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Detrital zircon analysis from the Neoproterozoic–Cambrian sedimentary cover (Cuyania terrane), Sierra de Pie de Palo, Argentina: Evidence of a rift and passive margin system?

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ABSTRACT

Metamorphic basement and its Neoproterozoic to Cambrian cover exposed in the Sierra de Pie de Palo, a basement block of the Sierras Pampeanas in Argentina, lie within the Cuyania terrane. Detrital zircon analysis of the cover sequence which includes, in ascending order, the El Quemado, La Paz, El Desecho, and Angacos Formations of the Caucete Group indicate a Laurentian origin for the Cuyania terrane. The lower section represented by the El Quemado and La Paz Formations is interpreted as having an igneous source related to a rift setting similar to that envisioned for the southern and eastern margins of Laurentia at approximately 550 Ma. The younger strata of the El Desecho Formation are correlative with the Cerro Totora Formation of the Precordillera, and both are products of rift sedimentation. Finally, the Angacos Formation and the correlative La Laja Formation of the Precordillera were deposited on the passive margin developed on the Cuyania terrane. The maximum depositional ages for the Caucete Group include *ca.* 550 Ma for the El Quemado Formation and *ca.* 531 Ma for the El Desecho Formation. Four different sediment sources areas were interpreted in the provenance analysis. The main source is crystalline basement dominated by early Mesoproterozoic igneous rocks related to the Granite-Rhyolite province of central and eastern Laurentia. Possible source areas for 1600 Ma metamorphic detrital zircons of the Caucete Group include the Yavapai-Mazatzal province (*ca.* 1800–1600 Ma) of south-central to southwestern Laurentia. Younger Mesoproterozoic zircon is likely derived from Grenville-age medium- to high-grade metamorphic rocks and subordinate igneous rocks that form the basement of Cuyania as well as the southern Grenville province of Laurentia itself. Finally, Neoproterozoic igneous zircon in the Caucete Group records different magmatic pulses along the southern Laurentian margin during opening of Iapetus and break-up of Rodinia. Northwestern Cuyania terrane includes a small basement component derived from the Granite-Rhyolite province of Laurentia, which was the source for detrital zircons found in the middle Cambrian passive margin sediments of Cuyania.

1. Introduction

Resolving the primary paleogeographic origin of displaced terranes remains problematic in most orogenic systems. Provenance studies on sedimentary rocks based on the morphological and U/Pb geochronological analysis of detrital zircons have proven useful in some cases (Mueller et al., 1994; Murphy et al., 2004; Samson et al., 2005). The technique provides estimates on the maximum depositional age and establishes characteristics of sediment source areas including age and composition. Detrital zircon age data are particularly useful in providing depositional age limits for unfossiliferous siliciclastic sedimentary sequences that have been metamorphosed and strongly deformed. In addition, detrital zircon analysis may discriminate whether a sedimentary basin evolved in an active or a passive margin setting (e.g., Cawood and Nemchin, 2001). Ultimately, the results of detrital analysis strengthen local and regional stratigraphic correlations and lead to more robust paleogeographic reconstructions (Fedo et al., 2003).

This contribution presents the results of a detrital zircon U/Pb study directed at better constraining the origin of the Cuyania terrane (Ramos et al., 1998), a composite terrane in northwestern Argentina that includes the Precordillera (Ramos et al., 1986; Astini

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et al., 1995) and Pie de Palo (Ramos et al., 1998; Ramos, 2004) terranes. Both are commonly interpreted as continental crustal fragments allochthonous to the Gondwana margin and derived from Laurentia during the early Paleozoic (e.g., Dalla Salda et al., 1992; Thomas and Astini, 1996; Dalziel, 1997; Ramos et al., 1998). There are however other competing models that propose a para-autochthonous Gondwanan origin for the Cuyania terrane with strike-slip displacement from the southern sector of Gondwana to its present position during the early Paleozoic (Baldis et al., 1989; Aceñolaza et al., 2002; Finney et al., 2005; Finney, 2007).

The Caucete Group (Borrello, 1969) is a cover sequence on Cuyania (Ramos et al., 1998; Ramos, 2004) of probable late Neoproterozoic–Early Cambrian age that is exposed on the western flank of the Sierra de Pie de Palo (Fig. 1), within the Sierras Pampeanas of northwestern Argentina. The sequence consists of unfossiliferous siliciclastic and carbonate units strongly affected by deformation and metamorphism during the Ordovician Famatinian orogeny (Ramos et al., 1998). Detrital zircon data from the Caucete Group and age-equivalent sequences in adjacent areas, in conjunction with structural and stratigraphic analysis, allows us to define a maximum depositional age for the units, evaluate the tectonic setting of deposition, and compare with possible source areas along the Laurentia and Gondwana margins. We report new data for charting dynamic terrane dispersal after the break-up of the Rodinia supercontinent (Fuck et al., 2008; Li et al., 2008) during the Neoproterozoic–Cambrian transition.

2. Geotectonic framework

The Cuyania terrane likely formed during opening of the Iapetus Ocean and break-up of Rodinia (Cawood et al., 2001; Mueller et al., 2007). The major Gondwana cratons in South America (i.e. Amazonian and Rio de la Plata) were amalgamated with the eastern margin of Laurentia before the break-up of Rodinia (*ca.* 1000 Ma) through the Grenville orogenic belt (Hoffman, 1991). The positions and the relative movements of these cratons after the break-up of the supercontinent have been extensively discussed (Cordani et al., 2003; Fuck et al., 2008; Li et al., 2008). Iapetus opened between Laurentia and Gondwana in Neoproterozoic time. Continental rifting produced a number of different crustal fragments, one of which could be the Cuyania terrane (Cawood et al., 2001).

Recognition of the Cuyania terrane as a distinct fragment along the Gondwana margin is based on stratigraphic, biostratigraphic, sedimentary, structural, isotopic, and paleomagnetic evidence. Ramos et al. (1998) defined the Cuyania composite terrane to include Mesoproterozoic metamorphic rocks of Western Sierras Pampeanas as depositional basement to the Cambrian–Ordovician limestones of the Precordillera (Fig. 1). Thus, the composite terrane comprises: (1) the Precordillera terrane as defined by Astini et al. (1995); (2) the basement of the Ordovician limestones of the San Rafael Block (Bordonaro et al., 1996), including the Cerro La Ventana Formation (Cingolani et al., 2005); and (3) the basement of the limestones and marbles of Las Matras Block (Cerros San Jorge

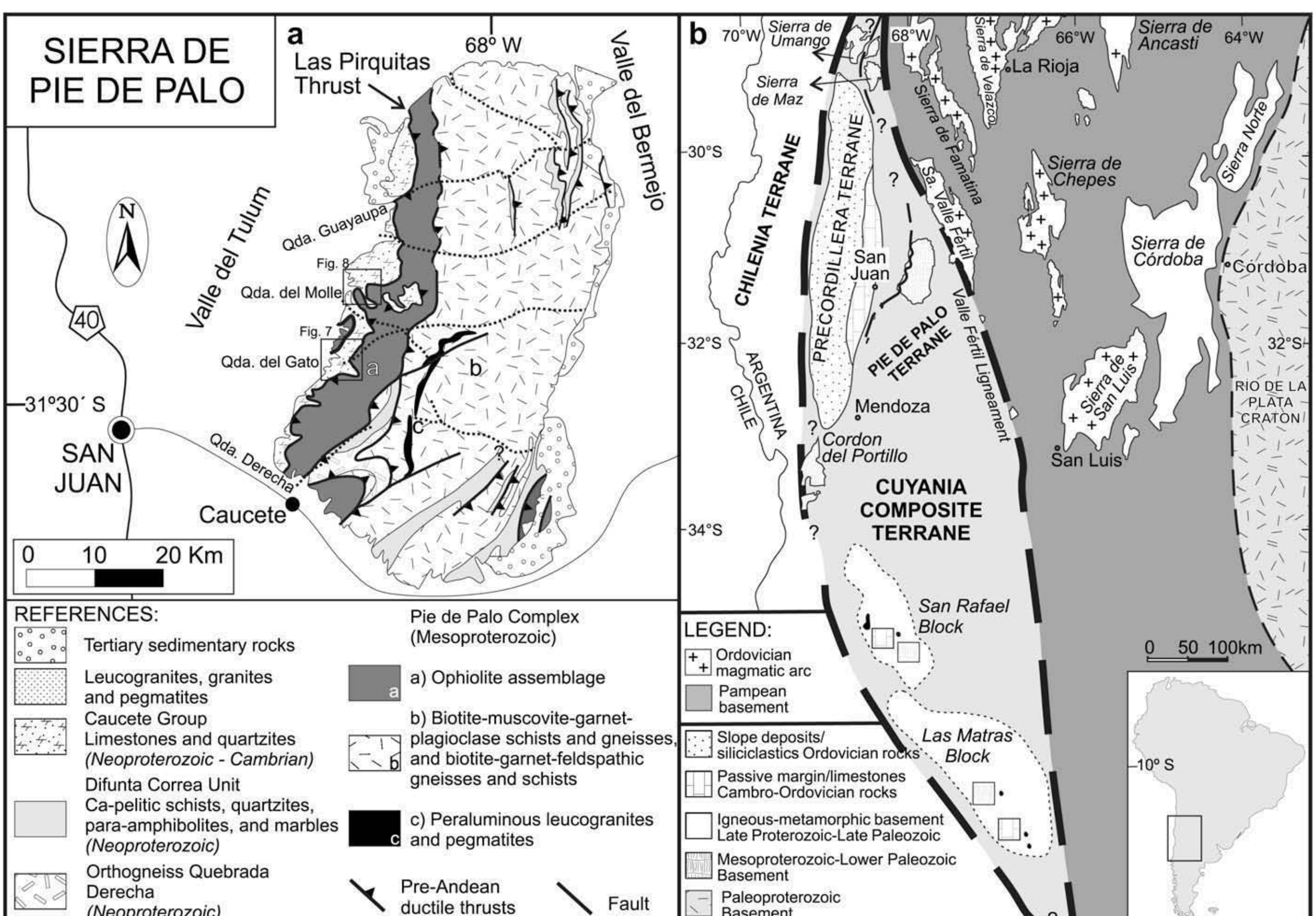

Fig. 1. (a) General geology and stratigraphy of the Sierra de Pie de Palo (Ramos and Vujovich, 2000; Baldo et al., 2006; Naipauer, 2007). (b) Regional geologic map of Cuyania composite terrane (Precordillera and Pie de Palo terranes, Ramos et al., 1998). Ordovician magmatic arc and Pampean basement after Sato et al. (2004). Rio de la Plata craton after Rapela et al. (2007).

and Rogazziano; Melchor et al., 1999) which is composed of trondhjemitic–tonalitic Mesoproterozoic plutonic rocks (Sato et al., 2000, 2004) (see Fig. 1b).

Several models for a Laurentian origin have been proposed for the Precordillera terrane. Dalla Salda et al. (1992) originally suggested that the Precordillera was part of a greater continental sliver rifted from North American following the collision with South America in the Ordovician. Astini and Benedetto (1993), Astini et al. (1995) and Thomas and Astini (1996) argued that the Precordillera terrane specifically originated in the eastern Ouachita embayment at the southern end of the Appalachian belt, rifted from the Laurentian margin, drifted away as a microcontinent across the Iapetus Ocean, and collided with the Gondwana margin during the middle Ordovician. The Texas Plateau model (Dalziel, 1997), based on comparison with the Malvinas Plateau, leaves the Precordillera terrane as a continental plateau that remained a marginal piece of Laurentia until the middle Ordovician collision of Gondwana and Laurentia. Subsequent rifting of Gondwana and Laurentia in the late Ordovician detached the Precordillera from Texas Plateau, leaving the terrane attached to Gondwana (Dalziel, 1997; Rapalini and Cingolani, 2004).

Additional models for a para-autochthonous origin of the Precordillera were proposed initially by Aceñolaza and Toselli (1988) and Baldis et al. (1989). These authors suggested that the terrane has migrated from the southern margin of Gondwana by strike-slip displacement. This model was primarily based on structural and stratigraphic analysis (Aceñolaza et al., 2002), but has recently been supported by interpretation of detrital zircon data from the Cuyania terrane (Finney et al., 2003, 2005).

3. Geology and stratigraphy of the study area

The Sierra de Pie de Palo is one of the westernmost fault-bounded igneous-metamorphic complexes of the Sierras Pampeanas which includes uplifts in the broken Andean foreland of western and central Argentina that have formed in response to the Andean orogeny (Jordan et al., 1983; Ramos et al., 2002). The range lies between the Tulum and Bermejo valleys in the San Juan province (Fig. 1) and is largely underlain by medium to high-grade metamorphic basement referred to as the Pie de Palo Complex (Ramos and Vujovich, 2000). Low-grade metamorphic rocks of the Difunta Correa Metasedimentary Sequence (Baldo et al., 1998) and Caucete Group (Borrello, 1969) are exposed near major faults along the southwestern flank of the range (Fig. 2). Intrusive granite bodies and pegmatites are present in restricted areas throughout the range.

3.1. Pie de Palo Complex

As originally defined, the Pie de Palo Complex includes a suite of schist, marble, migmatite, gneiss, leucogranite, and mafic to ultramafic metaigneous rocks (Fig. 1; Stappenbeck, 1910; Schiller, 1912; Stieglitz, 1914; Dalla Salda and Varela, 1982, 1984; Ramos and Vujovich, 2000). The units can be subdivided into several northeast-trending fault-bounded units (Fig. 1a). The structurally lowest unit consists of mafic and ultramafic metamorphic rocks on the western side of the range (Vujovich and Kay, 1998). In the northeastern portion of the range, crystalline marbles are structurally intercalated with biotite-garnet-rich gneisses and amphibolites (Ramos and Vujovich, 2000).

A Mesoproterozoic age for the Pie de Palo Complex was originally assigned on the basis of a 1060 ± 20 Ma $^{207}Pb/^{206}Pb$ age from discordant U/Pb analyses on zircon from gneisses in the central area of the mountain belt (McDonough et al., 1993). This age is consistent with Rb/Sr whole-rock isochron ages on metamorphic and igneous rocks in the central portion of the range (Varela and Dalla Salda, 1993; Pankhurst and Rapela, 1998). More recent studies have yielded older igneous ages of *ca.* 1204 Ma, 1174 ± 43 Ma, and *ca.* 1169 Ma for gabbroic pegmatite, leucogabbro/diorite, and calc-alkaline tonalite/granodiorite sills, respectively (Vujovich et al., 2004). A garnet-bearing two-mica granitoid (El Tigre Granitoid) emplaced in the Pie de Palo Complex gave U/Pb zircon (SHRIMP) age of 1104.8 ± 4.8 Ma (Morata et al., 2008).

3.2. Difunta Correa Metasedimentary Sequence

The Difunta Correa sequence includes amphibolite-facies Ca-pelitic schist, quartzite, meta-arkose, marble, and para-amphibolite exposed along the southern and eastern margins of the Sierra de Pie de Palo (Baldo et al., 1998). U/Pb SHRIMP analyses on detrital zircons from intercalated para-amphibolites indicate a maximum depositional age of 625 Ma (Rapela et al., 2005). Isotopic studies of $^{87}Sr/^{86}Sr$, C and O on carbonate units suggest a Neoproterozoic depositional age for the sequence (*ca.* 720–580 Ma; Galindo et al., 2004). Older detrital zircon ages range from 1032 to 1224 Ma and rim analyses record metamorphic overgrowths at 460 Ma (Casquet et al., 2001). Mylonitic orthogneiss within the Difunta Correa Metasedimentary Sequence in the southwestern portion of the range (Fig. 1a) is geochemically similar to intraplate A-type magmatism and gives a U/Pb SHRIMP crystallization age on zircon of 774 ± 6 Ma (Baldo et al., 2006).

3.3. Caucete Group

The Caucete Group includes low-grade calcareous units and quartzite on the western side of the Sierra de Pie de Palo (Borrello, 1963, 1969) that are in fault contact with the metamorphic basement (Fig. 3a and b; Schiller, 1912). The section is composed of the El Quemado, La Paz, El Desecho and Angacos Formations (Fig. 2; Borrello, 1969; modified by Vujovich, 2003). Two main components are recognized in the Caucete Group: one of silicilastic composition (El Quemado and La Paz Formations); the other of carbonate composition (El Desecho and Angacos Formations). The latter two formations have been correlated with basal Cambrian units of the eastern Precordillera succession (e.g. Cerro Totora and La Laja Formations, van Staal et al., 2002). However, the origin of the El Quemado and La Paz Formations and the correlation with the unmetamorphosed Precordillera stratigraphy is more difficult. Penetrative deformation and greenschist facies metamorphism (Ramos and Vujovich, 2000) of the Caucete Group has obscured the original stratigraphic relationships of the sequence. Structural relationships suggest that the El Quemado Formation was imbricated with the Pie de Palo Complex and both were subsequently emplaced westwards on top of the calcareous El Desecho and Angacos Formations of the Caucete Group (van Staal et al., 2002).

The depositional age of the sequence is unclear due to a lack of diagnostic fossils, uncertain stratigraphic relationships, and penetrative deformation. A lower Paleozoic age was first assigned based on correlation with units of the Precordillera (Schiller, 1912; Groeber, 1948). The Caucete Group has been specifically correlated with Late Cambrian and Early Ordovician limestone units of the Precordillera on the basis of carbon and oxygen isotopic studies (Linares et al., 1982; Abbruzzi, 1994; Sial et al., 2001). More recently, Galindo et al. (2004) considered the Caucete Group equivalent to the Precordilleran Cambrian carbonate platform based on $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and δO data. Naipauer et al. (2005a) established a possible Early to Middle Cambrian age (ca. 510 Ma) for the Angacos Formation and correlated it with the lower members of La Laja Formation in the Precordillera. Finally, possible ichnofossils described by Bordonaro et al. (1992) may indicate equivalence with the

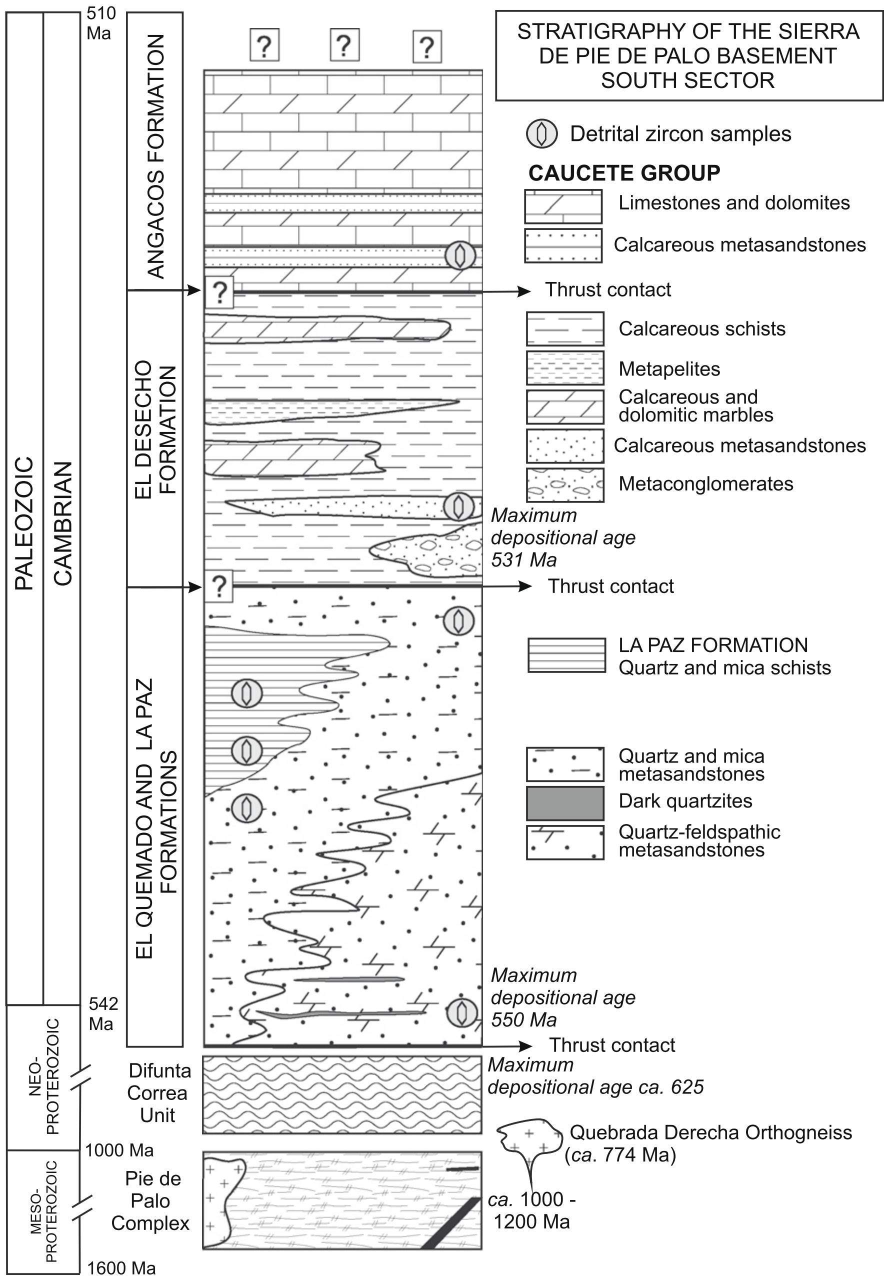

Fig. 2. Stratigraphic relationships and detrital zircon sample horizons of Grenville basement and Neoproterozoic and Cambrian metasedimentary units on the western flank of the Sierra de Pie de Palo, based on Vujovich (2003), Baldo et al. (1998, 2006) and Vujovich et al. (2004). The units and rock types of the Caucete Group are described in Naipauer (2007).

Neoproterozoic–Lower Cambrian Puncoviscana Formation in northwestern Argentina.

4. Analytical techniques

Detrital zircons were separated from seven samples of siliciclastic rocks in the Caucete Group for U/Pb analysis. Heavy mineral fractions from approximately 5 kg samples were concentrated and separated into 100, 150 and 250 μm size fractions by standard crushing, elutriation, heavy liquid, and magnetic susceptibility techniques at the Centro de Investigaciones Geológicas laboratories of the Universidad Nacional de La Plata (UNLP). Detrital zircon fractions of roughly 200 grains were randomly handpicked in alcohol under a binocular microscope, mounted in epoxy along with known standards, and polished to expose grain centers for cathodoluminescence (CL) imaging and U/Pb analysis.

U/Pb analyses were performed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) using a New Wave UP-213 (213 nm, Nd:YAG) laser system coupled to a ThermoFinnigan Element 2 ICP-MS instrument housed at Washington State University (USA) following procedure outlined by Chang et al. (2006). The laser operated with a fluency of 10–11 J/cm^2 and a frequency of 10 Hz, with a 30 μm diameter ablation spot. Signals were collected for 36 s in 300 sweeps with a counting efficiency of 86% per analysis. Blanks were measured before each analysis for blank correction. Standards with ages of 564 Ma (Dickinson and Gehrels, 2003) and 1099 Ma (FC1; Paces and Miller, 1993) were analyzed after 5–10 unknown minerals to correct for mass bias and fractionation of U and Pb. Laser induced time dependent elemental fractionation, was corrected using the regression line method (Sylvester and Ghaderi, 1997; Horn et al., 2000; Kosler et al., 2002). Data reduction was completed with an in-house program at Washington State

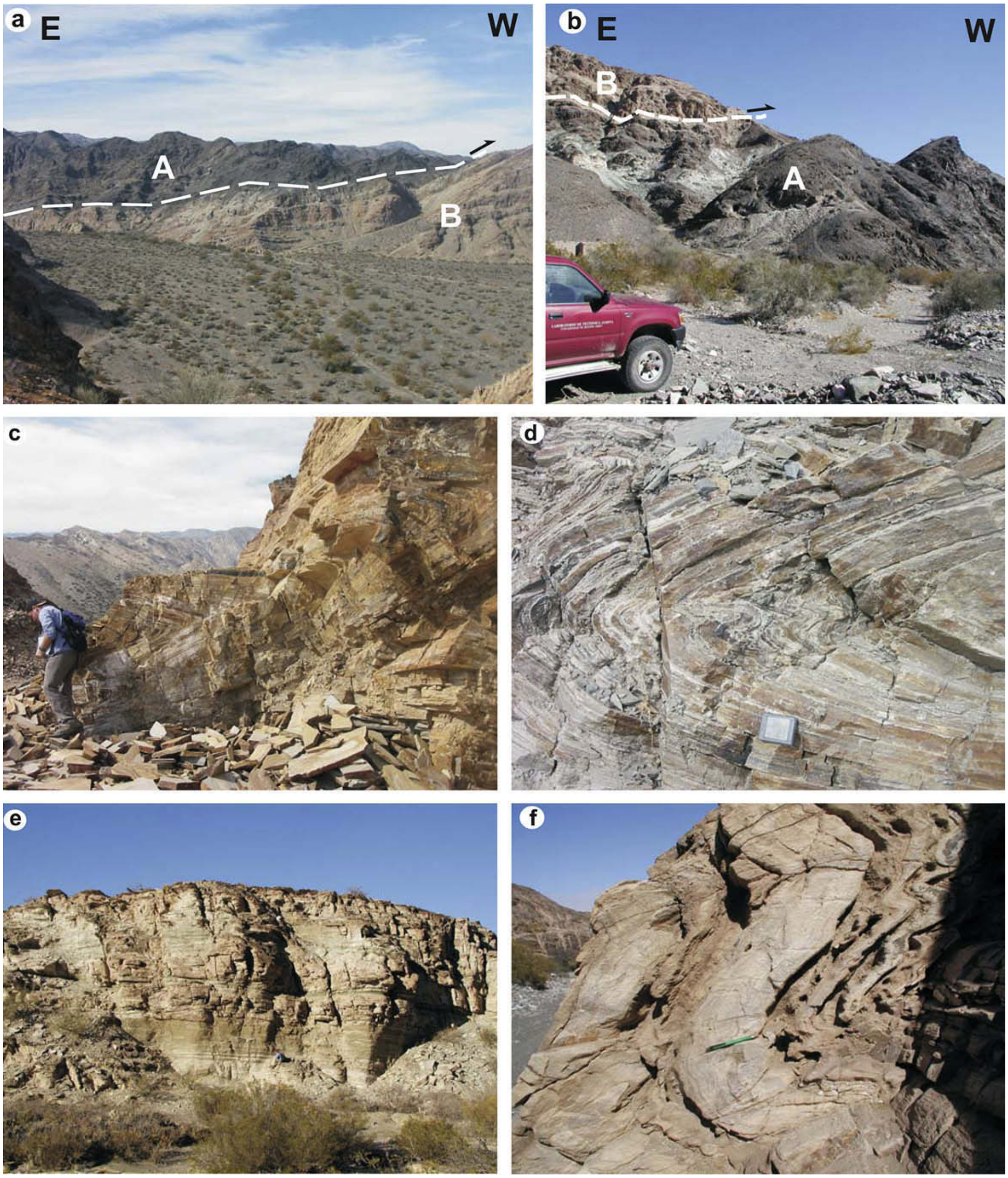

Fig. 3. Photographs of outcrops of the western flank of the Sierra Pie de Palo, (a) Pie de Palo Complex (A) in tectonic contact along the Las Pirquitas thrust with the El Quemado Formation (B), (b) Pie de Palo Complex (A) structurally overlain by the El Quemado Formation (B) in the Quebrada de las Burras area. White areas in A are ultramafic rocks (serpentine and schist), (c) and (d) El Quemado Formation composed of strongly folded, interbedded quartz-feldspathic metasandstone and green quartzite, (e) and (f) outcrops of La Paz Formation (green colors) interbedded with the El Quemado Formation in the Lomas Bayas area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

University (Chang et al., 2006). For cumulative probability plots was used the program of Ludwig (1999). Tera-Wasserburg and cumulative probability plots were constructed using analyses within 20% of concordance and reporting $^{207}Pb/^{206}Pb$ ages for analyses >1000 Ma (Dickinson and Gehrels, 2003).

5. Stratigraphic units of the basement cover sequence

5.1. El Quemado Formation

The El Quemado Formation includes siliciclastic units exposed on the western flank of Sierra de Pie de Palo that were originally referred to as the Cuarcita El Quemado (Borrello, 1963, 1969). The section is composed of quartz and feldspar-rich metasandstones, quartz–mica schists, black quartz sandstones, and their cataclastic equivalents. The section is well exposed from the Quebrada Agua del Conejo to the north (Ramos and Vujovich, 2000) to the Quebrada La Petaca to the south where the siliciclastic metasediments are replaced by calcareous rocks. The original thickness of units within the section is unknown due to the high degree of folding and faulting imposed on the sequence (see also Figs. 3c and d).

Metasandstone units are dominantly green and yellow, fine- to medium-grained with individual feldspar grains up to a few millimetres in diameter, and consist of quartz, feldspar, muscovite and lesser biotite. Minor disseminated opaques such as pyrite are common in cm-thick, yellowish, very fine-grained quartz arenites (Fig. 3d). A secondary fine lamination common in most units formed by deformation and mylonitic recrystallization (Fig. 4a and b). The protolith is interpreted to be an immature sandstone based on the high mica and feldspar content.

5.2. La Paz Formation

The La Paz Formation consists of variably mylonitized quartz and mica schist composed of muscovite, garnet and albite (Vujovich, 2003).The best outcrops are located between the Quebrada La Paz and Quebrada Las Pirquitas, and are widespread to the north of the range in the area of Lomas Bayas. Between the Quebrada El Molle and the Quebrada El Quemado, strata of the La Paz Formation are intercalated with metasandstone layers of the El Quemado Formation, suggesting a transitional contact between both units. A maximum structural thickness of 250 m for the La Paz Formation is observed in the El Quemado area. Individual beds vary from a few centimetres to 3 m in thickness. The unit is commonly dark in color, with greenish and greyish tones dominant (Fig. 3e and f). The grain-size ranges from very fine to medium, with albite porphyroclasts reaching 2 mm (Fig. 4c and d).

The La Paz Formation differs from the El Quemado Formation mainly in the presence of garnet, albite, epidote, and phyllosilicates in the mica schists. A protolith of interlayered volcanogenic pelite

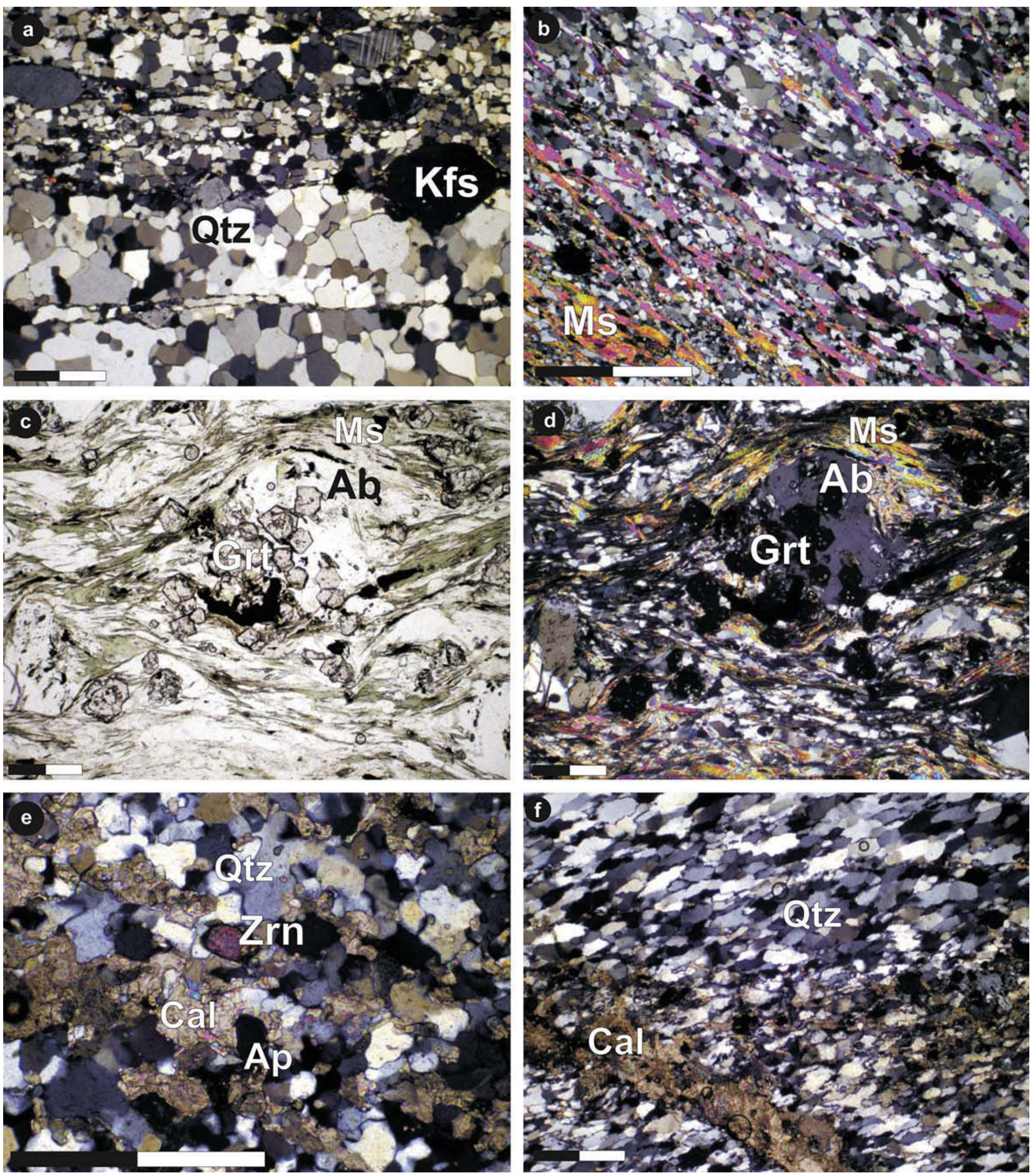

Fig. 4. Photomicrographs of the major textures from different units of the Caucete Group. El Quemado Formation: (a) polygonal texture in quartz with two well-marked domains of grain-size (transmitted light, crossed nicols); (b) foliation defined by muscovite and alternating with quartz-rich bands. La Paz Formation: (c) euhedral garnet inclusions in albite porphyroblasts, matrix composed of quartz and muscovite (transmitted light, parallel nicols), (d) same photomicrograph taken with crossed nicols. El Desecho Formation: (e) mosaic of quartz and carbonate, (Zrn) detrital zircon grain and (Ap) apatite grain, also rounded (crossed nicols). Angacos Formation: (f) mosaic of quartz and carbonate showing grain-size variation. Scale bar is approximately 0.5 mm in all photos. Mineral abbreviations after Kretz (1983).

and fine sandstone has been inferred based on the mineralogical characteristics and presence of small, clear prismatic zircons (Van Staal et al., 2002; Vujovich, 2003).

5.3. El Desecho Formation

The El Desecho Formation was originally described as the Puntilla Blanca Formation (van Staal et al., 2002), but later referred to as the El Desecho Formation (Vujovich, 2003), due to the fact that former name was used by Borrello (1969) for another unit of the Caucete Group. The unit includes carbonates and dolomitic rocks, marbles, calcareous schist, metapelites, calcareous metasandstones and subordinate metaconglomerates. The thickness is variable, ranging from a few meters to 40 m in the Quebrada El Desecho. The formation varies from red, yellow, to black and green in color (Fig 5a and b), and is a useful marker horizon that helps define structures. Fine- to medium-grained quartzite and calcareous metasandstone exposed in the area of La Olla, between the Quebradas La Cruz and Pecan reaches several meters in thickness and was selected for the provenance study (Figs. 4e and 5e).

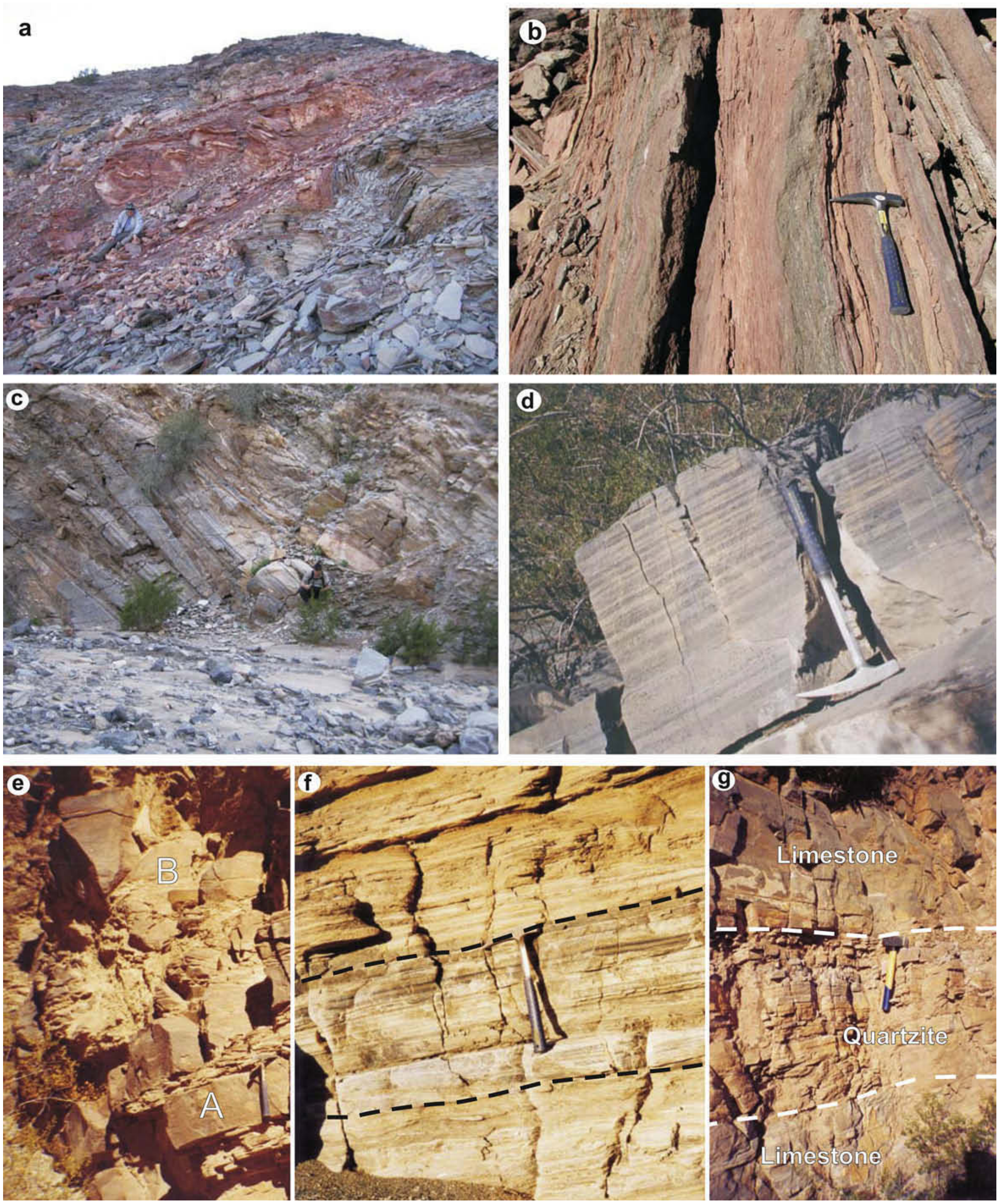

Fig. 5. Outcrop photographs of the El Desecho and Angacos Formations, Sierra Pie de Palo; (a) El Desecho Formation in the La Olla area, red and white calcareous and dolomitic marbles interbedded with gray calcareous schists; note the folding; (b) interbedded metapelites and reddish dolomitic marble, El Desecho Formation; (c) alternating limestone and calcareous schists of the Angacos Formation, Quebrada El Gato; (d) carbonates rhythmites of calcite and dolomite, Quebrada Las Pirquitas; (e) calcareous metasandstones (A) interbedded with calcareous marbles (B), El Desecho Formation; (f) Angacos Formation, light- and dark-colored quartzites interbedded with limestone, Quebrada El Gato; (g) siliciclastic rocks interbedded in the limestone of the Angacos Formation, Quebrada La Lichona. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Metaconglomerate, with rounded boulders ranging in size from 5 to 30 cm in diameter are exposed on the southwestern side of the Lomas Bayas. The clasts are mainly granitic and occur in a calcareous matrix.

5.4. Angacos Formation

The Angacos Formation (Caliza Angacos: Borrello, 1969) is composed of penetratively deformed limestone, calcareous schist and marble. The main outcrops are located in the Quebradas El Gato and La Petaca but extend to the south where Dalla Salda and Varela (1984) mentioned that calcareous schists and marbles are up to 200 m thick in the Quebrada Ancha de la Punilla. Grey to black, fine-grained schists and calcareous schists are found at the base (Fig. 5c) and massive marbles occur at the top of the Angacos Formation (Ramos and Vujovich, 2000). The mineralogy ranges from calcite to dolomite (Fig. 5f and g). In the southwestern area in the Quebradas El Gato, La Petaca and La Lichona the rocks show laminations from 2 to 30 mm thick (Fig. 5d) that correspond with the separation of calcite- from dolomite-rich layers. Under the microscope, quartz and organic layers are recognized (Fig. 6). These primary structures were interpreted as rhythmites by Naipauer et al. (2005c) within a sedimentary sequence of alternating carbonates and calcareous sandstone (Ramos and Vujovich, 2000).

6. Zircon description and U–Pb data

Seven detrital zircon samples from the Caucete Group were analyzed for external morphology and geochronology. Three samples from the El Quemado Formation correspond to quartz–mica metasandstone (QLPcz1) and quartzo-feldspathic metasandstone (QLPcz2) from the Quebrada La Petaca, and quartz–mica metasandstone (QPir3) from Quebrada Las Pirquitas (Figs. 7 and 8). Sample M4 was collected from quartz–mica metasandstone layer interleaved in the La Paz Formation between Quebradas El Molle and El Quemado (Fig. 8). In addition, detrital zircons were analyzed from a metasandstone Qtz-Alb-Ms-Grt (sample M5) from Quebrada Las Pirquitas (Fig. 8). Calcareous metasandstone from the El Desecho Formation (sample M8) was collected from the La Olla area (Fig. 5). A sample of calcareous metasandstones (QLli1) in the Angacos Formation was taken south of Sierra de Pie de Palo in Quebrada La Lichona (not shown in Figs. 7 and 8). The location and description of the samples is presented in Table 1.

6.1. Zircon morphology analysis

Morphological analysis of zircon grains was conducted under binocular and scanning electron microscopes. Four different populations were identified based on color, size, shape, habit, and elongation; the presence of internal cores, fractures, and inclusions was also recorded. Representative grains from the main morphological groups are shown in Fig. 9. The main groups include:

(i) Subrounded to idiomorphic, 100–150 μm zircons with aspect ratios of approximately 3:1 and numerous inclusions.
(ii) Subrounded to idiomorphic, 150 μm zircons with aspect ratios of approximately 4:1, intracrystalline fractures and numerous inclusions.
(iii) Prismatic, 150 and 250 μm zircons with aspect ratios >5:1 and abundant inclusions.
(iv) Small (<100 μm dark-colored, rounded zircons with many inclusions and aspect ratios of <2:1).

6.2. Detrital zircon U–Pb geochronology

6.2.1. El Quemado Formation

A total of 121 zircons from sample QLPcz1 were analyzed, but results from 57 grains were rejected due to discordance of >20%. Concordant zircon ages define four main intervals: 1169–1040 Ma (36%), 1289–1187 Ma (31%), 1350–1300 Ma (22%) and 1434–1391 Ma (8%) (Fig. 10a). There are two single ages at 506 Ma and 1540 Ma. Zircon grains that produce the main peak at *ca.* 1150 Ma are long prismatic crystals with oscillatory zoning typical of plutonic and/or volcanic rocks. The peak at *ca.* 1220 Ma corresponds to zircons with rounded shapes and complex metamorphic textures. Peaks at *ca.* 1310 Ma and 1400 Ma are from zircons with oscillatory zoning characteristic of magmatic origin (Fig. 10a).

Zircon from sample QLPcz2 provided 135 analyses, 36 of which were rejected due to discordance. The remaining 99 grains define three dominant age ranges of 697–532 Ma (peak at *ca.* 550 Ma; 12%), 1228–1042 Ma (peak at *ca.* 1110 Ma; 43%), and 1492–1273 Ma (peak at *ca.* 1360 Ma; 40%). Two grains give ages of *ca.* 1553 Ma and 1697 Ma (Fig. 10b). The youngest zircon group defines two peaks at *ca.* 550 Ma represented by 7% of the population (568–532 Ma) and *ca.* 640 Ma defined by 5% of the population (697–590 Ma) (Fig. 10b). The younger grains are typically large prismatic to moderately rounded crystals with fine oscillatory zoning (Fig. 10b) characteristic of a magmatic origin. The peak at *ca.* 1110 Ma is represented by two groups: oscillatory zoned prismatic grains of probable volcanic origin that yield an age of *ca.* 1090 Ma and round grains of probable metamorphic origin with complex internal textures defined by variable luminescence, recrystallized rims, and ages as old as *ca.* 1200 Ma. The peak at *ca.* 1360 Ma is characterized by large prismatic zircons with oscillatory zoning of magmatic origin (Fig. 10b).

Sample QPir3 was collected from the same unit as the previous sample. Of the total 125 detrital zircons analyzed, 16 were rejected due to discordance. Concordant zircons define three major intervals: 1166–1070 Ma (46%), 1262–1188 Ma (40%), 1340–1274 Ma (11%) and 1476–1439 Ma (3%) with the most representative peaks at *ca.* 1070 and 1120 Ma (Fig. 10c). In addition, there are elongate prismatic grains with igneous zoning textures suggestive of volcanic sources define a peak at *ca*. 1070 Ma. The remaining grains from this sample display metamorphic textures. Subequant prismatic grains with metamorphic textures give peaks at *ca.* 1220 Ma and 1250 Ma (Fig. 10c). An older peak at *ca.* 1340 Ma is defined by metamorphic zircons and a few oscillatory zoned crystals of probable magmatic origin (Fig. 10c). Single zircon ages appear at *ca.* 1476 Ma, 1464 Ma, and 1439 Ma.

6.2.2. La Paz Formation

The zircon grains analyzed in the M4 sample were 125; 13 grains of discordant age (more than 20%) were rejected. The 112 grains with concordant age (<20%) fall in three main age brackets: 977–1166 Ma (77%), 1275–1171 Ma (15%), and 1490–1303 Ma (7%) (Fig. 11a). The dominant peaks at *ca.* 1040, 1070 and 1145 Ma (Fig. 11a) are defined by round zircons of probable metamorphic origin and subordinate prismatic grains with magmatic textures that give ages of *ca.* 1040 Ma (Fig. 11a). Small prismatic, idiomorphic to subidiomorphic, oscillatory zoned igneous grains define the main peak at 1145 Ma as well. Zircons with ages between 1171 Ma and 1275 Ma are of probable metamorphic origin (Fig. 11a) whereas a peak at *ca.* 1360 Ma is defined by magmatic zircons (Fig. 11a). A small grain yielded a single age of 1925 Ma.

In sample M5, 130 detrital zircons were analyzed and 29 discarded. Concordant ages define five intervals: 1062–961 Ma (29%), 1118–1070 Ma (23%), 1171–1121 Ma (22%), 1257–1191 Ma

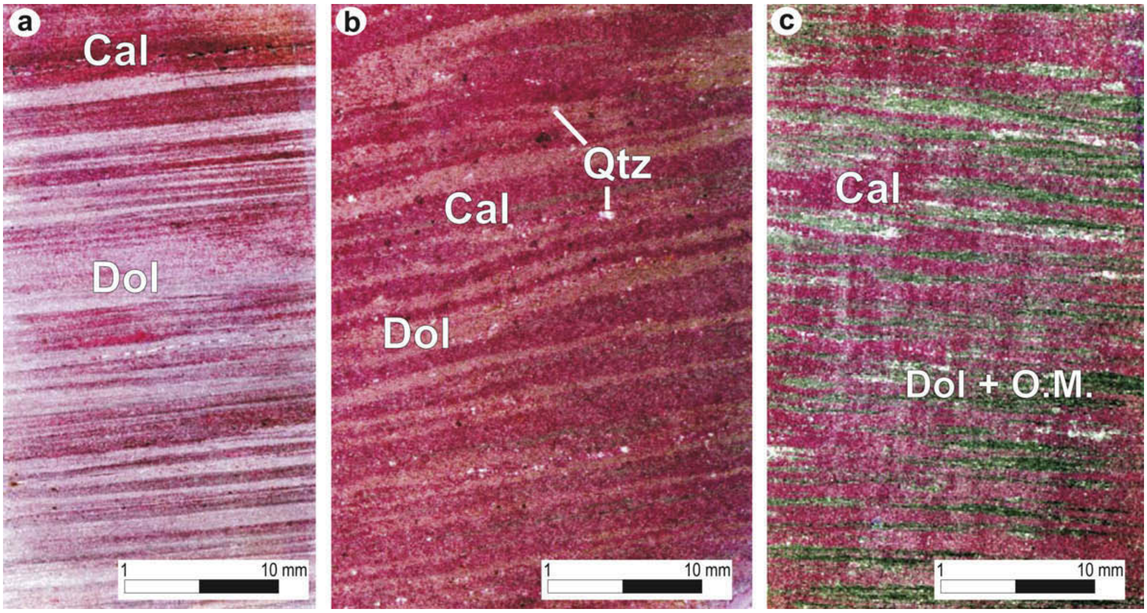

Fig. 6. Rhythmites from the Angacos Formation composed of cyclic alternating limestone and dolostone laminae. Thin sections were prepared with alizarine-red to distinguish calcite from dolomite and terrigenous material. (a) Rhythmites made up of alternating dolosiltites (light colors) and calcarenites (red). Carbonates are fine-grained and terrigenous materials are absent, San Ceferino area. (b) Cyclic laminae of dolosiltites and calcarenites and fine-grained calcarenites. Note detrital quartz and pyrite. Caliza Angacos, Estancia El Altillo area. (c) Rhythmites composed of dolosiltites and calcisiltites. Dolosiltite-layers are very fine-grained, dark, a product of higher organic matter content. Note foliation cross-cutting the original lamination, Quebrada Piedras Pintadas. Cal: calcite, Dol: dolomite, O.M.: organic matter, Qtz: quartz. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

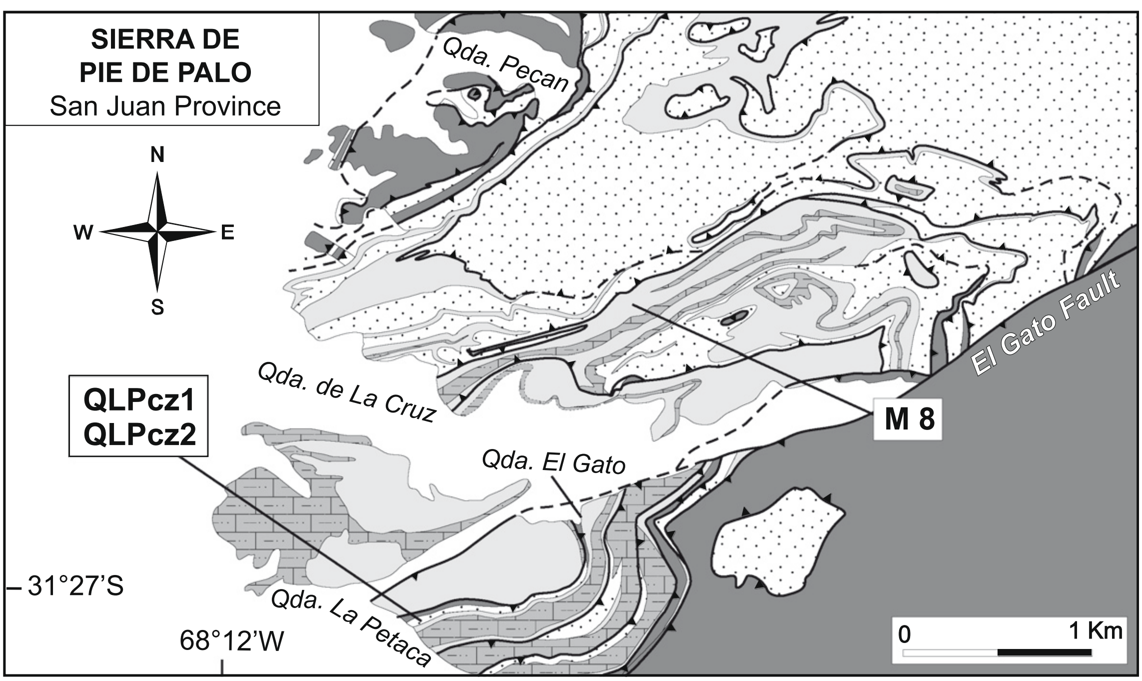

Fig. 7. Geologic map with sample locations in southwestern Sierra de Pie de Palo, El Quemado and El Desecho Formations. See explanation of the units in Fig. 8. Qda.: "Quebrada" (from Van Staal et al., unpublished map). Location in Fig. 1.

(15%) and 1276–1357 (7%) (Fig. 11b). The younger group is dominated by metamorphic zircons. However, prismatic oscillatory zoned zircons that define a peak at *ca.* 1035 Ma are likely of volcanic origin (Fig. 11b). Peaks at *ca.* 1080 Ma, 1135 Ma and 1220 Ma are formed by rounded and subrounded zircon grains, mostly of metamorphic origin. Finally, peaks at *ca.* 1300, 1360 and 1470 Ma are defined by large oscillatory zoned grains of igneous origin (Fig. 11b).

6.2.3. El Desecho Formation

A total of 118 zircon grains were analyzed from sample M8 and 16 were rejected due to discordance. The age produce six age intervals: 531–617 Ma (3%), 1186–1054 Ma (44%), 1293–1203 Ma (19%), 1460–1326 Ma (25%) 1527–1493 Ma (3%) and 1677–1574 Ma (7%) (Fig. 12a). The peak at *ca.* 550 Ma is defined by prismatic, subrounded oscillatory zoned grains with of probable igneous origin (Fig. 12a). The largest peak at *ca.* 1120 Ma is due

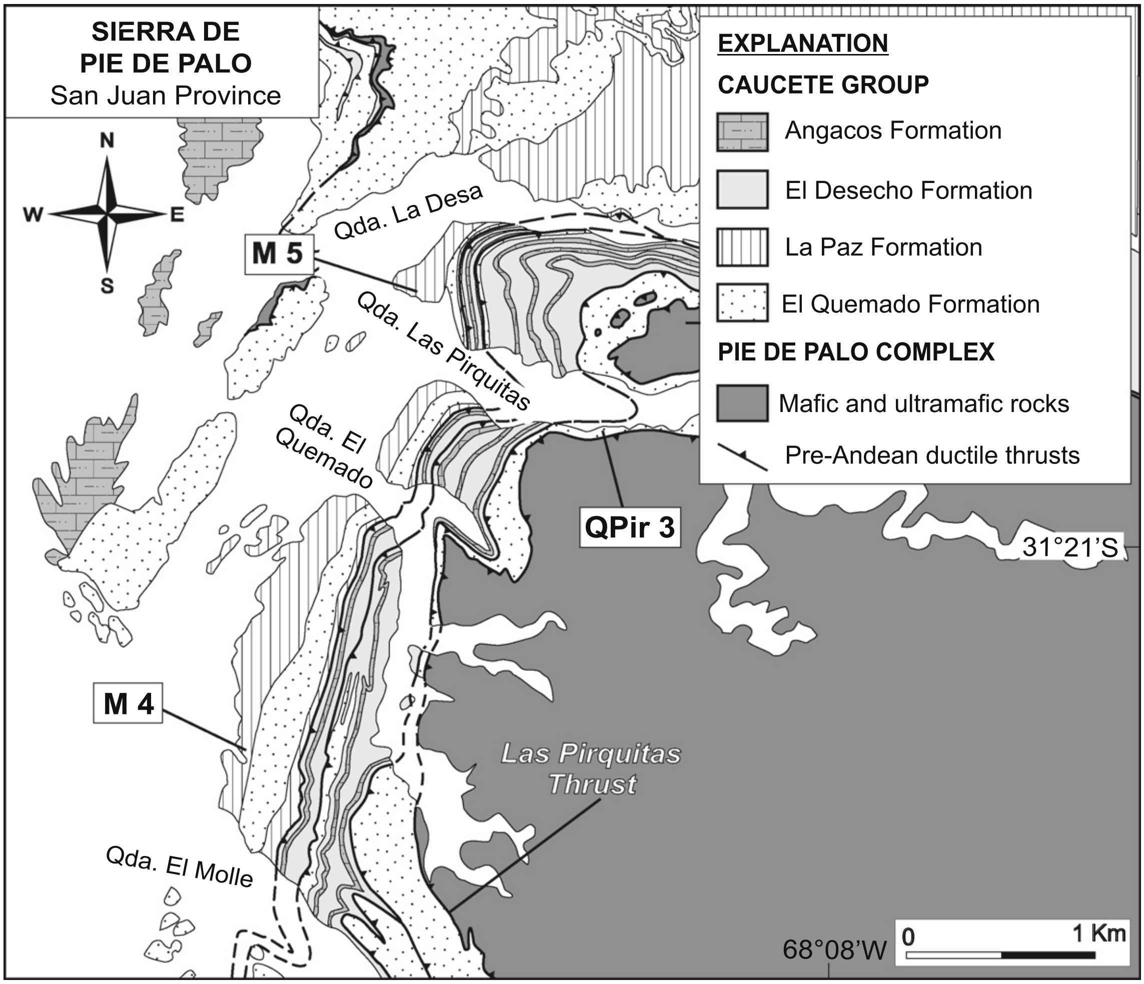

Fig. 8. Geologic map with sample locations of the La Paz and El Quemado Formations, central-western Sierra de Pie de Palo (from Van Staal et al., unpublished map). Location in Fig. 1.

Table 1
Location, major mineral composition and field classification of the analyzed samples, Caucete Group, Sierra de Pie de Palo, Argentina.

Sample location	Major mineral composition	Rock type
El Quemado Formation		
QLPcz1 La Petaca Creek	Qtz, Ms, Kfs, Plag, Zrn, Mo, Op	Meta-sandstone Qtz-Ms
QLPcz2 La Petaca Creek	Qtz, Kfs, Plag, Ms, Zrn, Mo, Op	Meta-sandstone Qtz-Kfs-Ms
QPir3 Las Pirquitas Creek	Qtz, Ms, Kfs, Plag, Zrn, Mo, Op	Meta-sandstone Qtz-Ms
La Paz Formation		
M4 La Paz Creek	Qtz, Plag, Ms, Zrn, Mo, Op	Meta-sandstone Qtz-Ms
M 5 La Paz Creek	Qtz, Plag, Ms, Grt, Zrn, Mo, Op	Meta-sandstone Qtz-Alb-Ms-Grt
El Desecho Formation		
M 8 La Olla area	Qtz, Ca, Kfs, Plag, Zrn, Mo, Op	Meta-calcareous sandstone
Angacos Formation		
QLli 1 La Lichona Creek	Qtz, Kfs, Ca, Zrn, Mo, Op	Meta-calcareous sandstone

to subrounded prismatic grains interpreted to be of metamorphic origin. Grains that yield a minor peak at *ca.* 1070 Ma are subrounded elongate prismatic grains with oscillatory zoning indicating magmatic origin (Fig. 12a). The peaks at *ca.* 1240 Ma and 1380 Ma are defined prismatic oscillatory zoned igneous zircons. Finally, the peaks at *ca.* 1450 Ma and 1600 Ma consist of low luminescence grains of probable metamorphic origin (Fig. 12a).

6.2.4. Angacos Formation

Sample QLli1 provided 142 analyses, 33 of which are discordant. The remaining 109 concordant analyses are distributed in two major intervals: 1148–1050 Ma (peak at *ca.* 1114 Ma, 35%) and 1471–1313 Ma (dominant peaks at *ca.* 1373 Ma, 1400 Ma and 1450 Ma; 58%). Isolated ages are present in the interval 1312 to 1149 Ma (7%) as well as in the Paleoproterozoic (Fig. 12b). Grains contributing to the peak at *ca.* 1114 Ma have complex internal textures characteristic of a metamorphic origin, but some grains with igneous textures are observed (Fig. 12b). The main peak at *ca.* 1373 Ma is defined by zircons with igneous textures with a minor proportion of grains displaying complex textures of probable metamorphic origin (Fig. 12b).

7. Discussion

7.1. Principal populations and age components

The morphological and CL analysis of detrital zircons allowed definition of two populations composed of zircon grains with prismatic habit, oscillatory zoning, cores and inclusions but with different sizes. These features indicate a source area dominated by

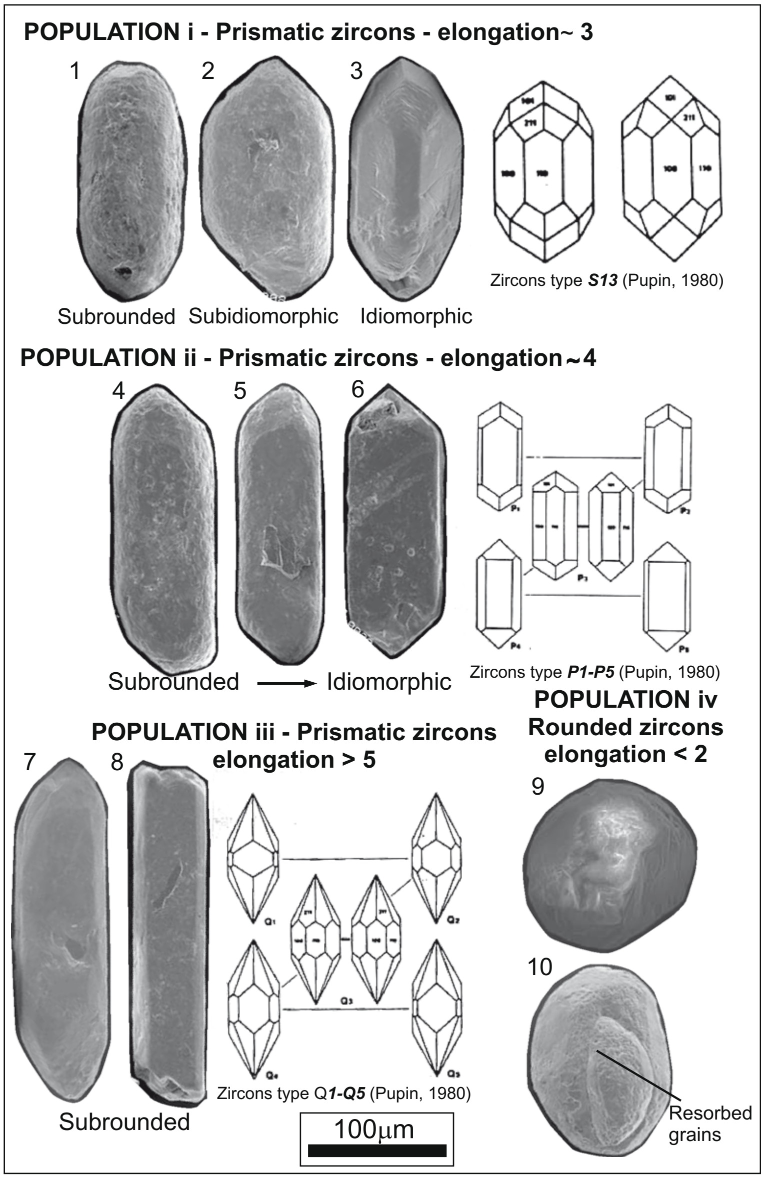

Fig. 9. Scanning electron microscope images of zircons showing external morphology. All grains were separated from rocks of the Caucete Group. Variable morphology in terms of length-to-width ratios; zircon grain classification of Pupin (1980).

plutonic igneous rocks. Moreover, the presence of zircons with long prismatic habit indicates a probable third source with input from volcanic rocks. Finally, a population of rounded zircons with complex internal zoning probably indicates origin from metasedimentary rocks that were products of various sedimentary cycles. These variations taken together with U/Pb (LA-ICP-MS) age determinations were used to characterize the main sources of sediment input for the Caucete Group.

Two Mesoproterozoic sources were identified (Table 2). The oldest source with early Mesoproterozoic ages (*ca.* 1450–1300 Ma) includes plutonic and volcanic rocks. A second source has metamorphic and subordinate igneous rocks of late Mesoproterozoic age (1300–1000 Ma; Grenvillian). Other subordinate zircons with Neoproterozoic and Paleoproterozoic ages indicate different sources.

The early Mesoproterozoic source furnished igneous zircons with three main frequency peaks: *ca.* 1370, 1360 and 1310 Ma. These zircons are present in all of the samples analyzed from the Caucete Group. It is the second dominant group in the El Quemado Formation, representing from 11% to 40% of the total population. In contrast, these ages are subordinate in the La Paz Formation with peaks at *ca.* 1360 Ma (7%). The *ca.* 1380 Ma peak in the El Desecho Formation represents 25% of the total population, whereas the dominant *ca.* 1373 Ma peak in the Angacos Formation is defined by 58% of the analyzed grains. This difference is interpreted to reflect a major change in source area for Caucete Group sediments (see Table 2).

The late Mesoproterozoic metamorphic zircons are distributed in a range between 1293 and 997 Ma. This group is the most statistically significant in both the El Quemado Formation with 43–86% of the population (Table 2) and the La Paz Formation (89–92%). This observation indicates that metamorphic basement of late Mesoproterozoic age was a constant source area during deposition of the La Paz and El Quemado Formations. The Mesoproterozoic "Grenvillian" population is represented by 63% of the grains from the El Desecho Formation and decreases to 42% in the Angacos Formation. This trend indicates that the Mesoproterozoic source area decreases in importance in the upper units of the Caucete Group.

A different Mesoproterozoic source is represented by a population of volcanic zircons with ages between *ca.* 1070 and 1030 Ma. This "Grenvillian" population is abundant in the La Paz Formation,

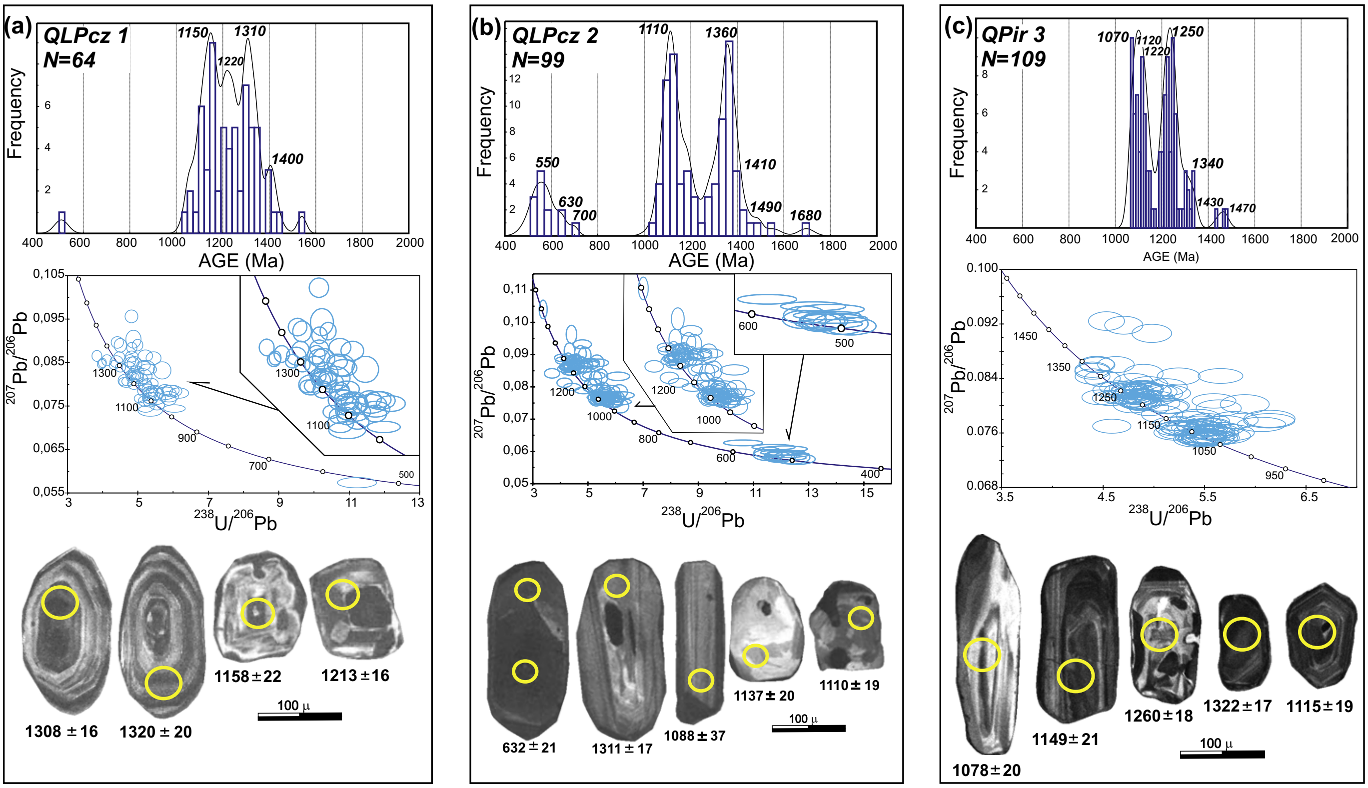

Fig. 10. Frequency histograms and relative probability plots of ^{207}Pb/^{206}Pb ages on detrital zircons from El Quemado Formation. (a) Sample QLPcz1; (b) sample QLPcz2; and (c) sample QPir3. Tera-Wasserburg concordia diagrams and cathodoluminescence images of representative detrital zircons are shown.

as well as the El Quemado and El Desecho Formations. Magmatism in the source region of the Neoproterozoic igneous grains was probably contemporaneous with, or slightly older than, deposition of the Caucete Group.

7.2. Maximum depositional age

Detrital zircon data can provide limits on the maximum depositional age of sedimentary rocks as long as the data set is representative and statistically robust and there is sufficient knowledge of the geological setting and possible source regions (Andersen, 2005). This approach is complicated in metasedimentary rocks such as the Caucete Group due to the potential presence of metamorphic overgrowths of grains.

The youngest zircons in the El Quemado Formation exhibit a range of ^{238}U/^{206}Pb ages between *ca.* 492 and 506 Ma. These ages are problematic because they are close to the 490–450 Ma interval, the time of the Famatinian orogeny. Similar ages obtained in the Sierra de Pie de Palo have been interpreted as results of the Famatinian orogenic event (Ramos et al., 1998; Casquet et al., 2001; Vujovich et al., 2004). Accordingly, the dominant peak of ^{207}Pb/^{206}Pb ages at *ca.* 550 Ma defined by 10% of total zircon grains analyzed from sample QLPcz2 is interpreted as the best estimate of the maximum depositional age of El Quemado Formation. This age may in fact be too young due to possible Pb loss due to Famatinian metamorphism. Several early Cambrian (*ca.* 531 Ma) zircons are present in the El Desecho Formation as well. By comparison with the *ca.* 550 population of the El Quemado Formation, a similar maximum age of deposition is interpreted for the El Desecho Formation.

7.3. Source regions

The detrital zircon results allow comparison of the Caucete Group sedimentary rocks with possible sources areas in either Gondwana or Laurentia. The detrital ages can also be compared with ages derived from basement areas of the Cuyania composite terrane, as well as sedimentary and metasedimentary rocks exposed in neighbouring areas that are similar in age to the Caucete Group.

7.3.1. Gondwanan sources

Mesoproterozoic detrital ages of the Caucete Group can be compared with Gondwana basement ages, especially those of the Amazonian craton. Ages between *ca.* 1450 and 1300 Ma are widely represented in the geochronological province of Rondonia – San Ignacio in the southwestern Amazonian craton, where gneisses, migmatites and granulites *ca.* 1550 to 1300 Ma are exposed (Tassinari et al., 2000). Moreover, ages of the "Grenvillian" zircons of the Caucete Group are comparable to those of the Sunsás belt, located in the southwestern Amazonian craton (Tassinari et al., 2000; Santos et al., 2008). Thus Gondwana is a possible source for Mesoproterozoic zircons of the Caucete Group.

However, significant differences exist between the Caucete Group and the Neoproterozoic–Cambrian metasedimentary rocks on the Gondwana margin. Gondwanan units in northern and central Argentina such as the Puncoviscana Formation and other units in the Sierras Pampeanas are characterized by an absence of *ca.* 1450–1300 Ma detrital zircon ages (see Rapela et al., 1998; Sims et al., 1998; Schwartz and Gromet, 2004; Adams et al., 2006; Escayola et al., 2007; Collo et al., 2009). Similarly, grains of this age are not common in the Neoproterozoic–lower Paleozoic cover of the Rio de la Plata craton either (Rapela et al., 2007; Gaucher et al., 2008). Thus, the Gondwana margin is not a likely source region for the Caucete Group.

7.3.2. Laurentian sources

There are numerous potential source areas in Laurentia for detrital zircons of the Caucete Group. In particular, we examine

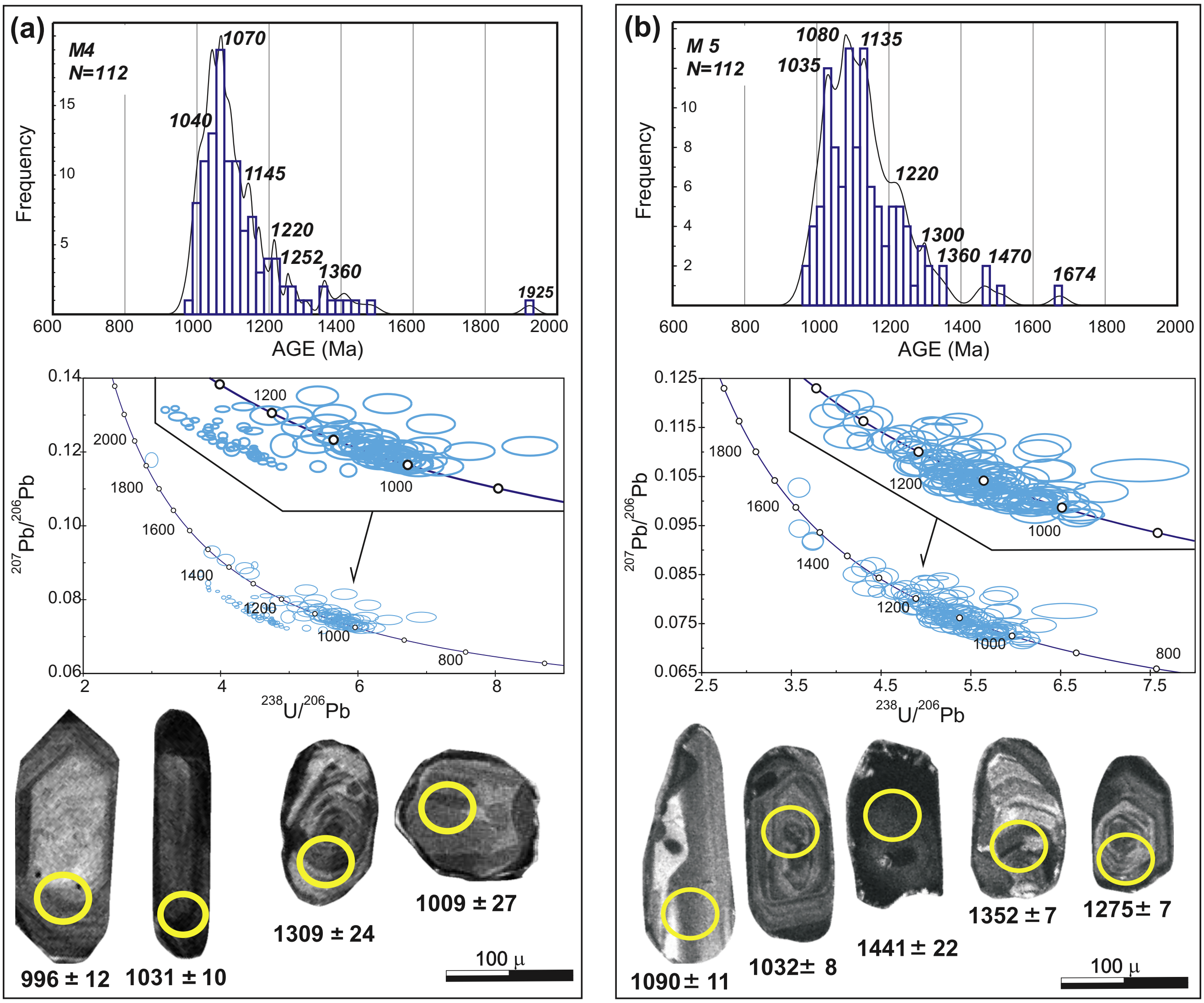

Fig. 11. Frequency histograms and relative probability plots of $^{207}Pb/^{206}Pb$ ages on detrital zircons from La Paz Formation. (a) Sample M4 and (b) sample M5. Tera-Wasserburg concordia diagrams and cathodoluminescence images of representative detrital zircons are also shown.

sources close to Ouachita embayment: Yavapai and Mazatzal provinces (south-central to southwestern Laurentia), Granite-Rhyolite province (central and southern Laurentia), and the Grenville province exposed in the southern Appalachian region (eastern Ouachita Basin) and Llano Uplift-Van Horn-Franklin Mountain areas in the western Ouachita Basin.

Sources for older grains are wide spread in Laurentia. Paleoproterozoic metamorphic detrital zircons of the Caucete Group are compatible with the *ca.* 1800–1600 Ma Yavapai-Mazatzal province of south-central to southwestern Laurentia. Paleoproterozoic detrital ages observed in the Cambrian Cerro Totora Formation from the Precordillera have been attributed to a Laurentian source as well (Thomas et al., 2004). Early Mesoproterozoic ages from plutonic and volcanic detrital zircons of the Caucete Group coincide with the ages of the Granite-Rhyolite province in southern and central Laurentia (Muehlberger et al., 1967; Van Schmus et al., 1987).

The Provenance of late Mesoproterozoic or "Grenvilian" detrital zircons in the Caucete Group is straight forward since Grenvillian basement is well documented along the southern Laurentian margin. The Llano Uplift (central Texas) and Van Horn-Franklin Mountain region (west Texas) contain exposures with ages of *ca.* 1320–1000 Ma (Roback, 1996; Mosher, 1998). Zircons with *ca.* 1300 Ma of the El Quemado, La Paz and El Desecho Formation are consistent with *ca.* 1330–1270 Ma magmatic rocks in the Llano Uplift (Roback, 1996). Igneous zircon ages *ca.* 1115, 1070 and 1030 Ma of the Caucete Group are compatible with *ca.* 1135–1070 Ma granite plutons in central Texas (Walker, 1992; Reed et al., 1995). The most representative outcrops of the southern Appalachian basement are in the Blue Ridge province. The *ca.* 1220–1160 Ma Caucete Group detrital zircon ages are comparable to the *ca.* 1190 Ma Grenvillian basement exposures in the southern Appalachians (Carrigan et al., 2003). Igneous zircon ages of *ca.* 1115, 1070 and 1030 Ma are compatible with the southern Appalachian basement as well (Bickford et al., 2000; Carrigan et al., 2003; Tollo et al., 2006).

Finally, the Neoproterozoic igneous zircons found in the El Quemado Formation (*ca.* 630–550 Ma) are interpreted to reflect magmatic activity in the source area. Rifting occurred along the southern and eastern Laurentian margins in Neoproterozoic to Cambrian times, in response to the opening of Iapetus and leading to terrane separation (Cawood et al., 2001; Tollo et al., 2004). The Neoproterozoic zircons from the El Quemado Formation are interpreted to have been derived source areas affected by rift-related magmatic activity at *ca.* 620–550 Ma. The *ca.* 531 Ma zircon ages of the El Desecho Formation may relate to a final magmatic stage (*ca.* 540–535 Ma) associated with the rift of the Cuyania terrane (Cawood et al., 2001).

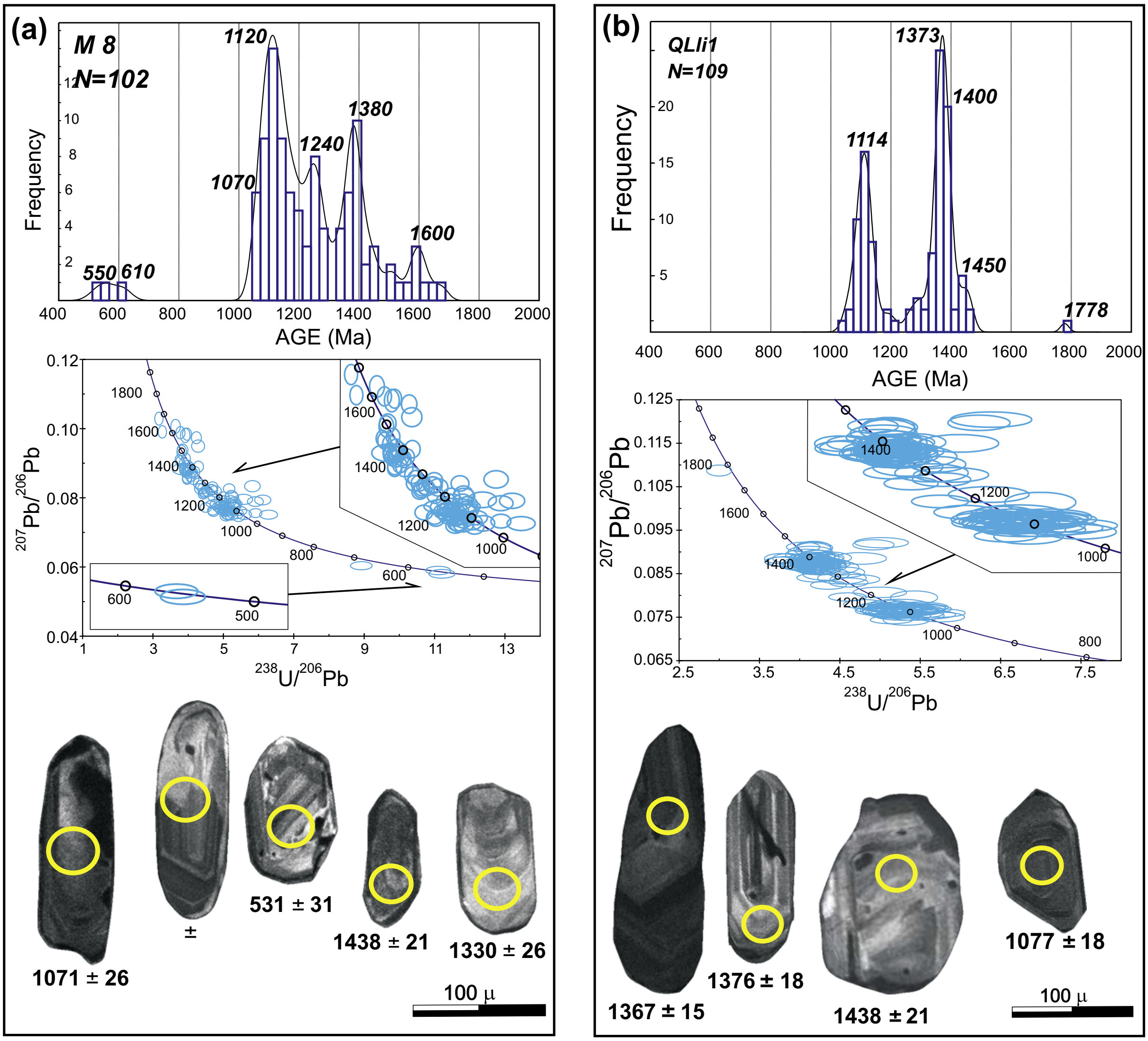

Fig. 12. Frequency histograms and relative probability plot of ^{207}Pb/^{206}Pb ages on detrital zircons from: (a) Sample M8, El Desecho Formation and (b) Sample QLli1 in a siliciclastic layer of the Angacos Formation. Tera-Wasserburg concordia diagrams and cathodoluminescence images of representative detrital zircons are also shown.

Table 2
Major detrital zircon age population defined for the Caucete Group, Sierra de Pie de Palo, Argentina.

Stratigraphic formation	Sample number	Major zircon age populations (Ma)	Neoproterozoic-Cambrian grains	Mesoproterozoic grains	
				(1.0–1.3 Ga) (%)	(1.3–1.45 Ga) (%)
El Quemado	QLPcz1	1169–1040 (36%), 1289–1187 (31%), 1350–1300 (22%) and 1434–1391 (8%)	<2	67	30
	QLPcz2	697–532 (12%), 1228–1042 (43%) and 1492–1273 (40%)	12	43	40
	QPir3	1166–1070 (46%), 1262–1188 (40%), 1340–1274 (11%) and 1476–1439 (3%)		86	11
La Paz	M4	977–1166 (77%), 1275–1171 (15%) and 1490–1303 (7%)		92	7
	M5	1062–961 (29%), 1118–1070 (23%), 1171–1121 (22%), 1257–1191 (15%) and 1276–1357 (7%)		89	7
El Desecho	M8	531–617 (3%), 1186–1054 (44%), 1293–1203 (19%), 1460–1326 (25%), 1527–1493 (3%) and 1677–1574 (7%)	3	63	25
Angacos	QLli1	1148–1050(35%), 1312–1149 Ma (7%) and 1471–1313(58%)		42	58

7.3.3. Cuyania basement source

The igneous zircon populations with ages of *ca.* 1115 Ma, 1070 Ma and 1030 Ma in the Caucete Group, are broadly similar to those of the Mesoproterozoic Cuyania basement (1060 ± 20 Ma, McDonough et al., 1993; 1021 ± 12 Ma, Rb/Sr isochron, Pankhurst and Rapela, 1998; 1105 Ma, U/Pb SHRIMP age, Morata et al., 2008). Caucete Group detrital zircon ages of *ca.* 1220 and 1150 Ma clearly match ages in the crystalline basement as well (Vujovich et al., 2004).

The U/Pb detrital zircon peaks at *ca.* 1160–1150 Ma and 1080–1050 Ma in the Neoproterozoic Difunta Correa Unit (Vujovich et al., 2004) are equivalent to peaks observed in the Caucete Group (*ca.*

1150 Ma, 1070 Ma and 1030 Ma). Zircon ages between 1100 and 1050 Ma from a para-amphibolite within the Difunta Correa Unit (Rapela et al., 2005) are similar to those in the Caucete Group as well. Finally, *ca.* 1220 Ma Caucete Group zircon ages match the age of the Las Matras pluton (1244 ± 42 Ma, Sato et al., 2004) and are similar to orthogneiss ages from the San Rafael block (1205 ± 1 and 1204 ± 2 Ma, Thomas et al., 2000) and other granitic rocks of the Cerro La Ventana Formation (1214.7 ± 6.5 Ma, Cingolani et al., 2005).

Mesoproterozoic ages are observed in the northern Cuyania terrane. The Juchi Orthogneiss of the Sierra de Umango gives an age of 1108 ± 13 Ma (Varela et al., 2003). Granitic mylonites and ultramylonites in the Jagüé area are similar in age (1118 ± 17 Ma, Martina et al., 2005). These crystallization ages are consistent with the *ca.* 1115 Ma igneous zircons in the Caucete Group. Moreover, detrital igneous zircon ages of *ca.* 1100–1080 Ma (Casquet et al., 2008) and metamorphic zircon ages of *ca.* 1220 Ma (Casquet et al., 2006) observed in the Sierra de Maz are similar to detrital zircon ages from the Caucete Group.

Crustal xenoliths in Miocene subvolcanic rocks in the Argentine Precordillera (Leveratto, 1968) show the existence of metamorphic basement beneath the Cambro–Ordovician carbonate platform. Kay et al. (1996) compared the Pb isotope signature from those xenoliths of the Cuyania basement with rocks of Sierra Pie de Palo and of the Llano Uplift (Texas) in Laurentia. The felsic and mafic xenoliths yielded U/Pb zircon ages about 1099 ± 3, 1102 ± 6, 1096 ± 3 Ma (Kay et al., 1996) comparable with ages between 1115 and 1070 Ma found in the Caucete Group and in the Grenvillian rocks of Texas.

In summary, detrital zircon ages from the Caucete Group are consistent with ages observed in Laurentia. Mesoproterozoic and older Laurentian sources are well represented in the Yavapai-Mazatzal province, Granite-Rhyolite province, and Grenville province. Neoproterozoic to Cambrian source regions include areas along the southern and eastern Laurentian margin affected by rift-related magmatic activity. The Laurentian basement of Cuyania itself may have contributed detritus as well (e.g. Sierra de Pie de Palo, Precordilleran basement, and Sierras de Umango and Maz).

8. Stratigraphic relationships and depositional associations

Deposition of the Caucete Group occurred from the late Neoproterozoic to early Cambrian (*ca.* 550–515 Ma) as constrained by U/Pb detrital zircon ages reported herein and by previous isotopic studies (Galindo et al., 2004; Naipauer et al., 2005a,b) (Fig. 13). Field relationships, petrographic and geochronologic data show different sedimentary protoliths and tectonic settings for the metasedimentary rocks of the Caucete Group.

The El Quemado Formation is attributed to a rift setting on the basis of the sedimentary protolith and the igneous zircon source that is close in age to the time of deposition. A similar tectonic setting has been proposed for the southern and eastern margins of Laurentia at approximately 550 Ma. The La Paz Formation, consisting of volcanogenic pelites interbedded with fine sandstones, was deposited in a more distal environment than that of the El Quemado Formation. A similar tectonic setting is inferred for the La Paz Formation on the basis of the interbedded and transitional boundary between the two units (Fig. 13). The El Desecho Formation is a heterogeneous sequence of pelites, calcareous and dolomitic marbles, calcareous sandstone, and subordinate conglomerates. This unit was correlated with the Cerro Totora Formation of the Precordillera and both are interpreted to reflect rift sedimentation (Fig. 13). Finally, the more homogeneous sedimentary protolith of Angacos Formation, composed mainly of limestone and marbles, is similar to the La Laja Formation (El Estero and Soldano Members) of the Precordillera (Fig. 13). The tectonic setting of sedimentation for these rocks inferred as a passive margin developed on the Cuyania terrane.

Accordingly, two events of rift-stage sedimentation are distinguished. The first is defined by the maximum depositional age of the El Quemado Formation (*ca.* 550 Ma) which interfingers with the La Paz Formation. The second stage is represented by the El Desecho Formation with a maximum depositional age of *ca.* 531 Ma. The late Mesoproterozoic (Grenvillian) detrital zircons in the El Quemado, La Paz and El Desecho Formations were probably derived from a nearby positive feature such as a rift bulge. Older detrital components were likely sourced by more distal areas in the interior of the Laurentia craton such as the Granite-Rhyolite province and Yavapai-Mazatzal area.

The Angacos Formation is interpreted as a platform carbonate sequence developed at *ca.* 520 and 515 Ma on the passive margin of the Cuyania terrane (Fig. 13). The provenance pattern for this unit is different from those for the El Quemado, La Paz and El Desecho Formations. Neoproterozoic–Cambrian zircons are absent and late Mesoproterozoic zircon ages are subordinate, indicating that these sources were partially covered by the carbonate platform. The most important sediment source was the Granite-Rhyolite province (Fig. 13). The Angacos Formation is interpreted to have developed upon Grenvillian basement and older units of the Caucete Group, only receiving more distally derived detrital components.

9. Tectonic model for the rift – passive margin transition

The tectonic evolution of Cuyania composite terrane that is most widely accepted initiates with rifting from the Ouachita embayment of Laurentia in the early Cambrian, development of a passive margin in latest early Cambrian to lower Ordovician, and collision with the Gondwana margin in the middle – late Ordovician (e.g., Astini et al., 1995; Thomas and Astini, 1996; Ramos, 2004). Rift sedimentation in the Precordillera region is only recorded by the Cerro Totora Formation (Astini and Vaccari, 1996); strontium data from this unit are consistent with continental rifting during early Cambrian (Thomas et al., 2001). The transition from the synrift deposition of the Cerro Totora Formation to the passive margin deposition is documented by the late Early Cambrian Los Hornos and La Laja Formations (Astini et al., 1996).

The detrital zircon record of the Caucete Group is generally consistent with the classical rift and passive margin stages of Cuyania terrane. However, the El Quemado and La Paz Formations record older stages of rifting not observed elsewhere in the Precordillera region. This observation indicates initial separation of Cuyania much earlier in the end of the Neoproterozoic (*ca.* 575–550 Ma), a view consistent with the age of rift-related magmatism in the western Precordillera (Davis et al., 2000). Also, the detrital zircons have demonstrated that the Cuyania basement have a portion of the Granite-Rhyolite province in the northern sector (Fig. 4).

The major stages that were distinguished in the tectonic–stratigraphic evolution in the Caucete Group were as following.

9.1. Rift stage I (ca. 550 Ma)

Initial rifting in the Ouachita embayment (Fig. 15a) likely started during a second extensional pulse between 620 and 550 Ma along the Laurentia margin (Tollo et al., 2004) that resulted in opening of Iapetus and separation of Laurentia from Gondwana at *ca.* 570 Ma (Cawood et al., 2001). Deposition of the Caucete Group within the Ouachita basin is inferred to start prior to final separation of Cuyania from Laurentia. The northern portion of the Cuyania terrane is interpreted to be part of the Granite-Rhyo-

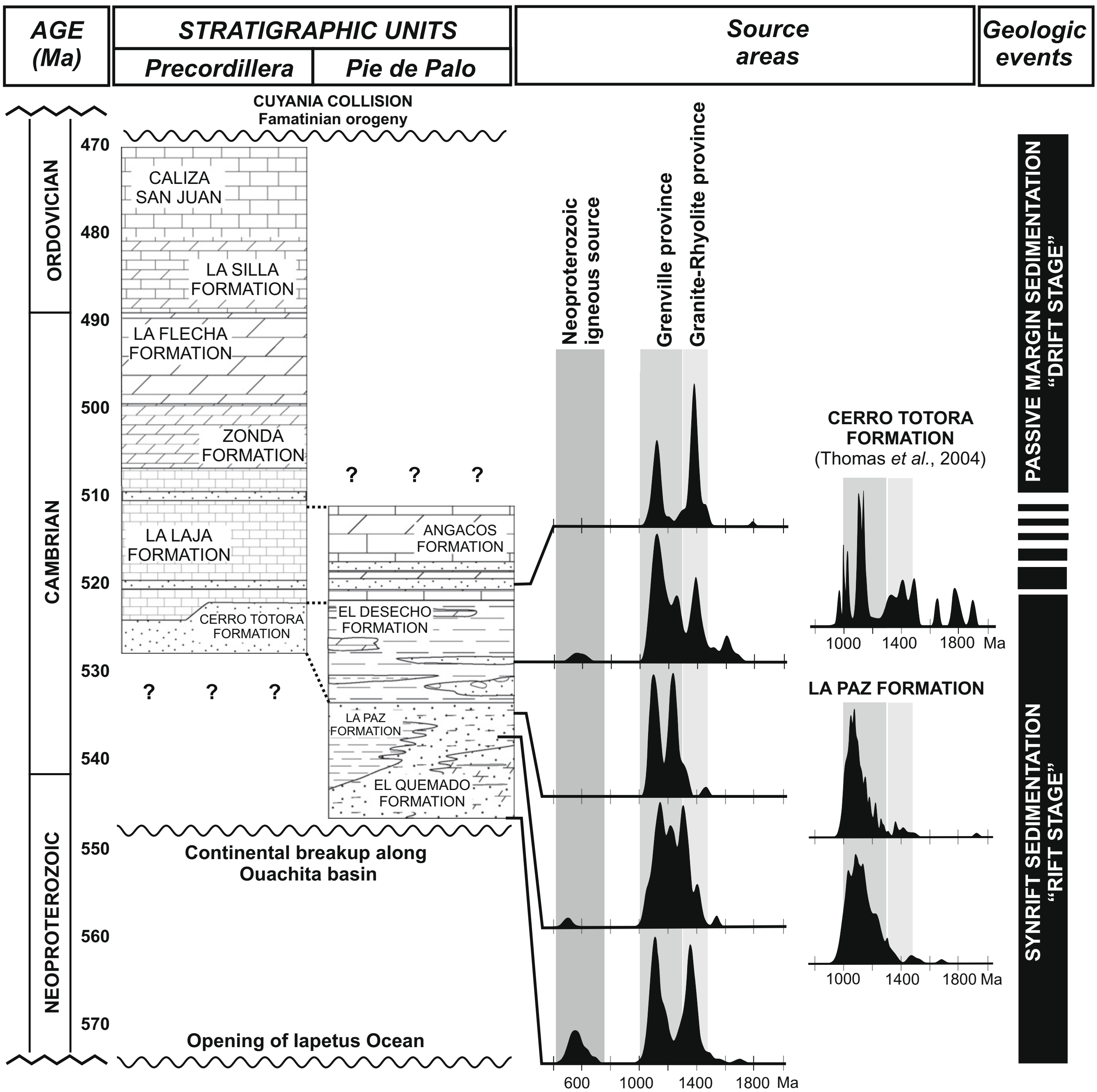

Fig. 13. Stratigraphic correlation of Caucete Group and Cambrian–Ordovician units of the Precordillera (after Thomas and Astini, 1999) and summary of detrital zircon ages and source areas for the Caucete Group. Ages of geological events summarized by black bars.

lite province (Thomas et al., 2000). The El Quemado and La Paz Formations reflect synrift sedimentation at *ca.* 545 Ma (Fig. 15b), prior to deposition of the Cerro Totora Formation. Provenance ages demonstrate a clear connection between the early sediments of the Caucete Group and the southern Laurentian margin (e.g., Granite-Rhyolite and Grenville provinces). The presence of igneous detrital zircons with ages close to 550 Ma allows the interpretation of rift-related magmatic rocks in the source area (Fig. 15b).

9.2. Rift stage II (ca. 531 Ma)

The southern Cuyania terrane is inferred to largely be underlain by Grenvillian basement (Fig. 16, see location of B–B′ in Fig. 14). The second sedimentary stage of the Caucete Group is recorded by synrift deposits of the El Desecho Formation with a maximum depositional age of *ca.* 531 Ma. This unit probably developed during transition to a thermal subsidence stage. El Desecho Formation is correlative with the synrift deposits of Cerro Totora Formation exposed in the northern Precordillera (Astini et al., 1995) (Fig. 16a), but the units accumulated in different depocentres as indicated by the differences in their detrital zircon signature.

U/Pb detrital zircon ages of *ca.* 1600, 1380, 1240, 1120, 1070 and 550 Ma from the El Desecho Formation are similar to those from the El Quemado Formation. Thus the basin configuration and source areas are interpreted to be similar and both record continued connection with Laurentia. Consistent with this hypothesis,

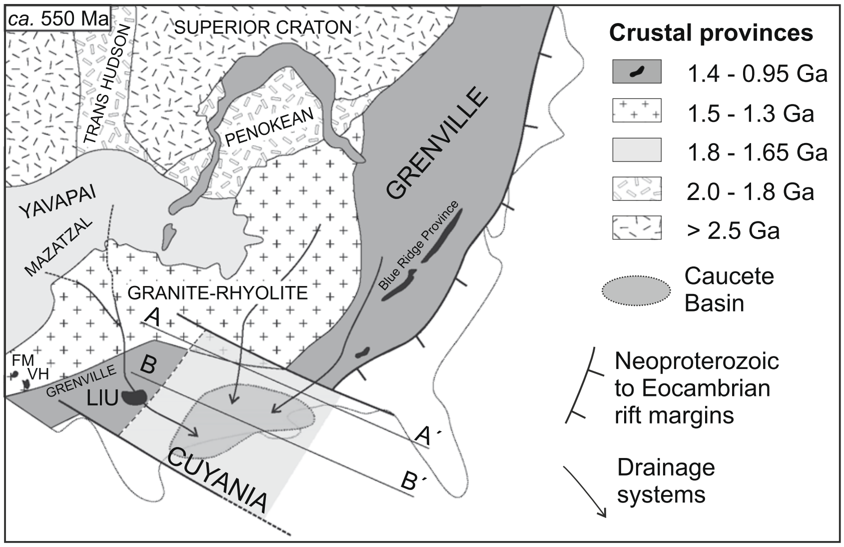

Fig. 14. Sketch map showing crustal provinces of Laurentia (after Van Schmus et al., 1996; Thomas et al., 2004) and the paleoposition of Cuyania in relation to potential source regions for Caucete Group sediments. A–A′ and B–B′ mark location of cross sections in Figs. 15 and 16. FM: Franklin Mountains; LlU: Llano Uplift; VH: Van Horn Mountains.

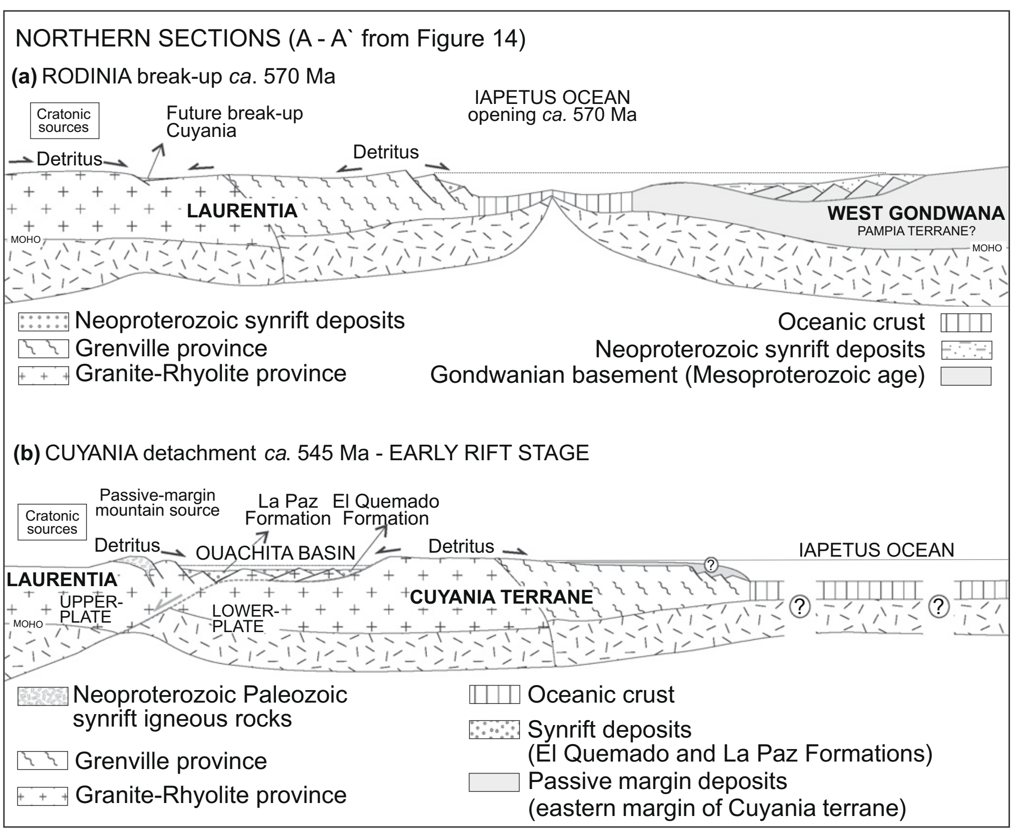

Fig. 15. Diagrams of the late Neoproterozoic and early Paleozoic evolution of the Cuyania terrane. Sedimentary basins have been exaggerated in thickness. (a) Sketch profile at Rodinia break-up at *ca.* 570 Ma (from Cawood et al., 2001). (b) Cuyania separation at *ca.* 545 Ma, early rift stage characterized by synrift sedimentation (El Quemado and La Paz Formations); upper- and lower-plate rift margins after Thomas and Astini (1999). Note that basement is interpreted as composed of rocks of both Granite-Rhyolite and Grenville provinces.

detrital zircons from the Cerro Totora Formation define populations of *ca.* 1490–1300 Ma and *ca.* 1890–1640 Ma that are characteristic of the Laurentian craton interior (Thomas et al., 2004).

9.3. Passive margin stage (ca. 520 Ma)

The initial separation of the Cuyania terrane and generation of a passive margin occurred at approximately 520 Ma (Fig. 16b). The

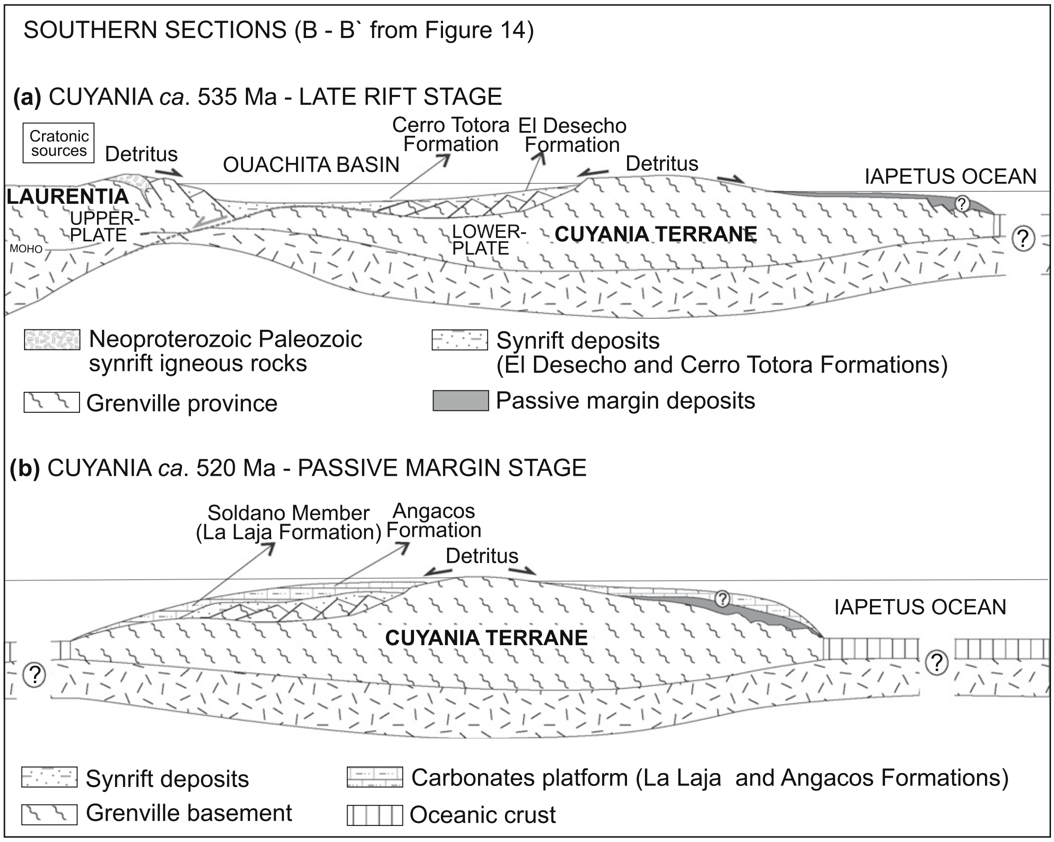

Fig. 16. Diagrams of the early Paleozoic evolution of the Cuyania terrane. Sedimentary basins have been exaggerated in thickness. (a) Sketch profile for late rift stage characterized by synrift sedimentation (El Desecho and Cerro Totora Formations); upper- and lower-plate rift margins after Thomas and Astini (1999). (b) Cuyania passive margin stage at *ca.* 520 Ma, characterized by carbonate platform deposits (Angacos and La Laja Formations). Note that basement is composed of Grenvillian components in the southern section.

Angacos Formation was deposited during a third stage in Caucete Group sedimentation. The unit is comparable in age and depositional setting to the limestones of the Los Hornos and La Laja Formations of the Precordillera (Fig. 16b). The occurrence of siliciclastic interbeds in the carbonates indicates a proximal uplifted area in the Cuyania terrane. In addition, lower members of the La Laja Formation contain many quartz sandstone interbeds (Pereyra, 1987; Finney et al., 2005). These siliciclastic interlayers reflect deposition in a basin near an exhumed basement area (Gómez and Astini, 2006).

The zircon population at *ca.* 1118 Ma from the Angacos Formation shows that Grenvillian basement of Cuyania was partially exposed at the time of deposition. However, this source was subordinate to the early Mesoproterozoic (*ca.* 1450–1300 Ma) source area. The Grenvillian basement was partially overlapped by deposits of the El Quemado, La Paz and El Desecho-Cerro Totora Formations, and by subsequent passive margin sediments. Detrital zircons with ages around 1360 Ma are dominant in the early to middle Cambrian units of the Angacos Formation. Thomas et al. (2000), suggest that the northwest corner of the Precordillera consists of a small portion of the Granite-Rhyolite province, as shown in the sections of northern Cuyania (Figs. 14 and 15b). This alternative is supported by data from basement clasts in conglomerate olistoliths in the western Precordillera, where zircon ages of *ca.* 1370 ± 2 and 1367 ± 5 Ma (Thomas et al., 2000) are similar to the ages from the Angacos Formation. Regardless of the basement correlations, deposition of the Angacos Formation likely records the post-rift phase as Cuyania started to drift through the Iapetus (Thomas and Astini, 1996). Since middle Cambrian to lower Ordovician ophiolitic rocks are not observed in Laurentia or Cuyania terrane (Dalziel, 1997; Keller, 1999), the presence of oceanic crust in the western sector of the Cuyania terrane is queried in Fig. 16b during the middle Cambrian to lower Ordovician. Nevertheless, the Angacos Formation and coeval units of the Precordillera were likely removed from Laurentian detrital sources.

10. Conclusions

Provenance analysis of detrital zircons from the Caucete Group supports the hypothesis that these metasedimentary rocks are partial equivalents to lower Paleozoic strata of the Precordillera and that the Cuyania terrane was an allochthonous Laurentian-derived microcontinent that collided against to Gondwana. The maximum depositional ages for the Caucete Group are *ca.* 550 Ma for the El Quemado Formation and *ca.* 531 Ma for El Desecho Formation. The El Quemado and La Paz Formations define an early rift stage and lack depositional equivalents in the Precordillera. A second pulse of rifting is represented by the El Desecho Formation and its correlative, the Cerro Totora Formation in the Precordillera. Limestones at the top of the Angacos Formation and correlative fossiliferous Los Hornos and La Laja Formations of the Precordillera suggest evolution toward a carbonate-dominated passive margin by latest early to middle Cambrian time. Detrital zircon in early - middle Cambrian passive margin stage sediments of Cuyania that were apparently derived from Laurentian source terranes indicate that Cuyania basement includes portions of both the Laurentian Granite-Rhyolite and Grenville provinces.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsames.2009.10.001.

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