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REVIEW ARTICLE

Accretion of Grenvillian terranes to the southwestern border of the Río de la Plata craton, western Argentina

Ricardo Varela · Miguel A. S. Basei · Pablo D. González · Ana M. Sato · Maximiliano Naipauer · Mario Campos Neto · Carlos A. Cingolani · Vinicius T. Meira

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Abstract A comprehensive review of the geological, geochronological, and isotopic features of the Mesoproterozoic Grenvillian terranes attached to the southwest of the Río de la Plata craton in Early Paleozoic times is presented in this paper. They are grouped into the northern (sierras de Umango, Maz and del Espinal and surroundings), central (Sierra de Pie de Palo, southern Precordillera and Frontal Cordillera), and southern (San Rafael and Las Matras Blocks) segments. The Mesoproterozoic basement consists mainly of arc related, intermediate to acidic and mafic–ultramafic rocks of 1,244–1,027 Ma, with juvenile, Laurentian affinity. Exception to it is the Maz Group, with a protracted history and reworked character. They are affected by 846–570 Ma, extensional magmatism in the northern and central segments, which represents the Neoproterozoic breakup of the Rodinia supercontinent. Successive passive margin sedimentation is registered in Late Neoproterozoic (~640–580 Ma) and Cambro-Ordovician (~550–470 Ma) times. The southern segment is noted for the younger sedimentation alone, and for showing the exclusive primary unconformable relationship between the Mesoproterozoic basement and Early Ordovician cover. The effects of Early Paleozoic Famatinian orogeny, associated with the collisions of Cuyania and Chilenia terranes, are recorded as *main phase* (480–450 Ma), *late phase* (440–420 Ma), and *Chanic phase* (400–360 Ma). Among them, the tectonothermal climax is the Ordovician *main phase*, to which klippe and nappe structures typical of collisional orogens are related in the northern and central segments. Preliminary data allow us to suggest a set of paired metamorphic belts, with an outboard high-P/T belt, and an inboard Barrowian P/T belt.

Keywords Grenville basement · Rodinia · Gondwana · Western Sierras Pampeanas · San Rafael Block · Las Matras Block

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R. Varela · P. D. González · A. M. Sato (✉) · C. A. Cingolani
CONICET, Centro de Investigaciones Geológicas, Universidad Nacional de La Plata, Calle 1 #644, B1900TAC, La Plata, Argentina
e-mail: sato@cig.museo.unlp.edu.ar

M. A. S. Basei · M. Campos Neto · V. T. Meira
Instituto de Geociências, Universidade de São Paulo, Rua do Lago 562, São Paulo, SP, Brazil

M. Naipauer
CONICET, Laboratorio de Tectónica Andina, Universidad de Buenos Aires, Pabellón II, Ciudad Universitaria, C1428EHA, Buenos Aires, Argentina

Introduction

Since the first isotopic age recognitions of Mesoproterozoic basement rocks in Sierra de Pie de Palo (Varela and Dalla Salda 1992; McDonough et al. 1993), much information has been gained on geological as well as isotopic basis, allowing the extension of a terrane with equivalent Mesoproterozoic rocks to the north and south of Sierra de Pie de Palo (Fig. 1), involving a wider range of morphostructural provinces in Argentina, such as Western Sierras Pampeanas (as defined by Caminos 1979), Precordillera, San Rafael Block and Las Matras Block, following a north–south belt between 28° and 37° south latitude. Envisaged as of Laurentian origin, the igneous and metamorphic rocks involved, together with Cambro-Ordovician sedimentary cover rocks, have been interpreted under a considerable

number of Ordovician collisional schemes, which explains the number of names proposed, e.g. Occidentalia (Dalla Salda et al. 1992), Precordillera (Astini et al. 1995, 1996), Cuyania (Ramos 1995; Ramos et al. 1996) and Texas Plateau (Dalziel 1997). Part of the Mesoproterozoic basement was involved in yet another tectonic scheme previously proposed as a Devonian accretion (Chilenia terrane, Ramos et al. 1986). More recent metamorphic, age, isotopic and geochemical constraints contributed on the one hand to the recognition of Neoproterozoic to Early Paleozoic sedimentary, metamorphic and igneous events in association with the Mesoproterozoic basement units (e.g. Varela et al. 2001; Casquet et al. 2001; Baldo et al. 2008). On the other hand, Gondwanan affinities were identified in a limited part of the northern Mesoproterozoic basement, which led to a proposal of a suspect terrane (Maz terrane) of proto-Gondwanan origin as opposed to the previous Laurentian origin (Casquet et al. 2006, 2008a). The heterogeneous distribution of the younger events argues for differences among the considered regions, while further provenance studies have arisen much debate about the autochthonous, allochthonous, or para-autochthonous derivation of the basement and cover rocks.

In this contribution, we review geological information for each of the basement exposures, with the addition of new geological and isotopic data for the Sierra de Umango and surrounding areas, and evaluate the possible geotectonic evolution of this part of the West Gondwana margin, within the context of dispersion of Rodinia supercontinent and accretion of Mesoproterozoic terranes to the west of the Río de la Plata craton as part of the final assembly. The autochthonous western border of Gondwana surrounding the Río de la Plata craton is the locus of the Late Neoproterozoic to Early Cambrian Pampean orogeny (Fig. 1), partly involved in the Pampia terrane (Ramos and Vujovich 1993; Ramos et al. 2010), and successively affected by regional metamorphism, deformation, and arc magmatism of the Late Cambrian to Devonian, Famatinian orogeny, together with the allochthonous terranes arriving further west.

For the above purpose, we divide the whole region with Mesoproterozoic basement rocks into three segments, the northern, central, and southern ones (Fig. 1), in order to facilitate the assessment of similarities and differences in stratigraphy, as well as overprinting igneous, metamorphic and tectonic effects covering Mesoproterozoic to Early Paleozoic time spans. In the Ordovician to Devonian times, we recognize heterogeneous effects of the Ordovician *main Famatinian phase* (480–450 Ma), the Silurian *late Famatinian phase* (440–420 Ma), and the Devonian *Chanic phase* (400–360 Ma). In the following description, the Sierra de Umango and Sierra de Pie de Palo are treated with more detail, while the rest of the areas considerably more synthetically.

Northern segment

The igneous and metamorphic rocks of this segment (28°10′S–29°30′S) are widely exposed through Sierras de Umango, Maz, Espinal, Toro Negro and surroundings (Fig. 2), within the Western Sierras Pampeanas. Mesoproterozoic felsic to mafic orthogneisses and minor paragneisses are reported as representing the basement to Neoproterozoic siliciclastic and calcareous, sedimentary cover rocks, also affected by high-grade metamorphism. Small plutons of varied compositions with ages between Neoproterozoic and Ordovician share the same deformation and metamorphism as their country rocks.

The primary stratigraphic relationship between the above-mentioned basement and metavolcanosedimentary cover has not been mapped yet. As all the units are tectonically juxtaposed (Fig. 2) through thrust faults or shear zones, described as nappe structures (Varela et al. 2003a), the cover relationship is claimed on the basis of isotopic rather than geological constraints.

In the following review, we will include our own geological, structural, and metamorphic observations throughout the region, with more detailed ones and additional isotopic data from the area of Umango. The new information helped the regional synthesis and correlation of Fig. 2 and resulted in the map of Fig. 3. The new isotopic data (Fig. 4) include two SHRIMP U–Pb ages and one Rb–Sr isochronic diagram drawn with the addition of 5 samples to those reported by Varela et al. (1996). We also provide full isotopic data and diagrams of eleven U–Pb results previously advanced in Varela et al. (2003b, 2008; two of them recalculated). Their analytical data and techniques are detailed in Electronic Supplementary Material, Tables A to C.

Comparative stratigraphy of each region of the three segments is depicted in Fig. 5, based on their geology and isotopic compilation of Fig. 6. Additional tectono-metamorphic information (Tables D to F), as well as comparative εNd-εSr diagram (Fig. G), is given in Electronic Supplementary Material.

Sierra de Umango

The Mesoproterozoic basement of this region corresponds to the high-grade metamorphic rocks of Juchi Orthogneiss (Varela et al. 1996) and Tambillito Unit (Varela et al. 2008) which crop out as wide N–S belts, while their proposed metasedimentary cover are the widespread high- to medium-grade rocks of the Neoproterozoic Tambillo Unit (Varela et al. 2003a). Low-grade metamorphic rocks of probable Cambro-Ordovician age of the La Troya Marble (new name) appear as a thin sliver along the westernmost slope of the Sierra de Umango. Paleozoic granitoid plutons,

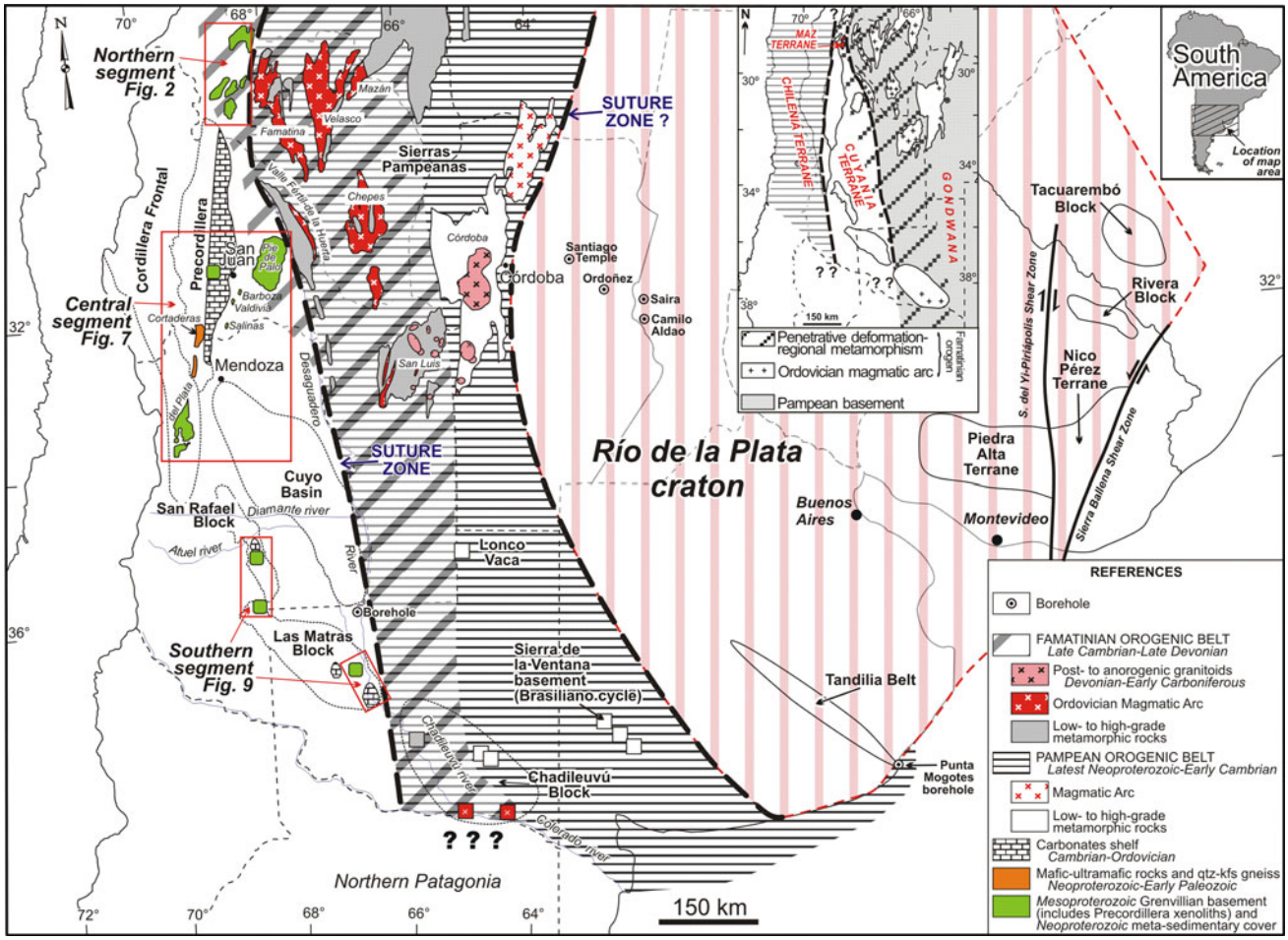

Fig. 1 Distribution of Mesoproterozoic basement rocks accreted to the west of the Gondwana continent. As shown in the inset, to the west of the Río de la Plata craton develops the latest Neoproterozoic—Middle Cambrian, Pampean orogen along the continental border of Gondwana, which is then involved in the Late Cambrian—Devonian, collisional Famatinian orogen, together with the Mesoproterozoic basements. *Red boxes* indicate the three segments considered in the text and shown in more detail in the numbered figures

e.g. Ordovician El Peñón Granite (Varela et al. 2000) and Carboniferous Los Guandacolinos (Varela et al. 2005) and Cerro Veladero granites (Cingolani et al. 1993) appear intruding the Tambillo Unit and Paleozoic sedimentary successions (Fig. 3a).

Mafic metaigneous rocks of El Cordobés Unit, with unconfirmed Ordovician age, crop out as a thin north–south belt between the Tambillito Unit and Juchi Orthogneiss. Other plutons of meta-gabbros of unknown age are emplaced in both the Tambillo and Tambillito units.

Mesoproterozoic basement

Juchi Orthogneiss The information about this unit is obtained mainly from the areas of Juchi, Seca, la Pereza, and la Champa creeks (Fig. 3a). It is composed of grayish, medium-grained hbl-bt ± grt tonalitic to granodioritic orthogneisses, and minor pinkish, bt-bearing granitic orthogneisses (mineral abbreviations after Siivola and Schmid 2007). Up to several cm thick, lens-shaped aplitic to trondhjemitic bands are often intercalated. Relics of retro-eclogites (terms of HP rocks after Desmons and Smulikowski 2007) containing eclogite and HP granulite facies assemblages appear as inclusions within orthoamphibolites at Puesto La Falda (Fig. 3a). Tabular dykes of mafic to felsic compositions cut the orthogneisses.

The overall polyphase deformation and metamorphic events are not yet well established in the Juchi Orthogneiss (Varela et al. 1996, 2003a; Vujovich et al. 2001; Porcher et al. 2004; González et al. 2005). However, five tectonic and metamorphic events can locally be identified in the area of Juchi (Meira 2010 unpublished thesis), where the D_2 structure makes up a distinctive klippe structure (Fig. 3a and b), associated with the main S_2 foliation. Relict S_1 foliation is only recognized as inclusion trails in porfiroblasts. A mylonitic zone associated with the western

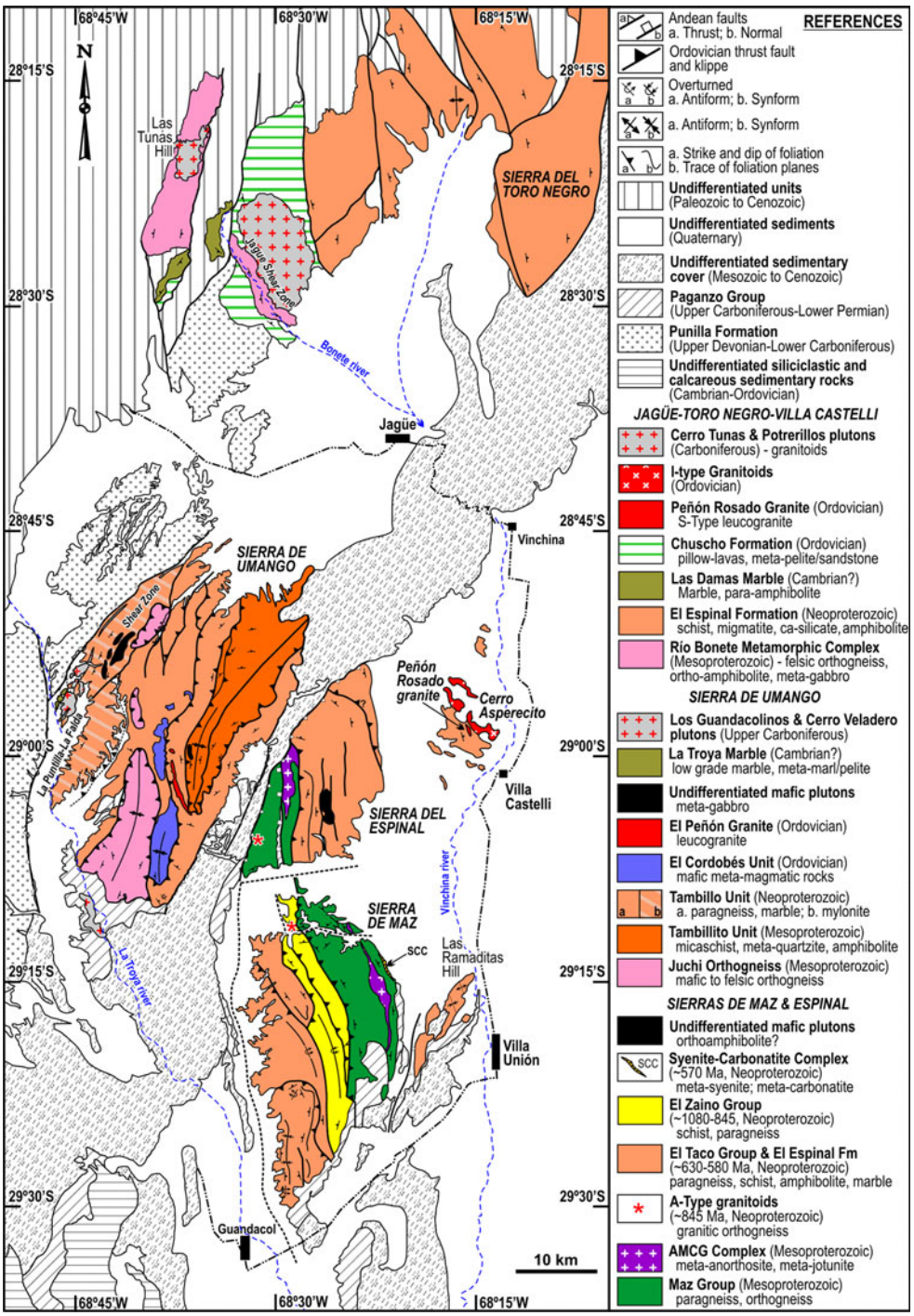

Fig. 2 Regional geological map of the northern segment, compiled from sources cited in text and with the addition of our own observations and interpretations. Highlighted are the Mesoproterozoic to Lower Paleozoic, igneous, and metamorphic basement rocks, under unmetamorphosed, Upper Paleozoic to Cenozoic cover rocks. The Sierra de Umango is described in detail in the text, while information from other areas is condensed. See general location in Fig. 1

side of the Juchi klippe develops a N–S trending S_3 mylonitic foliation, dipping ~48° to the E. Stretching lineation plunges 35° toward the NE and kinematic markers like cm-scale S–C shear bands suggest tectonic transport to the SW. Km-scale, synformal F_4 folding with southward dipping axis affects earlier foliations and thrust faults and is the responsible for the preservation of the klippe structure (Fig. 3b). This F_4 fold axis is gently refolded by an open F_5 fold related to the final D_5 deformation phase, in both Juchi and La Falda klippen. The last F_4 and F_5 foldings are Late Paleozoic or younger structures, since they are also identified in the Upper Devonian to Lower Carboniferous La Punilla Formation (Meira 2010, unpublished thesis). According to the tectonic relationship, the Juchi Orthogneiss structurally overlies the younger Tambillo and El Cordobés units (Fig. 3b).

A medium- to high-P/high-T, regional M_2 metamorphism of upper amphibolite transitional to granulite facies

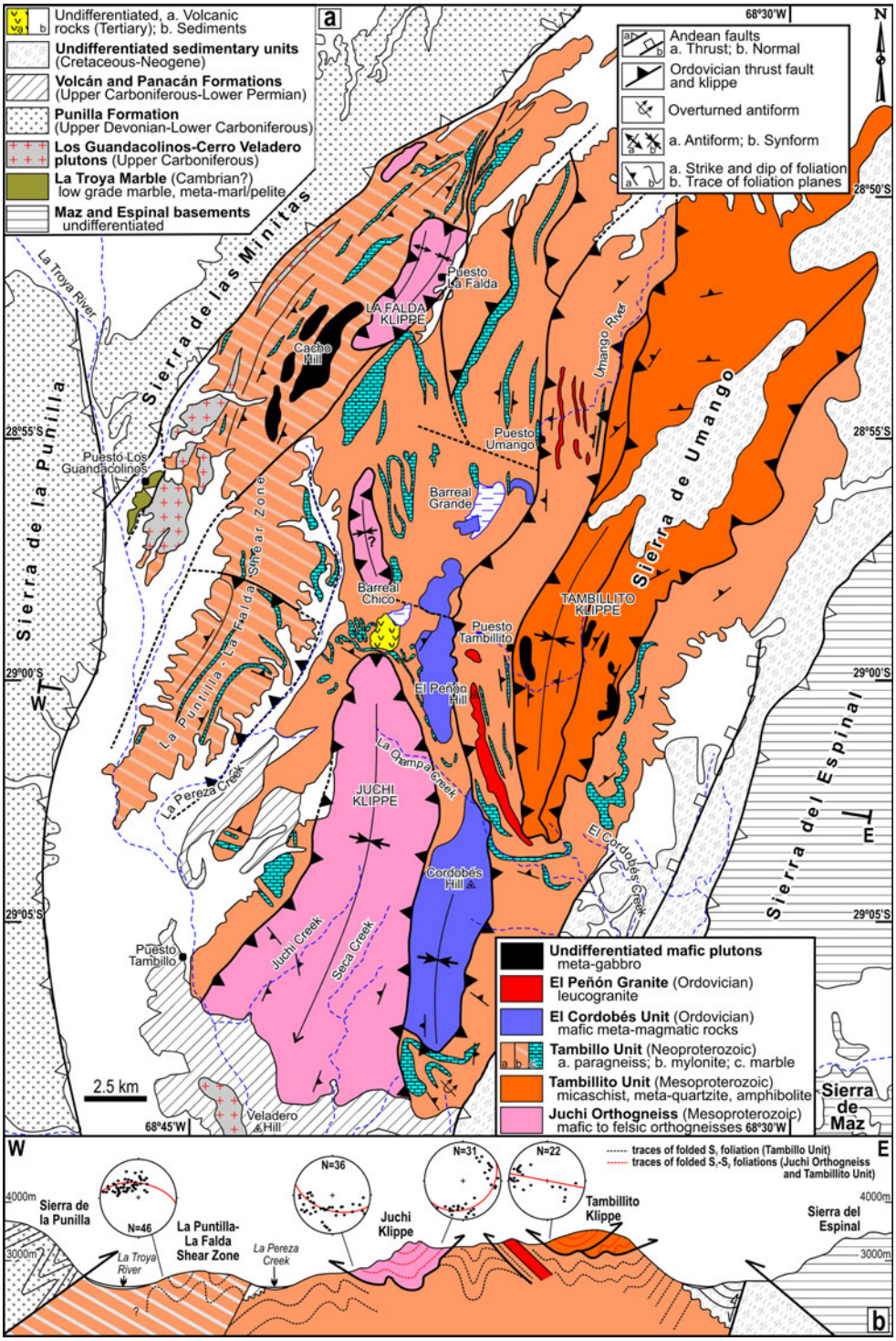

Fig. 3 **a** Geological map of the Sierra de Umango, with the main rock units and structures, based mostly on our own observations and Meira (2010, unpublished thesis). Note the Ordovician Juchi and Tambillito klippen juxtaposing Mesoproterozoic basement onto younger Tambillo Unit. **b** Simplified E-W profile across the southern part of the Sierra de Umango (location above in **a**). The Juchi and Tambillito klippen are affected by synformal F_4 folds of Carboniferous age or younger. Lower hemisphere, equal area stereoplots from klippen show the poles of folded S_1–S_2 foliations, aligned in great circle girdles marking the major F_4 folds. Remaining stereoplot from La Puntilla-La Falda shear zone also exhibits the poles of folded S_1 foliation and a great circle girdle of the major (F_2–F_3) fold

(Porcher et al. 2004; González et al. 2005) acted together with the D_2 deformation. A P–T range of *ca*. 1,200–1,400 MPa and 731–853°C is mentioned on retroeclogites from the Puesto La Falda klippe (González et al. 2005). Mineral and textural analyses suggest a possible relict eclogite facies metamorphism characterized by pl-free granoblastic grt + di + ilm + rt, in accordance with a previous description at the southernmost part of Sierra de Umango (Varela et al. 1996).

Seven TIMS U–Pb zircon ages from tonalitic to granitic orthogneisses vary between 1,216 and 1,090 Ma and constrain the Mesoproterozoic crystallization timing of the igneous protolith (Varela et al. 2003a; Fig. 4a, c, d, e, g, h). Two SHRIMP U–Pb zircon ages of 1,240 ± 60 Ma and

1,143 ± 100 Ma (Fig. 4b and f) enhance this interval, although concordia age of the first one is 1,205 ± 21 Ma. The addition of five new whole rock samples to the original Rb–Sr isochron date of 1,030 ± 30 Ma (Varela et al. 1996) resulted in an errochron of 1,085 ± 52 Ma (Fig. 4j).

Nd isotopic data from Varela et al. (2003a) and Porcher et al. (2004) recalculated with the two-stage model of DePaolo et al. (1991) present T_{DM} ages mostly between 1,318 and 1,559 Ma, with $\varepsilon Nd_{(t)}$ ranging from +4.1 to +1.3, which together with initial $^{87}Sr/^{86}Sr$ lower than 0.7034, indicate a juvenile Mesoproterozoic addition (Figs. 5 and 6), which is a common Laurentian feature (Mahlburg Kay et al. 1996).

The main D_2-M_2 deformation and high-grade regional metamorphism are constrained by two TIMS U–Pb zircon ages from a granitic orthogneiss and an amphibolite of 447 Ma (lower intercept) and 480 Ma, respectively (Fig. 4a and i), from an outcrop of La Falda klippe. A SHRIMP U–Pb age of 474 Ma from metamorphic rims of zircon crystals with 1,143 Ma cores of the granitic orthogneiss (Fig. 4b) confirms this Ordovician event over the Mesoproterozoic crystallization.

Tambillito Unit The information about this unit comes mostly from the area east of Puesto Tambillito (Fig. 3). It is composed of grayish, medium-grained qtz-ms-chl-bt-grt ± st ± tur ± gr schists and fine-grained meta-quartzites, with minor tr-act-tlc calcsilicate rocks, impure marbles, and chl-bt-hbl schists (Varela et al. 2008). Up to several m thick, tabular layers of amphibolites are often intercalated in this metasedimentary sequence.

A preliminary polyphase deformation and metamorphism similar to those in the Juchi Orthogneiss is described. The most distinctive feature is again a klippe structure (Fig. 3a and b, Tambillito klippe), also related to D_2 deformation phase, in association with the main S_2 foliation. On the western side of the klippe, N- to NNE-trending S_3 mylonitic foliation dips 35–50° to the E-ESE, whereas L_3 stretching lineation plunges between 10 and 31° to SSE. Local, cm-scale crenulation cleavage is also recognized as S_3 foliation. Kinematic indicators are consistent with dextral shear sense with tectonic transport to S-SSE. They are also affected by a km-scale, synformal F_4 folding, which is subsequently refolded by an open fold of the D_5 phase (Meira 2010, unpublished thesis). This description indicates that the Tambillito Unit rests tectonically over the Tambillo Unit, as does the Juchi Orthogneiss (Fig. 3a and b).

The main D_2 structures are related to the regional high-grade metamorphism M_2 set up at amphibolite facies (st-grt grade), partly retrogressed to chl-bearing assemblages at greenschist facies (Meira 2010, unpublished thesis).

TIMS U–Pb zircon dating from an amphibolite yielded an upper intercept of 1,108 ± 4 Ma and a lower intercept of 428 ± 12 Ma (Fig. 4k). The Mesoproterozoic age is interpreted as representing the crystallization timing of the mafic igneous protolith (e.g. dykes, Varela et al. 2008), while the 428 Ma age may be close to the main D_2-M_2 event.

An amphibolite sample corresponding to this unit and reported in Varela et al. (2003a) gives a recalculated T_{DM} model age of 1,485 Ma, with $\varepsilon Nd_{(1108)}$ +2.3 and 0.7055 as initial $^{87}Sr/^{86}Sr$. Although the rather high Sr value might represent a remobilization effect by metamorphism over the igneous protolith, the Nd signature is well within the characteristic value of the Juchi Orthogneiss.

Metavolcanosedimentary covers

Tambillo Unit This metavolcanosedimentary unit is the major component of the Sierra de Umango (Varela et al. 1996, 2003a). Main lithologies are grt-bt-ms-chl (±ky ±sil) paragneisses and schists, marbles, and amphibolites, with minor grt-bt-bearing meta-quartzites and calcsilicate rocks, which appear affected by a series of NNE-trending ductile shear zones. Migmatites, felsic dykes, and ky-grt-kf granulitic gneisses are locally present. It makes up the footwall of the La Falda, Juchi, and Tambillito klippen, through which the unit is overlain by the older Juchi Orthogneiss and Tambillito Unit (Fig. 3a and b). Although no detrital zircon data is available, isotopic Sr-C–O studies on marbles suggest a Neoproterozoic age of sedimentation (640–580 Ma, Fig. 6) of the siliciclastic-calcareous sequence (Varela et al. 2001).

Three tectono-metamorphic events are recognized in the Tambillo Unit. The pervasive S_1 foliation is folded by decameter-scale synformal and antiformal, tight to isoclinal F_2 folds related to D_2 event. S_1 foliation planes are oriented between NNW and NNE, dipping >50° to the E and W, with stretching lineation L_2 plunging mostly to NW-N. Major F_2 fold axis are subsequently refolded by km-scale open F_3 folds related to D_3 event.

High-grade metamorphism is associated with the D_{1-2} deformation, in which peak metamorphic conditions of 1,700 MPa and 840°C under high pressure granulite facies, and 900–1,000 MPa and 750°C for a retrogressive metamorphism at high amphibolite facies are obtained (Campos Neto personal communication).

Affecting all the western margin of the regionally metamorphosed Tambillo outcrop is the NE trending La Puntilla-La Falda ductile shear zone, along a belt of about 5 km in width and 32 km in length. Its western boundary is marked by an Andean thrust that juxtaposes the Upper Devonian-Lower Carboniferous Punilla Formation of Sierra de las Minitas over the shear zone (Fig. 3a). This

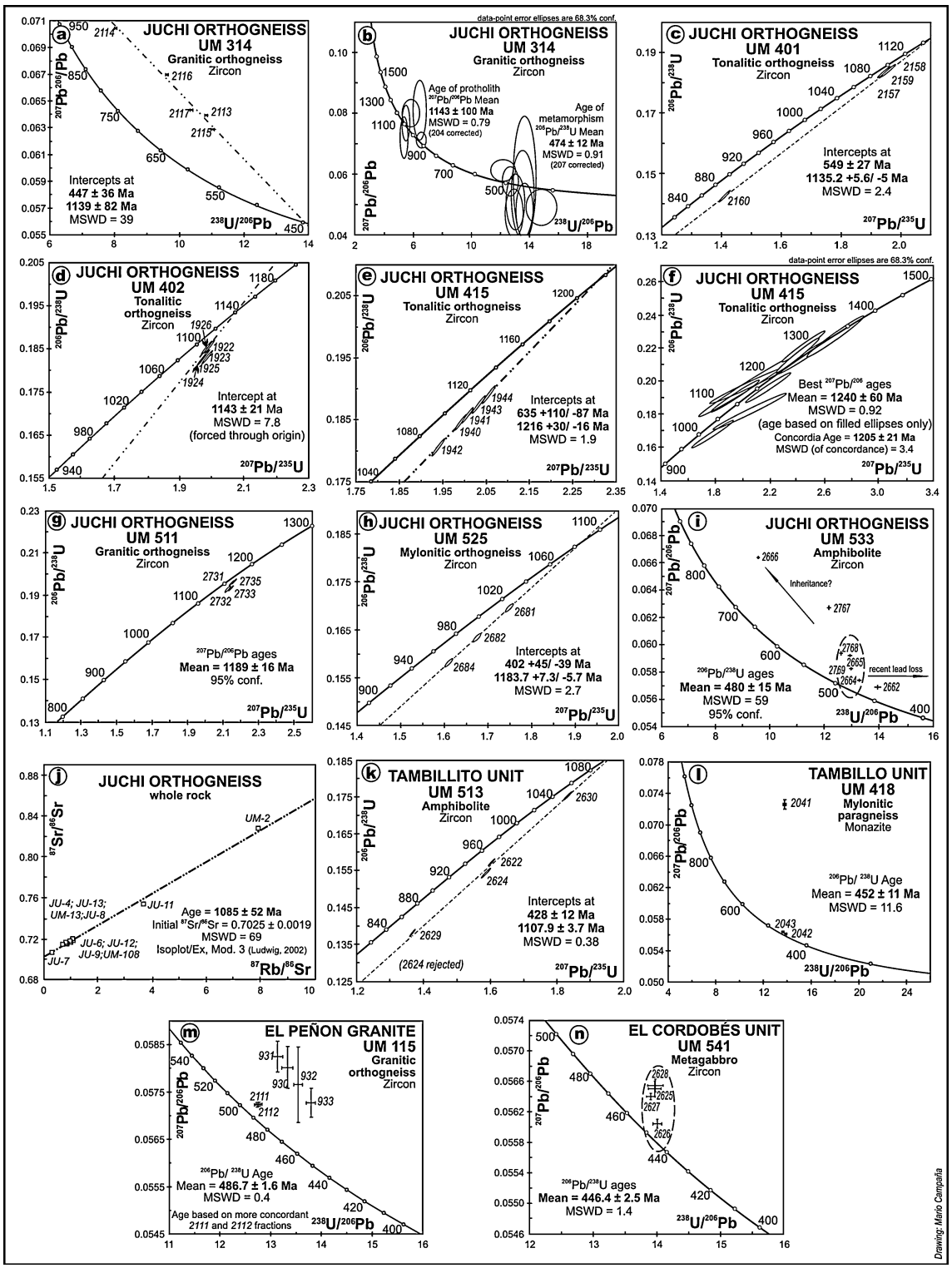

Fig. 4 New geochronologic data from basement units of Sierra de Umango, including ages advanced in Varela et al. (2003b, 2008). Mesoproterozoic Juchi Orthogneiss: TIMS zircon concordia diagrams (**a**, **c**, **d**, **e**, **g**, **h**, **i**), SHRIMP zircon diagrams (**b**, **f**), and Rb–Sr whole rock isochron plot (**j**). Mesoproterozoic Tambillito Unit: TIMS zircon diagram (**k**). Neoproterozoic, metasedimentary Tambillo Unit: TIMS monazite diagram (**l**). Deformed Ordovician Peñón Granite: TIMS zircon diagram (**m**). Deformed Ordovician (?) El Cordobés Unit: TIMS zircon diagram (**n**). Analytical data in Tables A to C of the Electronic Supplementary Material

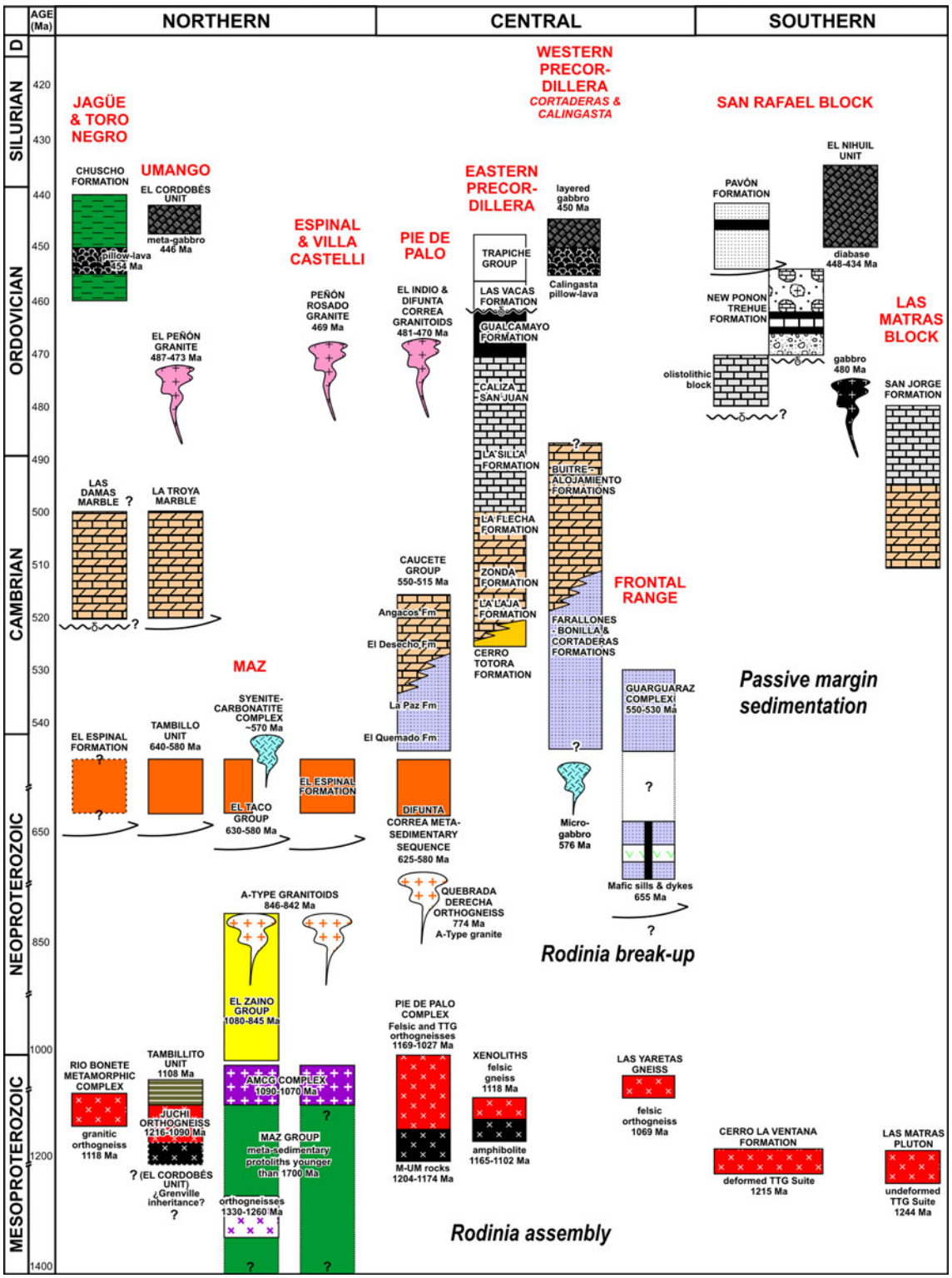

Fig. 5 Comparative stratigraphy and evolution of the considered basement units across the northern, central, and southern segments. Stratigraphic names, lithology, time constraints, and stratigraphic or tectonic relationships are indicated, in order to facilitate correlations. Stages of Rodinia supercontinent assembly and breakup are highlighted

dextral shear zone acted during D_2 and before D_3 originating a high-grade (grt-bt-sil), NE mylonitc foliation S_2, mostly dipping 50–60° to the SE and stretching lineation S_2 plunging 40–50° toward S-SE. Amphibolite facies, shear zone metamorphism is constrained by 700–800 MPa and ~715°C (Campos Neto personal communication). The

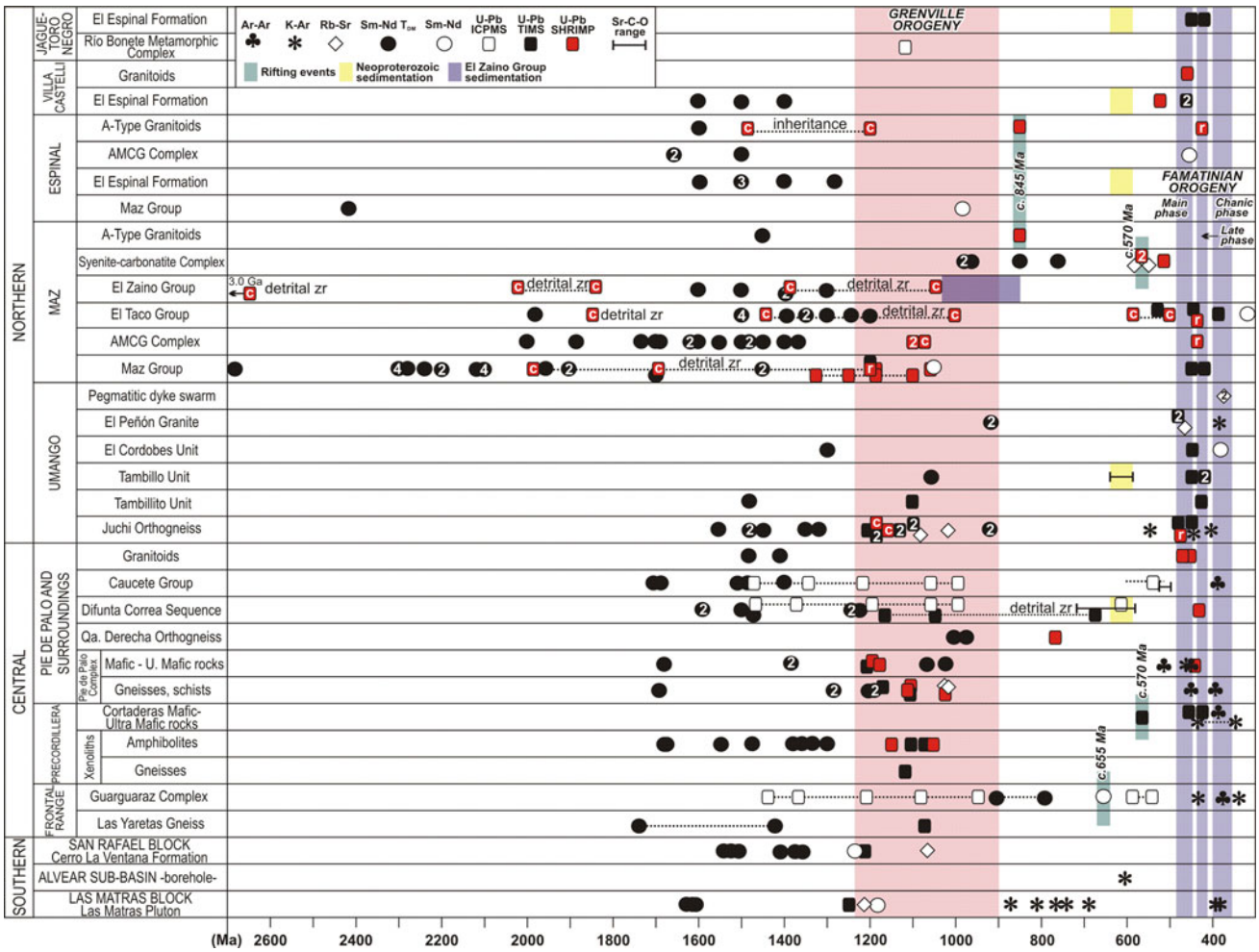

Fig. 6 Isotopic data compile of all the units considered in text. Data sources also in text. The Mesoproterozoic Maz Group and AMCG Complex (Maz terrane) are distinguished from other coeval units by their higher T_{DM} ages reaching Paleoproterozoic and latest Archean. The Mesoproterozoic Las Yaretas Gneiss (Chilenia terrane) is undistinguishable from the remaining coeval units belonging to Cuyania terrane. Detrital zircon data of metasedimentary units are easily compared. T_{DM} ages of igneous rocks calculated with DePaolo et al. (1991)

mylonitic foliation is folded by the same open F_3 folds affecting non-mylonitic rocks.

Isotopic constraints of peak metamorphic conditions are TIMS U–Pb monazite age of 452 ± 11 Ma on a mylonitic paragneiss (Fig. 4k) and titanite ages of 425 and 422 Ma on marbles (Lucassen and Becchio 2003) from the south-western area of the La Puntilla-La Falda shear zone.

El Cordobés Unit This orthogneissic unit (Fig. 3) has been assigned to the Ordovician on the basis of a U–Pb age (Varela et al. 2008; Fig. 4n), although some structural evidence may suggest similarity with the Mesoproterozoic group of rocks. It is composed of dark gray, fine-grained ep-grt-bt-hbl mafic orthogneisses, massive hbl-bearing meta-gabbros (±bt ±ttn), amphibolites, and minor mafic schists.

At El Cordobés Hill, it is observed that the sliver of mafic rocks is juxtaposed to the Tambillo Unit and Juchi Orthogneiss by thrust faults. Its structural feature is a km-scale synformal fold, refolded by a large open fold. It is noted that these two folding phases are also characteristic features of the klippen of Juchi Orthogneiss and Tambillito Units.

TIMS U–Pb zircon age from an amphibolite sample is 446 ± 3 Ma (Fig. 4n), interpreted as the timing of the magmatic crystallization of the igneous protolith in Late Ordovician (Varela et al. 2008). However, because of the metamorphic overprint of the unit, the alternative of representing a metamorphic crystallization cannot be discarded. On this and on structural grounds, we leave both Mesoproterozoic and Ordovician age alternatives in Fig. 5.

Recalculated data from Varela et al. (2003a) of a sample belonging to this unit gives a T_{DM} model age of 1,296 Ma, with $\varepsilon Nd_{(t)}$ of −1.4 and $^{87}Sr/^{86}Sr$ of 0.7078 when considering a crystallization age of 446 Ma. When an age of 1,150 Ma (average value for the Juchi Orthogneiss) is used, the values turn to 1,593 Ma, +1.3 and 0.7055, respectively, similar to the Tambillito Unit.

El Peñón Granite This is an 8-km long, lens-shaped deformed granitic pluton cropping out in the region of El Peñón Hill (Fig. 3). It consists of bt-bearing mylonitic granites, orthogneisses and pegmatites, and minor mylonitic granodiorites (Varela et al. 2000; Meira 2010; unpublished thesis). Granitoids are pinkish gray, fine- to medium-grained and show gneissose aspect due to banding and foliation. NNW- to N trending S_1 foliation dips between 50 and 80° to ENE-E. It is emplaced in the Tambillo Unit with sharp and concordant contacts with respect to the foliation of host rocks. A pegmatitic dyke swarm located to the east of Puesto Umango is also included in this unit.

TIMS U–Pb zircon ages from bt- bearing granitic orthogneisses are 473 ± 17 Ma (Varela et al. 2003a), recalculated to 487 ± 1 Ma (Fig. 4m), and constrain the crystallization timing of the igneous protolith to Early Ordovician, while the Rb–Sr isochron age is only slightly younger, 469 ± 9 Ma, with initial $^{87}Sr/^{86}Sr$ 0.7110 (Varela et al. 2000). Recalculated values at 487 Ma from Varela et al. (2003a) indicate T_{DM} model ages of 939 Ma and 911 Ma, $\varepsilon Nd_{(t)}$ of +3.1 and +3.4, and $^{87}Sr/^{86}Sr$ of 0.7091 and 0.7055 for two samples, which are Nd–Sr features rather difficult to reconcile, especially with the high initial $^{87}Sr/^{86}Sr$ mentioned.

Undifferentiated mafic plutons A group of mafic metamagmatic rocks has been identified in two localities, to the east of Puesto Tambillito and in the Cacho Hill area (Fig. 3). They are isolated, deformed plutons (?) emplaced in the Tambillito and Tambillo units, with sharp contacts concordant with the country rock foliation. Primary intrusive relationship is obscured by subsequent shearing.

They are thick and disrupted bodies consisting mainly of am-grt-pl-bt-scp meta-gabbros (Cacho Hill), ep-am-pl-rt ortho-amphibolites, and minor am-pl mafic schists (Puesto Tambillito). Meta-gabbros are greenish, medium-grained, and showing a weak NNW foliation that dips 65–70° to WSW. Ortho-amphibolites are dark green, medium to coarse grained, with gneissose aspect, whereas mafic schists are green, medium grained, with pervasive NNE schistosity dipping ESE. Albeit some compositional features are similar to those of El Cordobés Unit, the most remarkable attributes are their simple deformation and associated high-grade metamorphism.

La Troya marble They are unfossiliferous, low-grade metacalcareous rocks that might be comparable with the Early Paleozoic marbles and para-amphibolites of Las Damas Marble in NW of Jagüe (Aceñolaza et al. 1971; Martina and Astini 2009).

Sierra de Maz, del Espinal, and Toro Negro areas

The Mesoproterozoic basement of the Sierra de Maz and del Espinal corresponds to the high-grade metamorphic rocks of Maz Group (Kilmurray 1970, 1971) and Anorthosite-mangerite-charnockite-granite complex (Casquet et al. 2004; Rapela et al. 2010). Their sedimentary cover are the high- to medium-grade rocks of the Neoproterozoic El Taco and El Zaino Groups (Kilmurray 1970, 1971; Casquet et al. 2008a) and El Espinal Formation (Turner 1964), (Fig. 2). Neoproterozoic metaigneous rocks of Syenite-Carbonatite Complex (Casquet et al. 2008b) and dykes of A-Type Granitoids are additionally exposed in Sierra de Maz and del Espinal (Baldo et al. 2008; Colombo et al. 2009). The tectono-metamorphic events affecting the Maz, El Taco, and El Zaino groups, based mainly on Kilmurray (1970) and Kilmurray and Dalla Salda (1971), and their isotopic constraints are shown in Tables D and E (Electronic Supplementary Material).

The Maz Group is composed of grayish pink, medium-grained bt-grt-pl-qtz ± st ± sil or ky (±gr) paragneisses and schists, migmatites and quartzites, and minor intermediate to acidic orthogneisses and orthoamphibolites. Deposition of sedimentary protoliths is younger than Late Paleoproterozoic (*ca.* 1,700 Ma) as shown by detrital zircon core data (Casquet et al. 2006; Rapela et al. 2010), while igneous crystallization of orthogneisses varies between 1,330 and 1,260 Ma (Rapela et al. 2010). The Mesoproterozoic age of metamorphism and deformation is recorded as *ca.* 1,208 Ma by titanite and zircon (Lucassen and Becchio 2003; Casquet et al. 2006). The Early Paleozoic event in the Maz Group is dated at Early Silurian (436–428 Ma on calcsilicate rocks; Lucassen and Becchio 2003), which is at least ~20 Ma younger than the 480–447 Ma interval of the Juchi Orthogneiss in Sierra de Umango. T_{DM} model ages of the Maz Group are between 2,700 and 1,500 Ma, while $\varepsilon Nd_{(t)}$ varies between +4.1 and −7.1 (Porcher et al. 2004; Casquet et al. 2008a; Rapela et al. 2010; Fig. 6). These variable features for both the metasedimentary and the orthoderived rocks contrast with the juvenile Nd and Sr signatures obtained from the Juchi Orthogneiss (see above).

The 1,090–1,070 Ma anorthosite-mangerite-charnockite-granite (AMCG) complex is intruded into the already deformed and metamorphosed meta-sedimentary rocks of the Maz Group (Kilmurray 1970; Kilmurray and Dalla Salda 1971; Casquet et al. 2004, 2008a; Rapela et al. 2010).

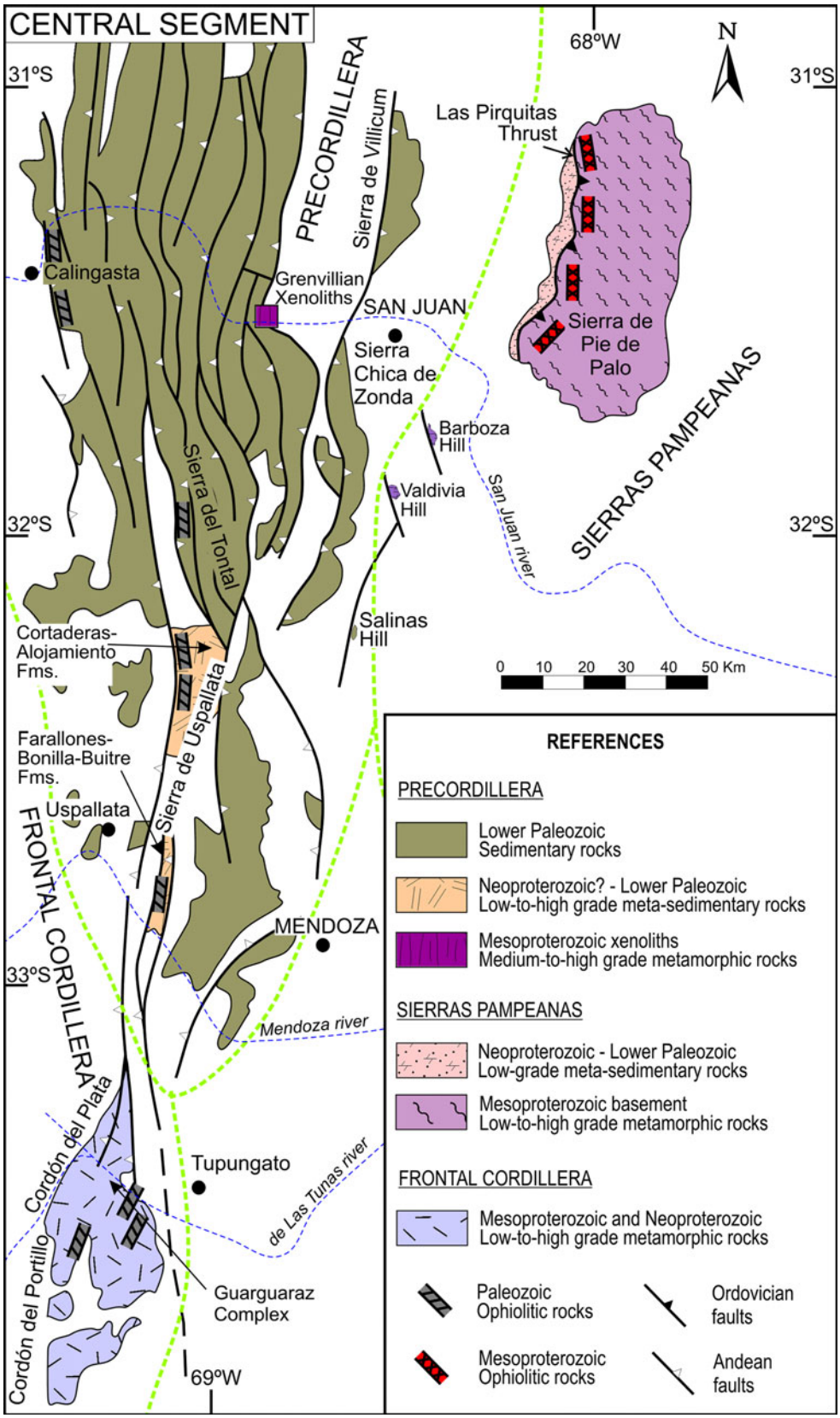

Fig. 7 Location of Mesoproterozoic and associated basement rocks in the morphostructural provinces of the central segment. Compiled from Achili et al. (1997), Ramos and Vujovich (2000) and Ramos et al. (2000)

These complexes were first compared with those of the Grenville province of Laurentia on petrologic and geochemical basis (Casquet et al. 2004), and then to those of the Arequipa-Antofalla craton (Casquet et al. 2008a). The Famatinian high-grade metamorphism and deformation of the complex is constrained between 431 and 463 Ma (Casquet et al. 2004; Porcher et al. 2004; Fig. 6). A *ca.* 570 Ma bt-bearing carbonatite with enclaves of syenites intruded the deformed Maz Group and AMCG Complex, along the eastern margin of the Sierra de Maz (Fig. 2).

The main metasedimentary cover is the supracrustal belts of El Zaino and El Taco groups (Kilmurray 1970; Kilmurray and Dalla Salda 1971; Figs. 2 and 5). They are composed of grt-chl (±gr) micaschists, grt-sil gneisses, bt-grt-sil-fk paragneisses and schists, grt-cpx-scp marbles and amphibolites. Casquet et al. (2008a) suggest depositional ages younger than 1,000 Ma (Neoproterozoic and/or Early Paleozoic) for both El Taco and El Zaino groups based on SHRIMP U–Pb zircon core data. The finding of A-type granitoids of 846 and 842 Ma intruding the El Zaino and Maz groups is interpreted as representing an early extensional event related to the breakup of the Rodinia supercontinent (Colombo et al. 2009).

El Espinal Formation (Turner 1964) consists of fine-grained qtz-pl-bt-grt (±ms) schists, qtz-fk-pl-sil (±grt ±ms) schists and migmatites, and minor amphibolites with lenses of banded cpx-esc-grt calcsilicate rocks. Due to certain similarities in composition, structure, metamorphic grade, and 1,200 and 1,500 Ma T_{DM} model ages (Fig. 6; Porcher et al. 2004; Casquet et al. 2008a), we consider that the El Espinal Formation might be comparable with the metasedimentary El Taco Group of the Sierra de Maz.

The basement that occurs in the Cerro Asperecito (Fig. 2) near Villa Castelli consists of El Espinal Formation composed of bt-sil (±grt ±ms) schists and bt-sil-grt migmatites, with minor amphibolites and intrusive granitoid bodies (Hausen 1921; Turner 1964; Lucassen and Becchio 2003; Dahlquist et al. 2007). T_{DM} ages are in the 1,400–1,600 Ma interval, similar to the same formation in Sierra del Espinal and to El Taco and El Zaino groups (Casquet et al. 2008a). A SHRIMP U–Pb zircon age of 529 ± 5 Ma from a migmatite is also mentioned by Rapela (2000). This basement is intruded by Famatinian, metaaluminous I-Type granitoids of Cerro Toro Complex (*ca.* 468 Ma; Rapela et al. 1999; Pankhurst et al. 2000; Fig. 2). In addition, the Peñón Rosado anatectic granitoid of 469 Ma is emplaced parallel to the pervasive S_{1-2} foliation (Dahlquist et al. 2007).

In the Sierra del Toro Negro, the El Espinal Formation consists of gneisses, schists and bt-fk-grt-sil-crd migmatites, and minor marbles, calc-silicate rocks and amphibolites (Turner 1964; Maisonave 1979). U–Pb TIMS titanite ages of 454 ± 3 Ma and 432 ± 2 Ma from calcsilicate boudins at the southern edge of the Sierra del Toro Negro (Lucassen and Becchio 2003) constrain the timing of the main deformation and regional high-grade metamorphism to Late Ordovician to Early Silurian.

The Mesoproterozoic Río Bonete Metamorphic Complex (Martino and Astini 1998, 2009) composed of felsic to mafic orthogneisses, together with minor marbles of Las Damas Marble, represent the basement rocks of Jagüe region (Figs. 2 and 5). A Mesoproterozoic ICP-MS-LA igneous crystallization age of 1,118 ± 17 Ma was obtained from a felsic orthogneiss (Martina et al. 2005). The mylonitized complex is non-conformably covered by Upper Ordovician Chuscho Formation and by Upper Devonian to Permian sedimentary units (Fig. 2). Both the Río Bonete Metamorphic Complex and the Chuscho Formation are in turn intruded by Carboniferous granitoids (Caminos and Fauqué 1999; Martina and Astini 2009).

Central segment

This segment (31°–34°S and 68°–69°W) is separated from the northern one by the Bermejo—La Troya lineament. Rocks of Mesoproterozoic age and associated basement appear in (1) the Sierra de Pie de Palo of Western Sierras Pampeanas, (2) Precordillera, as xenoliths from Tertiary volcanic rocks, and in the Cordón de Cortaderas area of the southern Precordillera, and (3) the Cordón del Portillo from southern Frontal Cordillera (Fig. 7). Mesoproterozoic rocks cropping out in the above-mentioned (1) and (2) regions are interpreted as belonging to the basement of Cuyania terrane (Mahlburg Kay et al. 1996; Ramos et al. 1998), while those in region (3) are interpreted as the basement of Chilenia terrane (Ramos and Basei 1997; Basei et al. 1998), even though differences between these basement rocks have not been assessed properly.

Sierra de Pie de Palo

The Mesoproterozoic to Early Paleozoic crystalline rocks from the Sierra de Pie de Palo and their southwestern extension in the Barboza and Valdivia hills represent the most important outcrops from the central segment (Figs. 7 and 8). Mesoproterozoic rocks are grouped into the Pie de Palo Complex (Ramos and Vujovich 2000). Neoproterozoic rocks include the Quebrada Derecha Orthogneiss (Baldo et al. 2006) cropping out in the southwestern part of Sierra de Pie de Palo, and the Difunta Correa Metasedimentary Sequence (Baldo et al. 1998), appearing in both the eastern and the central-western areas. In addition, the Neoproterozoic to Middle Cambrian, metasedimentary Caucete Group (Naipauer et al. 2010 and references therein) is recognized all along the western border.

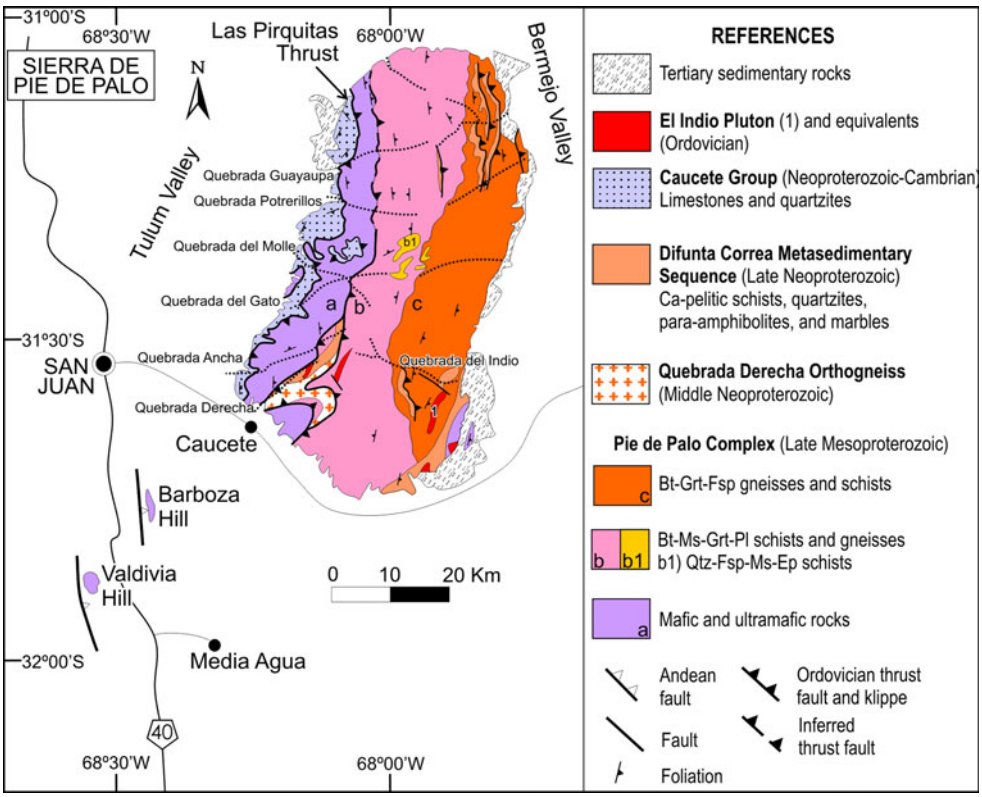

Fig. 8 Geological sketch map of Sierra de Pie de Palo, compiled from pre-existing maps with the addition of our own observations. Contacts between the basement units are controlled by Early Paleozoic, ductile thrust faults, which produce klippe and window structures along the western side of the Sierra

Ordovician granitoids and pegmatites are emplaced in restricted areas (Fig. 8).

The contacts between the metamorphic units are controlled by Early Paleozoic structures, characterized by an imbricate ductile thrust system with dominant top to west vergence (Dalla Salda and Varela 1984; Ramos et al. 1998; Ramos and Vujovich 2000). One of the most outstanding structures is the Las Pirquitas thrust that juxtaposes the Pie de Palo Complex with the Caucete Group (Ramos et al. 1996). Splaying of the thrust front and the gentle folding of the thrust originate klippen and tectonic windows along the western region of the Sierra de Pie de Palo (Fig. 8; Ramos et al. 1996, 1998). In the central and eastern regions, a series of west-verging thrusts brings together rock slices from the Pie de Palo Complex, Quebrada Derecha Orthogneiss, and Difunta Correa Metasedimentary Sequence (Casquet et al. 2001; Baldo et al. 2006).

Mesoproterozoic basement

Dalla Salda and Varela (1984) defined the Pie de Palo Complex to integrate all the metamorphic rocks derived from sedimentary and igneous protoliths, locally migmatized, as well as small intrusive granitic bodies, exposed in the southern third of the Sierra de Pie de Palo and in the Barboza hill. Ramos et al. (1998) and Ramos and Vujovich (2000) distinguished three main components in this complex: (1) A western belt of mafic to ultramafic rocks, composed of peridotites, metagabbros, serpentinites, and amphibolites, associated with am-mca-gr schists. (2) bt-ms-grt-pl orthogneisses together with qtz-fsp-ms-ep schists, located in the central region. (3) bt-grt-fsp gneisses and schists, dominant in the eastern region. In addition, granitic pegmatites are emplaced parallel to the schistosity of the former units, especially in the central region (Fig. 8).

The protoliths of the metamorphic rocks have been interpreted as ultramafic and mafic cumulates and flows, silicic calc-alkaline igneous rocks for the orthogneisses, and immature graywackes for paragneisses and schists, which as a whole make up an arc/back arc oceanic setting (Vujovich and Kay 1998; Ramos and Vujovich 2000). Identification of trondhjemitic, high-Na TTG-series rocks, common in the southern segment, has been increasing in recent years.

The first Mesoproterozoic age from the Pie de Palo Complex was obtained from a Rb–Sr isochron (*ca.* 1,027 ± 59 Ma, Varela and Dalla Salda 1992), confirmed by a considerable number of TIMS and SHRIMP U–Pb ages in the 1,204–1,027 Ma interval (McDonough et al. 1993; Vujovich et al. 2004; Morata et al. 2010; Rapela et al. 2010; Ramos et al. 1998).

The structures of the Pie de Palo Complex and the Neoproterozoic to Cambrian Caucete Group are explained by the same three main deformation events D_1, D_2, and D_3

(Table F, Electronic Supplementary Material), as originally described by Dalla Salda and Varela (1982) and confirmed by Ramos and Vujovich (2000). This implies that there was no deformation event affecting the Pie de Palo Complex prior to Early-Middle Cambrian, as also stated later by Vujovich et al. (2004).

Two main metamorphic facies have been identified in the Pie de Palo Complex: one of lower grade, greenschist to amphibolite facies along the western side of the range and in the southwestern area, and another reaching high amphibolite facies, in the central-eastern part of the range; only locally is the granulite facies described in the southernmost area (Dalla Salda and Varela 1984; Ramos and Vujovich 2000). Thermobarometric constraints from Baldo et al. (1998) on a Ca-pelitic rock intercalated with mafic and ultramafic rocks are 1,300 MPa and 600°C. Casquet et al. (2001) define two successive P/T conditions for a sample of mylonitic paragneiss from the Pie de Palo Complex: the first one in medium-P/T conditions (786 ± 40 MPa and 790 ± 17°C) for a pre-mylonitic assemblage, and then in high P/medium T conditions (1,140 ± 135 MPa and 615 ± 70°C) for the mylonitic stage of the Las Pirquitas thrust. Despite the lack of age constrain, the authors interpreted the first set of data as comparable to a Grenvillian M_2 event registered in the Llano uplift from Laurentia, and the second set to the peak P/T conditions obtained in another sample from the Difunta Correa Metasedimentary Sequence, in which the high-P metamorphism turned out to be Ordovician (*ca.* 460 Ma, Casquet et al. 2001). Therefore, the existence of Mesoproterozoic deformation and metamorphism in Sierra de Pie de Palo is in part speculative and still lacks unquestionable evidence.

These relatively high-P/T metamorphic conditions were also cited at Loma de las Chacras, in the westernmost side of Sierra de Valle Fértil, to the east of Sierra de Pie de Palo (1,210 MPa and 769°C in a migmatite, Baldo et al. 2001).

Although local data suggest the possibility of initiation of M_2 metamorphism during the Cambrian (510–515 Ma; Mulcahy et al. 2007), the most important metamorphic event M_2 associated with the penetrative D_2 deformation in the hanging wall of the Pirquitas thrust is most likely to be Ordovician. Apart from the above SHRIMP U–Pb age by Casquet et al. (2001), other U–Pb lower intercepts from titanite and zircon datings, as well as SHRIMP age of metamorphic zircon rims, are between 488 and 455 Ma (Vujovich et al. 2004), with additional Ar–Ar and K–Ar mineral ages (Table F, Electronic Supplementary Material). Other Siluro-Devonian Ar–Ar ages between 425 and 360 Ma in the central part of the Sierra de Pie de Palo and Barboza and Valdivia hills (Ramos et al. 1998) appear to record the late Famatinian uplift of the Pie de Palo region, with probable relation to the D_3 event.

Neoproterozoic magmatism

Neoproterozoic A-type magmatism is an important feature of the Western Sierras Pampeanas. In particular, in the Sierra de Pie de Palo is described the Quebrada Derecha Orthogneiss with 774 ± 6 Ma (Baldo et al. 2006), while igneous rocks with similar age are also mentioned in the adjacent Sierra de la Huerta (*ca.* 839 ± 10 Ma; Mulcahy et al. 2003; McClelland et al. 2005) within the latitudes of the central segment.

The Quebrada Derecha Orthogneiss is exposed in the southwestern area of the Sierra (Baldo et al. 2006), where mylonitic orthogneisses with A-type granitoid geochemistry are tectonically interleaved with rock units belonging to the Difunta Correa Metasedimentary Sequence. Its Neoproterozoic timing of crystallization is based on a SHRIMP U–Pb age, and isotopic signatures indicate low initial $^{87}Sr/^{86}Sr$ of 0.7006 and 0.7031 and positive εNd of +4.1 and +4.9, with T_{DM} ages 1,060 and 990 Ma (Fig. G, Electronic Supplementary Material).

The shear zone affecting the orthogneisses is characterized by foliations and σ-type kinematic markers indicating a top to the southwest relative movement, which is consistent with the penetrative D_2 structure of the Pie de Palo Complex, the Las Pirquitas thrust, and the mylonite-ultramylonite belt of The El Tigre Granitoid (Castro de Machuca et al. 2008a; not depicted in Fig. 8 because of its small size). Garnet-amphibole thermometry of the orthogneisses provides T values of metamorphism between 620° and 550°C, whereas garnet-biotite exchange thermometry provides a range of 400°–410°C (Baldo et al. 2006).

Neoproterozoic and lower Paleozoic sedimentary cover

Two sedimentary units are part of the basement of Sierra de Pie de Palo. The older one, described as Difunta Correa Metasedimentary Sequence, was proposed as the sedimentary cover to the Grenvillian Pie de Palo Complex (Casquet et al. 2001). The younger one, Caucete Group, may be a metamorphic counterpart of the Cambrian platform sequence of Precordillera (Galindo et al. 2004; Naipauer et al. 2005, 2010).

Difunta Correa Metasedimentary Sequence Baldo et al. (1998) assembled in this unit the Ca-pelitic schists, quartzites, meta-arkoses, marbles, and para-amphibolites exposed in the southern and eastern areas of the Sierra de Pie de Palo (Fig. 8), in contact with the Quebrada Derecha Orthogneiss and the Pie de Palo Complex through ductile thrusts.

Amphibolite facies metamorphic conditions at relatively high pressure were constrained in a Ca-pelitic schist through three stages: the first two corresponding to a

prograde path under relatively high-P/T conditions (peak at 1,300 MPa and about 600°C) and the third related to mylonitization with $P < 1{,}000$ MPa and T about 575°C (Baldo et al. 1998).

Detrital zircon dating revealed Grenvillian igneous cores of 1,032–1,224 Ma and metamorphic rims of *ca.* 460 Ma (Casquet et al. 2001) and another sample with 1,050–1,150, 1,200–1,500 Ma and *ca.* 625 Ma zircon cores, with an average of 439 ± 34 Ma in metamorphic rims (Rapela et al. 2005). A further set of six TIMS ages in the 1,160–670 Ma interval is additionally reported by Vujovich et al. (2004). These findings show a major Grenvillian provenance for the Difunta Correa sequence, which was then involved in the Famatinian metamorphism and deformation.

On the basis of these detrital zircon data added to C, O and Sr isotopic features (Galindo et al. 2004), this sequence is interpreted to represent a 625–580 Ma, Neoproterozoic sedimentary cover to the Pie de Palo Complex, and is additionally correlated with the Tambillo Unit cropping out in the Sierra de Umango of the northern segment. Also equivalent are the T_{DM} values of Difunta Correa sequence (1,100–1,500 Ma) to El Zaino Group (1,300–1,600 Ma) and El Taco Group (1,200–1,600 Ma) in the Sierra de Maz of the northern segment (Rapela et al. 2005; Casquet et al. 2008a). Therefore, these units constitute an important element for comparison between these two segments, which are not found up to now in the southern segment.

Caucete Group This group consists of four formations (references in Vujovich 2003 and Naipauer et al. 2010) that can be grouped according to two main lithologies: one with siliciclastic composition (El Quemado and La Paz formations) and the other with carbonatic composition (El Desecho and Angacos formations). The latter two formations may be correlated with the basal Cambrian units of the eastern Precordillera succession (e.g. Cerro Totora and La Laja formations; van Staal et al. 2002; Naipauer et al. 2010). Depositional ages between *ca.* 550 and *ca.* 510 Ma are constrained on the basis of detrital zircon and isotopic Sr, C, and O data (Linares et al. 1982; Sial et al. 2001; Galindo et al. 2004; Naipauer et al. 2005, 2010).

Regarding the timing of the penetrative deformation and metamorphism in the Caucete Group, the tentative suggestion of van Staal et al. (2002) of an Ordovician age is sustained by the *ca.* 450–488 Ma ages obtained in the hanging wall of the Las Pirquitas thrust (see Table F, Electronic Supplementary Material, Pie de Palo Complex), affected by the same D_2 event. An additional Devonian Ar–Ar age of 396 ± 0.2 Ma from a muscovite quartzite of the Caucete Group in the footwall of the Las Pirquitas thrust is similar to ages obtained in the hanging wall of the same mylonitic zone and interpreted as the cooling of the last pre-Andean tectonic event in the Pie de Palo region (Ramos et al. 1998).

Ordovician magmatism

Two Ordovician, peraluminous granitoid plutons have been reported as emplaced in rough concordance with the foliation of the Pie de Palo Complex and Difunta Correa Metasedimentary Sequence: the El Indio and Difunta Correa plutons in the southeastern part of the Sierra de Pie de Palo. Both are garnet-bearing, two-mica granites, with SHRIMP U–Pb ages of 481 ± 6 Ma (Pankhurst and Rapela 1998) and 470 ± 10 Ma (Baldo et al. 2005), respectively. T_{DM} model ages and $\varepsilon Nd_{(t)}$ are 1,480 Ma and −3.6 for the El Indio pluton, and 1,410 Ma and −2.6 for the Difunta Correa pluton, which suggest the magma was probably derived by partial melting of crustal rocks (Baldo et al. 2005).

Precordillera

Mesoproterozoic, high-grade metamorphic xenoliths found in Miocene volcanic rocks (31°30′S, Fig. 7; Leveratto 1968; Abbruzzi et al. 1993) are interpreted as derived from an unexposed Grenvillian basement (Mahlburg Kay et al. 1996). The igneous crystallization of the mafic xenoliths is constrained by U–Pb zircon ages between 1,102 and *ca.* 1,165 Ma, while that of the acidic ones by a U–Pb upper interception at 1,118 Ma (Mahlburg Kay et al. 1996; Rapela et al. 2010). Evidence of Grenvillian metamorphism in mafic xenoliths comes from two fractions of rounded zircons with significantly lower U and Pb concentrations, of *ca.* 1,083 Ma (Mahlburg Kay et al. 1996), and a similar age of *ca.* 1,060 Ma interpreted by Rapela et al. (2010) to reflect a period of zircon growth during a metamorphic event. Nd and Pb signatures suggest a juvenile Mesoproterozoic addition of Grenvillian affinity (Mahlburg Kay et al. 1996).

Whether mafic or acidic, these xenoliths are pervasively deformed and metamorphosed, according to the description of Mahlburg Kay et al. (1996). This deformation may be considered as pre-Paleozoic, given the lack of similar levels of deformation and metamorphism in the Cambro-Ordovician carbonatic rocks of the Precordillera. In this sense, the deformation is more likely to be a Grenvillian event, as sustained by the above mentioned metamorphism ages.

Despite the isotopic similarity between the basements of Precordillera and Sierra de Pie de Palo, the 1,080–1,060 Ma Grenvillian metamorphic event is up to now unique to the Precordillera and has not been established in the Pie de Palo Complex of the central segment.

The Sierras de Cortaderas and Alojamiento and their southern extension in the Sierra de Uspallata are the main basement outcrops in the southern Precordillera between

32° and 33°S (Fig. 7), in which a series of clastic and carbonatic sequences is associated with mafic and ultramafic igneous rocks and affected by a general low-grade metamorphism. The mainly siliciclastic Cortaderas Formation is comparable to the Farallones and Bonilla Formations along the western side, while the more carbonatic Alojamiento Formation containing trilobite fossils is likely to be comparable to the Buitre Formation along the eastern side (Cucchi 1972a; Caminos 1993; Banchig 2006).

Detailed mapping of Davis et al. (1999) and Gerbi et al. (2002) in restricted areas of Cortaderas and Bonilla formations shows that within a W-verging brittle thrust system (of Permian and Tertiary events), the mafic to ultramafic rocks are bound by an older, E-verging, ductile shear system, which is subsequently folded and reactivated by the younger event. This successive tectonism results in nappes or klippe-like structures, where sheets of ultramafic complexes are totally disconnected and surrounded by ductile thrusts (see Figs. 6 and 12 of Davis et al. 1999) that juxtaposes older and higher metamorphic rocks onto younger and lower grade rocks (Gerbi et al. 2002). These features are strikingly similar to those described above in Pie de Palo area as well as in Umango and Maz areas of the northern segment.

TIMS U–Pb zircon ages between 576 ± 17 Ma (Neoproterozoic) and 418 ± 10 Ma (late Silurian) are reported from the Cortaderas Formation in their associated mafic rocks (Davis et al. 2000). K–Ar and Ar–Ar constraints for the low-grade metamorphism in the area are mostly Devonian (Fig. 6, Cucchi 1972b; Buggisch et al. 1994; Davis et al. 1999).

The siliciclastic Cortaderas, Farallones, and Bonilla Formations could be compared with the El Quemado and La Paz Formations of the Caucete Group (Fig. 5), and the carbonatic Alojamiento and Buitre Formations to the Angacos limestones of the Caucete Group. Nevertheless, southern Precordillera lacks Ordovician deformation and metamorphism—the most important ones in Sierra de Pie de Palo—but instead Devonian tectono-metamorphic activity is the main Early Paleozoic event.

Southern Frontal Cordillera

South of 33° the Frontal Cordillera makes up the extension of the above-described metamorphic basement belt (Fig. 7), with low- to high-grade rocks and associated mafic–ultramafic rocks exposed along the Cordón del Plata and Cordón del Portillo (Caminos et al. 1979; Caminos 1993; Vujovich 1998; Basei et al. 1998; Villar 1969).

TIMS U–Pb, Grenvillian magmatic ages of 1,069 ± 36 or 1,081 ± 45 Ma have been reported from the Las Yaretas bt-hbl orthogneisses cropping out in the southern part of the Cordón del Portillo area (Ramos and Basei 1997), although their relationship with other paragneisses and schists of the area remains unsolved.

The Guarguaraz Complex, recognized in the northern portion of the Cordón del Portillo, is composed of a passive margin metasedimentary association (quartzites, mica schists and marbles) in tectonic contact with ultramafic intrusive bodies, both associated with basic magmatism, as sills coeval with the sedimentation and dykes intruding the ultramafic bodies (López and Gregori 2004; López de Azarevich et al. 2009). They are involved in a fold and thrust belt deformation with SE-vergence, associated with a regional metamorphism (López and Gregori 2004). The thrust system juxtaposes two parallel metamorphic belts of low and high grade (López de Azarevich et al. 2009), assigned to Chilenia collision, with contrasting P–T ranges, one with high-P amphibolite-granulite facies with baric peak at 1,350 MPa and 500°C, and the other with greenschist facies (Ruviños et al. 1997; Massone and Calderón 2008).

Detrital zircon maximum deposition age at *ca.* 550 Ma for this complex (Willner et al. 2008) is consistent with the Neoproterozoic-Cambrian age derived from the preservation of cianobacteria, acritarchs, and stromatolitic structures, although they do not totally agree with the 655 ± 76 Ma Sm–Nd isochron age derived from basaltic sills and dykes (López de Azarevich et al. 2009). It is noted that their detrital zircon pattern has a striking similarity with that of the siliciclastic units of the Caucete Group (Fig. 6).

For the low- to high-grade metamorphism affecting the basement of southern Frontal Cordillera, Rb–Sr, K–Ar, and Ar–Ar data suggest certain possibility of a 500–515 Ma Cambrian event, and a more reliable Devonian one between 378 and 362 Ma (Dessanti and Caminos 1967; Caminos et al. 1979; Basei et al. 1998; Davis et al. 1999). These Devonian ages are equivalent to those found in the southern Precordillera, from which it is suggested as the most important deformation and metamorphism event occurring in these regions, affecting marginally the Sierra de Pie de Palo to the east (Ramos et al. 1998).

Southern segment

Mesoproterozoic basement exposures in the southern segment extend south of 34°S, within the San Rafael Block and Las Matras Block. The basement rocks presently known to be of Mesoproterozoic origin had already been correlated with the metamorphic rocks located at the base of exploration wells in the southern border of the Triassic Cuyo basin, and in addition, to the large outcrops of Sierra de Pie de Palo, on the basis of lithologic comparison and few available K–Ar dates (Criado Roqué 1979; Linares

et al. 1980). Moreover, basement rocks recognized at the bottom of exploration wells in the central part of the Cuyo basin had also been correlated with similar rocks in Valdivia and Barbosa hills (Rolleri and Fernández Garrasino 1979) of the above-described central segment.

Basement exposures in this segment are extremely small, with only km-scale outcrop sizes and generally poor outcrop situations, particularly in the Las Matras Block, located in the foreland region barely affected by Cenozoic Andean tectonism (Linares et al. 1980). As a consequence, field observations are discontinuous and stratigraphic relationships are scarce.

The maps showing the basement rocks of these regions (Fig. 9) were compiled on the basis of Holmberg (1973), Núñez (1979), Tickyj (1999), Melchor and Casadío (1999), Sato et al. (2000), Narciso et al. (2001), Melchor and Llambías (2004), and Sepúlveda et al. (2007).

San Rafael Block

Mesoproterozoic basement

The main outcrop within the San Rafael Block is a tectonic sliver of 10 km by 2 km, oriented NNW to SSE from Arroyo Ponon Trehue in the north to Arroyo Seco Los Potrillos in the south (Fig. 9a). The Cerro La Ventana Formation (Criado Roqué 1972), also referred to as La Ventana Formation (Núñez 1979), was first mapped by Padula (1951). This author described granitic orthogneisses supporting Ordovician limestones in unconformity, and with tectonic contacts with younger, Upper Paleozoic sedimentary and volcanic rocks. The compressive character and Cenozoic timing of this tectonism were pointed out by Núñez (1979), who showed a series of east-verging thrusts juxtaposing the basement rocks with both the Ordovician and Upper Paleozoic rocks.

The Cerro La Ventana Formation consists of amphibolites, quartz micaschists, quartzites, gneisses, and amphibolic schists intruded by dioritic to granitic rocks and pegmatitic to aplitic dykes (Núñez 1979). They are affected by heterogeneous, ductile shear zones. Field observations of part of us along the Río Seco de los Leones suggest the possibility that the assemblage correspond to a metamorphosed volcano-plutonic complex with hardly any sedimentary protolith. Main rocks are granodioritic to dioritic and minor granitic orthogneisses, with abundant angular microgranitoid enclaves now deformed and stretched (see field pictures in Fig. 9c, d). Deformation and associated low-grade metamorphism heterogeneously affect this association, originating discrete belts of gneisses, schists, and amphibolites within which leucocratic dykes show tight to isoclinal folding. The basic to acidic volcanic origin of part of the host rocks of the granitoids is inferred on the basis of relict porphyritic to seriate volcanic textures. The pervasive foliation S_1 is subvertical, oriented to the NNW. Ductile shear zones overprint these rocks, originating thin mylonitic zones of tens of centimeters in width, which show S–C structures. Mylonitic foliations are oriented to the NE, dipping around 60° to the SE, with stretching lineation plunging toward E to ESE. Similar microgranitoid enclave and chemical features currently under study by Cingolani and coworkers suggest similarities to the TTG-series rocks of the Las Matras Pluton described in the next section. The main difference is the pervasive foliation and subsequent mylonitization that affect the Cerro La Ventana Formation.

Mesoproterozoic crystallization and/or metamorphism ages of this basement are based on a Rb–Sr isochron of 1,063 ± 106 Ma with initial $^{87}Sr/^{86}Sr$ 0.7032 ± 0.0004 (Cingolani and Varela 1999), an age recalculated to 1,127 ± 130 Ma and initial $^{87}Sr/^{86}Sr$ 0.7030 with the addition of new analytical data (Cingolani, unpublished data), TIMS U–Pb age of 1,214.7 ± 6.5 Ma and Sm–Nd isochron of 1,228 ± 63 Ma with initial $^{143}Nd/^{144}Nd$ 0.51126 ± 0.00004 (Cingolani et al. 2005; see summary of isotopic data in Fig. 6). Nd isotopic data recalculated from Varela et al. (2003a) and Cingolani et al. (2005) with DePaolo et al. (1991) yield a main T_{DM} interval of 1,361–1,534 Ma and $\varepsilon Nd_{(1215)}$ range of +2.8 to +4.7. From these data, it is clear that the magmatic crystallization age is ~1,215 Ma, with a possibility of a younger metamorphism age.

Two additional very small basement outcrops south of Cerro La Ventana Formation were described by Holmberg (1973), who named them Cerro Las Pacas Formation (Fig. 9a). The first mention corresponds to dark-colored biotitic micaschists with vertical foliation oriented N10°E and intruded by a hornblende bearing granodiorite and covered by other volcanic strata, both belonging to the Permian magmatism. The second one is described as dark migmatites with orientation of banding N20°E dipping to the west. No further detailed or analytical information is available from the Cerro Las Pacas Formation.

Another possibility of finding additional Mesoproterozoic basement in the region is in the area of Loma Alta, about 50 km to the NW of Cerro Ponon Trehue (not included in the map of Fig. 9). Within the so-called Nihuil basic unit extending for around 20 km to the NNE of the El Nihuil dam, small, meter-scale relics of orthogneissic rocks of intermediate compositions bear a foliation with orientations similar to those found in Cerro La Ventana Formation, a situation that might imply a common origin. The surrounding basic rocks consist of partly deformed gabbroic rocks, in tectonic contacts with the Lower Paleozoic Río Seco de los Castaños Formation and intruded by porphyritic dolerites that make up the main outcrops

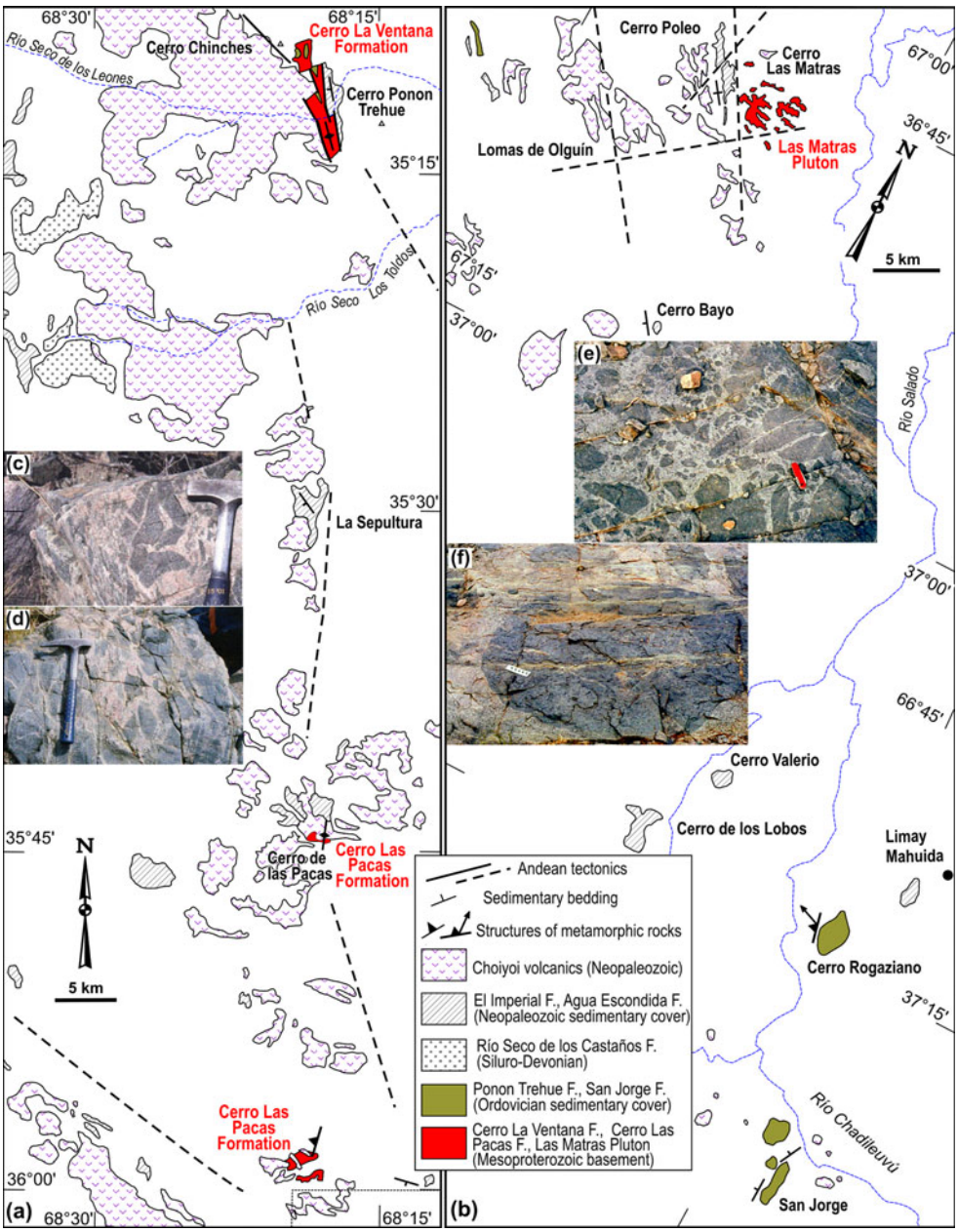

Fig. 9 Regional geological relationships of Mesoproterozoic basement and Paleozoic cover rocks in the San Rafael Block (**a**) and Las Matras Block (**b**) of the southern segment. General locations in Fig. 1, and data source detailed in text. **c** and **d** Field photographs showing less deformed areas of Cerro La Ventana Formation, containing angular dioritic enclaves. See textural similarity to Las Matras Pluton. **e** and **f** Field photographs showing angular to round enclaves in undeformed tonalitic-trondhjemitic Las Matras pluton

(Cingolani et al. 2000). These dolerites are constrained by Ordovician K–Ar ages (Cingolani et al. 2005) and tholeitic, N-MORB compositions. No contact relationship has been found with the Rodeo de la Bordalesa Tonalite, cropping out in the surroundings and yielding 401 ± 3 Ma U–Pb crystallization age (Cingolani et al. 2003).

Lower Paleozoic sedimentary cover

One stratigraphic relationship that must be emphasized is the unconformity between the Cerro La Ventana Formation and the overlying sedimentary cover of Ordovician rocks, the only primary depositional contact identified over the Grenvillian basement across the Cuyania terrane. Totalizing around 250 m of thickness, the carbonate and clastic strata of the former Ponon Trehue and Lindero formations were integrated within only one unit, the newly defined Ponon Trehue Formation (Heredia 2002, 2006), in agreement with descriptions by Astini (2002). This unit includes a lower, Peletay Member, consisting of conglomerates, sandstones, limestones and black shales, and an upper, Los Leones Member, with sandstones, green shales, conglomerates and olistolithic blocks of platform carbonatic rocks and basement granitic rocks (Heredia 2006). Integrated biostratigraphic evidences suggest a Llanvirn to Caradoc time span for its in situ sedimentation over the Cerro La

Ventana Formation, whereas an earlier, Tremadoc to Arenig time span biostratigraphically constrained by Bordonaro et al. (1996) is interpreted as representing a separate platform deposition, with its olistolithic blocks incorporated later as a result of local tectonism.

These evidences and interpretations support the idea that the Grenvillian basement had already been exhumed by the beginning of Ordovician. Recent detrital zircon study from the Ponon Trehue Formation has identified almost only Mesoproterozoic ages narrowly peaked around 1,213 Ma, implying a local, restricted provenance from the Grenvillian basement (Abre et al. 2010), in agreement with the proposed sedimentation model within an extensional regime ruled by tectonic instability (Astini 2002; Heredia 2006). The detrital zircon ages are also consistent with the U–Pb crystallization age of ~1,215 Ma mentioned for the basement. Based on these relationships, we consider that the deformation and metamorphism affecting the Cerro La Ventana Formation should have occurred long before its exhumation before Early Ordovician and probably during the late stages of the Mesoproterozoic, Grenville orogeny. Nevertheless, a Neoproterozoic to Cambrian event cannot be ruled out.

Las Matras Block

Mesoproterozoic basement

The virtually flat morphology of this foreland region only allows the uncovering of a single exposure of undeformed, tonalitic-trondhjemitic pluton of Mesoproterozoic age. Mapped and compared with the basement outcrops of the San Rafael Block by Linares et al. (1980), the Las Matras Pluton was then studied in detail by Tickyj (1999, unpublished phD thesis) and Sato et al. (2000, 2004). It is poorly exposed in an area of 4 km by 4 km (Fig. 9b), with apparent lack of country rock relationship but covered by modern sediments, which additionally obscure the stratigraphic relations with the strata of Carboniferous Agua Escondida Formation and Permian Choiyoi volcanics. Arc-related, medium-grained trondhjemitic rocks dominate over fine-grained tonalitic ones, which appear as mafic microgranitoid enclaves of variable size, morphology, and roundness (Fig. 9e and f). Na-rich character of the feldspars confirms the general TTG rock compositions, while the amphibole compositions constrain the final shallow emplacement level of the pluton between 1.9 and 2.6 km, in accordance with the common granophyric textures.

The Mesoproterozoic crystallization age of the pluton is constrained by a TIMS U–Pb zircon age of 1,244 ± 42 Ma, with consistent Rb–Sr isochron of 1,212 ± 47 Ma, with initial $^{87}Sr/^{86}Sr$ 0.7030 ± 0.0004, and Sm–Nd isochron of 1,178 ± 47 Ma with $\varepsilon Nd_{(1244)}$ +2. Available K–Ar dates show an interval of 869–690 Ma from tonalites and 392–382 Ma from trondhjemites. As shown in Fig. 6, Nd T_{DM} model ages are between 1,613 and 1,604 Ma, within the typical timing of the previously described, Laurentian Mesoproterozoic basement.

Even though some compositional and emplacement features are similar to those of the Cerro La Ventana Formation, Las Matras pluton lacks deformation and metamorphism, which suggest that the pluton was not affected by the effects of both the Mesoproterozoic, Grenville orogeny and the Early Paleozoic, Famatinian orogeny.

Lower Paleozoic sedimentary cover

The Ordovician sedimentary cover of the San Jorge Formation appears in scattered outcrops, the most important ones to the west of Limay Mahuida (Fig. 9b), where two members were defined, the sedimentary, San Jorge Member and the metamorphic, Cerro Rogaziano Member, which not only differ in their metamorphic character, but also in their structural attitude (Tickyj 1999, unpublished phD thesis; Melchor and Casadío 1999). Pb–Pb and U–Pb isochrones and $^{87}Sr/^{86}Sr$ compositions constrain the depositional age of limestones most favorably to about 500 Ma (Melchor et al. 1999), supported by conodonts of late Tremadoc age (Tickyj et al. 2002; Albanesi et al. 2003), which allows their correlation with La Flecha and La Silla Formations of Precordillera. Calcite twinning features in the marbles of the metamorphic member suggest a low-grade metamorphism between 150°C and 300°C (Tickyj 1999, unpublished phD thesis), similar to that obtained by conodont color alteration index CAI 5 (Albanesi et al. 2003). The deformation and metamorphism are tentatively attributed to the Devonian *Chanic phase* (Melchor et al. 1999), on the basis of whole rock K–Ar dates between 392 and 382 Ma of the Las Matras pluton (Linares et al. 1980).

Underground basement of Cuyo basin

As a result of exploration work carried out prior to the 1970s in the underground of the extensional, Triassic Cuyo basin, basement rocks correlated with the Cerro La Ventana Formation were recognized to the east of the San Rafael Block (Criado Roqué 1979), in the northern and southern borders of the Alvear sub-basin, which corresponds to the southern depocentre of the Cuyo basin. At its southern edge, the well IV-D (see location in Fig. 1) cut through 280 m of garnet-hornblende-biotite schists with dark green to blackish colors, densely cut by veinlets and showing metamorphic overprintings. A K–Ar age of 605 Ma is reported from these rocks (Criado Roqué 1979). In the central part of the Cuyo basin, a topographic high

bounded by high-angle faults of almost E-W direction following the Diamante River course was recognized by Criado Roqué (1979) and Rolleri and Fernández Garrasino (1979). The wells located immediately south of the Diamante River touched at their bottoms garnet-mica schists, which were considered equivalent to the southern basement rocks. North of the Diamante River, the distribution of this basement was assessed by other borings along a sliver oriented to the NW, parallel to the Triassic extensional structures, up to the southern tip of Precordillera at 33°S. Rolleri and Fernández Garrasino (1979) mention micaschists, slaty schists and metaquartzites, and correlate them with the basement outcrops of Cerro Valdivia and Cerrillos de Barboza of the central segment.

Summary, discussion, and early Paleozoic tectono-metamorphic implications

The geological complexities of the above-described basement terranes can be explained in relation to the widely accepted premise that the Mesoproterozoic rocks record the successive effects of the breakup of Rodinia supercontinent and the subsequent accretion to western Gondwana in Early Paleozoic times (Li et al. 2008; Fuck et al. 2008), with the addition of their later involvement in Late Paleozoic to Meso-Cenozoic fragile tectonics. The attribution of the Mesoproterozoic basement units to three different terranes—Cuyania and Chilenia of Laurentian origin, and Maz of proto-Gondwanan origin—opens such a wide range of alternatives in tectonic configuration and correlation prior to their final positioning to the present arrangement that they are beyond the scope of our contribution, especially for Mesoproterozoic and Neoproterozoic times. Therefore, for the rocks formed in these times we will mainly point out their most distinguishing features (depicted in Figs. 5 and 6) together with their original tectonic interpretations. However, for the Early Paleozoic times we are in a better condition to evaluate the role played by each of the basement assemblages within the frame of collisional Famatinian orogeny.

Mesoproterozoic basement terranes related to Rodinia amalgamation

Among all the units considered, the Maz Group of the northern segment registers the most complete Mesoproterozoic history, with the oldest depositional constraints (1,700–1,200 Ma) in association with the highest T_{DM} ages and radiogenic Pb features. It also includes the oldest 1,330–1,260 Ma arc magmatism, followed by ~1,208 Ma deformation and metamorphism, and subsequent intraplate magmatism (Rapela et al. 2010).

In the rest of the units, the magmatic arc rocks are younger (Fig. 5). Although intermediate to acidic rocks (1,244–1,027 Ma) dominate, mafic to ultramafic rocks (1,204–1,102 Ma) are abundant in the Sierra de Pie de Palo (Ramos and Vujovich 2000) and are also common in the Precordillera xenoliths (Mahlburg Kay et al. 1996) of the central segment. In the Sierra de Umango, orthoamphibolites are included in the Juchi Orthogneiss (Varela et al. 2003a). TTG-suite rocks, common in the southern segment (Sato et al. 2004), are also described in the Sierra de Pie de Palo of central segment (Vujovich et al. 2004; Morata et al. 2010; Rapela et al. 2010). All these rocks share their juvenile Nd–Sr features, and a non-radiogenic Pb character when available.

Apart from rocks of magmatic origin, the Tambillito Unit is described as a distinct unit of sedimentary origin (Varela et al. 2008), disconnected from the Juchi Orthogneiss but sharing its distinctive structural features.

Grenville-age high-grade metamorphism is only proven in the xenoliths of Precordillera (Mahlburg Kay et al. 1996; Rapela et al. 2010), in addition to the Maz Group. Postdating this metamorphism, the intraplate AMCG Complex is also unique to the Maz Group. Though without time constraint, we favor a Grenville timing for the heterogeneous deformation and low-grade metamorphism of Cerro la Ventana Formation of southern segment, because the stratigraphic relation indicates that this basement was already exhumed by Early Ordovician.

The inclusion of the major part of the Mesoproterozoic units to the Laurentia-derived basement of the Cuyania terrane has been widely accepted (e.g. Vujovich et al. 2004; Baldo et al. 2006; Morata et al. 2010). However, more controversial is the proposition of proto-Gondwanan derivation of the Maz terrane (Casquet et al. 2008a) and its paleogeographical relationship with the rest of the Mesoproterozoic units (Casquet et al. 2008b), because it is mostly based on geochronologic and isotopic basis. They are still liable to different interpretations, as can be seen from the changing tectonic schemes that involve this terrane, positioning the sierras de Umango, Maz and Espinal of the northern segment separately in Cuyania, Maz and Famatina terranes (Ramos 2009), or all of them included within a single Famatinian terrane (Ramos 2010). The Las Yaretas orthogneiss of Frontal Cordillera is the unit with the least basic geological information with only preliminary U–Pb age (Ramos and Basei 1997), which is weak support for the proposed basement of Chilenia terrane.

Neoproterozoic magmatism related to Rodinia continental rifting

Independently of their Meso to Neoproterozoic paleogeography, the basement units of the northern and central

segments record felsic to mafic magmatic events associated with extensional regimes (Fig. 5) prevailing in the Rodinia breakup stage (Li et al. 2008). Part of these events is attributed to the opening of the Iapetus (Dalziel et al. 1994) and Clymene (Trindade et al. 2006) oceans. They are represented by the A-type granitoids emplaced in the Maz and El Zaino groups (846–842 Ma; Baldo et al. 2008; Colombo et al. 2009), the Quebrada Derecha Orthogneiss of Sierra de Pie de Palo (774 Ma; Baldo et al. 2006), basaltic sills and dykes of Guarguaraz Complex in southern Frontal Cordillera (655 ± 76 Ma, López de Azarevich et al. 2009), a microgabbro associated with Cortaderas Formation of southern Precordillera (576 Ma; Davis et al. 2000), and the Syenite-Carbonatite Complex intruding the Maz Group (c. 570 Ma; Casquet et al. 2008b). According to their isotopic and geochemical features, they represent juvenile additions to the Neoproterozoic crust in most of the cases. Evidence of this extensional stage is not observed in the southern segment.

Late Neoproterozoic and Cambro-Ordovician, post-rifting sedimentary cover

Siliciclastic and carbonatic sedimentary cover of these ages can be interpreted in terms of passive margin sedimentation covering the margins of continental blocks separated from Rodinia.

From their deposition age control, two groups of units can be distinguished (see Fig. 5): a Late Neoproterozoic group (~640–580 Ma) and a mostly Cambro-Ordovician group (~550–470 Ma). In the northern and central segments, both sedimentary groups are represented, whereas in the southern segment only the younger group is present.

One exception to the above grouping is the El Zaino Group of Sierra de Maz, whose minimum sedimentation age is constrained by the intrusion of A-type granitoid of ~845 Ma (Colombo et al. 2009), and therefore should have an older deposition age, despite its generally similar lithology. Assuming the validity of a passive margin origin, it may have followed the continental extension registered in Sierra de Maz by the intrusion of the AMCG Complex.

Rock units included in the older group are El Taco Group, El Espinal Formation and Tambillo Unit of the northern segment, and Difunta Correa Sequence and Guarguaraz Complex of the central segment. They are siliciclastic and carbonate deposits with age constraints based on Sr, C, and O isotopes, detrital zircon provenance, and other controls. The age of the El Taco Group is inferred on the ground of similar lithology, detrital zircon age pattern, and Pb ratios with the Difunta Correa Sequence, although they are associated with different terrane (Maz and Cuyania) proposals (Casquet et al. 2008a).

None of these Late Neoproterozoic units shows a primary unconformable relationship with the Mesoproterozoic basement. The reported contacts are tectonic, and basement as well as cover rocks share their Ordovician penetrative deformation and metamorphism. Therefore, the cover relationship is only interpretative.

The younger, Cambro-Ordovician cover rocks include the Las Damas Marble and La Troya Marble in the northern segment, Caucete Group and a series of formations of Precordillera in the central segment, and Ponon Trehue Formation and San Jorge Formation in the southern segment (Fig. 5). The Guarguaraz Complex of the central segment may have developed through both sedimentary periods, though the Cambro-Ordovician timing is better constrained on detrital zircon basis. An older, mostly Early Cambrian, siliciclastic lower section can be recognized in some of the central segment units, while upper sections are dominantly carbonatic and cover mainly Mid-Cambrian to Mid-Ordovician times. Their time controls are based on scarce C isotope, detrital zircons, fossil contents or simple, loose lithologic correlation with the unmetamorphosed Cambro-Ordovician carbonate rocks of the Precordillera. Here again, the Guarguaraz Complex and Caucete Group show similar detrital zircon age patterns (Fig. 6, Willner et al. 2008; Naipauer et al. 2010), despite having been included in different terrane proposals (Chilenia and Cuyania). In northern and central segments, the units bear Early Paleozoic metamorphic overprint, while those of the southern segment are almost devoid of metamorphism.

Like the Late Neoproterozoic sedimentary units, these Cambro-Ordovician rocks lack primary unconformable relationships with the Mesoproterozoic basements, with the sole exception of the Ponon Trehue Formation over the Cerro La Ventana Formation, suggesting that this basement was already exhumed by Early Ordovician times. When both sedimentary units are exposed together, their contacts are invariably tectonic.

Assuming the opening of the Iapetus ocean at ~570 Ma (Cawood et al. 2001), the older units should have deposited prior to it, and the younger ones after it.

Early Paleozoic orogenic overprints

In relation to the final Gondwana assembly, the western margin of this continent between 28° and 38°S of present latitudes records a superposed westward succession of orogenic cycles, west of the Paleoproterozoic Río de la Plata craton (Fig. 1): (1) the Pampean cycle (latest Neoproterozoic—Middle Cambrian, Aceñolaza and Toselli 1976), evidenced primarily in Sierras Pampeanas of Córdoba (e.g. Rapela et al. 1998 and Siegesmund et al. 2009), and (2) the Famatinian cycle (Late Cambrian-Devonian, Aceñolaza and Toselli 1976), widely developed involving

the previous Pampean orogen in all the remaining Sierras Pampeanas (e.g. Pankhurst et al. 2000 and Sato et al. 2003) and the Chadileuvú Block (Tickyj et al. 2002). The latter cycle is associated with the proposed collisions of Mesoproterozoic Cuyania and Chilenia basement terranes to the west, in Ordovician and Devonian times.

This collisional Famatinian orogeny is the most important feature in the above region, with a conspicuous Ordovician magmatic arc developing along the autochthonous Gondwana border (mostly eastern Sierras Pampeanas), and pervasive Ordovician tectono-metamorphic effects overprinting this border and the allochthonous Mesoproterozoic basement together. Locally, high-P metamorphism is reported, close to the proposed suture zone with Cuyania.

For Devonian times, orogenic overprints seem to be weaker and spatially more restricted to the western side of the region reviewed in this contribution. Nevertheless, high-P metamorphism is recorded in Frontal Cordillera, a generally low-grade metamorphism in the southwestern Precordillera and fragile to ductile shear zone deformation and metamorphism through all the remaining regions considered.

In our review, a few U–Pb ages between 533 and 525 Ma (Rapela 2000; Lucassen and Becchio 2003; Casquet et al. 2008b) are reported from El Espinal Formation in Cerro Asperecito, El Taco Group and the Syenite-Carbonatite Complex in the easternmost area of the northern segment. Although the ages are well within the typical interval for the Pampean orogenic climax (Rapela et al. 1998), they are difficult to reconcile with Pampean orogenic effects, because the area was at that time subjected to a clear extensional regime.

Famatinian orogenic cycle

In the regional literature, all the geological events occurring in Late Cambrian to Devonian times were included in the Famatinian cycle (Aceñolaza and Toselli 1976), in which according to Ramos (1999), the main orogenic events or phases are those known as *Ocloyic* and *Chanic*. As these phases were originally defined based on particular unconfirmable relationships between unmetamorphosed sedimentary units of the northwestern Argentina (Turner and Méndez 1975), when applied to ductile basement geology of the Sierras Pampeanas, Sato et al. (2003) preferred to refer to Famatinian *main phase* (instead of *Ocloyic phase*) for a period of more than 30 million years of intense magmatic and tectonic activities, and to *late to post-orogenic* stage (instead of *Chanic phase*) for the mainly Devonian events in Sierra de San Luis of eastern Sierras Pampeanas.

In the present analysis of Early Paleozoic orogenic overprints on the Mesoproterozoic basement units, the tectono-metamorphic features and their isotopic constraints described in previous sections allow the recognition of three successive events for the Famatinian evolution, which we consider more appropriate to refer to as Famatinian *main phase* (480–450 Ma), *late phase* (440–420 Ma), and *Chanic phase* (400–360 Ma), see Fig. 6.

The *main phase* corresponds to the Ordovician tectono-metamorphic climax of the Famatinian cycle, with crustal shortening and thickening originated by the collision of the Cuyania terrane. Associated arc magmatism starting at around 500 Ma is widely developed in eastern Sierras Pampeanas (e.g. Pankhurst et al. 2000).

The most notable tectono-metamorphic features of the *main phase* in the northern and central segments are their nappe and klippe structures, like the Juchi and Tambillito klippen in the Sierra de Umango (Fig. 3b) and Las Pirquitas thrust in Sierra de Pie de Palo (Ramos et al. 1996). Broad ductile shear zones (e.g. La Puntilla-La Falda zone in Sierra de Umango) and N- to NNE-trending, penetrative foliations, associated with high-grade metamorphism of high-P/T conditions like in Sierra de Umango and Pie de Palo (Fig. 10) are also distinctive. The vergence of the klippe structures and shear zones does not coincide between the northern and central segments, being to the SSW in the Juchi klippe and associated ones, and to the WNW in Las Pirquitas thrust. This suggests that the transport of the tectonic sheets were both parallel and oblique to the N–S axis of the orogen.

The autochthonous Gondwana margin also exhibits equivalent ductile deformations and regional metamorphism originated during the *main phase* (e.g. Sato et al. 2003 and Otamendi et al. 2008). N- to NNE-trending penetrative foliations are associated with medium to high-grade metamorphism, with generally lower P/T conditions than those registered in the Mesoproterozoic rocks of the Cuyania terrane (Fig. 10). Major Ordovician shear zones in this region show more homogeneous orientations and vergence, of reverse character and top to the NNW movement (Martino 2003; González et al. 2006).

These strong tectonic and metamorphic effects of the *main phase* in the northern and central segments are not seen in the southern segment. The Mesoproterozoic Cerro La Ventana Formation is already exhumed by Early Ordovician times, as shown by its unconformable cover of the mainly carbonatic Ponon Trehue Formation (Fig. 5). The undeformed Las Matras pluton might as well have exhumed by Ordovician times. The low-grade metamorphism and deformation of the Upper Cambrian to Lower Ordovician San Jorge Formation (Fig. 5), its probable sedimentary cover, were attributed to the Devonian *Chanic phase* (Melchor et al. 1999). Nevertheless, the adjacent Chadileuvú Block does record the effects of this Ordovician *main phase* (Tickyj et al. 2002).

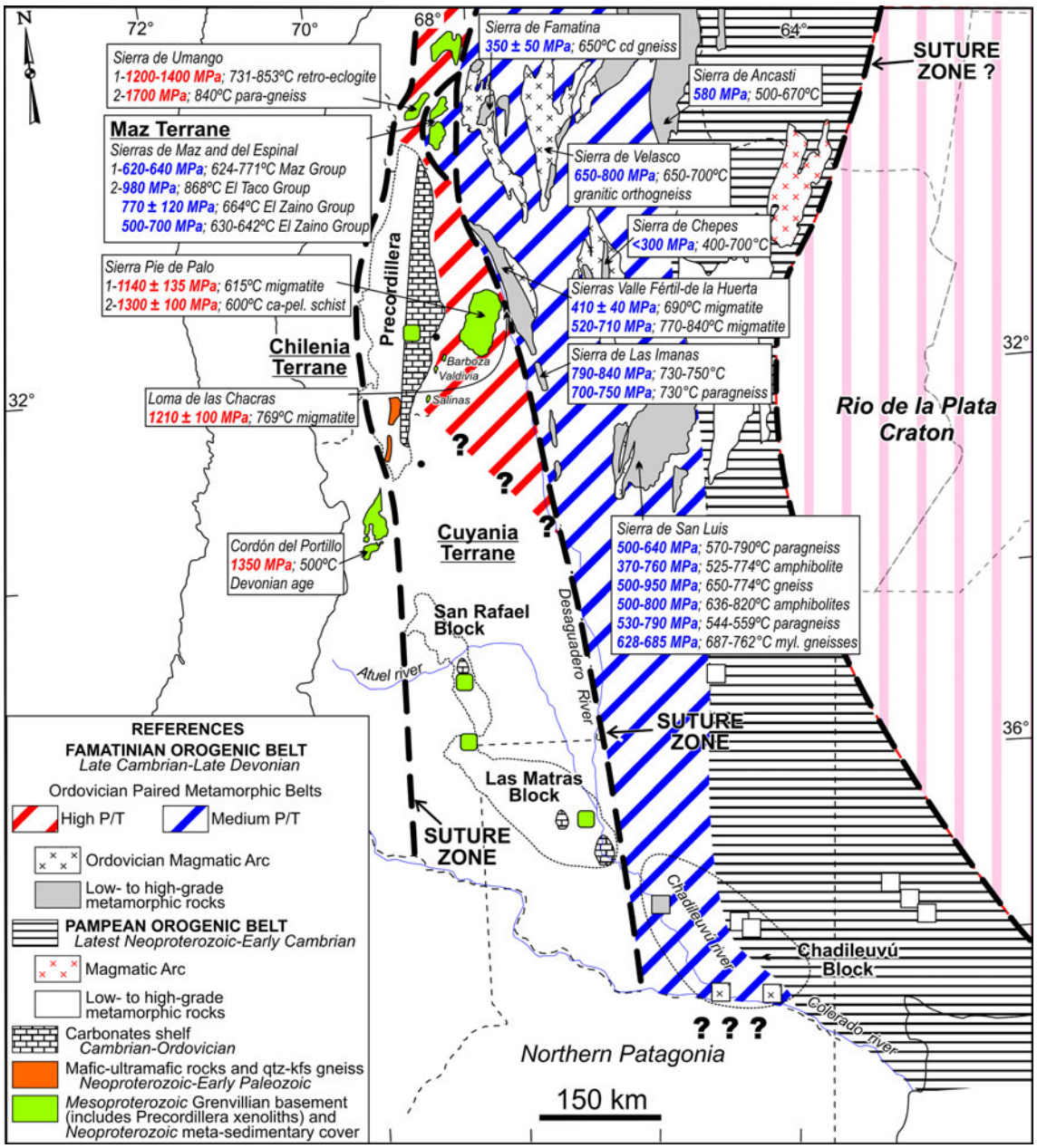

Fig. 10 Geological sketch map depicting our suggestion of Ordovician paired metamorphic belts associated with the collision of Cuyania terrane against western Gondwana, with the supporting thermobarometric data. Western, high-P/T outboard belt along the *lower plate*, and eastern, medium-P/T inboard belt along the *upper plate*. Notice that in Maz terrane, the P/T ranges similar to the eastern belt represent Silurian events. P–T data compiled from Knüver (1983), Bachmann and Grauert (1987), Dahlquist and Baldo (1996), Baldo et al. (1998, 2001), Rossi et al. (2002), Casquet et al. (2001, 2008a), González et al. (2004, 2005), Porcher et al. (2004), Murra et al. (2005), Rapela et al. (1998, 2005), Otamendi et al. (2008), Colombo et al. (2009), Hauzenberger et al. (2001), Delpino et al. (2007), Ortiz Suárez (1999, unpublished thesis) and Campos Neto (personal communication). Devonian P–T range after Massone and Calderón (2008) is placed only for comparison purpose (see discussion in text)

The undeformed and unmetamorphosed character of the Las Matras pluton might be related to a shallower emplacement level than the northern and central segments, to a heterogeneous deformation that has not affected the observed rocks, to a local tectonic situation that protected the pluton from the collisional effects (Sato et al. 2004), or to a considerable distance from the suture zone, like in the case of the San Rafael Block.

As a result of comparison of thermobarometric data from the Ordovician regional metamorphism (Fig. 10), we notice that high-P conditions are found almost exclusively overprinting Mesoproterozoic basement rocks of northern

and central segments, while medium-P conditions are described along the autochthonous Gondwana border. For this reason, we consider that a set of N–S trending, paired metamorphic belts with contrasting P/T types might be suggested. It is characterized by an outboard, high-P/T belt (Cuyania terrane, lower plate), and a parallel, inboard medium-P/T belt of Barrowian type (autochthonous Gondwana margin, upper plate). Nomenclature of paired metamorphic belts is after Miyashiro (1961), Smulikowski et al. (2007) and Brown (2010). A high P/T range of 1,140–1,700 MPa and 750–850°C may be outlined from Baldo et al. (1998 and 2001), Casquet et al. (2001) and our preliminary results obtained from Sierra de Umango. For the Barrowian belt, a medium-P/T range of mostly 500–800 MPa and 500–750°C may be constrained based on references in Fig. 10. Within the first belt, local high-P granulite and eclogite facies are identified in felsic and mafic rocks of Sierra de Umango (González et al. 2005; Campos Neto, personal communication). South of 33°S, only the eastern Barrowian belt may be followed in the Chadileuvú Block along the autochthonous border (qualitative P–T estimations, Tickyj et al. 2002), because as stated before, the southern segment of Mesoproterozoic basement lacks Ordovician metamorphism.

The Ordovician magmatic arc partly overlaps the Barrowian belt in time and space. In the region considered, the arc develops along an N–S axis between the Sierras de Famatina and Velasco in the north and the Chadileuvú Block in the south (Fig. 10). Granitoid plutons are mainly pre- to syntectonic like in the Sierra de San Luis (Llambías et al. 1998), and their emplacement produces little thermal effect on the country rocks. However, local areas exhibiting deep roots of the magmatic arc and abundant gabbros (e.g. Sierras de Valle Fértil—de la Huerta) show significant thermal upgrade of the country rock metamorphism, reaching up to 840°C (Otamendi et al. 2008; Gallien et al. 2010). These T values, the highest across the Barrowian belt, are explained by these authors as mafic underplating causing gabbroid emplacement into a country rock already affected by high-grade regional metamorphism, at 20–25 km crustal level.

The Silurian *late phase* (440–420 Ma, Fig. 6) is a restricted event, separated only around 10 Ma from the tectono-metamorphic climax of the main phase (480–450 Ma). This phase affected the major parts of the northern and central segments, but is conspicuous in the Sierras de Maz and Espinal, where it caused their most important, medium-P, high-grade metamorphic overprint (Table D and F, Electronic Supplementary Material), in association with mostly W-verging structures (D_1 in El Taco and El Zaino groups, equivalent to D_2 in Maz Group).

In the Sierra de Umango (Tambillito and Tambillo units), the penetrative structures formed by the *main phase* are refolded in association with amphibolite to greenschist facies metamorphism. Ductile shear zones of compressive character locally transpose previous penetrative structures.

Silurian ductile shear zones are abundantly dated in the autochthonous border of Gondwana (e.g. Castro de Machuca et al. 2008b, Steenken et al. 2010), which represent late stages of the collisional orogeny started with the *main phase*.

The *Chanic phase* (400–360 Ma) is distinctly observed in the western part of the central segment: (a) A 378–362 Ma, fold and thrust belt deformation with SE-vergence, in the Guarguaraz Complex of southern Frontal Cordillera, juxtaposing high-P (1,350 MPa at 500°C, Massonne and Calderón 2008) and greenschist facies rocks. (b) E-verging, ductile deformation related to klippe-like structures (Davis et al. 1999) of mainly Devonian age (Gerbi et al. 2002) affecting siliciclastic and carbonatic rocks and associated mafic–ultramafic rocks of southern Precordillera. They are associated with mainly low-grade and local granulite facies metamorphism. The vergence of these two areas is opposed to the Ordovician main vergence of the Sierra de Pie de Palo.

In the remaining areas of the northern and central segments, the *Chanic phase* is revealed as reactivations or transpositions of preceding penetrative structures, in association with medium- to high-grade and ductile to fragile, shear zone metamorphism (Tables D to F, Electronic Supplementary Material). A certain southward weakening tendency of its effects is perceived in the southern segment. They are observed in the northwestern area of the San Rafael Block, where the 379–371 Ma (Rb–Sr whole rock), low-grade metamorphism is associated with NE-verging, overturned folding of the Lower Paleozoic La Horqueta Formation (Tickyj et al. 2001). Further south in the Las Matras Block, it is only hinted by the 392–382 Ma K–Ar dates in the Mesoproterozoic Las Matras pluton, and the tentative assignment of the metamorphism of the San Jorge Formation to this phase (Melchor et al. 1999).

In the autochthonous margin, the *Chanic phase* is represented by shear zone reactivations and tectonic events associated with exhumation and orogenic collapse of the collisional Famatinian orogen (e.g. Sims et al. 1998).

All the above characterization of the protracted Famatinian orogenic cycle, outlined by successive stages and involving nappe and klippe structures as well as a paired metamorphic system like the one we suggest here, is typical features of collisional orogens (Beaumont et al. 1996; Brown 2010).

Conclusions

The Mesoproterozoic basement units accreted to the west of the Río de la Plata craton between 28° and 37°S are

dominated by intermediate to acidic and mafic–ultramafic, arc-related magmatism of juvenile character, registered between 1,244 and 1,027 Ma. Among them, the Maz Group stands out for the associated protracted history and reworked character. Grenville-age metamorphism is demonstrated only in the xenoliths of Precordillera and in the Maz Group.

Neoproterozoic breakup stage of the Rodinia supercontinent is represented in the northern and central segments by felsic to mafic, extensional magmatism of 846–570 Ma. Siliciclastic and carbonate, passive margin sedimentation is mainly recorded in Late Neoproterozoic (~640–580 Ma) and Cambro-Ordovician (~550–470 Ma) times. The southern segment registers only the younger group of rocks, in which the unmetamorphosed, Ordovician Ponon Trehue Formation shows the only primary, unconformable relationship over the Mesoproterozoic Cerro La Ventana Formation.

The Late Neoproterozoic to Early Cambrian, Pampean orogenic belt is developed along the western border of the Río de la Plata craton, involving mainly the eastern Sierras Pampeanas. The final Gondwana assembly is completed through the Late Cambrian to Devonian, Famatinian orogeny, attributed to two successive collisions, of Cuyania and Chilenia terranes, respectively, in the Ordovician and Devonian times. The timing and mechanism of accretion of the Maz terrane are still unsettled matter. Collisional deformation effects overprinted the Mesoproterozoic basement rocks, through the Famatinian *main phase* (480–450 Ma), *late phase* (440–420 Ma) and *Chanic phase* (400–360 Ma).

The klippe structures and associated ductile shear zones that we find in Sierra de Umango corresponds to the tectonothermal climax of the *main phase*, as does the similar nappe tectonics previously documented in Sierra de Pie de Palo. In addition to these deformation styles characteristic of collisional orogens, available data, though scarce, allow us to suggest the recognition of a paired metamorphic belt system, with an outboard high-P/T belt and a parallel, inboard Barrowian P/T belt, respectively, along the lower and upper plates.

The effects of the *Chanic phase* are better registered in the western part of the central segment. We would like to highlight certain klippe-like structures in the southern Precordillera, and the mention of high-P/T and low-P/T metamorphism associated with ductile shear zones in Frontal Cordillera, as possible effects related to collision.

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