complex that was previously considered to be Precambrian, were intruded at 221 ± 17 Ma; the S-type Marcabeli pluton and the Limon Playa intrusion yielded ages of 227.5 ± 0.8 Ma and 200 ± 30 Ma (Noble et al., 1997). Recent Ar–Ar dating on the orthogneisses and foliated granitoids has yielded ages of 227–211 Ma (Vinasco, 2004; Sánchez et al., 2006). The deformation is interpreted as result of a collision that took place during the Permian as established by U/Pb sensitive high-resolution ion microprobe (SHRIMP) and Ar–Ar dating of the metamorphic event that affected the Illescas Massif (Cardona et al., 2008) This massif represents the southernmost extension of the late Paleozoic metamorphic belt along the northeast coast of Peru. It is interesting to remark that the metamorphic peak in these South American basement inliers is younger than the metamorphic peak registered further north in the Alleghanides. This younger metamorphism is also recorded in the Mexican and Central America terranes, which may indicate that the closure of the Rheic Ocean occurred first in the north between Laurentia and Gondwana (present northwest Africa), and later in the Late Permian in the south, involving a series of terranes located between Laurentia and South America (as a part of Gondwana at that time). Some authors have interpreted these inliers as accreted in an accretionary orogen (see Cardona et al., 2008, 2009b).

Those Triassic ages are interpreted as associated with crustal melts during the collapse of the southern Alleghanides orogen and subsequent break-up of Pangea (Aleman and Ramos, 2000; Cediel et al., 2003; Martin-Gombojav and Winkler, 2008). Ramos (2009) proposed that the Tahuín terrane of Feininger (1987) collided against the Gondwana margin in Permian times, possibly as part of the Middle America terrane, and it was left on the Gondwana side after the break-up of Pangea. As a partial evidence of its Laurentian origin, the zircon multigrain analyses of the Tres Lagunas granitoids suggest the presence of a Grenville-age inheritance. The Nd isotope data also indicate that Mesoproterozoic protoliths may have contributed to the Tres Lagunas and Tahuin igneous rocks. Nd-depleted mantle model ages (TDM) calculated from the data of Harrison (1990), Aspden et al. (1992) for the Tres Lagunas and Marcabeli granitoids, together with paragneiss representing potential protoliths to the S-type granites, range from 1300 to 1600 Ma (Noble et al., 1997).

Continental fragments may have been transferred between the Americas during the Pangea break-up, as suggested by U–Pb and Sm–Nd isotope evidence from Mexico. According to Yañez et al. (1991) the most likely source area for this crust is the Grenvillian Oaxaca terrane based on the TDM ages for Acatlan pre-Carboniferous granitoids and sediments, and the age of the Oaxaca basement. These relationships were confirmed by recent studies of Keppie et al. (2008a,b), Weber et al. (2008), that clearly show the strong affinities with an Amazonian craton source for their detrital zircons, and the Grenville-age of the major Middle America terrane, term coined by Keppie (2004) to include all or part of the Oaxaquia, Mixteca and Chortis terranes (see discussion in Keppie and Ortega-Gutiérrez, 2010).

Based on the affinities in inherited and detrital zircons of the Middle America terrane, their Nd model TDM ages, analogous metamorphic grade, Permian to Triassic age for the metamorphism and partial melts of these crustal blocks, a robust match can be also proposed for the probably Grenville-age basement of the Tahami, Tres Lagunas and Tahuin terranes. These terranes, together with the Middle America terrane, were located along the eastern margin of Laurentia that collided against Gondwana to form Pangea.

3. Laurentian and Gondwanian terranes along the Terra Australis orogen accreted during the Paleozoic

Several terranes have been identified along the western Gondwana margin outboard of the Neoproterozoic continental margin (Fig. 4). This margin had a complex history of subduction since the Rodinia break-up, and was open to the Iapetus Ocean during most of the Paleozoic. Continental fragments detached from Gondwana after the Brasiliano-Pan African amalgamation were accreted during the early Paleozoic to form the Terra Australis accretionary orogen (Cawood, 2005). The northern part of the Terra Australis orogen participated of the Rheic ocean closure, when the Middle America terrane, already amalgamated to Laurentia collided with northern South America (see discussion in Ramos, 2009).

The succession of terrane amalgamation, rifting, and subsequent accretion that led to the construction of the present continental margin of South America was interpreted as the result of

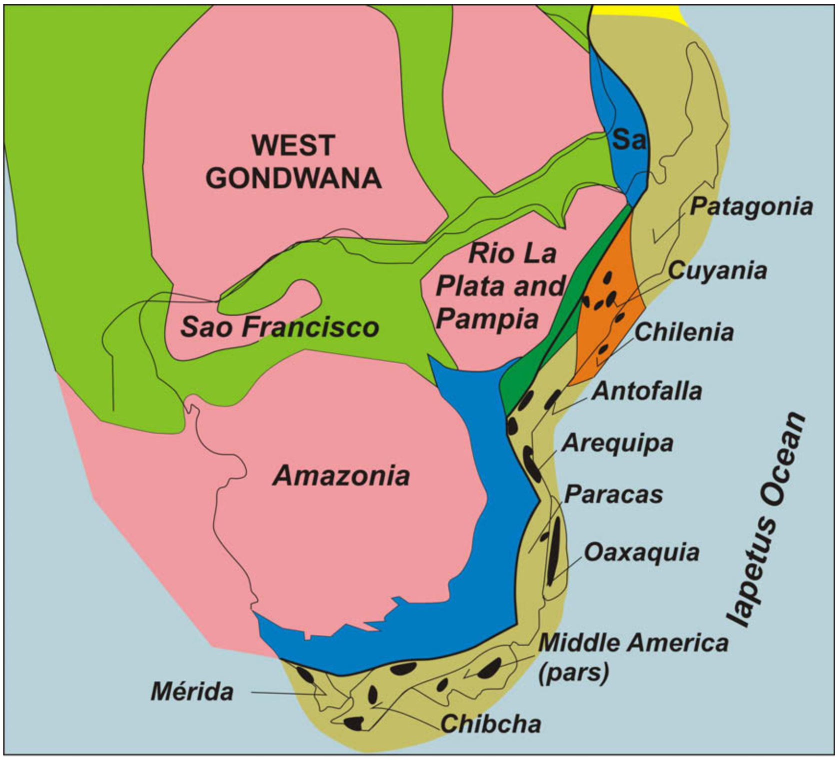

Fig. 4. Southern segment of the Terra Australis orogen showing the terranes accreted during early and late Paleozoic times (modified from Cawood, 2005). The black areas in the terranes represent basement outcrops.

global plate reorganization that affected Gondwana (Ramos, 2008a). The absolute motion of Gondwana produced a series of extensional and compressional regimes, tracked in the geological record of these terranes.

The terranes that are presently forming the basement of the Andes can be subdivided in two large groups, the para-autochthonous and the exotic terranes.

3.1. The para-autochthonous terranes

There are some continental blocks accreted to the margin of the Amazonian craton during the Rodinia amalgamation in Mesoproterozoic times as part of the Grenville-Sunsas orogeny. A later rifting episode led in some cases to the formation of new oceanic crust, detaching the previous terranes from Amazonia. A brief description of these terranes is presented from north to south (present coordinates).

3.1.1. Mérida terrane

This continental block constitutes the basement of the Venezuelan Andes. It was identified as a terrane that collided against the protomargin of Gondwana during late Ordovician times by Bellizzia and Pimentel (1994), Aleman and Ramos (2000). An early Paleozoic magmatic arc was developed on the Gondwana side over orthogneisses of Brasiliano age preserved in the Caparo Block. These igneous rocks have inherited zircons of Grenville age (see Cardona et al., 2009a). The Merida basement is composed by metamorphic rocks intruded by Carboniferous-Early Permian granites. There are no isotopic studies available on the basement of this terrane. The magmatic arc developed during the closure of the Rheic Ocean prior to the collision of the Maya terrane to form Pangea (Cardona et al., 2006; Weber et al., 2007).

3.1.2. Chibcha terrane

This continental basement block (Fig. 5) was defined by Restrepo and Toussaint (1982, 1988), and considered by Forero-Suárez (1990) as derived from North America. The boundary with the autochthonous Gondwana runs along the Borde Llanero fault, where there is evidence of ophiolitic remnants (Cáceres et al., 2003; Ramos, 2009). There is good evidence of a Grenvillian basement along the eastern Cordillera Central and in the Eastern Cordillera (Restrepo-Pace et al., 1997; Cordani et al., 2005; Jiménez et al., 2006). Some authors considered this terrane as autochthonous while others considered para-autochthonous (see discussion in Aleman and Ramos, 2000; Cardona et al., 2009a). It collided against Gondwana during the formation of Rodinia, and later on detached from Gondwana to collided back in early Paleozoic times (Forero-Suárez, 1990; Aleman and Ramos, 2000; Cordani et al., 2005).

3.1.3. Paracas terrane

Along the Eastern Cordillera of Perú there are plutonic, metamorphic, and metasedimentary rocks that have been studied in the Cordillera de Marañón by Cardona et al. (2005, 2007), Cardona

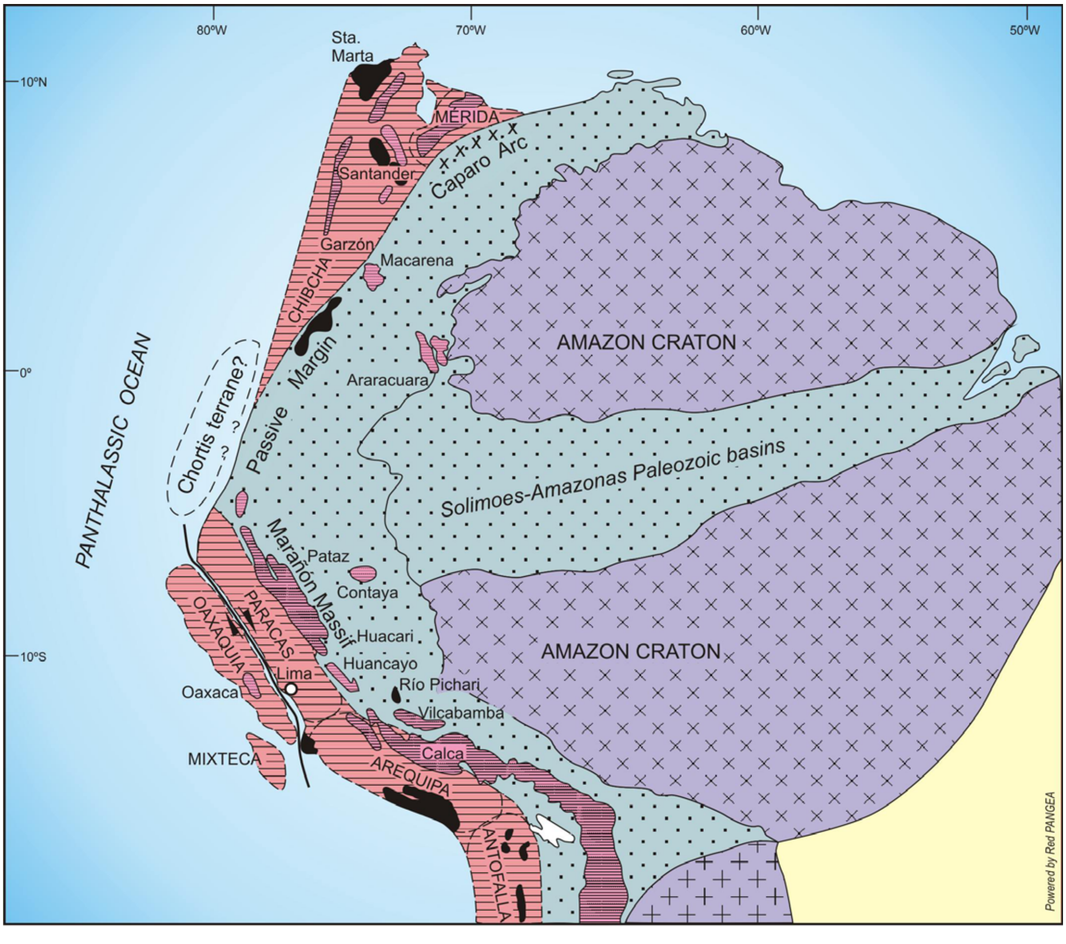

Fig. 5. Early Paleozoic reconstruction of the margin of Gondwana before the detachment of the Oaxaquia (and Mixteca?) terrane. Note the lack of accretion of Grenville-age basement terranes between the Chibcha and Paracas terranes in South America (based on Ramos, 2009). Compare with the location of Maya and Chortis terranes proposed by Weber et al. (2006) and Cardona et al. (2006). Mixteca and Chortis terranes were used after Keppie (2004) definition. The black areas in the terranes and surrounding areas represent main Precambrian basement inliers and the hachured areas Paleozoic basement outcrops.

et al. (2009b), Chew et al. (2007). These authors recognized an Early to Middle Ordovician magmatic arc, which was deformed at ca. 475 Ma, as inferred by the age of the metamorphism. Chew et al. (2007) suggested that the origin of this arc was related to the presence of an original embayment in the western Gondwanan margin during the early Paleozoic. The oceanic embayment was suggested to explain the present 400 km distance from the present trench to the Ordovician magmatic front. In order to compute the distance in Ordovician times it is necessary to add at least 100 km of crust eliminated by subduction erosion in the margin (200 km is the average retreat of the Peruvian trench assumed by Von Huene and Scholl, 1991), plus a minimum Andean shortening of 175 km (Introcaso and Cabassi, 2002), which result in a restored distance of 675 km. At this distance it is not possible to generate such a magmatic arc as identified in the Marañón Massif. On the other hand, Ramos (2008a) favored the hypothesis that this area was occupied by a basement block, the Paracas parautochthonous terrane, which collided during the late Early Ordovician against the Gondwana margin. This continental metamorphic basement block is on-land covered by thick younger sequences, but it is observed in the continental shelf as the Paracas High (Ramos and Alemán, 2000). The presence of this sialic basement in the offshore platform of central Perú, north of the Abancay deflection at ~14°S, between the localities of Paracas and Trujillo, is well established by gravimetric and refraction data. The data show a high-density (2.7–2.8 g/cm^3) and high-velocity (5.9–6.0 km/s) continuous continental ridge (Thornburg and Kulm, 1981; Atherton and Webb, 1989), exposed in the Las Hormigas de Afuera Islands at the latitude of Lima. It has also been intersected in some exploration wells at the latitude of Trujillo (Ramos, 2008a).

3.1.4. Oaxaquia terrane

The detachment of a basement block from the Peruvian margin north of the Abancay deflection, may explain the geological affinities of the Oaxaquia terrane with this part of the Gondwana margin (Keppie and Ortega-Gutiérrez, 1995; Ramos and Alemán, 2000). A more southern location along the margin is favored in the present interpretation, based on the contrast between the typical Gondwanan fauna of Oaxaquia, with the Avalonian fauna of the northern Andes platform. The Cambrian carbonates of Colombia are characterized by *Paradoxides*, a key Avalonian trilobite (Ramos, 2009), which rules out the proposal to consider it as attached to the Colombian or Venezuelan present margin.

The Arequipa and Oaxaquia terranes share a common high-grade metamorphic basement of Grenville age and similar unique Gondwanan trilobites as described by Moya et al. (1993), Ortega-Gutiérrez et al. (1995), Sánchez-Zavala et al. (1999), which are different from the typical Laurentian fauna. Besides, the geological evolution of Oaxaquia and Arequipa presents many common events as the age of the main arc magmatism, the presence of Grenvillian anorthosites, the peak of metamorphism, the isotopic composition, and the early Paleozoic cover (Ramos, 2009; Keppie and Ortega-Gutiérrez, 2010). The detrital zircons of the present sedimentary cover of Oaxaquia terrane (Fig. 6) confirm the Gondwanan affinities and show a Mesoproterozoic probability peak of 993 Ma and a subordinate cluster of ~472 Ma (Ordovician age; Gillis et al., 2005). The main peak coincides with the late Grenvillian ages of the Eastern Cordillera region (Miskovic et al., 2009), and the minor peak coincides with the age of the Cordillera de Marañón plutonic-metamorphic belt (Chew et al., 2007; Cardona et al., 2009b). Following the collision of the Paracas block with the margin in the Middle Ordovician, the Oaxaquia terrane was detached from Gondwana in Late Ordovician–Silurian times and preserved in central Mexico (Keppie and Dostal, 2007).

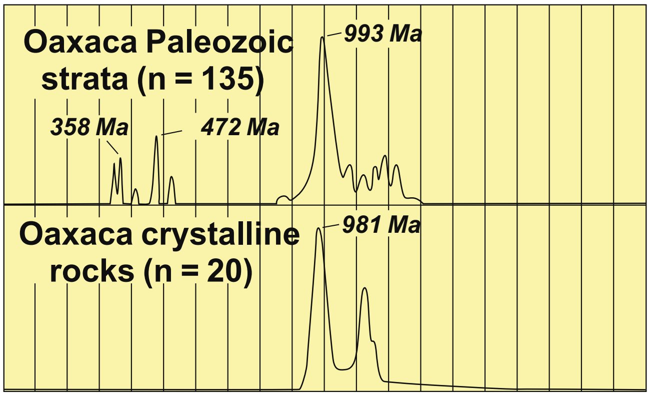

Fig. 6. Detrital zircon from the Cambrian–Ordovician cover of the Oaxaquia terrane and its underlying crystalline basement (modified from Gillis et al., 2005). Compare the distribution with the Mesoproterozoic inherited zircons from the Marañón Complex in Fig. 1.

North of the proposed location of the Paracas and Oaxaquia terranes, there is room to reconstruct the margin with part of the basement of Middle America terrane, such as the Chortis terrane among others (Keppie et al., 2008a,b). The Chortis and Mixteca terranes have isotopic, geochronological, and detrital zircon affinities (Sánchez-Zavala et al., 2008) with the Grenville-age belt in South America described by Bettencourt et al. (2009), Teixeira et al. (2010). The older zircons from the Middle America terrane could have been derived from the Amazon craton as proposed by Keppie (2004), Weber et al. (2006), Keppie and Ortega-Gutiérrez (2010) among others, but with a position near present off-shore of Ecuador.

3.1.5. Arequipa terrane

This terrane proposed in the Andean basement by Coira et al. (1982) was considered either an exotic or a parautochthonous basement block (see Ramos, 2008a). The occurrence of a Grenville-age basement was established by Wasteneys et al. (1995) who identified two domains with different metamorphic ages along the coast of Perú: the Quilca orthogneisses dated at c. 1198 ± 4 Ma and the Mollendo high-grade rocks dated at c. 970 Ma. These data were complemented by new geochronological data by Wörner et al. (2000), Loewy et al. (2004), who recognized an older protolith in the northernmost segment with juvenile magmatism and metamorphism between 1.9 and 1.8 Ga. Inherited zircons in both domains suggest a c. 1900 Ma age for the protolith of the Arequipa Massif, as indicated by previous ages.

The axis of the Ordovician plutonic and metamorphic arc recognized in the Marañón Massif is offset southwestward, continuing along the western margin of the Arequipa basement (Chew et al., 2007). Here, an Ordovician magmatic arc and important metamorphism were documented by Loewy et al. (2004) prior to the intrusion of massive granodiorites at 473 Ma. These rocks are emplaced over the Grenville-age basement (Loewy et al., 2003, 2004; Chew et al., 2008) which has isotopic and geochronological affinities with the Oaxaquia terrane. This block was not detached from the Amazonian craton during Ordovician times, but a back-arc basin was developed along the old Mesoproterozoic suture (Sempere, 1995; Díaz-Martínez et al., 2000). This episutural area recorded a continuous weakness-zone, where Late Paleozoic and Oligocene-Early Miocene granites were emplaced during extensional regimes, and even controlled the crustal delamination at late Cenozoic times (Jiménez and López-Velásquez, 2008; Beck and Zandt, 2002).

3.1.6. Antofalla terrane

The basement rocks exposed in northwestern Argentina and northern Chile (Fig. 7) have been recognized as an accreted terrane

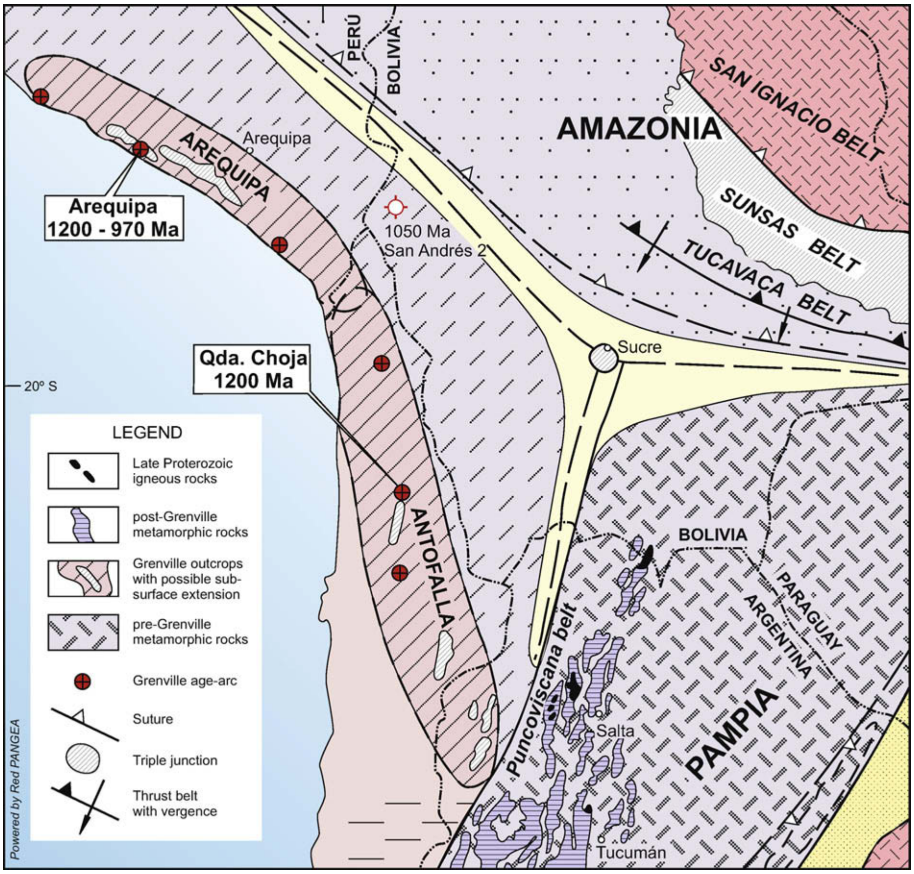

Fig. 7. The Arequipa and Antofalla terranes considered as independent Grenville-age blocks re-accreted to the Gondwana proto-margin during Ordovician times (modified from Ramos, 1988). Note the episutural basin developed in early Paleozoic times along the Grenville sutures among Arequipa, Antofalla, Amazonia, and Pampia terranes that defines a triple junction in Sucre.

associated with the Arequipa terrane (Ramos, 1988; Forsythe et al., 1993; Casquet et al., 2008). There is some evidence of Grenville-age rocks in the scarce exposures of its metamorphic basement (see Ramos, 2008a; van Staal et al., 2009). However, the early Paleozoic history of this terrane was different from the Arequipa, as oceanic rocks were formed between this block and the protomargin of Gondwana in Ordovician times. The best evidence for these rocks is exposed in the Sierra de Calalaste in southern Puna. There, a series of ophiolitic rocks interpreted as pre-Ordovician by Zimmerman et al. (1999) or Precambrian by Coira et al. (2009) have been recently dated by U–Pb in zircons as Ordovician by Pinheiro et al. (2008). This belt continues further north in the Pocitos area as proposed by Allmendinger et al. (1982). These oceanic rocks fade away to the north, where are only perceived by a robust gravimetric anomaly near the boundary with Bolivia (Gangui, 1998). North of that area, there is no clear evidence of oceanic rocks separating the northern Antofalla block and the Arequipa terrane in Paleozoic times.

3.1.7. Famatina terrane

At first, this terrane was proposed as an island arc block accreted to the Pampean terrane by Astini (1998), but was subsequently interpreted as a piece of attenuated crust accreted to the continental margin in Ordovician times as part of the Terra Australis accretionary orogen (Quenardelle and Ramos, 1999; Astini and Dávila, 2004; Cawood, 2005). These proposals were partially supported by the paleomagnetic data of Conti et al. (1996), which coincide with the presently more robust paleomagnetic data base of the area (Spagnuolo et al., 2008). These authors proposed a large clockwise rotation to close the back-arc oceanic basin, proposed by Miller and Sollner (2005), which was developed between Famatina and Pampia.

The studies of Casquet et al. (2006, 2008) identified the Maz terrane in western Sierras Pampeanas. This is another minor accretionary terrane here included as part of the Famatina terrane (sense Ramos, 2009).

Recent studies on the Famatina belt indicate that Pampean (~520 Ma), Brasiliano (~635 Ma), and typical Grenville (ca. 1000 and ~1200 Ma) sources were relatively close to the Famatina Basin during sedimentation of the Negro Peinado and the Achavil formations (Collo et al., 2009). This assumption is based on detrital ages recovered from largely immature rock successions from the low-grade cover, together with the absence of strike-slip displacements within this segment. This Grenville-age source is a common feature in most of the sequences of central western Argentina that show frequent Mesoproterozoic ages. Some authors have proposed a strong link between Arequipa, Antofalla, and western Sierras Pampeanas based on the apparent continuity of their basements, which share a common Grenville age (Omarini et al., 1999; Casquet et al., 2006, 2008). However, further studies as the analyses of Rapela et al. (2010), confirm the Grenville age of the Famatina basement and the striking isotopic differences with the Pie de Palo basement of the Cuyania terrane.

3.1.8. Pampia terrane

This terrane is a cratonic block accreted to the Amazonia craton (Fig. 7) during a Grenville-age orogeny locally known as the Sunsas orogeny (see Teixeira et al., 2010 and Bettencourt et al., 2009). It was proposed by Ramos and Vujovich (1993) as part of the previous poorly defined Pampean terrane (Ramos, 1988). The boundaries of this terrane are somewhat difficult to establish due to a thick Cenozoic cover. The most precise paleogeographic reconstruction with the neighboring cratons is the reconstruction of Brito Neves et al. (1999), who identified the importance of this large cratonic block. Subsequent papers, as the schemes of Kröner and Cordani (2003), Cordani and Teixeira (2007), Fuck et al. (2008), recognized the importance that the Transbrasiliano lineament had as a major structure defining its eastern boundary. However, the problem still exists as recent data have demonstrated that the Rio Apa is a cratonic fragment amalgamated to the Amazon craton in early Mesoproterozoic times (Cordani et al., 2009).

Escayola et al. (2007) presented evidence that the western part of this terrane has a strong Grenville-age source opposite to a Brasiliano source in its western margin (present coordinates).

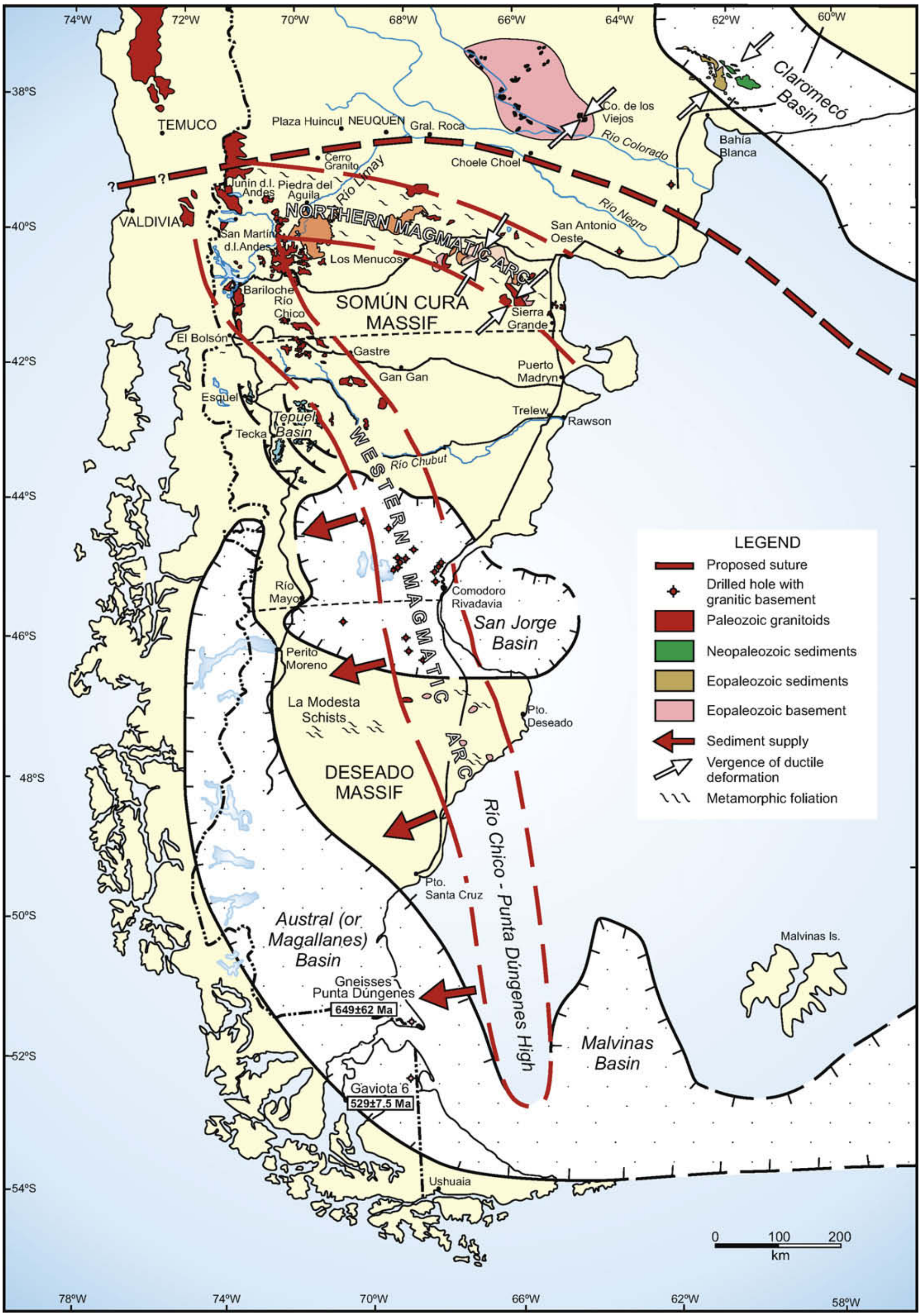

Fig. 8. Main tectonic feature of Patagonia with location of the proposed suture with Gondwana (modified from Ramos, 2008b). See the location of the Somún Cura and Deseado Massifs discussed in the text, and their relative position with the Malvinas Islands.

Detrital zircons studies performed in the cover of the Pampia terrane and surrounding areas yielded conspicuous Grenville-age peaks: in the Sierra de Los Llanos cover (921–1230 Ma, Dávila et al., 2007); in the southern Pampia cover (950–1100 Ma, Ramos

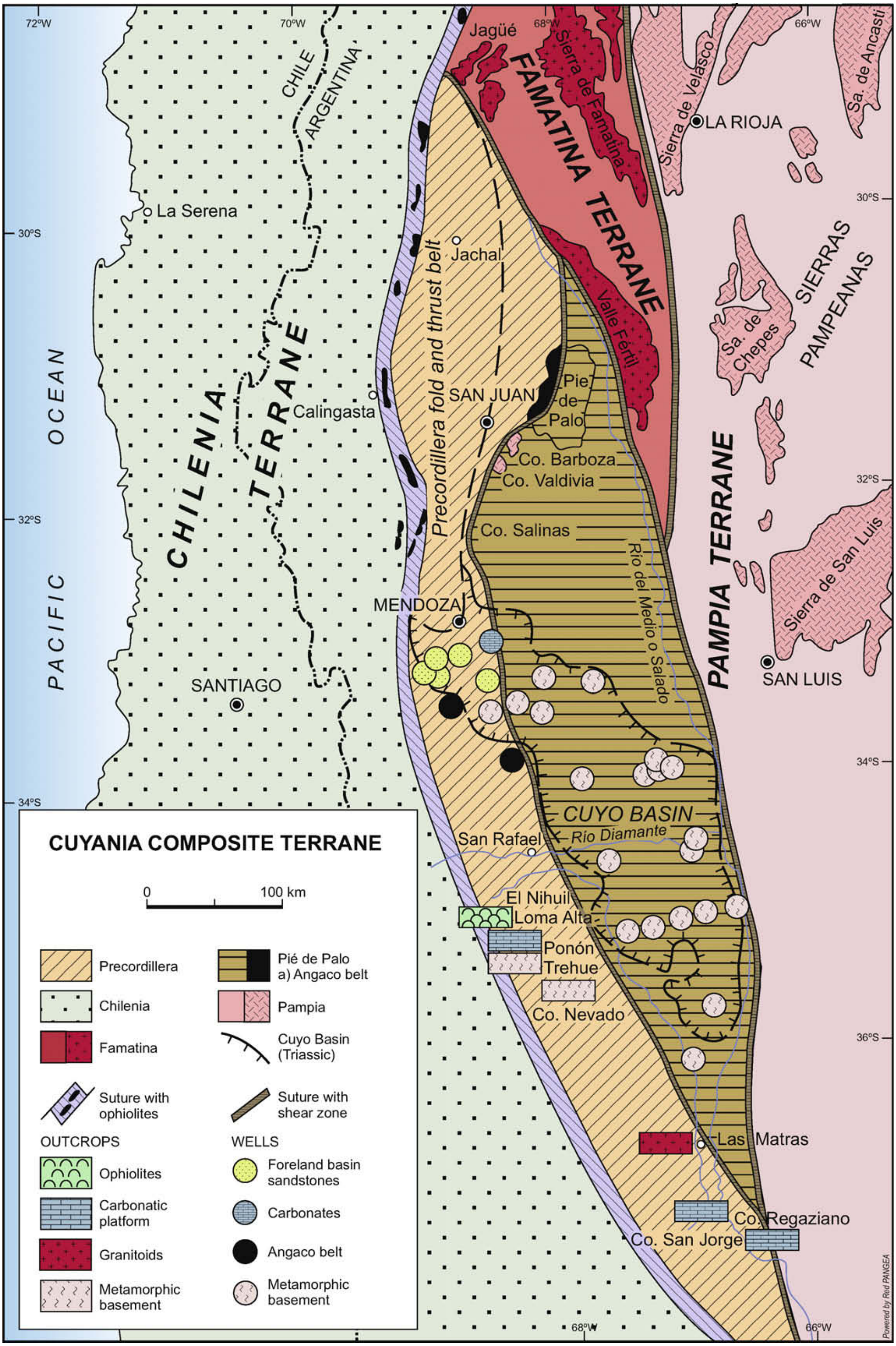

Fig. 9. Cuyania composite terrane formed by accretion of the Pie de Palo and the Precordillera terranes during Mesoproterozoic times as part of Laurentia that finally collided against Gondwana in Ordovician times (modified from Ramos et al., 1998).

et al., 2008a); in the western margin of Pampia in the Puncoviscana belt (1000–1100, Hauser et al., 2009), and in the central western margin of Pampia (1000–1200 Ma, Ramos et al., 2008a,b), among many others. These Grenville ages were correlated with the Sunsas belt in Brazil (Adams et al., 2008), but there are some striking differences between the two belts. The Pampean Grenville-age sources have a more juvenile signature as inferred by the zircon positive Hf values (+6 to +9) obtained by Hauser et al. (2009), Tunik et al. (in preparation). There is an important contrast with the crustal recycling observed in the Sunsas belt at these ages (see Bettencourt et al., 2009 and Teixeira et al., 2010).

The Pampia terrane was part of the Rodinia supercontinent during Mesoproterozoic times with a Neoproterozoic oceanic realm in its eastern side, known as the Pampean Ocean (Dalziel, 1992; Kröner and Cordani, 2003; Cordani et al., 2009) or the Clymene Ocean (Trindade et al., 2006). This ocean separated the Pampean terrane from the Rio de La Plata Craton (Rapela et al., 2007).

3.1.9. Patagonia terrane

For many years, Patagonia was considered a suspect terrane accreted to Gondwana in Paleozoic times (Ramos, 1984). Recent studies have demonstrated the existence of two magmatic-metamorphic belts (Fig. 8), which were interpreted as late Paleozoic magmatic arcs (Pankhurst et al., 2006; Ramos, 2008b). The northern area, exposed in the Somún Cura Massif, has a magmatic and metamorphic belt with typical Grenville-age inherited zircons (Pankhurst et al., 2001). The southern area, exposed in the Deseado Massif, has metamorphic rocks with inherited zircons between 1000 and 1060 Ma (Pankhurst et al., 2003), similar to the age obtained in Cabo Belgrano (*Cape Meredith*) in the Malvinas (*Falkland*) Isles by Cingolani and Varela (1976). These regions seem to be the source of the detrital zircons studied by Hervé et al. (2003) in the accretionary prism of Patagonia, where Grenville-age sources are frequently detected.

Although there is not yet a significant amount of data, it seems that Patagonia as a whole could have been part of Rodinia. This terrane detached during the Rodinia break-up, was later on accreted to the Gondwana margin during Neoproterozoic times. Patagonia underwent early Paleozoic rifting and was finally re-accreted to Gondwana during Permian times (see Ramos, 2008b; von Gosen, 2009, for details).

3.2. The exotic terranes

There are two blocks which were part of Laurentia and were accreted to Gondwana during the Paleozoic. These blocks are known as the Cuyania composite terrane (Ramos et al., 1998) and the Chilenia terrane (Ramos, 1984).

3.2.1. Cuyania terrane

This composite terrane (Fig. 9) is also known as Precordillera (Astini et al., 1995, 1996), although this terrane encompasses different areas and different concepts according to several authors (see Finney, 2007; Thomas and Astini, 2003, among others).

The basement of Cuyania is composed by Grenville rocks that constituted the southern extension of the Appalachian system in the Ouachita embayment (Thomas and Astini, 1996). This basement and its sedimentary cover comprise one of the best studied terranes in the continental margin (see Vujovich et al., 2004; Thomas and Astini, 2003). There are numerous studies on the biostratigraphy, geochronology, isotopic composition, paleoclimatology, and paleomagnetism that show one of the best documented accretionary histories of Gondwana. Its basement is composed by juvenile rocks formed in an intraoceanic arc (Kay et al., 1996; Vujovich and Kay, 1998), with similar characteristics to the western Sierras Pampeanas basement. The age based on U–Pb in zircons varies from 1000 to 1200 Ma in different sectors of Cuyania (McDonough et al., 1993; Kay et al., 1996; Casquet et al., 2001; Sato et al., 2004; Vujovich et al., 2004). The paleomagnetic data (Rapalini and Astini, 1998) as well as the *Olenellus* and related fauna (Benedetto, 2004) indicate a Laurentian provenance. The lack of Pampean or Brasiliano metamorphic events in the Cuyania basement indicates that this terrane has not been part of the Neoproterozoic amalgamation of Gondwana.

3.2.2. Chilenia terrane

This terrane was defined by Ramos et al. (1986) and is poorly exposed along the main axis of the Cordillera de Los Andes (Mpodozis and Ramos, 1990). One of the best exposures is preserved in the Cordón del Portillo in central western Argentina (Fig. 10). High grade metamorphic rocks are exposed west of the ophiolitic rocks that separate Cuyania from this terrane. There are geochronological preliminary studies that yielded U–Pb ages in zircons between 1060 and 1080 Ma (Ramos and Basei, 1997a,b). The age spectrum of the detrital zircon from the Guarguaráz Complex located along the western margin of Cuyania, and the assumed early Paleozoic depositional age of its metasediments suggest that their main

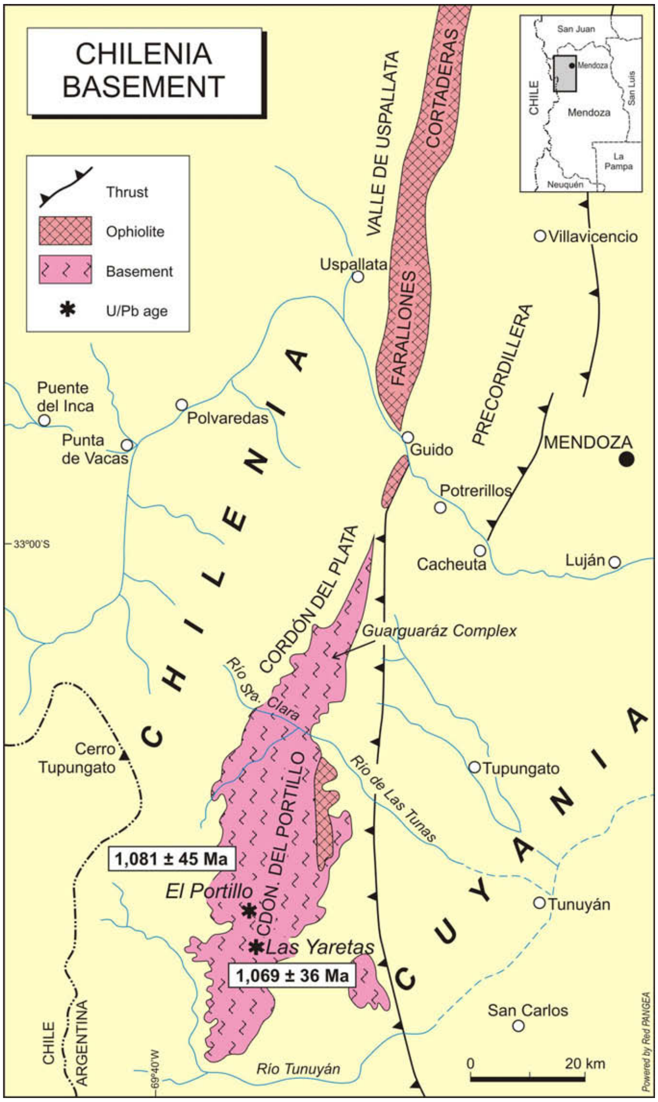

Fig. 10. Location of the samples in the inliers of the Chilenia basement dated by Ramos and Basei (1997a,b), and the exposures of the Guarguaráz Complex basement studied by Willner et al. (2009).

source was the Cuyania terrane. These sediments were subducted along the suture zone between Cuyania and Chilenia forming the HP collisional Guarguaráz Complex (Massonne and Calderón, 2008). This fact contrasts with earlier suggestions by López and Gregori (2004) that the Guarguaráz Complex would represent the accretion complex corresponding to the Famatinian magmatic arc (Willner et al., 2009). This last study shows detrital zircons with a dominant Grenville peak between 1098 and 1228 Ma, probably derived from the Cuyania basement (see further details in López de Azarevich et al., in press). Based on this scarce evidence it is interpreted that the Chilenia inliers could be part of Laurentia, although there are not enough exposures studied along the continental margin to confirm this assertion.

4. Concluding remarks

The brief description of the different blocks that constitute the basement of the Cordillera de Los Andes shows a complex history of accretion, detachment and re-accretion. The persistent Grenville-age in the inherited zircons, as well as the metamorphic ages recorded in several terranes from Colombia to northern Chile and Argentina, clearly show that most of these blocks were part of the Rodinia assemblage (Li et al., 2008). Based on isotopic and geochemical characteristics, together with geochronological and other geological data, it is evident that after Rodinia break-up some blocks stayed as part of Laurentia. Cuyania and possibly Chilenia are within this group, and were respectively amalgamated in Ordovician and Late Devonian times to the protomargin of Gondwana.

Some other terranes were left in Gondwana, as for example the Arequipa and the Pampia terranes. The suture between Arequipa and Amazonia has been extensional reactivated during early Paleozoic times and in the latest Paleozoic, but Arequipa was never detached again from Amazonia. This suture remains as a weakness zone controlling the Oligocene extension, the emplacement of several granitic rocks in Early Miocene times and even is localizing the late Cenozoic crustal delamination in the Bolivian Altiplano. Pampia remained attached to Amazonia after the Rodinia amalgamation, and during the Neoproterozoic and early Paleozoic was extensionally attenuated forming the Tucavaca aulacogen.

Other terranes that have been part of Rodinia were also left in the Gondwana side as Chibcha, Paracas, Antofalla, and possibly Patagonia. Most of these terranes were partially detached forming an oceanic basin in the Neoproterozoic, but later on amalgamated again to the margin. Scarce magmatic rocks of Neoproterozoic-Early Cambrian age together with a strong deformation related to the Pampean orogeny mark this episode. These sutures have been reactivated in early Paleozoic times; oceanic rocks have been generated and subducted in the Ordovician, to finally amalgamate as part of the Famatinian orogeny.

The last transfer between Laurentian and Gondwanian terranes occurred in late Paleozoic times as part of the Alleghanian Orogeny, when some minor blocks as the Tahami, Tres Lagunas and Tahuin terranes were left in Gondwana after Pangea break-up.

These tectonic events along the Terra Australis accretionary orogen seem to be the result of global plate reorganizations associated with changes in the absolute motion of Gondwana, which controlled the superposition of extensional and compressive regimes along the margin.

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