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Cuyania, an Exotic Block to Gondwana: Review of a Historical Success and the Present Problems

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Abstract

A review of the early history of the Cuyania terrane and the numerous pioneering works of the past century provides the present robust framework of evidence supporting a derivation from Laurentia, travel towards Gondwana as an isolated microcontinent, and final amalgamation to the protomargin of western Gondwana in Middle to Late Ordovician times. The major remaining uncertainties and inconsistencies, such as the time of deformation and collision with Gondwana, the lack of evidence of Famatinian-derived zircons, the effects of strike-slip displacements proposed along the suture, as well as the potential sutures defined by ophiolite assemblages, are discussed. The precise boundary along the northern and southern limits is not yet well defined.

The most suitable hypothesis based on present data is that Cuyania originated as a conjugate margin of the Ouachita embayment, south of the Appalachian platform during Early Cambrian times. The subsequent travel toward the Gondwana protomargin is clearly depicted by the changing faunal assemblages in the carbonate platform. New geochemical and age data on K-bentonites presented by several authors reinforce the strong connection between Cuyania ash-fall tuffs and Famatina volcanics by 468–470 Ma, indicating Cuyania and Gondwana were in close proximity at that time.

Extension related to flexural subsidence, preceded by the drowning of the carbonate platform in early Llanvirnian times, is recorded by abrupt facies changes in the sedimentary cover during late Llanvirnian and early Caradocian times. This episode marked the beginning of contact between Cuyania and Gondwana. The subsequent evolution of the foreland basin indicates that deformation lasted until latest Silurian–Early Devonian times.

The time of collision is tracked by the cessation of arc-related magmatic activity in the upper plate (Gondwana protomargin), at about 465 Ma in western Sierras Pampeanas, and ages around 454 Ma corresponding to syncollisional and postcollisional magmatism. The age of the collision is also preserved in the lower plate (Cuyania), where both angular unconformities in the sedimentary cover and the ages of peak of regional metamorphism in the basement rocks point to 460 Ma as the most probable age for the beginning of the collision. Evidence from the upper plate is essentially identical with an age of 463 Ma. Thermal gradients along this suture vary from 13°C/km in the lower plate, to 18°C/km in the fore arc upper plate, reaching more than 30°C/km along the Famatinian arc. Based on these data, a Llandelian-Caradocian age for the collision can be postulated on firm grounds. Deformation continued through most of the early Paleozoic until amalgamation of the Chilenia terrane by the Late Devonian.

Key words: West Gondwana, Laurentia, Cuyania, accretion, early Paleozoic, Precordillera.

Introduction

Research conducted in the last 10 years has produced a general consensus that a large terrane, exotic to Gondwana, detached from Laurentia in Cambrian times, was transferred to western Gondwana in Early to Middle Ordovician times, and finally amalgamated to the early protomargin of Gondwana by the Late Ordovician (Thomas and Astini, 2003). This terrane is known as the Cuyania terrane, and is preserved in the basement of the southern Central Andes. It is partially exposed in the Argentine Precordillera fold and thrust belt, and in scattered ranges further south. Although acceptance of the exotic nature of the Cuyania terrane has become widespread within the geological community, several recent studies have raised doubts about its Laurentian affinities, and have reclaimed a para-autochthonous Gondwanan origin (Aceñolaza et al., 2002; Finney et al., 2003a, b; Peralta et al., 2003). The objective of this review is to analyze the bases upon the allochthonous nature of the Cuyania terrane were built, and to evaluate the new data within the tectonic framework of this sector of western Gondwana.

In order to provide a comprehensive understanding of the present hypotheses, a brief summary and analysis of the early attempts to explain the exotic nature of this terrane will be presented, as well as the different assumptions followed by different research groups. This information will be presented in stages that take account of the different partial consensus obtained and the main problems that still remain.

The Early Evidence

The first report of a North American olenellid fauna in the Precordillera of San Juan (Borrello, 1963a), was followed by the finding of *Olenellus* in other Early Cambrian outcrops of central-western Argentina (Borrello, 1965). These studies produced the first well-documented evidence of olenellids outside of the well known (at that time) fragments of Laurentia. Earlier contributions such as those of Rusconi (1956, 1958) recognized the occurrence of olenellids in the Precordillera of Mendoza, and the study of Poulsen (1958) emphasized the striking similarities between the Laurentian and the Precordilleran trilobites. However, the dominant explanation at those times was that larva transfers produced these occurrences in the early stage of growth of these trilobites (Ross, 1975), as assumed by Baldis and Bordonaro (1985), and Bordonaro (1990, 1992).

As a result of the presentations and discussions on suspect terranes in western North America by Peter Coney, Robert Speed and Jim Monger at a COPSTOC symposium on terranes at Cornell University in late 1981, and their classic contribution published in Nature (Coney et al., 1980), the first essays on suspect terranes in the basement of the Andes were produced. The term Cuyania was coined as a terrane that collided against the Gondwana margin during the Ocloyic deformation by the end of the Ordovician, and linked to the magmatic arc developed in the present Sierras Pampeanas, followed by the collision of Chilenia in Late Devonian times (Ramos, 1982).

A strong impulse to this hypothesis was the study of Bond et al. (1984) on the tectonic subsidence of carbonates platforms of Laurentia. These authors compared the subsidence curve of the San Juan limestones of Central Argentina based on the stratigraphic sections of Baldis et al. (1981) and the central Appalachian platform curves, and pointed out the striking coincidence on their rift-drift transitions. This observation was complemented by the common olenellid fauna described by Borrello (1971). Bond et al. (1984) suggested as a highly speculative possibility, that Argentina could be a displaced terrane of the central Appalachian platform. In order to prove this hypothesis they recommended that the age of the Precordillera basement should be determined, because if it were Grenvillian (middle Proterozoic) instead of Brasiliano (late Proterozoic), this assertion could be demonstrated.

A series of geological transects through the Andes conducted by the joint efforts of researchers at Cornell University and the Servicio Geológico of Argentina resulted in several reports where the presence of allochthonous terranes was recognized (Allmendinger et al., 1982; Ramos et al., 1984, 1986). These observations were extended to the Pacific margin of Chile, and subsequent research resulted in the recognition of Precordillera and Chilenia as allochthonous terranes to present South America (Mpodozis and Ramos, 1985, 1989; Ramos, 1988a, b, 1989).

On the other hand, many in the local geological community were influenced by the ideas of Baldis (1989), who argued that the Precordillera was part of a stable and autochthonous margin of western Gondwana (Baldis and Bordonaro, 1985; González Bonorino and González Bonorino, 1991).

A para-autochthonous origin was later proposed by Baldis et al. (1989), who were the first to assume a para-Gondwanic origin. This hypothesis assumed that Precordillera was displaced by strike-slip transcurrent faults from the Pampean region further south. This proposal recognized a displaced terrane in Precordillera, associated with the Pie de Palo dragged block, all together outlining the present limits of the Cuyania terrane. However, this idea was not accepted due to the striking differences between the clastic facies of the western Gondwana margin in the Pampean region and the carbonate platform of Cuyania.

Cuyania as an Allochthonous Terrane

The hypothesis that the Taconic and Famatinian deformations were parts of a single orogen produced as a result of continent-continent collision between Laurentia and West Gondwana brought new attention to the problem (Dalla Salda et al., 1992a, b; Dalziel et al., 1994). An important contribution of these papers was the recognition that the Cuyania (Precordillera) terrane could have lain adjacent to the Ouachita embayment, south of the Appalachian system, although the main idea of a continent-continent collision was slowly being abandoned.

A milestone in the present knowledge of the Cuyania terrane was the proposal that the Precordillera was a far-traveled microcontinent derived from Laurentia, as proposed by Benedetto and Astini (1993), Benedetto (1993), Ramos (1995), and Astini et al. (1995, 1996). More recently several hypotheses have spurred detailed studies of the accretionary history of Cuyania (see review in Ramos and Keppie, 1999). These hypotheses are discussed below along with descriptions of the main peculiarities of this terrane.

Extent and present boundaries

The present extent of the fragments of Laurentia found along in the western Gondwana margin is grouped in the Cuyania terrane (see present definition in Keller, 1999). Four sectors encompass in this terrane: The Precordillera fold and thrust belt, the San Rafael block, the Pie de Palo area and the Las Matras block (Fig. 1).

There is a general agreement that after a palinspastic restoration of the Precordillera fold and thrust belt, the present carbonates thrust slices outline a broader platform. If the Miocene deformation is undone, the platform is over 100 to 130 km wider than present exposures (Cristallini and Ramos, 2000), yielding a reconstructed early Paleozoic carbonate platform of 300 km (east-west) by almost 500 km north-south.

The present northern boundary is tectonic, truncated by the Valle Fértil-Desaguadero lineament located north of Guandacol in La Rioja province. The extent of this boundary toward the west coincides with the Valle Ancho structure along the Chilean border. This boundary has been recently challenged by the occurrence of strong positive gravity anomalies between the Sierras de Famatina and the westernmost Sierras Pampeanas, which may indicate the northern continuity of the Cuyania terrane into this area (Martínez and Giménez, 2003).

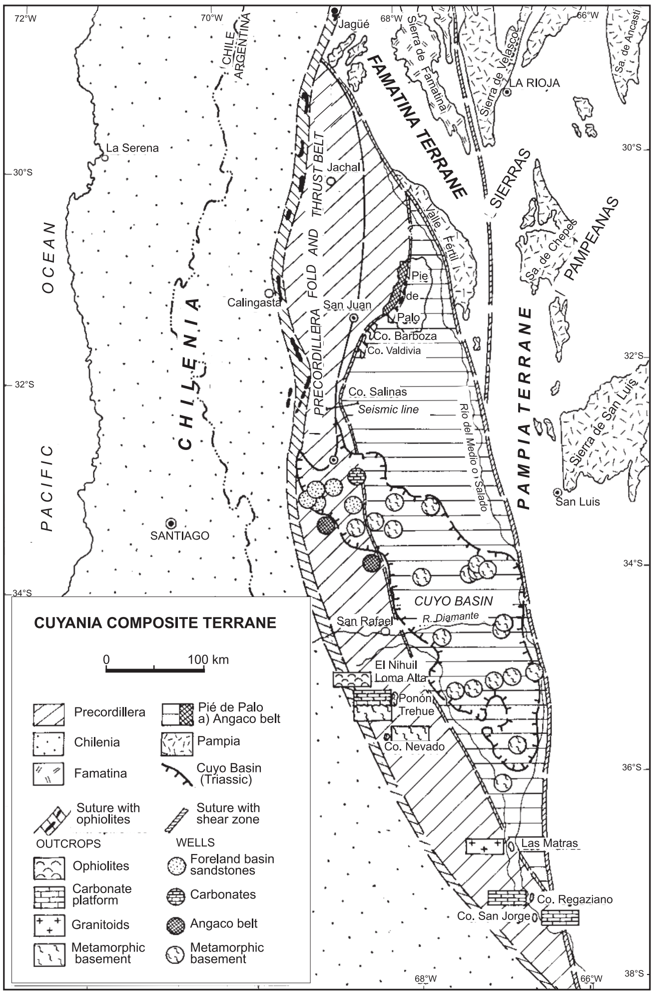

Fig. 1. Outline of the Cuyania composite terrane (modified from Ramos et al., 1998).

The present western boundary corresponds to the tectonic depression between Frontal Cordillera and Precordillera, running through the Iglesias, Calingasta, Barreal and Uspallata valleys. This depression coincides with a series of mafic and ultramafic rocks, identified as an ophiolite assemblage by Borrello (1963b, 1969). Based on their geochemistry and isotopic signature these rocks are presently interpreted as fragments of an oceanic crust obducted during Ordovician times (Haller and Ramos, 1984, 1993; Kay et al., 1984; Davis et al., 1999). These bodies are well preserved and identified for more than 1,000 km along strike (see Ramos et al., 2000).

The present eastern boundary coincides with the Valle Fértil lineament, along the western foothills of the Sierras of Valle Fértil, La Huerta, and the small ranges further south. Reprocessing of some industrial seismic reflection lines shows the tectonic truncation of the carbonate platform along this lineament (Zapata, 1998). Evidence of mafic and ultramafic rocks with oceanic characteristics have been described along this boundary (Vujovich and Kay, 1998; Vujovich et al., 1998; Ramos et al., 2000).

The southern limit of the present Precordillera basement is more difficult to outline because the region south of Cacheuta, along the Mendoza River canyon, has not been uplifted during the Andean deformation and the platform is not exposed.

There are two groups of outcrops south of the Mendoza River, outside the Precordillera fold and thrust belt, which are partially covered by younger sediments and volcanics. The first group is exposed in the San Rafael block, 200 km south of the city of Mendoza (Fig. 1). The carbonate platform crops out in the Ponon Trehue area where fossils were first found by Nuñez (1962). Although several fossils have been described by numerous authors, only the more recent studies of Bordonaro et al. (1996) and Lehnert et al. (1998) have demonstrated a correlation with the carbonate platform of Precordillera.

The second group of outcrops is located 650 km south of Mendoza, in the Las Matras Block (Sato et al., 2000), in the vicinity of the Colorado River, where strongly deformed limestones have been known since the early work of Wichman (1928). Exposures located in the Cerro San Jorge area in La Pampa province were barren of fossils, but the recent findings of Melchor et al. (1999) and Tycyk et al. (2003) has demonstrated the correlation with the carbonate platform of Precordillera.

Oil exploration drilling in the Cuyo basin, a Triassic rift depocenter extending between Mendoza and the southernmost exposures in La Pampa, has intersected Precodilleran limestones in the subsurface in different locations. This indicates that the carbonate platform continues in the subsurface and underlies a much larger region (Ramos et al., 1998).

Some strongly deformed limestones of the Caucete Group, east of the Precordillera, are exposed in the eastern foothills of Sierra de Pie de Palo. These were described long ago by Schiller (1912) as deformed equivalents of platform carbonates of the Precordillera. Recent studies of Vujovich (2003) have shown at least late Proterozoic detrital zircons are present in this group. These exposures and the deformed limestones of western Sierra de La Huerta (described by Bastías et al., 1984 in the Cerro Pan de Azúcar, between Las Chacras and Marayes) are presently interpreted as metamorphic equivalents of the Cambro-Ordovician limestones of Precordillera.

Based on the different exposures of the early Paleozoic limestones, the Cuyania terrane can be reconstructed as having once extended well to the east and south of present Precordillera, with a total north-south length of over 1,000 km (Fig. 1). This area is several times larger than the present exposures of the Precordillera fold and thrust belt.

Basement characterization

The recommendation of Bond et al. (1984) to determine the age of the basement rocks to the carbonate platform was difficult to follow, as there are no exposures of the basement of the limestone sequences. This problem was undertaken by studying basement xenoliths found in the Miocene volcanics exposed in the Cerro de Ullúm, just west of San Juan city (Leveratto, 1976). U-Pb dating of zircons yielded the first reports of Grenvillian basement, with ages of 1118±54 Ma and 1101.8±5.8 Ma in mafic to acidic gneiss xenoliths (Abruzzi et al., 1993; Kay et al., 1996).

These ages are similar to the U-Pb ages previously reported in zircons from basement rocks of Pie de Palo, further to the east of Ullúm. Euhedral zircons from metamorphic rocks yielded an age of 1060±20 Ma and zircons from a granodiorite yielded an age of 1079 Ma. Additionally, some small metamorphic zircons yielded an age of 1066 Ma, all of the above being typical of Grenvillian basement (McDonough et al., 1993 and Ramos et al., 1993). These ages confirmed some of the preliminary Rb-Sr ages presented by Varela and Dalla Salda (1993). The metamorphic conditions and the protolith of the Pie de Palo region show two different series, one of medium- to-high-grade (Dalla Salda and Varela, 1984) affecting a complete ophiolite sequence of Grenvillian age known as the Pie de Palo Metamorphic Complex (Vujovich and Kay, 1998), and one of low-grade affecting carbonates and sandstones of the marine platform facies correlated with the Precordillera carbonate platform (Vujovich, 2003).

Casquet et al. (2001) established the P-T conditions of the Pie de Palo Metamorphic Complex as 11 Kb and 600±50°, with peak conditions reached at ca. 460 Ma, as indicated by dating unzoned, low-U zircon overgrowths using SHRIMP technology. It is striking that the zircons have two distinct domains as indicated by their U concentrations and ages, one as cores with ages between 1,000 and 1,200 Ma and the other as overgrowths related to the peak Ordovician metamorphism. These zircons lack any components with Gondwanan ages (Fig. 2).

Further to the east in Loma de Las Chacras at Sierra de la Huerta, metasediments and metabasites were metamorphosed to medium-to-high grade (Vujovich, 1994). The metamorphic rocks of this locality indicate pressures of about 12 Kb and temperatures of 769°, with a main peak at 463±2 Ma (SHRIMP data from Baldo et al., 2001). The Tera-Wasserburg diagram of these SHRIMP data indicates several populations of zircons (Fig. 2), including a well defined one around 600 Ma typical of Gondwana (Baldo et al., 2001). On these bases, a boundary between Laurentia- derived terranes and Gondwana can be located along the Bermejo valley, in coincidence with the Valle Fértil lineament as indicated in figure 2.

Basement rocks are also known in the San Rafael Block, where metamorphic rocks with U-Pb zircon ages between approximately 1190 and 1200 Ma (Ramos and Vujovich, unpublished data) underlie the carbonate platform deposits in Ponon Trehue. The only published ages were the Rb-Sr data around 1100 Ma presented by Cingolani and Varela (1999). New U-Pb zircon ages of 1205±1 and 1204±2 Ma have been obtained in the same locality by Thomas et al. (2000), confirming the Grenville ages. Further south in Las Matras Block, tonalites and trondhjemites rocks were emplaced at shallow levels at 1244±42 Ma (Sato et al., 2004, this volume).

To summarize, the existing U-Pb zircon ages of the Precordillera basement xenoliths and the rocks of the Sierra de Pie de Palo, and the San Rafael and Las Matras blocks show common Middle Proterozoic ages, indicating a similar basement without any evidence of the late Proterozoic Gondwanan signature. The lack of Brasiliano or Pampean ages indicates an exotic origin of this basement with contrasting differences with the Pampia terrane metamorphic rocks (Ramos and Vujovich, 1994). Recent descriptions of detrital zircons of the eastern Sierras Pampeanas basement shows that besides the typical Brasiliano ages (588–659 Ma), the basement has an important contribution of middle Proterozoic zircons (1014–1051 Ma), and even older ages (1912±53 Ma) as established by Schwartz and Gromet (2004). These zircon ages are typical of the metamorphic and igneous rocks exposed at these latitudes further to the east in the basement of Uruguay and southernmost Brazil (Basei et al., 2001).

The metamorphic rocks of the Cuyania terrane as established by Abruzzi et al. (1993) and Kay et al. (1996), based on the basement xenoliths brought to the surface by Miocene volcanic rocks of Precordillera, have a typical geochemical signature. These authors proposed an oceanic arc to back-arc environment for the Grenvillian protolith of these rocks. The protolith of the metamorphic rocks of Sierra de Pie de Palo is considered an ophiolitic sequence of Grenvillian age, based on oceanic-arc and back-arc chemical characteristics (Vujovich and Kay, 1998; Ramos et al., 2000; Vujovich et al., 2004 this volume).

The Pb isotopic character of the basement xenoliths and the Pie de Palo metamorphic rocks as established by Kay et al. (1996) have an unique nonradiogenic Pb signature that allowed these authors to interpret these rocks as equivalent of the basement of the Ouachita region, different from the more radiogenic basement of the Andean volcanic arc in central and southern South America. These rocks from Precordillera and Pie de Palo basement strongly contrast with the isotopic signature of the Arequipa-Antofalla and the Amazonia cratons as demonstrated by Tosdal (1996) (Fig. 3). Recently, Schwartz and Gromet (2004) contrasted the Pb isotopic compositions of the Precordillera and Pie de Palo basement with granitoids of eastern Sierras Pampeanas, confirming the most enriched character of the Sierras Pampeanas basement and its similarity to the Arequipa-Antofalla and Amazonia Cratons.

Therefore, based on the U-Pb zircon ages, geochemical, and isotopic signatures (Fig. 4), the Cuyania terrane has a typical Laurentian character. It is distinctive from Gondwanan para-autochthonous or autochthonous terranes, which may have similar middle Proterozoic ages but are associated with Brasiliano late Proterozoic ages and they have a distinctive isotopic signatures. The Cuyania basement shares common characteristics with the more juvenile Grenvillian terranes outboard of southern Laurentia at the latitude of El Llano uplift in Texas as described by Nelis et al. (1989) and Mosher (1993). Mafic to rhyolitic protoliths of El Llano uplift range in age between 1288 to 1070 Ma (Walker, 1992). These ages are compatible with the proposed derivation of Cuyania basement from the Ouachita embayment (Dalla Salda et al., 1992a; Astini et al., 1995).

The ophiolitic belt that separates the Precordillera basement from the Pie de Palo metamorphic rocks is interpreted as an old suture produced during the Grenville orogeny in mid Proterozoic times (Ramos et al., 1998; Vujovich and Kay, 1998; Vujovich et al., 2004 this volume). Since these basement terranes and oceanic rocks were already amalgamated prior to the collision with Gondwana

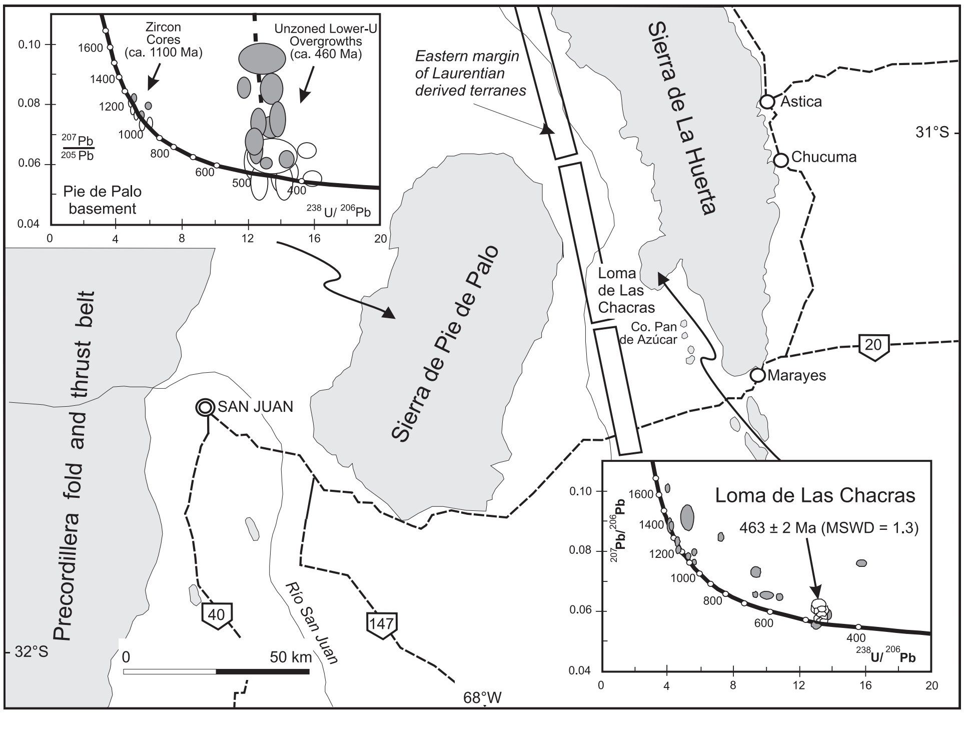

Fig. 2. Eastern margin of Laurentia-derived terranes with proposed boundary between Cuyania terrane and Pampia terranes, which was already amalgamated to western Gondwana. U-Pb in zircon ages are based on the Tera-Wasenberg diagrams of Casquet et al. (2001) and Baldo et al. (2001). Note the lack of Brasiliano-age zircons in the Cuyania terrane.

(Ramos et al., 1996), Cuyania is considered a composite terrane, following the definition of Monger (1984).

Synrift deposits

Synrift deposits in the Cuyania terrane are only exposed in the northern sector of the Precordillera, in the La Rioja province at 29°30'S latitude. There, a sequence of redbeds, evaporites and dolostones recognized as Cerro Totora Formation underlies platform carbonates bearing a typical Early Cambrian olenellid fauna (Astini and Vacari, 1996). Indirect evidence of the synrift deposition is observed in western Precordillera, where large olistoliths formed by coarse conglomerates with clasts of basement rocks have been described (Banchig et al., 1990). One of this large olistoliths has a stratigraphic sequence similar to the Cerro Totora Formation with Early Cambrian trilobites (Astini and Thomas, 1999).

Strontium isotopes studies of evaporate from the Cerro Totora are indistinguishable from the synrift Rome Formation of Alabama (Thomas et al., 2001) indicating similar age and depositional settings. Both units have $^{87}Sr/^{86}Sr$ ratios with maximum peaks between 0.70877 and 0.70867, characteristic of the mid- Early Cambrian world-wide strontium seawater curve.

The U-Pb zircon ages of basement clasts from the northern sector of western Precordillera are 1367±5 and 1370±2 Ma, in concordance with the 1.3–1.4 Ga ages of the Granite-Rhyolite province located west of the Grenville Front in the northwestern corner of the Ouachita embayment (Thomas et al., 2000). Time of rifting is constrained in this area by synrift rhyolites with U-Pb zircon ages of 539±5 and 536±5 Ma (Thomas et al., 2000), consistent with the proposed rift-drift transition on the subsidence curve of Precordillera carbonate platform (Thomas and Astini, 1999).

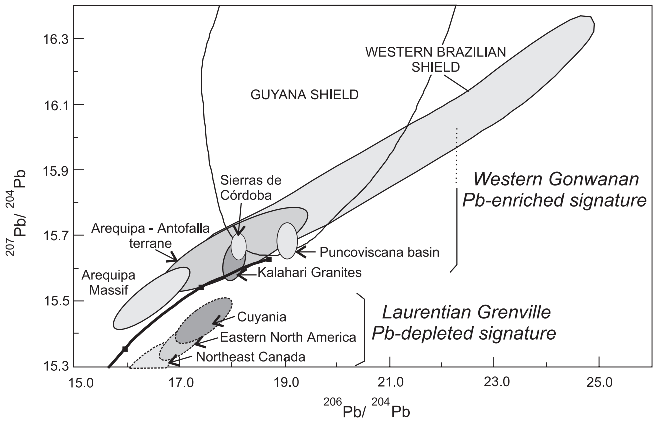

Fig. 3. Lead isotopes of the Cuyania terrane and other basement provinces of South America (data after Kay et al., 1996; Tosdal, 1996; and Schwartz and Gromet, 2004). Note that only the Precordillera and Pie de Palo (grouped as the Cuyania terrane) have the distinctive nonradiogenic signature of Laurentia (eastern North America and Northeast Canada). The western Brazilian and Guyana shields, Arequipa-Antofalla terrane, Arequipa Massif, Kalahari granites and Sierras Pampeanas (Córdoba and Puncoviscana basin) all have the more radiogenic signature typical of this part of Gondwana.

The recent report that Cerro Totora Formation lacks Grenville age zircons (Finney et al., 2003a, b, c) is now recognized as incorrect, being due to sample mislabeling (see Finney et al., 2004). Correction of this problem indicates the Cerro Totora Formation from the type locality contains zircons with a typical Laurentian provenance (Fig. 5).

Carbonate platform

Since the pioneering work of Baldis et al. (1981, 1982), significant advances have been achieved in our understanding of the stratigraphy, depositional environments, and evolution of the carbonate platform of Precordillera (see Peralta, 2003) and its southern extension in the San Rafael block and in the Las Mahuidas area.

A thick sequence of Early Cambrian to Ordovician carbonates displays a complex interplay between thermo tectonically driven subsidence and eustasy, resulting in changes in time and space of the platform styles (Cañas, 1999). Detailed analyses of the different facies by Keller (1999) recognize at least 13 third-order sequences, with variable biostratigraphic control of the sequence boundaries. Early Cambrian near-shore facies, with some clastic intervals, grades transitionally to open marine environments in Arenig times. C-, O- and Sr-isotope chemostratigraphy corroborate the large positive excursion in ^{13}in the eastern Precordillera during the Late Cambrian (Sial et al., 2003), known as the SPICE excursion in North America (Saltzman et al., 2000).

The onset of black shales signals that drowning of the platform started in early Llanvirnian times, but was not coeval across the region (Astini, 1994; Peralta, 1995). Extension-controlled subsidence started at late Llandeilian and early Caradocian times (base of Caradocian at 458 Ma or 461 Ma after Gradstein and Ogg, 1996, or Benedetto, 2003) and dominated in the central and eastern Precordillera in Caradocian times (Astini, 1988). This extension is related to flexural subsidence in a foredeep in the early stage of a collision, as recognized in the Appalachian platform during Caradocian times and in the Alps in Mesozoic times (Bradley and Kidd, 1991). These conglomerates have been interpreted as evidence of the Guandacolic orogenic phase in Precordillera, but as proposed by Astini and Thomas (1999), the facies, the provenance of the clasts, and the tectonic setting are more in agreement with flexural extension (Fig. 6) associated with an early stages of the collision in late Llandeilian to early Caradocian times (460 to 446 Ma).

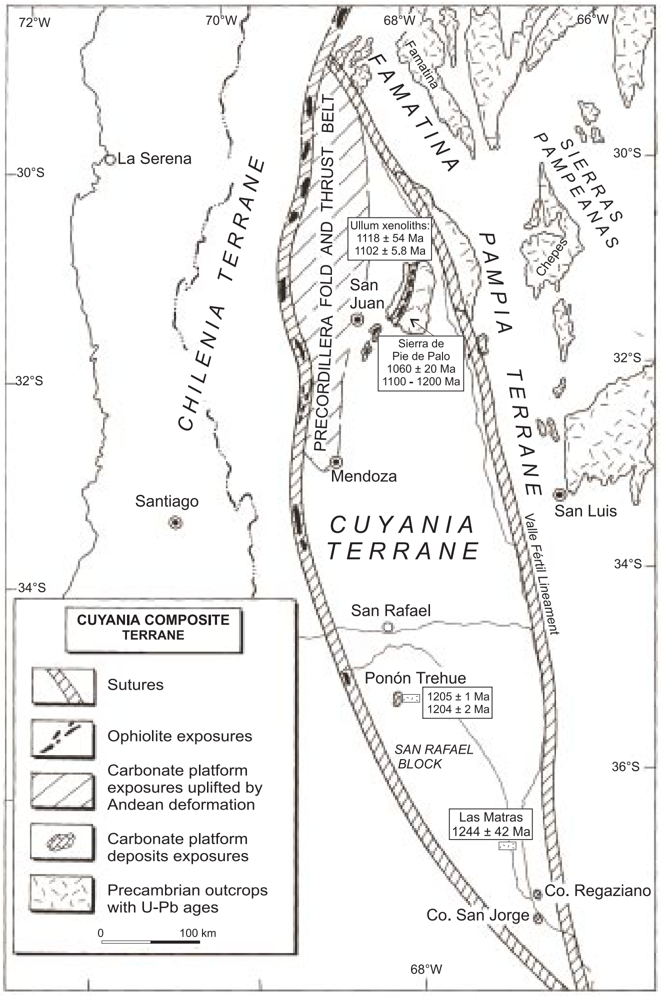

Fig. 4. U-Pb Grenville ages in zircons of the diferent basement exposures and xenoliths of the Cuyania composite terrane. Source of ages: (1) Kay et al., 1996; (2) McDonough et al., 1993; (3) Casquet et al., 2001; (4) Vujovich et al., 2004 (this volume), (5) Thomas et al., 2000; and (6) Sato et al., 2004, this volume).

The biostratigraphic control and the faunal affinities clearly indicate that an original Laurentian fauna was gradually isolated in Arenigian times, and eventually became endemic by the mid Ordovician, as proposed by Benedetto and Astini (1993), Benedetto (1993), Benedetto et al. (1999), and Keller (1999) (Fig. 7). Gondwanan forms arrived by the Llanvirnian and became dominant in Caradocian to Ashgillian times (see discussion in Benedetto, 2004, this volume).

The limestones of the Angaco belt in the western flank of the Sierra de Pie de Palo were interpreted as equivalent of the early Paleozoic carbonate platform of Precordillera (Vujovich, 2003, Galindo et al., 2004). Sr-isotopes of these rocks seem to indicate a Middle to Late Cambrian age, but this was interpreted as reflecting a secondary alteration by Cingolani et al. (2003), since a Pb/Pb isochron of ca. 546 Ma was interpreted as a last diagenetic or metamorphic age for these crystalline limestones. Equivalent carbonate rocks of this area have been examined by Sial et al. (2001), who proposed a Vendian to Early Cambrian age for its deposition.

Similar deformed limestones were interpreted, further south in La Pampa province, as part of the same carbonate platform of late Tremadocian to early Arenigian age (Tickyj et al., 2003).

Passive and active margins

There is a general consensus that the Precordillera had passive margins on both its western and eastern sides (Dalla Salda et al., 1992a, b). The alternative proposal of Loske (1994), interpreting the Precordillera as a back-arc basin, does not appear to have received any support. The lack of Cambrian and Ordovician magmatism in the entire Cuyania terrane precludes its interpretation as part of an active subduction system during that period. At that time a magmatic arc was developed in the western Sierras Pampeanas, as proposed by Ramos et al. (1984, 1986). This area was the locus of intensive work on petrology, geochemistry, isotopic composition, and geochronology in the last 10 years (Toselli et al., 1996; Pankhurst et al., 1998; Rapela, 2000a, b; Rapela et al., 1998a, b, 1999, 2002; Sato et al., 2003). The arc magmatism is represented by tholeiitic gabbros, tonalites, diorites, granodiorites, and granites (Ramos et al., 1984; Rapela et al., 1992; Coira et al., 1999; Quenardelle and Ramos, 1999). Based on these studies it is clear that a typical calcalkaline magmatic arc was developed along 1,750 km of the proto-continental margin of Gondwana, from the Puna at 22°S to the Colorado river in La Pampa at 38°S (Coira et al., 1982 and 1999; Ramos, 1999; Sato et al., 2004, this volume). The arc-related magmatism climaxed between 490 and 470 Ma as indicated by U-Pb ages in zircons (Pankhurst et al., 1998; Sims et al., 1998; Stuart-Smith et al., 1999), and numerous U-Pb SHRIMP analyses (Pankhurst et al., 1998, 2000; Rapela et al., 2001). The beginning of the arc is not yet well established. Some U-Pb ages as old as 507 Ma in the Sierra de San Luis may have problems in inheritance (Sato et al., 2003). However, further north as in the Sierra de Chango Real, ages of 515–505 Ma are recorded (K-Ar in whole- rock) in pre-orogenic orthogneiss with a syenogranitic to monzogranitic composition (Lazarte, 1991).

The transition between arc-related to syncollisional and postcollisional granitoids has been established between 460 and 435 Ma, mainly based on the structural relationships observed in the Sierras de San Luis and Ancasti (Quenardelle and Ramos, 1999; Sato et al., 2003). However, the magmatic activity lasted until Devonian times (Achalian magmatism of Sims et al., 1998).

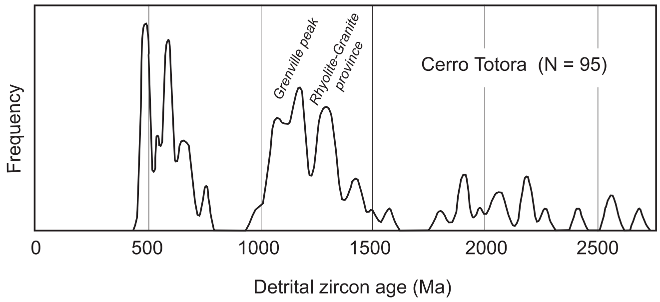

Fig. 5. Detrital zircon U-Pb ages from sandstones of Cerro Totora Formation in the type locality (data modified from Finney et al., 2003a, correcting for sample mislabeling based on Finney et al., 2004).

Thus there is a close relationship between the previously described evolution of the sedimentary sequence in the Cuyania terrane and the magmatic activity in the Sierras Pampeanas (Ramos, 2003).

Deformation and metamorphism

The reconstruction of the onset of deformation related to the collision of Cuyania is derived from four different data series: (1) the angular unconformities between different sequences, changes in the sedimentation pattern, and ages of low grade metamorphism of the sedimentary cover in the upper crustal lower plate (Cuyania eastern margin); (2) peak of regional metamorphism in the crustal basement of the lower plate; (3) cessation of subduction related magmatic activity in the upper plate (Pampia western margin); and (4) peak of regional metamorphism in the crustal basement of the upper plate. These ages have a strong coherence and define middle to late Ordovician time span. Despite this, some authors have favored a Devonian age (Rapela et al., 1998b) or a Late Silurian–Early Devonian age (Keller, 1999, Finney et al., 2003a, b) for the collision.

Lower plate sedimentary cover: There is consensus that a conglomeratic facies that interrupts black shale sedimentation was caused by flexural extension in the carbonate platform during Llandeilian to Caradocian times, as proposed by Astini and Thomas (1999). This episode postdates the drowning of the platform in Llanvirnian times (Dalla Salda et al., 1992a, b) and indicates the initiation of the collision (compare with Bradley and Kidd, 1991).

An erosional unconformity described by Astini and Cañas (1995) between Llandeilian-Caradocian deposits and Early Ordovician rocks in the Sassito creek in central Precordillera of San Juan is interpreted as a discontinuity generated in the peripheral bulge. This indicates that the beginning of deformation also took place in this sector in pre-Caradocian times. This unconformity could be correlated with the unconformity first described by Rolleri (1947) in Talacasto and Cuerda et al. (1988) separating the Ordovician from the Silurian, but recently interpreted by Peralta (2003) as pre-Ashgillian. The unconformity between Silurian shales and Arenigian carbonates in Tambolar (Bracaccini, 1949) may also represent the inception of the deformation at these latitudes. However, some authors have interpreted these unconformities as related to the beginning of extension in this part of the Precordillera (Keller and Lehnert, 1998).

Particularly strong deformation is associated with the limestones of Pan de Azúcar in Sierra de la Huerta (Vujovich et al., 1998), interpreted as a low-grade metamorphic carbonate sequence equivalent to the San Juan Limestone (Bastías et al., 1984). Equivalent strongly deformed limestones and quartzites are also preserved at low-grade greenschist-facies in western Sierra de Pie de Palo as part of the Caucete Group (Van Staal et al., 2002).

The oldest age of deformation obtained by K/Ar in the eastern clastic facies by Buggish et al. (1994) in mudstones of the Rinconada area yielded 454.4±4.6 Ma. This age is similar to the 463±0.3 Ma (Ar-Ar age in hornblende) obtained in amphibolites of Pie de Palo rocks by Ramos et al. (1996, 1998).

Similar deformed limestones are known in Las Mahuidas area where Tickyj et al. (2003) described crystalline limestones, affected by ductile deformation with tight NE-verging folds and a penetrative foliation. The age is constrained by $^{87}Sr/^{86}Sr$ ratios that indicate 530–500 Ma, which is corroborated by well-preserved conodonts of latest Tremadocian to early Arenigian age, with an alteration index that indicates temperature of the order of 300°C (Cheng, 2001).

Based on these features, it is possible to bracket the beginning of collisional deformation in the cover of the lower plate as approximately Late Llandeilian–Early Caradocian boundary, and lasting through most of the Caradocian.

Lower plate basement: The lower crust in the lower plate of a collision is affected by high to medium pressure metamorphism with a medium to low temperature gradient. This scenario was described by Dalla Salda and Varela (1984) and confirmed by precise assessments by Casquet et al. (2001). These authors established the pressure conditions in the Pie de Palo Metamorphic Complex at about 11 to 13 Kb at 600°C, with a peak metamorphism at ca. 460 Ma. These conditions show a depth of the order of 45 km for the basement Cuyania as it was overridden by the protomargin of Gondwana, and indicates an low-intermediate gradient of ca. 13°C/km. The age of this metamorphic peak also confirms a Late Llandeilian to Early Caradocian age for the deformation.

New U-Pb zircon SHRIMP data from the Pie de Palo Complex show that outer rims of zonned zircons also have similar ages (Vujovich et al., 2004, this volume).

Upper plate cessation of subduction related igneous activity: Geochemical and isotopic data clearly demonstrate the subduction-related affinities of the Famatinian magmatic rocks (Rapela et al., 1992; Rapela, 2000b; Pankhurst et al., 1998; Coira et al., 1999). Subduction-related magmatism ceased at about 465 Ma, and was associated with important deformation, crustal thickening with west-vergence, and regional metamorphism at about 470–460 Ma (Rapela et al., 2001). Several metamorphic units, previously considered as part of the Precambrian–Cambrian basement, have proven to contain detrital zircons of Ordovician age. Recent studies in detrital zircons of La Aguadita Formation in the Sierra de Famatina clearly demonstrate a minimum Early Ordovician age for these rocks (480±5.7 Ma, Astini et al., 2003). The magmatic activity lasted up to 454 Ma in the Sierra de San Luis, where plutons such as the Paso del Rey and Río de la Carpa crystallized under active deformation according to Sato et al. (2003). These data indicate that cessation occurred between 465 and 454 Ma, and was associated with important penetrative deformation.

Upper plate crustal basement: Metamorphic studies of the Sierra de la Huerta, interpreted as the forearc of the upper plate protomargin of Gondwana, indicate pressures of about 12 Kb and temperatures of 769°, with a main peak at 463±2 Ma (Baldo et al., 2001). This gives a thermal gradient of ca. 18°C/km, contrasting with thermal gradients of 30°C/km established by Grissom et al. (1998) in Fiambalá, or even higher gradients of Saal (1993) in the southernmost part of Famatina along the Famatinian magmatic arc. The age of the metamorphic peak with low temperature gradients is associated with the burial of the crust during collision, which is slightly older in the upper plate than in the lower plate, but within Late Llandeilian– Early Caradocian. Similar metamorphic ages were obtained by Rapela et al. (2001) in Valle Fértil, with ages between 465.9±4.4 Ma and 466.5±7.7 Ma. These characteristic changes in the conditions of metamorphism are well established across Sierras Pampeanas, where the high temperature gradients coincide with the axis of the Ordovician magmatic arc (see summary in Rossi et al., 2003).

K-bentonites

The discovery of K-bentonites in the Cuyania terrane, deposited in the upper part of the carbonate succession and in black shales of Arenigian to Llanvirnian age (Bergström et al., 1996; Huff et al., 1996, Cingolani et al., 1997), showed a contrasting distribution in time and space from the typical K-bentonites of the Appalachian system. In North America and in the related European areas, the giant K-bentonites were deposited during Middle to Late Ordovician times, but those in Precordillera are older. This fact indicates that Laurentia and Gondwana were not adjacent by Middle to Late Ordovician times (Huff et al., 1997, 2003).

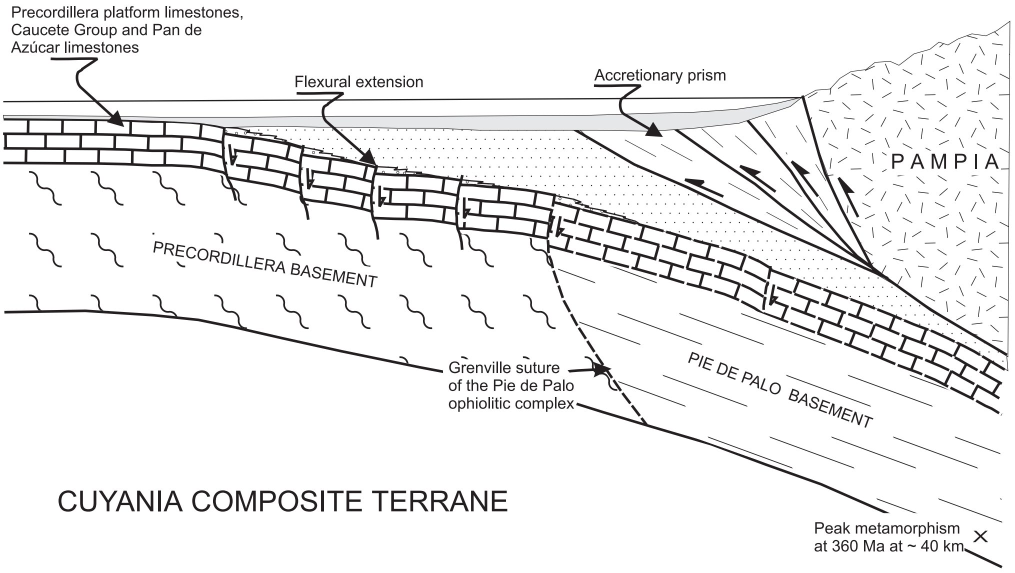

Fig. 6. Schematic section showing the relationship between flexural extension in the Cuyania terrane and the basement exposed in the Sierras de la Huerta and Valle Fértil corresponding to the Pampia terrane, at that time already amalgamated to the protomargin of Gondwana. Note the location of the Grenville suture between Precordillera and Pie de Palo basements, reactivated during latest Ordovician to Silurian times as a result of the collision (modified from Ramos et al., 1996).

Huff et al. (2003) used the geochemical characteristics of the K-bentonites of central and eastern Precordillera to confirm the striking difference with equivalent beds of Laurentia. Recent U-Pb SHRIMP zircon ages obtained from Talacasto K-bentonites of Precordillera and the volcanic rocks of the Famatina show a conspicuous coincidence in age (Fig. 8). K-bentonites in Precordillera have an age around 464±2 Ma (Huff et al., 1997). Recent precise U-Pb SHRIMP in zircons dating in Talacasto K-bentonites yield 469.5±3.2 Ma and 470.1±3.3 Ma, and the Famatinian volcanics yield 468.3±3.4 Ma (Baldo et al., 2003).

The southernmost evidence of K-bentonites was reported interbedded with the San Jorge Limestones in La Pampa (38°S), and may be as old as Arenigian age (Tickyj et al., 2003).

Finney et al. (2003b) proposed an actualistic complex model for Ordovician trade winds to justify the terrane displaced from the present south, assuming a Gondwanan origin for the Cuyania terrane. However, it is much simpler to assume that as the terrane was approaching from the west (present coordinates), the continental protomargin of Gondwana received the ash-fall tuffs directly from the Famatina arc.

Paleomagnetic data

Recently obtained paleomagnetic results from Early Cambrian synrift deposits of Cuyania confirm that this terrane was part of Laurentia at that time (Rapalini and Astini, 1998). The paleopole obtained is not consistent with any expected pole position of South America in the Phanerozoic, suggesting that a post-Cambrian remagnetization is unlikely. This pole also disagrees with the Cambrian path for the already assembled Gondwana (Rapalini et al., 1999). The paleomagnetic pole position at 37°N and 314°E (in present South American coordinates) is consistent with the Early Cambrian segment of the Laurentia apparent polar wander path if Cuyania is positioned as the conjugate margin of the Ouachita embayment in southeast North America.

The alternative origin deriving Cuyania from Gondwana, as argued by Aceñolaza et al. (2002) is not supported by paleomagnetic data. This hypothesis would require an anomalous paleolatitude and a prominent counterclockwise rotation (more than 90°), as shown by Astini and Rapalini (2003). The alternative position proposed by Finney et al. (2003a) within Gondwana, although has a similar paleolatitude, requires a 180° rotation in the orientation of the Cuyania terrane. On paleomagnetic grounds, no serious challenge can be made against the derivation of Cuyania from the Ouachita embayment in Early Cambrian times.

The paleopole obtained from the San Rafael Block for the Caradocian times (ca. 455 Ma) poses some problems for the far-traveled terrane hypothesis of Astini et al. (1995, 1996). The paleolatitude of 25.7°S (see Rapalini and Cingolani, 2004, this volume) is compatible with the Texas plateau hypotheses of Dalziel (1997). According to this model, Cuyania was still attached to Laurentia in Ordovician times as an attenuated crustal block that faced the Ouachita embayment. The modified alternative of Keller (1999) proposed that stretching produced oceanic crust in Caradocian to Ashgillian times, and the collision took pace in Silurian or Devonian times.

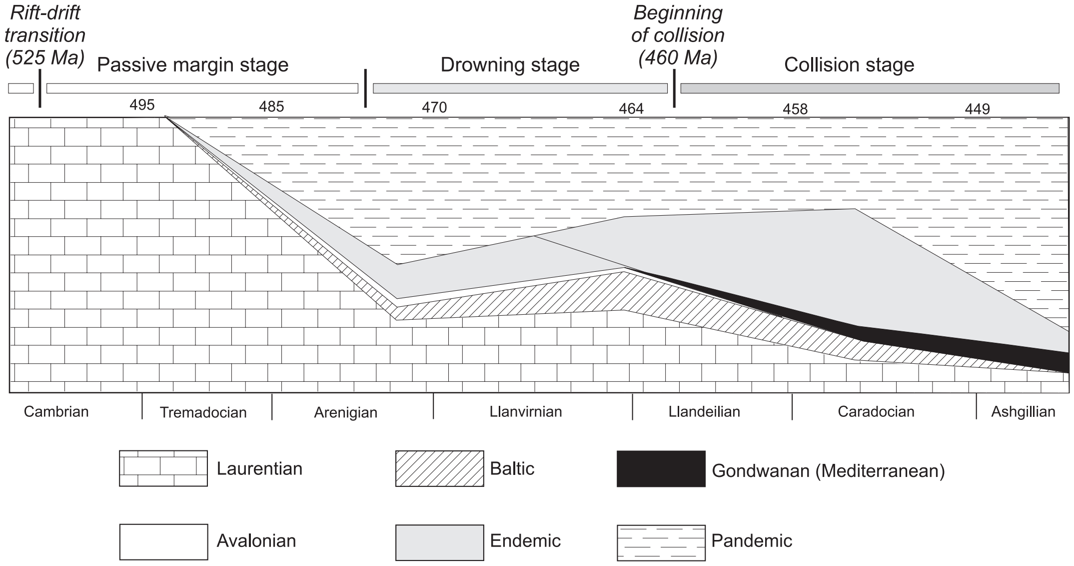

Fig. 7. Composition of benthic fauna communities in the Cuyania terrane (modified from Benedetto et al., 1995 and Keller, 1999). This diagram shows the influence of Gondwana fauna starting in Llandeilian times. Rift-drift transition after Thomas and Astini (1999).

The proposal of Rapalini and Cingolani (2004, this volume) is a third alternative that, in our estimation, better explains the paleomagnetic results. The collision of Cuyania seems to have taken place prior to 455 Ma, and a few millions year later in Ashgillian times glacial deposits covered the eastern Precordillera (Peralta and Carter, 1990; Astini, 2001). If these premises are accepted, the paleomagnetic data can only be explained by assuming an important block rotation of Cuyania during the final amalgamation (the docking of Chilenia to Gondwana) in Devonian times.

On paleomagnetic grounds the position of Cuyania in the Early Cambrian is well established as part of Laurentia. However, further data are required for Middle to Late Ordovician in Cuyania and in western Gondwana, due to the poor constraints on the Gondwana polar apparent wander path.

Alternative Hypotheses

Several alternatives have been proposed for the origin and the evolution of the Cuyania terrane. The early proposals of Dalla Salda et al. (1992a, b) and Dalziel et al. (1994) that called for a continent-to-continent collision were eventually abandoned (see discussion in Thomas et al., 2002; Thomas and Astini, 2003). An alternative with some modifications to this idea was proposed as the Texas plateau hypothesis. The existence of a continental attenuated plateau facing the Ouachita embayment as proposed by Dalziel (1997), and modified by Keller (1999), could explain the faunal difference between Laurentia and the distal Texas plateau. This model requires a soft collision between Laurentia and Gondwana, and extension to separate Laurentia from the Cuyania terrane after the collision. The relative timing of the collision and the extension, as well as the age of glacial deposits in eastern Precordillera, makes this alternative difficult to accept (see further discussion in Rapalini and Cingolani, 2004, this volume).

Displaced hypothesis

A modification of the original Baldis et al (1989) hypothesis of a Gondwanan derivation has been proposed recently by Aceñolaza et al. (2002). Instead of displacing Cuyania a relatively short distance, from southern Sierras Pampeanas as postulated from Baldis et al. (1989), these authors propose that a composite terrane, named Safran, was located between South Africa and the Antarctic terranes. The terrane was composed by continental fragments that constitute today the Cuyania, the Malvinas Plateau and the Patagonia terranes (Aceñolaza et al. 2002). The main problems with this proposal are that it cannot satisfactorily explain the faunal differences between Cuyania and Gondwana, or the Laurentian affinities of Cuyania (for details see Benedetto, 2004, this volume). There are additional problems with this hypothesis, such as: (1) requiring a long period of strike-slip displacement along the continental protomargin of Gondwana, making it unlikely that it could also produce the western Sierras Pampeanas magmatic arc above a subduction zone; (2) requiring a late collision in Devonian time, for which evidence against was previously discussed; (3) a misfit with the Early Cambrian magnetic pole (Astini and Rapalini, 2003); and (4) ductile deformation between the basement of Precordillera and Sierras Pampeanas has kinematic indicators showing a predominantly orthogonal, west-vergent contraction (Martino et al., 1993).

Recent data on detrital zircons from the synrift deposits of Cuyania produced a short-lived reinforcement of the Gondwana-derivation hypothesis for Cuyania (Finney et al., 2003a, b; Peralta et al., 2003). As previously discussed, labeling problems caused a misinterpretation of the zircon age data, assigning a typical assemblage from Gondwana at La Cébila, province of Catamarca, to be representative of Cerro Totora synrift deposits (see clarification in Finney et al., 2004). With the Grenville ages of detrital zircons from Cerro Totora now confirmed, a perfect match is revealed between the mid Proterozoic detrital zircon ages of Late Ordovician deposits from Quebrada Don Braulio in San Juan and the same-aged deposits of Empozada shales at Mendoza (Finney et al., 2003 c). The ages of these zircons also match the 1.1 Ga ages of detrital zircons previously described by Loske (1995) from the Devonian deposits of central Precordillera, derived from the Pie de Palo basement.

As a preliminary conclusion it can be established that there is no sound evidence to claim a Gondwanan origin for Cuyania based on faunal evidence. The proposed location in Gondwana is inconsistent with the paleomagnetic data, and middle Ordovician Famatinian zircons were identified by the precise study of Baldo et al. (2003).

Present Problems

Northern boundary

One of the outstanding problems still not resolved is the northern continuation of the Cuyania terrane. There is good evidence that the eastern border along the Valle Fértil lineament is tectonic. In addition to being an important crustal structure, these zone hosts' mafic and ultramafic rocks interpreted as an ophiolitic sequence (Vujovich et al., 1998). However, geophysical evidence suggests the existence of magnetic and gravity anomalies along the Bermejo valley that separate the Sierra de Famatina from the westernmost basement exposures of

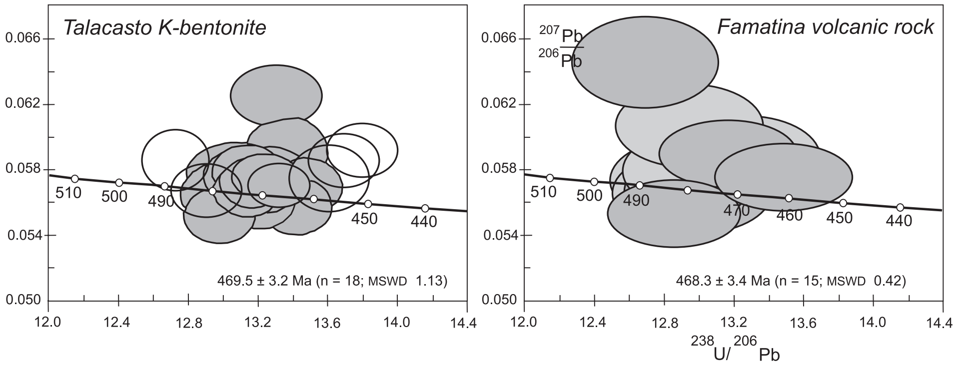

Fig. 8. Comparison between zircon U-Pb ages in the Tera-Wasserburg plots: (a) K-bentonites from Talacasto, central Precordillera on the Cuyania terrane; (b) Rhyolitic rocks from Sierra de Las Planchadas, Famatina, along the magmatic arc of the protomargin of Gondwana. Data after Baldo et al. (2001).

Sierras Pampeanas (Martínez and Gímenez, 2003). There are several alternatives: (1) the former indeed could be a suture marked by the emplacement of ophiolitic rocks, but its age is older (Precambrian), as has been demonstrated along the suture between Pie de Palo and Precordillera basements; (2) the anomalies correspond to the mafic crustal root of the Famatinian magmatic arc and therefore the zone is not a suture; and (3) the suture is early Paleozoic in age and separates the protomargin of Gondwana from allochthonous terranes.

To address these alternatives it is necessary to have better ages from the basement of westernmost Sierras Pampeanas, and to establish the structural evolution of this region, particularly the age and vergence of deformation. The finding of Grenville ages (mid-Proterozoic) in the basement of Cuyania was relevant because where these ages were not associated with Brasiliano ages (Late Proterozoic–Early Cambrian), it had been taken as a proof of the Laurentia derivation (Ramos et al., 1993). On the other hand, in recent years Grenville ages have been found elsewhere, even within the core of Sierras Pampeanas, as shown by Schwartz and Gromet (2004) and further east (Basei et al., 2001). But all these ages are associated with typical Brasiliano or Pampean ages, which show that the continental fragments have participated in the collision and amalgamation processes that led to the formation of west Gondwana (Ramos, 1988a; Ramos and Basei, 1997).

Based on these criteria it will be possible to recognize within the present basement fragments of Sierras de Umango, Maz and Espinal, the derivation and eventual ownership to Cuyania.

Southern boundary

A similar problem arises with the southern extension of the Cuyania terrane. Although there is good evidence for structural truncation of the main early Paleozoic terranes in northern Patagonia, as observed by aeromagnetic and gravity surveys (Chernicoff and Zappettini, 2003), some authors favored the continuation of the Famatinian arc in the eastern sector of the North Patagonian massif. The fact that some common Ordovician ages are found associated with granitoids and metamorphic rocks in the eastern sector of the massif points to an early Paleozoic subduction event as proposed by Ramos (1984). The orientation of this subduction, as evidenced by the penetrative deformation and the elongation of the granitoids, clearly indicates a west-northwest trend, typical of the North Patagonian massif. This trend coincides with the truncation observed in the Neuquén basin along the Huincul fault and the similar structural trends observed further east. As pointed out by Rapalini et al. (1999), more paleomagnetic data are required to decipher the relationship of these fragments with the rest of the Cuyania terrane.

Concluding Remarks

The Laurentian affinities of Cuyania proposed by many authors through the years remain the most acceptable hypothesis to explain the faunal characteristics and the temporal changes in the provincialism of this fauna. The basement of the Ouachita embayment has remarkable coincidences with the Cuyania basement, and has been identified as the area of provenance of this terrane. Cuyania has originated in the Cambrian as a conjugate margin pair from this Laurentian area based on their rift-drift transitions, subsidence curves, isotopic and geochemical characteristics, age of their basements, paleomagnetic data, and clasts provenance and age of their synrift deposits.

The far-traveled terrane (or 'funeral ship' of some authors) hypothesis is still the best to explain the transfer of Cuyania terrane to the Gondwana margin and all of the known paleontological and geological facts associated with this transfer. The implied ridge jump from the western side of Cuyania to its eastern side is analogous to the jumps commonly observed in small microplates in the late Cenozoic to Recent, such as for the Easter microplate (Tebbens and Cande, 1997).

The controversial analyses of the detrital zircons from Cuyania presented by Finney et al. (2002, 2004) produced a new wave of data that further contributed to the robust evidence supporting a Laurentian derivation for Cuyania.

The time of docking of Cuyania during late Middle to Late Ordovician times is constrained by a wide variety of sedimentary evidence from the cover of the lower plate, the age and character of peak metamorphism of basement rocks from both the lower and upper plates, and by the cessation of the subduction-related magmatism. Deformation and crustal stacking associated with the collision started in Late Llandeilian to Caradocian times, but remained active until the Late Devonian, the time of collision and final amalgamation of Chilenia to the Pacific side of Cuyania.

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