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The Basement of the Andean Frontal Cordillera in the Cordón del Plata (Mendoza, Argentina): Geodynamic Evolution

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ABSTRACT. The Andean Paleozoic basement of the Cordón del Plata (Argentina) consists of two sets of rocks showing different stratigraphy, structure and metamorphism. The lower one is represented by the pre-Carboniferous (Devonian?) Vallecitos beds. These rocks have been affected by folds and associated cleavage, developed under low-grade metamorphic conditions and related to the Chanic orogenic event of the Famatinian Orogenic Cycle (Upper Devonian-Lower Carboniferous). The Vallecitos beds is pre-orogenic to the Chanic deformation event and must have been deposited in a fore-arc basin located on the active margin of Chilenia, before its collision with the passive margin of Gondwana. The upper set unconformably rests on the Vallecitos beds and consists of the Late Carboniferous El Plata Formation, and the Río Blanco Conglomerates, probably Late Carboniferous-Permian in age. These rocks have been affected by east-directed thrusts and associated folds formed under very low-grade to non-metamorphic conditions. This deformation can be related to the San Rafael phase (Gondwanan Orogen). The El Plata Formation was deposited in an extensional back-arc basin while the Río Blanco conglomerates must have been deposited in a retro-arc basin, both of them on the active margin of Gondwana. The Choiyoi Group, essentially volcanic and Permo-Triassic in age, rests unconformably on the previously described successions and was deposited in an extensional setting (pre-orogenic stage) associated with the beginning of the Andean Cycle. This cycle led to the uplift of the Frontal Cordillera during the Cenozoic and the deposition of thick continental units at the base of the Cordón del Plata in Neogene-Quaternary times.

Keywords: *Paleozoic Basement, Chanic Orogeny, Gondwanan Orogeny, Geodynamic Evolution, Frontal Cordillera, Andes, Argentina.*

RESUMEN. El Basamento de la Cordillera Frontal de los Andes en el Cordón del Plata (Mendoza, Argentina): Evolución Geodinámica. El basamento paleozoico de los Andes, que aflora en el Cordón del Plata (Argentina), está formado por dos conjuntos de rocas con diferente estratigrafía, estructura y metamorfismo. El conjunto inferior está representado por las capas de Vallecitos, de edad precarbonífera (posiblemente devónica). Estas rocas se encuentran afectadas por pliegues y clivajes asociados, formados en condiciones metamórficas de bajo grado y relacionados con la Orogenia Chánica del Ciclo Famatiniano (Devónico Superior-Carbonífero Inferior). Las capas de Vallecitos tienen un carácter preorogénico y se habrían depositado en una cuenca de antearco situada sobre un margen activo de Chilenia, antes de su colisión con el margen pasivo de Gondwana. El conjunto superior, discordante sobre las capas de Vallecitos, está constituido por la Formación El Plata, de edad Carbonífero Superior, y los Conglomerados de Río Blanco, discordantes sobre la anterior, de probable edad Carbonífero Superior-Pérmico. Todas estas rocas han sido afectadas por corrimientos y pliegues asociados, vergentes al este, generados en condiciones epimetamórficas y relacionables con la Fase Orográfica San Rafael del Ciclo Gondwánico. La Formación El Plata se depositó en una cuenca de trasarco mientras que los Conglomerados de Río Blanco lo hicieron en una cuenca de antepaís de retroarco, ambas sobre el margen activo de Gondwana. Discordantemente, sobre todas las rocas antes mencionadas se apoya el Grupo Choiyoi, de naturaleza fundamentalmente volcánica y edad pérmico-triásica, que ha sido depositado en un contexto extensional preorogénico, característico del comienzo del Ciclo Andino. Este ciclo culmina con el levantamiento de la Cordillera Frontal durante el Cenozoico y el depósito de espesas secuencias continentales neógeno-cuaternarias a los pies del Cordón del Plata.

Palabras clave: *Basamento Paleozoico, Orogenia Chánica, Orogenia Gondwánica, Evolución geodinámica, Cordillera Frontal, Andes, Argentina.*

1. Introduction

The Cordón del Plata is a mountain range located 50 km west of Mendoza (Argentina) and is part of the Frontal Cordillera of the Andes (Groeber, 1938) (Fig. 1).

The Frontal Cordillera contains a Paleozoic basement constituted by sedimentary, metamorphic and igneous rocks (Fig. 2), which was strongly deformed during the Famatinian and Gondwanan orogenic cycles (Ramos, 1988) and is intruded by Upper Paleozoic granitoids. An Andean cover lies unconformably over the Paleozoic basement, and is constituted by Permo-Triassic and Cenozoic sedimentary, volcanic and volcanoclastic rocks (Fig. 2), intruded by Mesozoic and Cenozoic granitoids. This cover was deformed in Cenozoic times, during the Andean Orogenic Cycle. The main Andean orogeny uplift is linked with the Nazca plate subhorizontal subduction, located between 27° and 33°30' S latitude along the Pampean flat-slab segment (Gutscher *et al.*, 2000). The absence of recent volcanism in the Pampean flat-slab segment allows the observation of the Paleozoic, Mesozoic and Cenozoic rocks and structures.

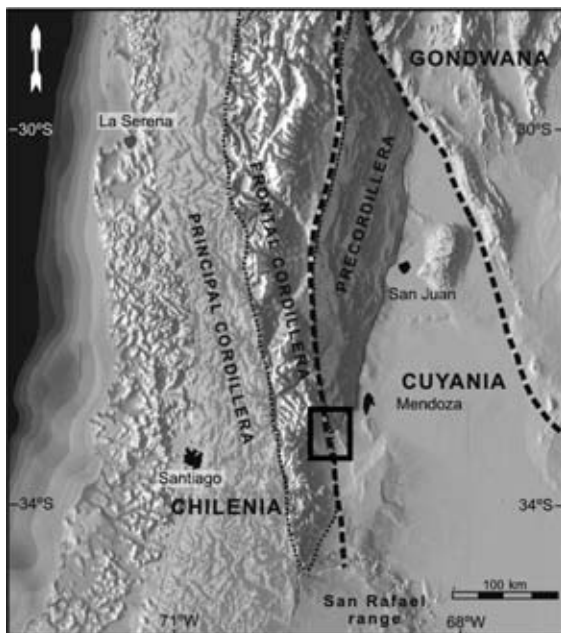


FIG. 1. Morphostructural map of the Andes between 29° and 35°S, showing the location of the Paleozoic terranes and sutures. The box indicates the location of the study area shown in figure 2. Based on Ramos (2004).

The study area is more than 6,000 m high and contains an extensive outcrop of the Paleozoic basement of the Andes (Fig. 3), formed by two sets of rocks with different deformational features and metamorphic grades. Permo-Triassic volcanic rocks of the Choiyoi Group and Cenozoic sedimentary rocks unconformably overlie this basement (Figs. 2 and 4).

The N-S trending La Carrera fault system (Camínos, 1965; Polanski, 1972), whose main faults from west to east are: Arenal, Médanos and Río Blanco (Fig. 2), has been traditionally recognized as responsible for the Andean uplift of this range, although the first development of these structures has been recently assigned to the Permian San Rafael phase of the Gondwanan Orogen (Giambiagi *et al.*, 2011). This fault system, composed by several N-S trending thrusts, uplifted the basement rocks of the Cordón del Plata range during the Cenozoic Andean Orogen. The easternmost faults of this system (between Médanos and Río Blanco faults) affect the Neogene synorogenic deposits (Folguera *et al.*, 2003; Casa, 2005), and show evidence of Quaternary activity (Fauqué *et al.*, 2000; Casa, 2005).

The aim of this study is to characterize the basement rocks outcropping in the eastern slope of the Cordón del Plata and compare them with studied sequences of neighbouring areas. By analyzing the deformation history and metamorphism, we attempt to establish the tectono-stratigraphic evolution of these rocks and fit them into a coherent evolution model for the Andes during the Late Paleozoic.

2. Stratigraphy

There are four main stratigraphic units, separated by unconformities in the study area (Figs. 2 and 4):

I. The oldest unit consists of centimeter to decimeter scale, well-stratified beds of dark quartzites and laminated shales (Fig. 5A), where cross- and flaser-laminations can often be recognized. Meter thick beds of clast-supported conglomerates, including centimeter-sized clasts of quartz, plutonic, volcanic and other metamorphic rocks can occasionally be observed. Until now, no sedimentologic studies have been made on these rocks, although their stratigraphic characteristics could indicate a turbiditic origin.

The age of these rocks is not well known due to the absence of fossils. Based on lithological characteristics and stratigraphic position, this sequence is very

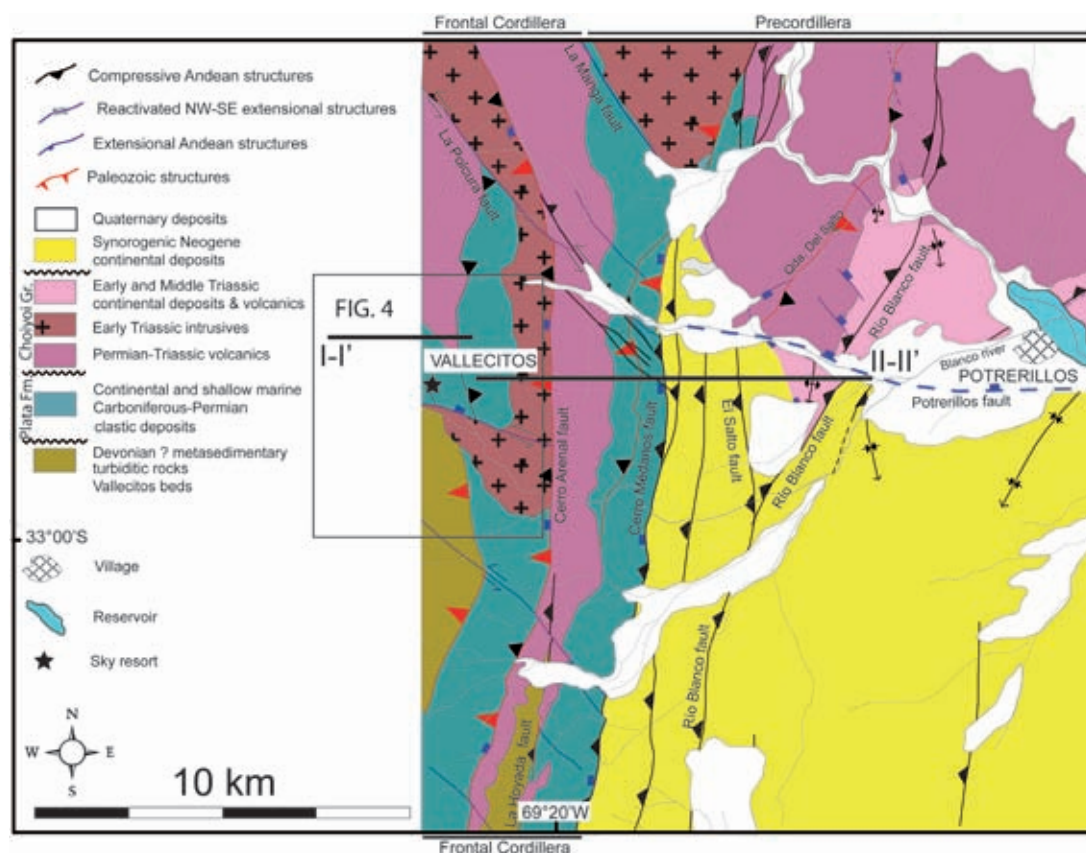


FIG. 2. Geological sketch map of the study area, including the Frontal Cordillera and Precordillera of the Andes. Modified from Folguera *et al.* (2003).

similar to the Alto Tupungato Formation, described by Polanski (1959) in the western part of the Cordón del Plata massif, which has been assigned to Early Carboniferous or older. However, this formation was attributed to the Late Carboniferous (López Gamundí *et al.*, 1987), which would invalidate this possible correlation. In addition, sucesions with similar facies, covered unconformably by Late Carboniferous rocks, have been assigned to the Devonian in the Frontal Cordillera of the San Juan province (Gutiérrez, 1983; Azcuy *et al.*, 1999; Heredia *et al.*, 2002). Recently, south of the study area, Tickj *et al.* (2009) have described Late Ordovician beds in the eastern side of the Frontal Cordillera (Las Lagunitas Formation); but their stratigraphic features are different (more slates and lithic sandstone predominance) from those described for the Cordón del Plata area and they could be older. For all these reasons, we provisionally named these rocks as Vallecitos beds and assigned them to the Devonian.

The absence of subaerial volcanism older than Late Carboniferous in the eastern part of the Frontal Cordillera (including the Precordillera), suggests a western origin for the volcanic clasts included in the conglomerates of the Vallecitos beds.

This succession is intruded by many deformed dykes of quartz and pegmatites of granitic/granodioritic composition, which do not affect the overlying El Plata Formation.

The Vallecitos beds have similar facies to the Devonian sucesions described in the central and eastern Precordillera, which are part of the Gualilán Group (Baldís and Sarudiansky, 1975) (Fig. 6). The same Devonian age has been assigned to the Villavicencio and El Codo formations, described in the western part of the Precordillera (Harrington, 1941; Guernstein *et al.*, 1965; Sessarego, 1988; Baldís and Peralta, 1999; Amenabar and di Pasquo, 2004). In contrast to the Vallecitos series, the Gualilán Group has an eastern non-volcanic source area (González Bonorino, 1975),

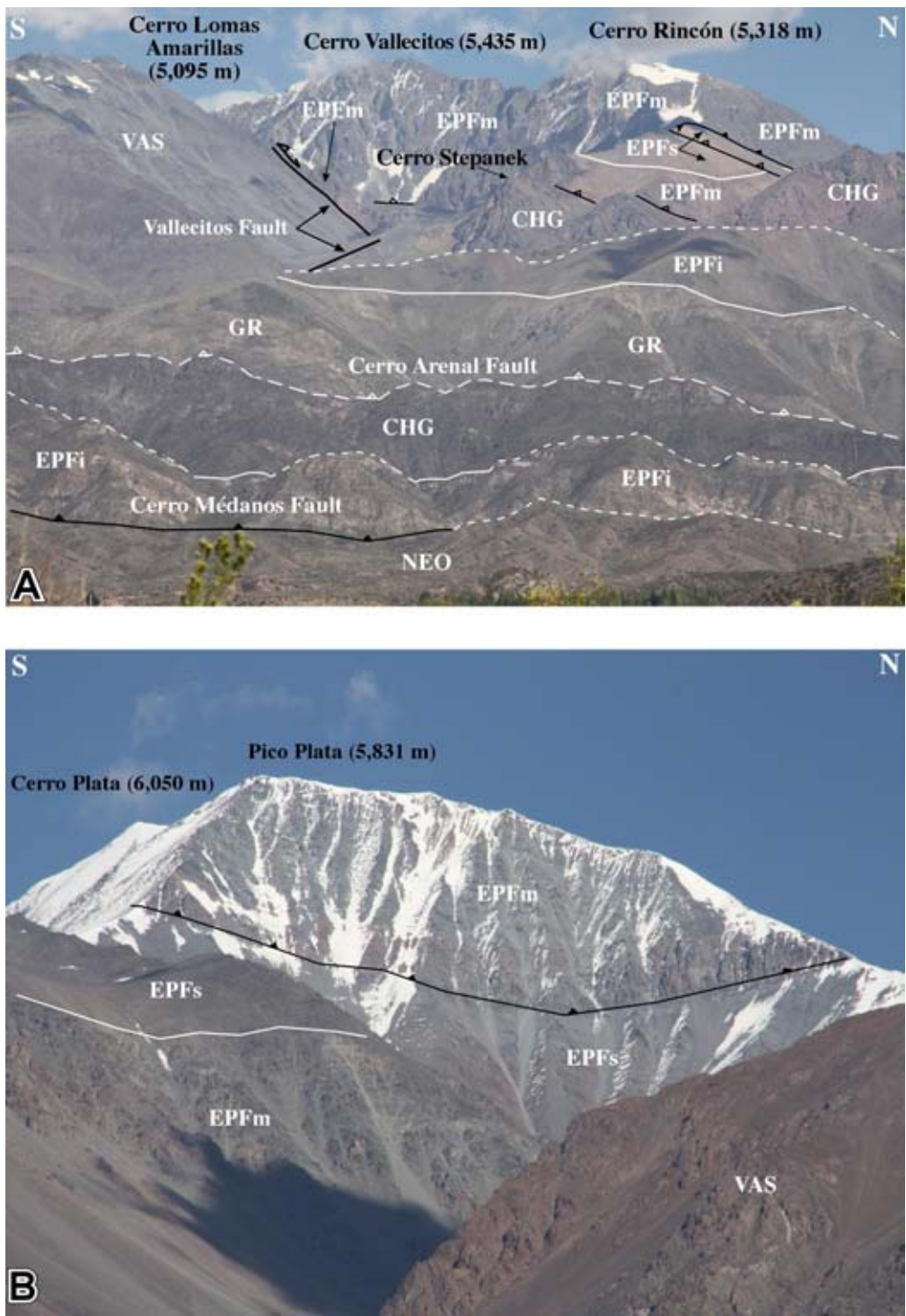


FIG. 3. Photographies showing the main geological features of the east side of the northern (A) and southern (B) Cordón del Plata. **VAS**: Vallecitos beds; **EPF**: El Plata Formation; **i**: lower member; **m**: middle member; **s**: upper member; **CHG**: Choiyoi Group; **GR**: Cerro Arenal granite; **NEO**: Neogene deposits. **White lines**: lithostratigraphic contacts; **Dotted white lines**: Apparent lithostratigraphic boundaries in the picture; **Black triangles**: Gondwanan thrust; **Blank triangles**: Andean thrust.

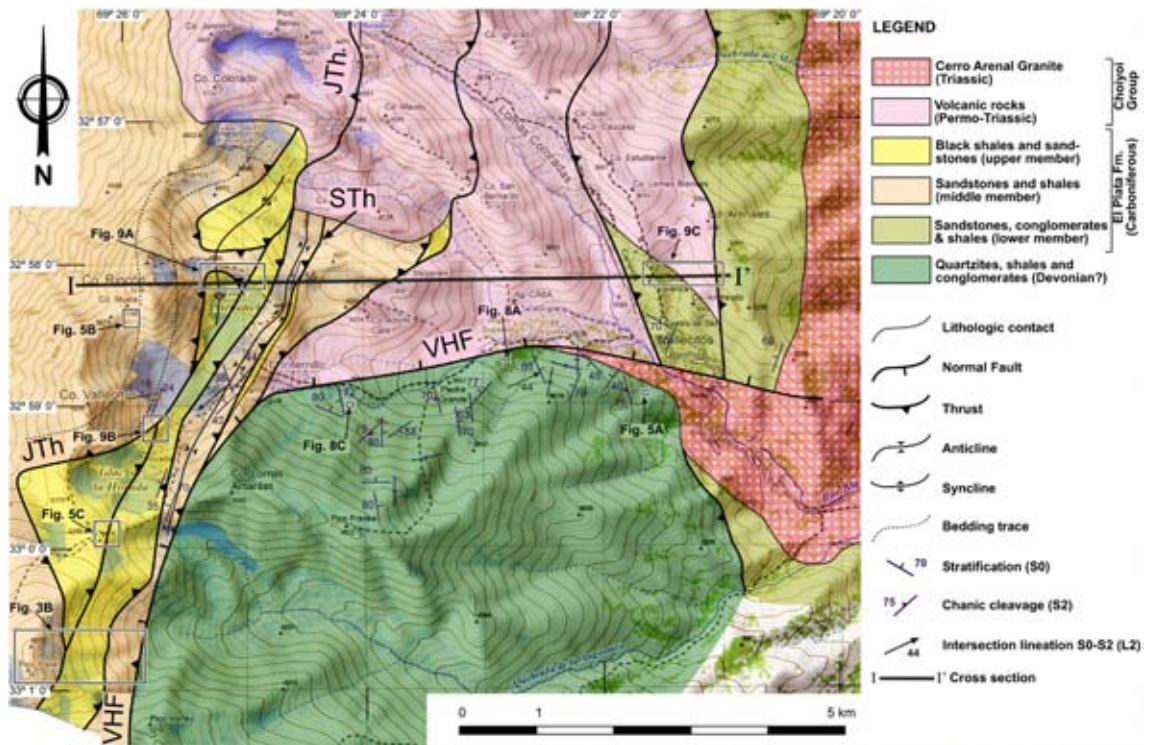


FIG. 4. Geological sketch map of the Frontal Cordillera in the Cordón del Plata area. **VHF**: Vallecitos-La Hoyada fault; **JTh**: La Jaula thrust; **STh**: El Salto thrust.

which hamper the correlation between the two stratigraphic units. As in the Vallecitos beds, the Ratón Formation from the western Precordillera, included in the Angualasto Group (Early Carboniferous) (Fig. 6), contains conglomerates with volcanic clasts of western origin. Although the Agualasto Group and the Vallecitos beds have similar deformational style, these units do not seem to correlate, since the Angualasto Group shows different facies and unconformably overlies the Devonian series (El Codo Formation).

II. A thickening siliciclastic succession rests unconformably over the Vallecitos beds. It is composed of the El Plata Formation (Camino, 1965, 1979) at the bottom part and the Río Blanco Conglomerates at the top (Fort, 1944; Camino, 1965).

The El Plata Formation has a thickness of nearly 3,300 m in the study area, and includes three members (Camino, 1965):

- The lower member crops out along several bands bounded by thrusts in the lower part of the eastern slope of the Cordón del Plata massif (Fig. 3A) and it can reach a thickness of 1,200 m in nearby areas. Its

lower part consists of conglomerates with plutonic and metamorphic pebbles. In the upper part, the conglomerates change to alternating arkosic and quartz sandstones, interbedded with gray-green shales and some quartzitic microconglomerates. This member is very similar to the Loma de los Morteritos Formation, defined by Polanski (1959) in nearby areas, and is assigned to the Late Carboniferous (Folguera *et al.*, 2003).

- The middle member is almost 1,500 m thick and is composed of gray medium to coarse-grained quartzitic litarenites, in meter to decimetre thick beds with thin interbedded shales. These rocks form the eastern wall of the Vallecitos and Rincon peaks and the east-southeast face of the El Plata peak (Figs. 3 and 5B).
- The upper member can exceed 4,000 m in thickness (Azcuay *et al.*, 1999), although in the study area it does not exceed 600 m as it is covered by thrusts. This member is mainly composed of shales (Fig. 5C) with centimetre thick intercalations of fine-grained sandstones with ripple lamination towards the top. At its base, it contains a very characteristic carbonaceous shale intercalation that is intensely tectonized.



FIG. 5. Photographies of the main Paleozoic stratigraphic units.

A. Fine-stratified quartzites of the Vallecitos beds; B. Sandstones of the El Plata Formation middle member; C. Shales and fine-grained sandstones of the El Plata Formation upper member. Note the presence of tectonic duplications in this member. **EPF**: El Plata Formation; **m**: middle member; **s**: upper member.

Freije *et al.* (1999) described basaltic pillow lavas, up to 5 m thick, interbedded in the sediments of the El Plata Formation. The sedimentary environment of the El Plata Formation ranges from shallow marine platform facies in the lower member to fluvial and deltaic in the middle and upper ones respectively (Folguera *et al.*, 2003).

The Río Blanco Conglomerates (Fort, 1944; Caminos, 1965) crop out in the La Manga Quebrada, located in the northern part of the study area (Fig. 2). Due to their moderate thickness of 20-80 m, they have not been represented on the geological map of the figure 2. These conglomerates contain metamorphic, sedimentary and volcanic pebbles and unconformably overlie the El Plata Formation, being unconformably covered by the Tambillos Formation (Choiyoi Group) of lower Permian age (Cortés *et al.*, 1997).

The El Plata Formation is similar in lithology and stratigraphic characteristics to the Agua Negra Formation (Polanski, 1970), which outcrops in the Frontal Cordillera to the west of San Juan province (Fig. 6). Moreover, the lower part of the San Ignacio Formation (Carboniferous-Permian), which overlies unconformably the Agua Negra Formation (Heredia *et al.*, 2002; Busquets *et al.*, 2005), is similar to the Río Blanco Conglomerates (Fig. 6). Both formations, San Ignacio and Río Blanco, could represent an alluvial fan system in which volcanic levels are interbedded.

III. The Paleozoic basement is unconformably covered by the Choiyoi Group volcanics (Figs. 4, 7 and 9C) of Permian-Triassic age (Groeber, 1946; Roller and Criado, 1969). In the study area, this group is composed of acidic to intermediate volcanic and volcaniclastic rocks as well as plutonic or subvolcanic intrusions with the same composition (Cortés *et al.*, 1997). The upper part is composed of sedimentary rocks (only in the Precordillera, Fig. 2), that are mainly constituted by clastic continental deposits with some interbedded volcanic rocks.

The Paleozoic and Early Mesozoic rocks are intruded by Triassic granitoids that produced a thermal metamorphism with amphibole and biotite hornfels. The outcrops of these granitoids show an elongated N-S trend (Fig. 2 and 4), running parallel to the Andean structures. Caminos *et al.* (1979) dated Cerro Arenal and Cerro Médanos (Precordillera) batholiths in the study area as Middle Triassic (K-Ar ages of 237 ± 10 and 244 ± 10 Ma respectively).

IV. Finally, in the foothills of the Cordón del Plata massif, Cenozoic (Neogene) conglomerates, sandstones and shales of continental origin rest unconformably on the rocks described above. They are part of the alluvial fans that drain the relief of the Frontal Cordillera (Figs. 2 and 3A) and they represent the synorogenic deposits of the Andean Cycle.

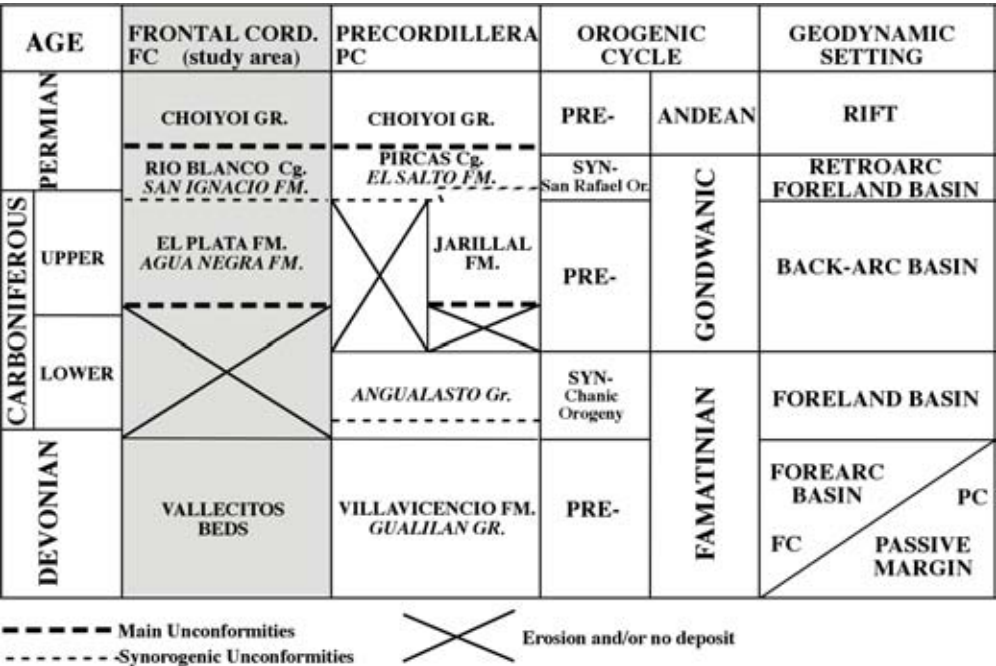


FIG. 6. Stratigraphic correlations panel. **Fm**: formation; **Gr**: group; **Or**: orogeny; **Cg**: conglomerates; **In Italics**: the equivalent lito-stratigraphic units of nearby areas.

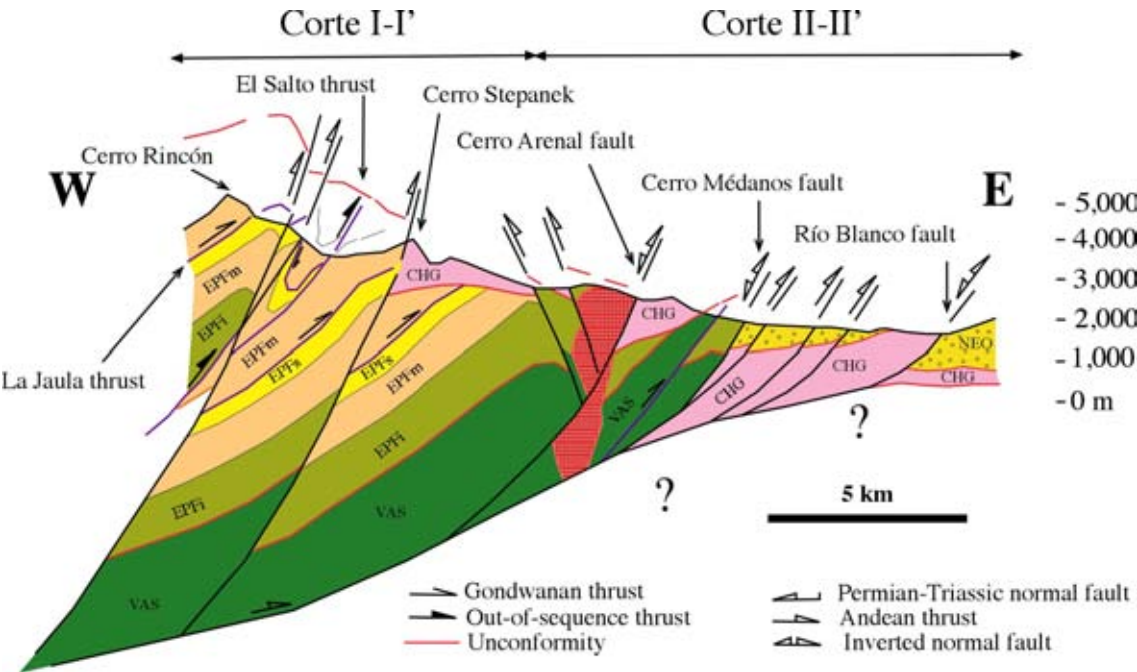


FIG. 7. Geological cross section. Location in Fig. 2 (II-II') and 4 (I-I'). Legend for stratigraphic units located in figure 4. Horizontal and vertical scale is the same. **VAS**: Vallecitos beds; **EPF**: El Plata Formation; **i**: lower member; **m**: middle member; **s**: upper member; **CHG**: Choiyoi Group; **GR**: Cerro Arenal granite; **NEO**: Neogene deposits.

3. Structure and Metamorphism

The pre-Andean basement of the Cordón del Plata massif is affected by Paleozoic to Cenozoic structures, developed during four deformation episodes. The oldest one (I) took place in pre- to Early Carboniferous times under low-grade metamorphic conditions and can be linked to the Famatinian Orogenic Cycle. The second episode (II), Late Carboniferous-Permian in age, was developed in very low grade to non-metamorphic conditions during the Gondwanan Cycle. The last two episodes (III and IV) belong to the Andean Cycle and took place without metamorphism.

3.1. Pre-Late Carboniferous Famatinian structures

This deformation episode only affects Vallecitos beds and is characterized by centimeter to decimeter scale close to tight subvertical folds. These structures are folding an S1 slaty cleavage (Figs. 8A and B), which forms an angle lower than 10° with bedding (Fig. 8A). In the shaly layers, S1 is defined by shape preferred orientation of chlorite and muscovite porphyroblasts and quartz crystals. In the quartzites, S1 is only recognized by the orientation of some phyllosilicates and opaque minerals (Fig. 8C), and can be classified as a spaced disjunctive cleavage. In the microlithons, quartz is accompanied by plagioclase and K-feldspar. The slaty cleavage (S1) is usually crenulated (Figs. 8A and C) and sometimes develops a crenulation cleavage (S2). At the microscopic scale, S2 is a rough, anastomosing and discontinuous crenulation cleavage (Fig. 8C), associated to the folds (Fig. 8A). Both foliations, S1 and S2, are sometimes partially obliterated by the growth of biotite and amphibole associated to the thermal Triassic metamorphism, related to magmatic activity.

3.2. Late Carboniferous-Permian Gondwanan structures

These structures are represented by westward dipping and east-directed thrusts (Fig. 4 and 7) with associated subhorizontal N-S meter sized folds. Some of the folds have an associated rough cleavage in shaly beds. The thrust detachment is located in the basal member of the El Plata Formation, in the easternmost sector of the El Plata range, but in the western part it develops in the basal sandstones

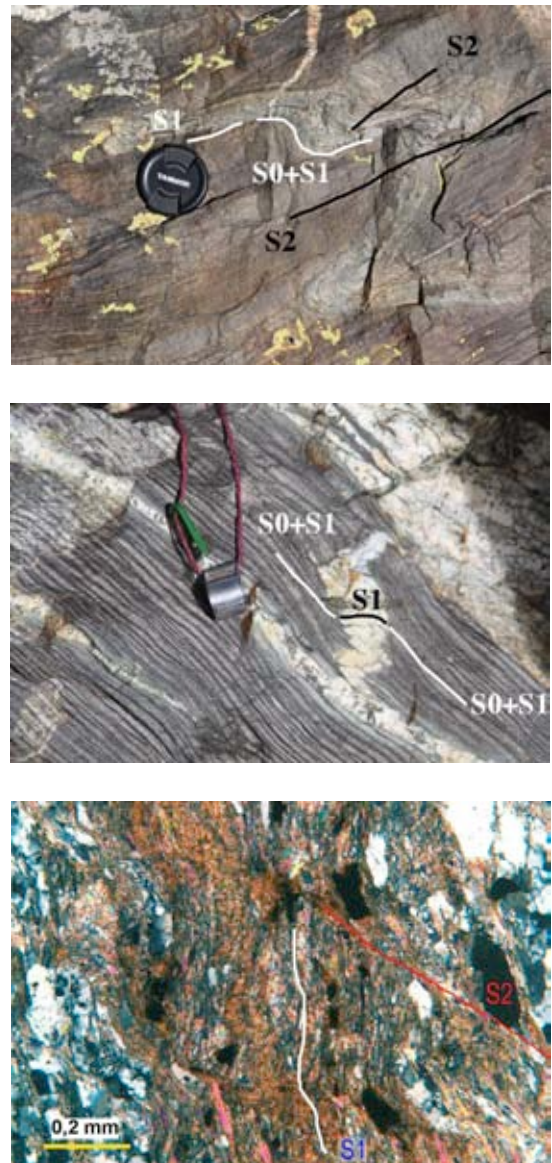


FIG. 8. Photographies of the main Chanic macro- and microstructures. A. Metric-scale fold with a S2 associated cleavage and folding a previous S1; B. S1 affecting small quartz dyke; C. Microstructure of the Vallecitos beds quartzites showing the S1 and S2 traces. Crossed polars.

of the middle member (Figs. 3B, 4 and 7). Another detachment is located at the base of the upper slate member of the El Plata Formation (Fig. 5C, 7 and 9B). Some of these thrusts produce a kilometer scale shortening, which is greater than 5 km in the La Jaula thrust. An out-of-sequence thrust, El Salto Thrust, cuts a previous one producing the

folding of the La Jaula thrust (Figs. 3, 4, 7 and 9A) and is covered unconformably by the Choiyoi Group, allowing the dating of these structures as pre-Andean (Fig. 4).

3.3. Andean extensional structures

From the Late Permian to the Middle Triassic this part of the Frontal Cordillera was affected by extensional tectonics (Mpodozis and Ramos, 1989; Uliana *et al.*, 1989; Llambias *et al.*, 1993) that started the Andean Cycle (Heredia *et al.*, 2002). The Permo-Triassic normal faults show a N-S preferred trend, with some segments oriented NE-SW to NW-SE (Figs. 2, 4 and 10). These faults are contemporaneous with the deposition of the Choiyoi Group, and produced significant variations in its thickness and lithological characteristics (Heredia *et al.*, 2002). The elongated geometry of the Triassic granitoids (Figs. 2 and 4), with the same trend of the normal faults, indicates that their intrusion could be structurally controlled by these faults.

The Vallecitos-La Hoyada normal fault must have developed during this period, as the Choiyoi Group does not exist to the south and east of this structure (Fig. 4). The change in the trend of the fault, from N-S to E-W (Figs. 4 and 10), could be controlled by the presence of pre-Andean structures with the same directions. This fault is very steep in the segment with E-W trend (Vallecitos Fault, Fig. 10), allowing to interpret it as a transfer zone of the Permian-Triassic extensional system, which mainly trends N-S in this area of the Frontal Cordillera (Fig 10).

The Río Blanco, Cerro Médanos and Cerro Arenal faults (Figs. 2, 3A and 7), located at the eastern border of the Cordón del Plata massif, could also be considered as related with the Permo-Triassic extension (Fig. 10), although they were reactivated and inverted during later Cenozoic compression. In the northern part of the Río Blanco fault, coinciding with the southern outcrops of the Precordillera, the thickness of the Choiyoi Group is similar in both the eastern and western fault walls. However, the Choiyoi Group in the southern part of the fault is very thin, and is only represented by the lower volcanic part, or is even entirely absent in the eastern hanging wall (Fig. 7). This coincidence could be explained by the existence of an E-W trending transfer fault (Fig. 10), which is now covered by Cenozoic rocks (Potrerillos

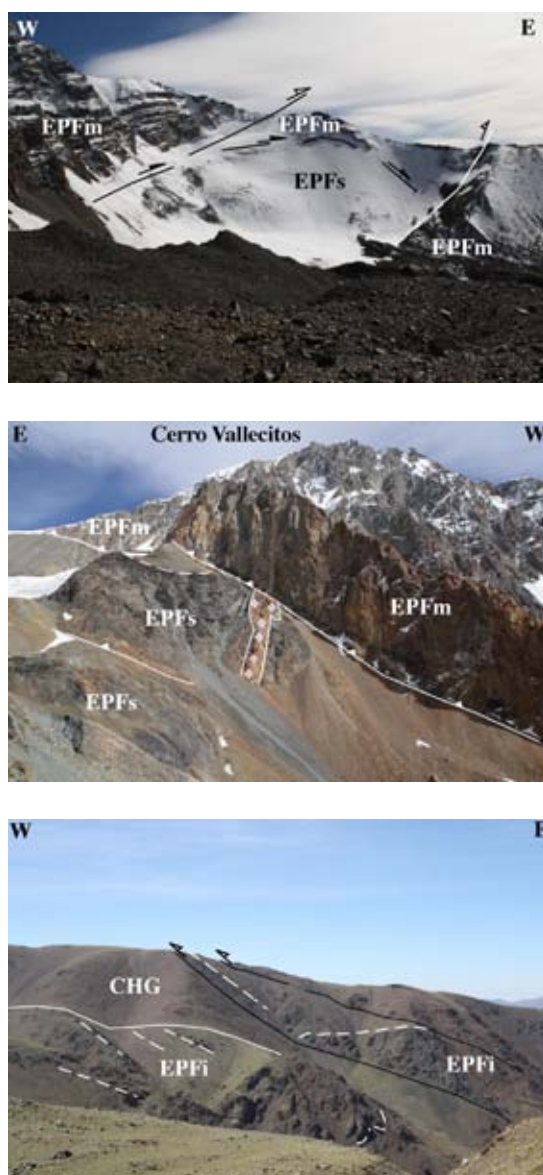


FIG. 9. Photographies of the main Gondwanan and Andean structures. **A.** Gondwanan thrust (simple arrow) and Andean thrust (blank arrow) that folds a previous Gondwanan thrust. The Andean thrust reactivates a previous Gondwanan thrust. La Jaula glacier cirque; **B.** Andean thrust deforming a Gondwanan thrust, cutting a Triassic dyke and superimposing the middle member of the El Plata Formation above its upper member. La Hollada glacier cirque; **C.** Andean back-thrusts superimposing the lower member of the El Plata Formation above the Choiyoi Group, which unconformably overlies it. Vallecitos Quebrada, southern slope of the Andresito peak. **EPF**: El Plata Formation; **i**: lower member; **m**: middle member; **s**: upper member; **CHG**: Choiyoi Group; **Dashed white lines**: Stratification traces.

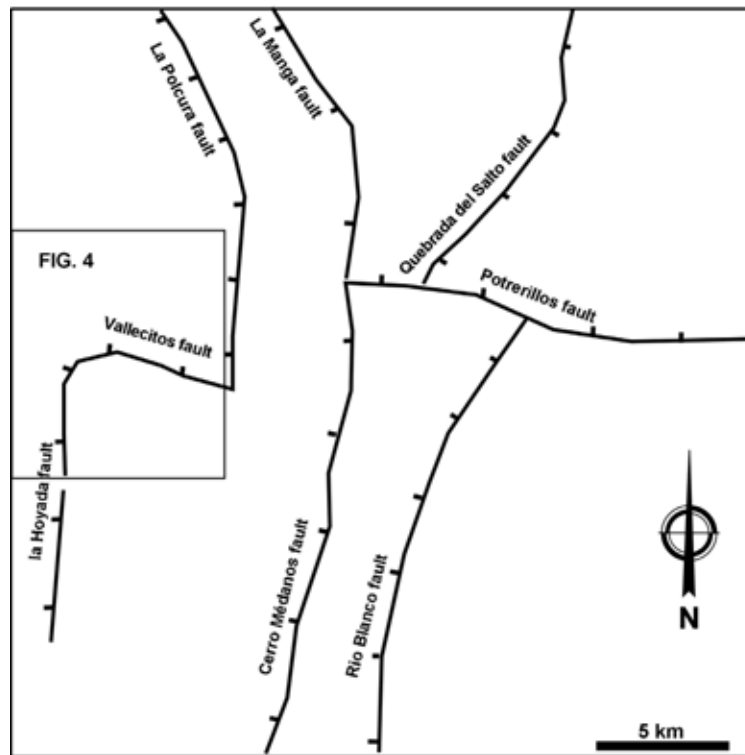


FIG. 10. Geological sketch showing the main faults of the Permian-Triassic extensional system of the Andean Orogenic Cycle.

fault in this paper, Fig. 2). Finally, in the hanging wall of the N-S trending Cerro Medanos fault, the thickness of the Choiyoi Group is around 2,000 m, the common thickness in the Frontal Cordillera, where it can exceed 4,000 m (Heredia *et al.*, 2002).

3.4. Andean compressive structures

In the Cenozoic, the Cerro Arenal, Médanos and Río Blanco faults produced the main uplift of the Cordón del Plata massif juxtaposing the pre-Andean basement and the Neogene rocks (Cerro Médanos fault, Figs. 2, 3A and 7). The Andean compressive faults are usually subvertical and merge in a common detachment dipping to the west (Folguera *et al.*, 2003, Giambiagi *et al.*, 2010) (Fig. 7). Displacements of these faults range from hundreds of meters to kilometers (Fig. 7). As shown in the geological map and cross-sections (Figs. 2, 4 and 7), the Andean faults reactivated some Gondwanan thrusts and Mesozoic extensional structures. In this way, the La Hoyada-Vallecitos normal fault could also have been active during the Andean Orogeny as a

lateral ramp, as indicated the absence of back-thrusts in the southern block. The Cenozoic deformation could also be responsible for the Potrerillos Fault reactivation as a lateral ramp of an Andean thrust. Such reactivation could cause the steep plunge of the folds axes in the Precordillera and its abrupt southern termination (Fig. 2).

4. Proposal of Geodynamic Evolution during the Late Paleozoic

In recent years, several models on the Late Paleozoic geodynamic evolution of the southern Central Andes have been published (Ramos *et al.*, 2000; Davis *et al.*, 2000; Ramos, 2004; Massonne and Calderón, 2008). In these models, the geodynamic evolution is linked to the accretion of the Chilena terrane (Fig. 1) to the Gondwana margin, formed by the Cuyania terrane (Fig. 1) previously accreted during Silurian-Early Carboniferous times (Famatinian Orogenic Cycle). The subsequent development of a subduction in the western margin of the Chilena terrane was mainly developed during de Gondwanan

Orogenic Cycle in Late Carboniferous-Early Permian times (Rebolledo and Charrier, 1994).

New details of the geodynamic evolution of the southern Central Argentine Andes during the Late Paleozoic can be obtained from our study; based on the presence in the Cordón del Plata of three rock sets with different structural and metamorphic history, separated by two major unconformities (Figs. 2 and 6). Our data was completed and compared with that obtained by different authors in surrounding areas of the Cordillera Frontal and also in the Precordillera.

The main structures affecting the rocks of the Vallecitos beds in the Cordón del Plata must have been generated during the Famatinian Orogenic Cycle. The possible Devonian age of these rocks and their location in the eastern part of the Frontal Cordillera, suggest that their structures are related to the Chanic Orogeny of that cycle, produced by the accretion of Chilenia to the Gondwana margin, formed by the Cuyania terrane (Fig. 1), previously accreted in Late Devonian times (Ramos *et al.*, 1984). This collision left remnants of Late Proterozoic-Silurian rocks with ophiolite affinities on the western side of the Precordillera, (Davis *et al.*, 1999) that marked the separation (suture) between these two terranes (Fig. 1). If this interpretation is correct, Vallecitos beds should correspond to sediments deposited on the continental margin of Chilenia (Fig. 11A) while the coeval series in the Precordillera (Fig. 5) were deposited on the continental margin of Gondwana (Fig. 11A). The volcanic clasts in the Vallecitos beds point to the existence of an active volcanic area in the Chilenia terrain. This volcanism would imply a west-dipping subduction, in which the oceanic crust that separated the two continents was completely consumed under Chilenia (Davis *et al.*, 1999; Gerbi *et al.*, 2002; Giambiagi *et al.*, 2009), although the separation between both continents should not have been very wide (Rapela, *et al.*, 1998; Busquets *et al.*, 2005). In addition, Tickyj (2011) describes Lower Devonian calc-alkaline granitoids (Fig. 11A) in the eastern part of the Frontal Cordillera (Cordón del Carrizalito), just south of the study area, which have been interpreted as belonging to a magmatic arc. In this context, the rocks of Vallecitos beds were deposited in the active margin of Chilenia, probably in a fore-arc basin associated with the subduction (Fig. 11A). It has not been possible to deduce the vergence of the Chanic structures in the study area. West-verging structures of this age (Fig. 11A) have

been described in northern parts of the Frontal Cordillera (Heredia *et al.*, 2002) and also further south (Tickyj *et al.*, 2009). On the other hand the presence in the Frontal Cordillera, further to the south and east, of high-grade metamorphic rocks (Bjerg *et al.*, 1990) and granitoids (Caminos *et al.*, 1979; Tickyj, 2011) of Early Devonian to Early Carboniferous age, point to the presence of the Chanic Orogen hinterland in the eastern Frontal Cordillera. In contrast, the Chanic structures in the Central and Western Precordillera show a general vergence towards the east (Davis *et al.*, 1999; Álvarez Marrón *et al.*, 2006; Alonso *et al.*, 2008) and the metamorphic grade increases westward (Von Gosen, 1992), as it might be expected from its location on the Gondwana passive margin (Alonso *et al.*, 2008), prior to the collision of Chilenia (Fig. 11A).

On the other hand, no Chanic synorogenic rocks have been found in the study area, as in the rest of the Frontal Cordillera. However in the Precordillera, these rocks are well represented by the Early Carboniferous Angualasto Group (Limarino and Cesari, 1992, Limarino *et al.*, 2006) (Fig. 6). The presence in this stratigraphic unit of conglomerates with volcanic and plutonic clasts of western provenance and Early Carboniferous age, represents the erosion of the magmatic arc from Chilenia during the Chanic Orogeny (Fig. 11B). The Chanic plutonic activity must be linked with the subduction in pre-collisional times and with the crustal thickening that occurred during the orogenic process, in syn-collisional times. The presence of low-grade regional metamorphism, scarce plutonism and westward verging structures in nearby areas, supports the conclusion that this sector of the Frontal Cordillera was located in the hinterland of the western segment of the Chanic Cordillera (Fig. 11B).

After the Gondwana-Chilenia collision, a new subduction zone developed on the western margin of accreted Chilenia (Ramos, 1988; Rebolledo and Charrier, 1994), beginning the Gondwanan Orogenic Cycle (Fig. 11C). In the Late Carboniferous, the sedimentation of the El Plata Formation took place in a back-arc extensional basin (Fig. 11C), representing the first Gondwanan pre-orogenic sequence (Mpodozis and Ramos, 1989; Fernández Seveso *et al.*, 1993; Astini, 1996; Azcuy *et al.*, 1999; Charrier *et al.*, 2007). The Carboniferous rocks of the study area are part of the Río Blanco-Calingasta-Uspallata basin (Amos and Rollieri, 1965). The Protoprecordillera (Amos and

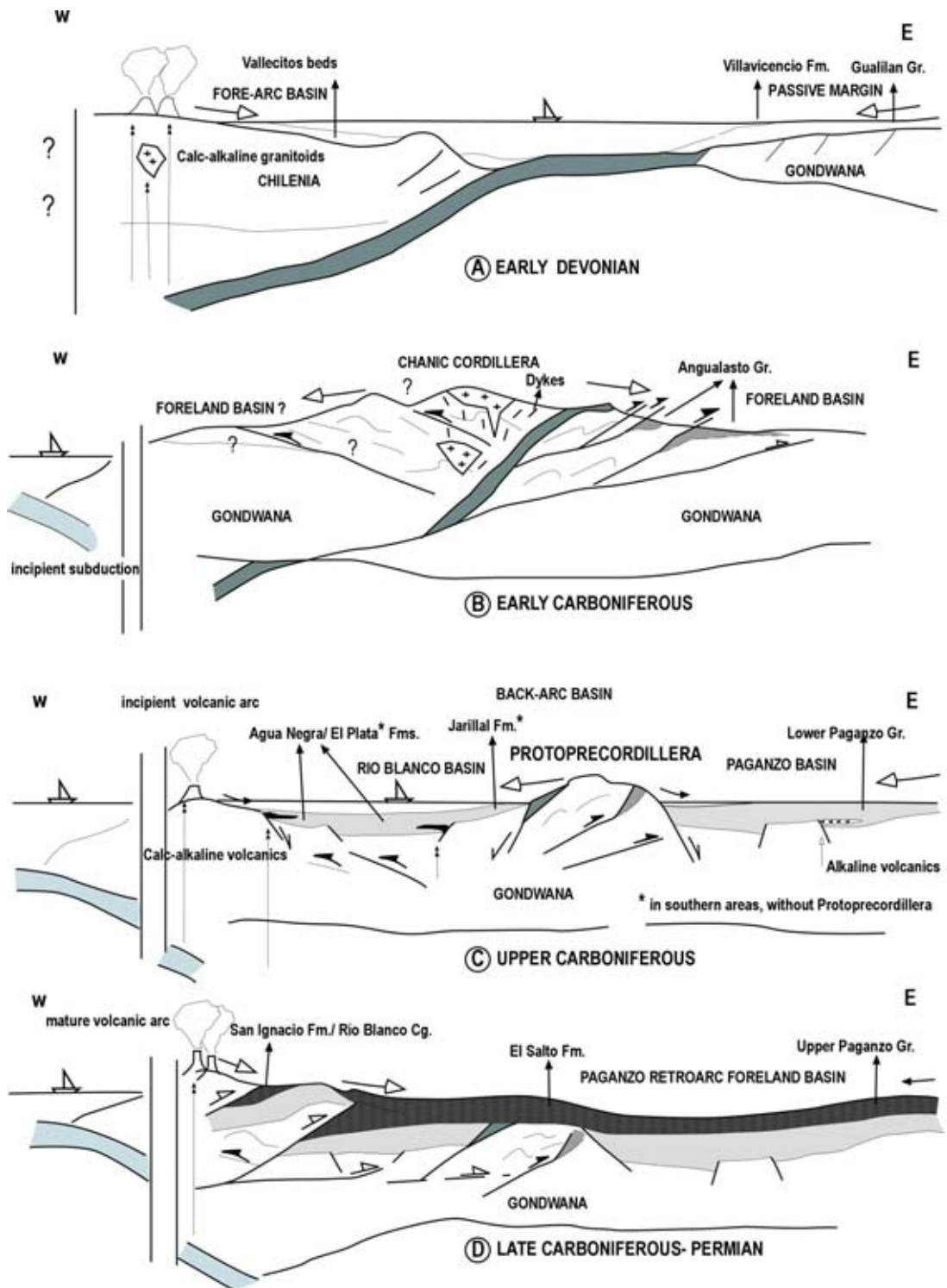


FIG. 11. Geodynamic evolution sketch of the Andes between 30° and 33°S latitude, during Late Paleozoic times. Figures are not to scale. **Blank Arrows:** main areas of sediment supply. **Black arrows:** other areas of sediment supply; **Fm:** formation; **Gr:** group; **Cg:** conglomerates.

Rollieri, 1965) (Fig. 11C) developed during most of the Late Carboniferous and appears to have been a horst-like topographic high that was inherited from the Chanic Cordillera and separated the Río Blanco basin from the Paganzo basin farther east (Azcuy and Morelli, 1970; Salfity and Gorustovich, 1983; López Gamundi *et al.*, 1987; Azcuy, 1985; Fernández Seveso *et al.*, 1993; Azcuy *et al.*, 1999; Limarino y Spalletti, 2006; Limarino *et al.*, 2006). The change in lithologic characteristics described earlier, of time-stratigraphic equivalent rocks (*i.e.*, Agua Negra, El Plata, and Jarillal Formations in Fig. 6) reflects the relative influence of this Protoprecordillera high, that appears to have become progressively less prominent to the south and was absent south of the study area. These Gondwanan pre-orogenic rocks are mainly sourced from the East, in the present-day Sierras Pampeanas (Limarino, 1987; Heredia *et al.*, 2002). However, where the Protoprecordillera was present, it provided a local source of sediment. On the far west, in Río Blanco basin, a western source of sediment (from the volcanic arc) can be recognized, but it is rare because, the arc was not well developed at this time (Fig. 11C). Río Blanco basin probably began as an extensional back-arc feature that was initially filled largely with marine deposits. The pre-orogenic extensional character of this basin is compatible with the moderate calc-alkaline volcanism found in the Frontal Cordillera and Precordillera (Freije *et al.*, 1999; Koukharsky *et al.*, 2009) and the alkaline volcanism (Koukharsky *et al.*, 2002) in eastern areas, away from the Gondwanic subduction zone (Paganzo Basin) (Fig. 11C). In the later phases of the Gondwanan Cycle (San Rafael orogenic phase of Late Carboniferous-Permian times) contractional deformation, with east-directed thrusts and folds, produced a retro-arc foreland basin that was filled with synorogenic continental deposits (Río Blanco Conglomerate in the Cordón del Plata area and San Ignacio Formation farther north). These synorogenic deposits (Fig. 6) contain clasts of volcanic origin and, only in the San Ignacio Formation, volcanic and volcano-sedimentary rocks sourced from the active volcanic arc. Moreover, the volcanic intercalations in these successions indicate that the volcanic arc remained active during the entire orogenic process (Fig. 11D). Except in the Paganzo Basin, the source area of the Gondwanan synorogenic deposits was located to the west, forming part of a retro-arc foreland basin that shows isolated outcrops at present (Busquets

et al., 2005). The Protoprecordillera disappeared at this time (Fig. 11D), and the El Salto Formation, the Pircas Conglomerates and other equivalent synorogenic series (Fig. 6) were deposited in the Precordillera area (Fig. 11D).

Considering the deformation style and the absence of metamorphism and plutonism, the Frontal Cordillera can be interpreted as part of the foreland of the Gondwanan Orogen, which was far away from the subduction zone (Fig. 11D). Finally, the Choiyoi Group rests unconformably over all the rocks described above and represents the Permo-Triassic extensional episode (Ramos, 1988; Uliana *et al.*, 1989; Llambias y Sato, 1990), which started the Andean Orogenic Cycle (Heredia *et al.*, 2002).

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