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Reactivation of Paleozoic structures during Cenozoic deformation in the Cordón del Plata and Southern Precordillera ranges (Mendoza, Argentina)

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Abstract

The tectonic style of the eastern morphostructural units of the Central Andes between 32°20´ and 33°20´S is strongly influenced by pre-Andean structures, especially those developed during the late Carboniferous-Early Permian San Rafael orogeny of the Gondwanan orogenic cycle. Moreover, in the study area pre-Carboniferous rocks were deformed in Late Devonian-early Carboniferous times by the Chanic orogeny. In this paper we argue that the Cordón del Plata and the Southern Precordillera ranges, first order features of the eastern ranges of the Andes, have been shaped in large part by the Permian event. Our data suggest that the double verging character of the Andean Precordillera fold- thrust belt is mainly the result of the reactivation of Gondwanan structures which conform a fold-thrust belt with distinct characteristics north and south of 33°S. The northern sector of this belt corresponds to a bivergent system, while the southern sector had a widespread east vergence. The vergence of the Chanic structures is more difficult to determine, but we infer a westward vergence in the Frontal Cordillera and western sector of Precordillera, and an eastern vergence in the eastern sector of the Precordillera. The sharp disappearance of the Precordillera morphostructural unit south of 33°S is inferred here to be related to the distribution of inherited Permian structures.

Keywords: Southern Central Andes, Permian fold-and-thrust belt, Andean thrust front, Chanic orogeny, Frontal Cordillera

Resumen

El estilo tectónico del sector oriental de las unidades morfoestructurales de los Andes Centrales entre los 32°20´y 33°20´S se encuentra fuertemente influenciado por estructuras pre-andinas, especialmente aquellas desarrolladas durante el Carbonífero superior-Pérmico Inferior y asociadas al orógeno San Rafael del ciclo orogénico Gondwánico. Además, en el área de estudio, las rocas pre-carboníferas se deformaron durante el Devónico Superior y Carbonífero inferior, en relación con la orogenia Chánica. En este trabajo discutimos los rasgos de primer orden del sector oriental de los Andes, que comprende al Cordón del Plata y a la Precordillera Austral, fueron en gran parte modelados a partir del evento pérmico. Nuestros datos sugieren que la doble vergencia de una faja plegada y corrida en la Precordillera Andina es el resultado principalmente de la reactivación de estructuras gondwánicas que conformaron una faja plegada y corrida con características distintivas al norte y sur de los 33°S. El sector norte de la faja corresponde a un sistema bivergente, mientras que el sector sur posee una vergencia predominantemente oriental. La vergencia de las estructuras chánicas es más difícil de predecir, pero se sugiere aquí una vergencia hacia el oeste para las estructuras de la Cordillera Frontal y el sector occidental de la Precordillera y otra hacia el este para las estructuras del sector oriental de la Precordillera. Se infiere que la marcada desaparición de la Precordillera como unidad morfoestructural andina al sur de los 33° está relacionada a la distribución de estructuras chánicas y gondwánicas.

Palabras clave: Andes Centrales del Sur, faja plegada y corrida pérmica, frente de deformación andino, orógeno Chánico, Cordillera Frontal

1. Introduction

The Southern Central Andes are a linear orogenic belt resulting from subduction of the Nazca oceanic plate beneath the South American continental plate. At latitudes 32-33°S they include different N-S trending morphostructural units, which from west to east are (Fig. 1): the Coastal, Principal, Frontal Cordilleras, and the Precordillera. The study area covers the Frontal Cordillera and the southernmost sector of the Precordillera, between 32°20´ and 33°20´ S (Fig. 1). The Frontal Cordillera corresponds at these latitudes to the Cordón del Plata range which forms a NNE trending mountain chain, 100 km long and 50 km wide, extending from the Mendoza river to the Las Tunas river. The present morphology of the range at its eastern margin is shaped by approximately NNE-trending reverse faults. NW-trending strike-slip faults cross the entire belt. The Precordillera forms a north-south trending mountain chain, 450 km long and 100 km wide extending from 29° to 33°S. The southernmost sector of this range, where the study area is located, has been named Southern Precordillera by Cortés *et al*. (2005) due to the particular geological and structural characteristic that distinguish it from the northern and central parts of this range.

Although the nowadays morphology of the Southern Precordillera and Cordón del Plata ranges is the result of contractional strain at the convergent plate margin during the Andean orogeny, since Miocene to present times, these ranges also show clues of previous periods of deformation along the proto-Pacific margin of southern Gondwana. The aim of this paper is to present a detailed investigation of Andean and pre-Andean structures in these ranges, focusing on the control of the Paleozoic structures on the subsequent Andean deformational event. We present evidences of two Paleozoic orogenic belts, developed in Late Devonian-early Carboniferous (Chanic belt) and in Late Carboniferous-Early Permian (San Rafael belt). In addition, we demonstrate that some structures have been partially reactivated during the Andean orogeny and controlled the morphology of the present mountain ranges. Here we argue that first order structural features of the eastern ranges of the Andes at the study latitudes have been shaped in large part by the Paleozoic compressional events.

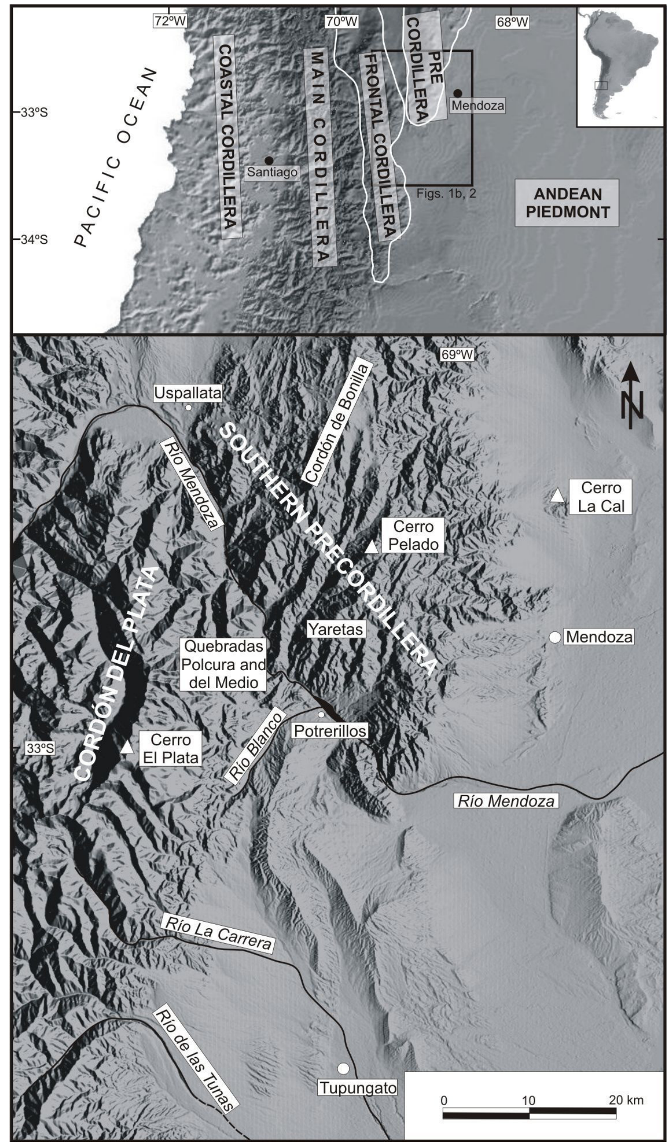

Fig. 1.- Location maps of the study area showing the morphostructural units of the Southern Central Andes between 32° and 35° S and geographical features.

2. Tectonic setting

The present-day architecture of the Andean Mountains is largely the result of the interplay between the Pacific-Nazca and South American plates. However, these mountains preserve evidence of previous periods of contractional, extensional, and strike-slip deformation along the proto-Pacific margin of southern Gondwana. During the Paleozoic, the tectonic history of this margin of Gondwana was mainly controlled by the accretion of exotic terranes and associated subduction processes grouped into the Famatinian and Gondwanan orogenic cycles (Keidel, 1921; Aceñolaza and Toselli, 1976), which culminate in two major orogenic events, the Chanic and Gondwanan orogenies (Ramos, 1988, 1999, 2004; Mpodozis and Ramos, 1989). In the study area, the Late Devonian- early Carboniferous Chanic orogeny has been inferred to be related to the collision between the Chilenia exotic terrane and the proto-margin of Gondwana (Ramos, 1988, 2004; Davis *et al*., 2000; Massone and Calderón, 2008; Heredia *et al.*, 2012). The Chanic orogen had a characteristic double vergence with west-directed structures in the Frontal Cordillera and east-directed structures in the Precordillera (Heredia *et al*, 2012). The internal zones of the Chanic orogen are well exposed in the Frontal Cordillera, where rocks deformed under high metamorphic conditions are found (Willner *et al*., 2011, Heredia *et al.,* 2012). It is commonly accepted that the suture between Chilenia and the proto-margin of Gondwana is located between the Frontal Cordillera and Precordillera (Ramos *et al*., 1989; Davis *et al*., 2000; Heredia *et al*., 2012), even though the position and polarity of the related subduction zone has remained a controversial topic.

The Gondwanan cycle began in the early Carboniferous with the subduction inception near the present continental Pacific margin, constituted by the old western passive margin of Chilenia (Ramos, 1999). During the late Carboniferous-Early Permian, this plate interaction results in an important compressional event, locally known as the San Rafael orogeny (Azcuy and Caminos, 1987; Ramos, 1988), which generated a wide NW to NNW-trending orogenic belt with important crustal thickening (Llambías and Sato, 1990; Mpodozis and Kay, 1990; Giambiagi *et al*., 2012).

During the Late Permian to Early Triassic period, the southwestern sector of South America, between 31º and 36º S, was characterized by the effusion of a great amount of bimodal volcanism (Llambías *et al*., 1993) under oblique extensional conditions (Giambiagi and Martinez, 2008; Kleiman and Japas, 2009). The extensional regime continued during the Triassic and led to the formation of a series of rift systems, with overall NNW trend, formed along the western margin of Gondwana (Charrier, 1979; Uliana *et al*., 1989; Alvarez, 1996).

Andean deformation and uplift are the cause of the present elevation of the Precordillera and the Frontal Cordillera. At 33ºS, the Andean orogenic phase started in Early Miocene times in the Principal Cordillera (Ramos, 1988; Pérez, 2001), reaching the Frontal Cordillera during the middle-late Miocene (Irigoyen *et al*., 2000; Pérez, 2001; Giambiagi *et al*., 2003, 2012).

3. Geological background

In the study area, rocks ranging from Neo-proterozoic (Ediacaran) to Holocene age crop out (Fig. 2). Ediacaran to Paleozoic rocks are exposed in the Precordillera and Frontal Cordillera, and include pre-Carbonifeous metamorphic rocks unconformably overlain by upper Carboniferous marine and continental sedimentary rocks, locally intruded by Upper Permian granitoids (Folguera *et al*., 2004).

Near the Las Tunas River, located in the eastern part of the Frontal Cordillera, a high metamorphic unit crops out (Fig. 2). This unit, named Guarguaraz Complex, is composed by pre-Carboniferous metasedimentary and metabasic (mafic and ultramafic) rocks (López de Azarevich *et al*., 2009; Gargiulo *et al*., 2011) deformed under HP (high pressure) conditions in Middle Devonian times, and later under LP (low pressure) conditions in early Carboniferous (Willner *et al*., 2011).

The Ediacaran-Ordovician rocks known as Bonilla Group (Folguera *et al*., 2004), which are exposed in the western part of the Precordillera, west of the Villavicencio fault, are similar to the metasedimentary (sandstones, shales and thin interbedded carbonates) and metaigneous rocks (basic plutonic and volcanic rocks) of the southernmost sector of the Cordón del Plata and the northern part of the Cordón del Portillo, near Las Tunas river (Fig. 2). These series are different from the Cambro-Ordovician carbonates and shales that outcrop in the eastern part of the southern Precordillera. A succession of Silurian-Devonian clastic sediments unconformably overlaps these rocks, although this succession has different facies in the Precordillera (Villavicencio Formation) and in the Cordón del Plata (Vallecitos beds, from Heredia *et al*., 2012). These Ediacaran to Devonian rocks correspond to the pre-orogenic Chanic succession.

The Manto del Jagüelito unit unconformably covers the Ediacaran-Ordovician rocks of western Precordillera. This unit is composed by sandstones and shales, and subordinated conglomerates with clasts from the Bonilla Group. These strata could be related to synorogenic deposits of the Chanic orogeny (Heredia *et al*., 2012), which constitute the Angualasto Group of early Carboniferous age (Limarino y Cesari, 1992) in the rest of the Precordillera.

The upper Carboniferous marine clastic deposits, with intercalated basaltic lavas, are separated from the pre-Carboniferous deposits by an angular unconformity attributed to the Chanic orogeny (Furque and Cuerda, 1979; Azcuy and Caminos, 1987). These deposits are composed by conglomerates, sandstones, and shales that represent a pre-orogenic succession of the Gondwanan cycle, being similar in the Frontal Cordillera (El Plata and Loma de Los Morteritos Fms.) and in the Precordillera (Santa Máxima and Jarillal Fms.).

Permo-Triassic bimodal volcanic and related plutonic rocks of the Choiyoi Group unconformably overlay and intrude the rocks previously deformed during the Chanic and San Rafael orogenies. This magmatism has been associated with an extensional regime, probably related to the final stage of the Gondwanan subduction process (Llambías *et al*, 2003; Kleiman and Japas, 2009, Heredia *et al*, 2002). Lower to Upper Triassic continental sediments and subordinate volcanic rocks were deposited in the Cuyo rift basin along the Southern Precordillera range, and are unconformably covered by a thin Paleocene sedimentary unit and by more than 4,000 m of Miocene-Pleistocene continental synorogenic strata (Caminos, 1965; Polanski, 1972; Irigoyen *et al*., 2000).

4. Structural analysis

The structural analysis consisted of detailed structural mapping of the Southern Precordillera and Cordón del Plata ranges. Two E-W geological transects are presented to illustrate the major structures of the upper crust (Fig. 3). The cross-sections were originally constructed at 1:25,000, integrating surface geological and structural data. The age of fault activity was bracketed by taking into account the ages of rock units affected or unaffected by faulting. The criteria used to recognize reactivation in the geological record include stratigraphic criteria of fault/unconformity relationships, as well as structural criteria of changes in kinematic history recorded by overprinted structures. The palinspastic reconstruction of Neogene-Quaternary structures is an important tool for examining and understanding late Paleozoic deformation. We systematically back-tilted the Permo-Triassic volcanic rocks and the Triassic continental strata to the horizontal position and reconstructed the pre-Andean orientation of structures in order to determine and separate Andean and pre-Andean structures. We carried out forward modelling of the Gondwanan fault movement to achieve the present configuration of pre-Choiyoi angular unconformities, which allow us to postulate a pre-Triassic kinematic model.

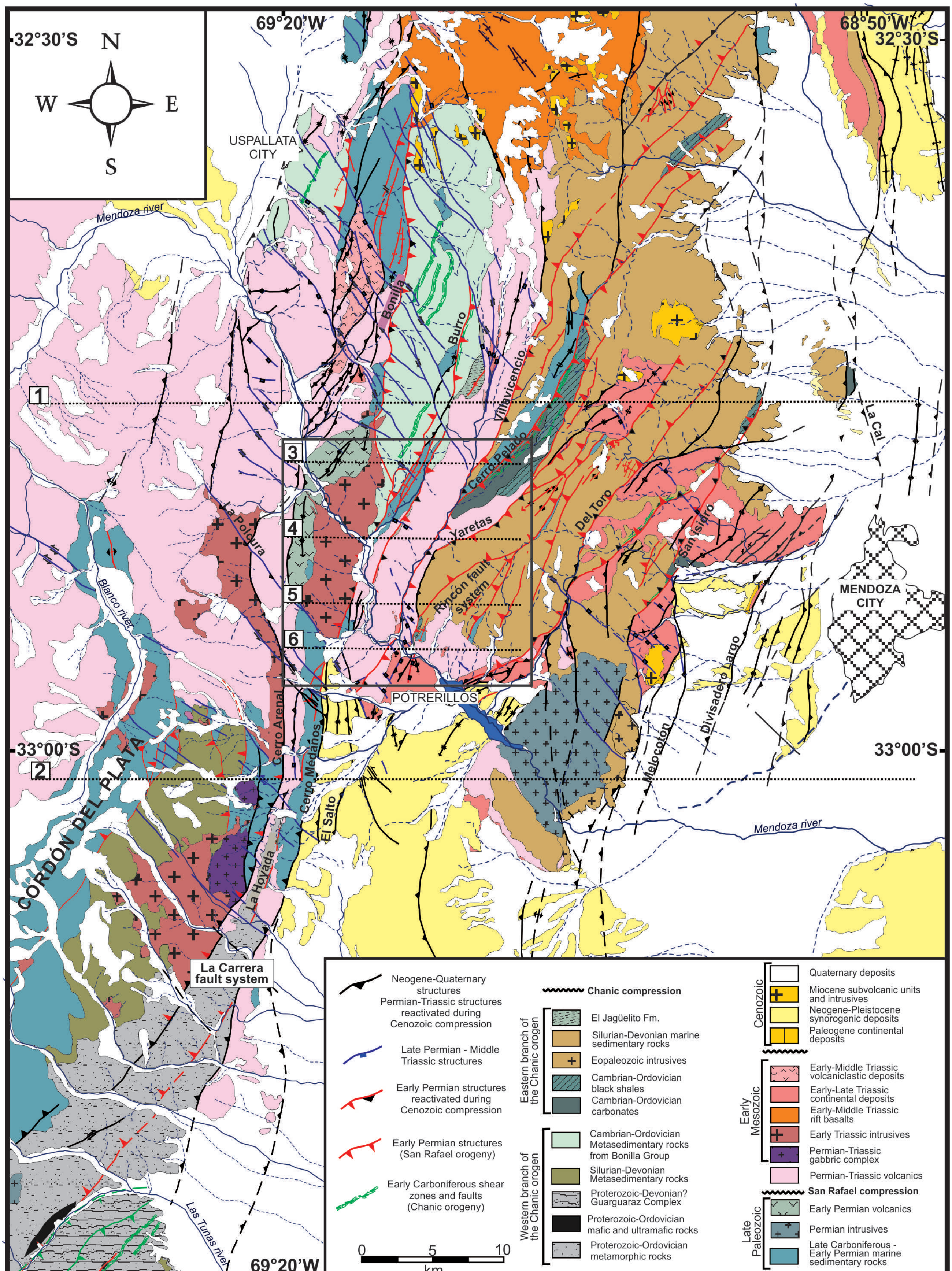

Fig. 2.- Geological-structural map of the Southern Precordillera and the Cordón del Plata range (modified from Giambiagi *et al*., 2011 and Heredia *et al*., 2012). The different colors in the structural traces represent different deformational phases. The box indicates the Quebrada de La Polcura and Quebrada del Medio area. Dotted lines with numbers are the traces of cross-sections (see Figs. 3 and 5B).

4.1. Chanic deformation.

Shear zones and folds developed in the Paleozoic rocks under metamorphic conditions during the Chanic orogeny, of Late Devonian-Early Carboniferous age. These rocks were subsequently thrusted and folded under non-metamorphic conditions during the San Rafael Orogeny. In the Cordón del Plata range, the Chanic orogeny is characterized by centimeter- to decimeter- scale close to tight subvertical folds. These structures fold an S1 slaty cleavage, which forms an angle lower than 10° with bedding. In the shaly layers of the Vallecitos beds, 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 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 and sometimes develops a crenulation cleavage (S2). At the microscopic scale S2 is a rough, anastomosing, and discontinuous crenulation cleavage associated to the folds (Heredia *et al*., 2012). This deformation has been developed under low-metamorphic grade conditions (Greenschist facies).

The lithologies of the metasedimentary rocks of the Guarguaraz Complex (Cordón del Portillo) are similar to the lithologies of the Ediacaran-Ordovician successions of the Cordón del Plata and western Precordillera (west of the Villavicencio fault), showing up to three superimposed cleavages, the second of these developed under HP conditions (Wilner *et al*., 2011). The main Chanic structures of the Guarguaraz Complex are folds and thrusts with basal shear zones. This HP unit overlies the Cambrian-Ordovician rocks that outcrop further west, which were never deformed under HP conditions, showing a similar deformation to the Cordón del Plata pre-Carboniferous rocks.

In the Precordillera range, the Chanic orogeny shows different structural patterns east and westward of the Villavicencio fault, which also limited different pre-Silurian succes-

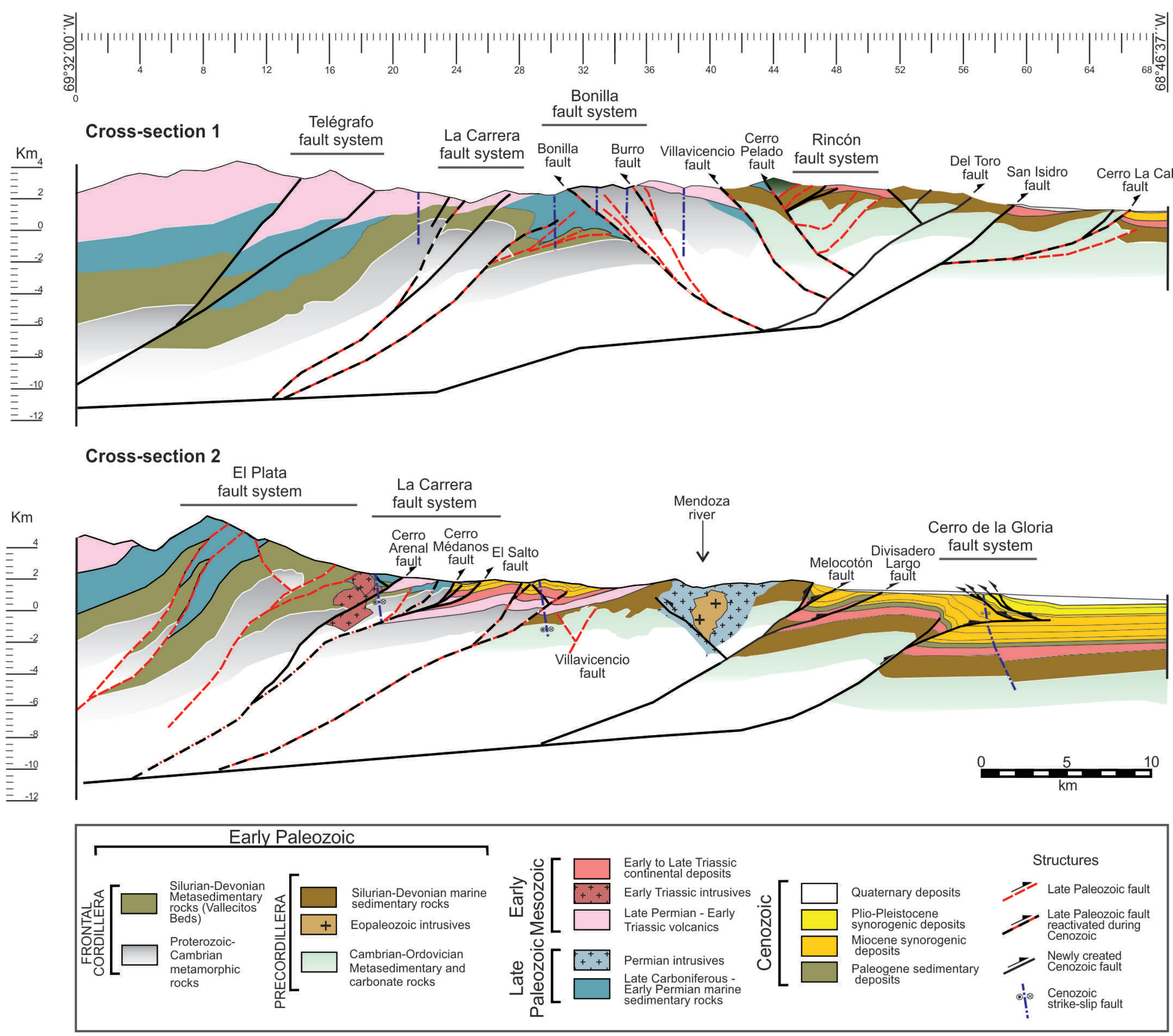

Fig. 3.- Balanced cross-sections 1 and 2 (see locations in Fig. 2), showing the relationship between Andean (black lines), Permo-Triassic (blue lines) and late Paleozoic Gondwanan (red lines) and Chanic (green lines) structures.

sions, suggesting that this fault has affected a main Chanic structure (Giambiagi *et al*., 2010, 2011). The Chanic deformation west of this fault affects metasedimentary and metabasic rocks of the Bonilla Group. The main structures are west-directed ductile thrusts (shear zones in Fig. 2) and folds with two related cleavages, developed under low grade metamorphic conditions (von Gosen, 1995), very similar to those described in the Frontal Cordillera. In the metasedimentary rocks the first cleavage (S1) is generally arranged parallel to stratification (S0) and is defined by preferred orientation of chlorite and sericite porphyroblasts. The S1 can be related with west-vergent to subvertical isoclinal folds with N-S trend and centimetre- to meter- scale. In the same rocks, the S2 is a spaced crenulation cleavage related with smaller-scale folds of WNW and ESE vergence.

The Chanic Villavicencio fault puts in contact rocks with different pre-Carboniferous history, with different metamorphic grade and paleogeographic positions. To the east of this fault, the Chanic deformation affects the Silurian-Devonian rocks of the Villavicencio Formation and pre-Silurian carbonates and shales. In this area, the main structures are east-directed thrust and related folds (Fig. 3), with a S1 rough cleavage associated to them and developed in shaly beds.

4.2. Gondwanan deformation.

The last Paleozoic contractional brittle deformation can be related to a regional event, locally known as San Rafael orogeny of the Gondwanan cycle or Gondwanan orogeny. It affects the late Carboniferous marine deposits but it does not affect the Upper Permian to Lower Triassic rocks, indicating a late Carboniferous to Middle Permian age. An angular unconformity between the Choiyoi Group volcanics and older rocks is present all along the study area (Fig. 4A). The brittle structures related to this orogeny are very difficult to distinguish from Andean structures, except when they are unconformably covered by the Permo-Triassic volcanics. The strike of the recognized late Paleozoic Gondwanan faults is N-S to NNW in the western domain, and NNE to NE in the eastern domain. Folds trend from NNW to NE, and their axial planes dip either to the west or the east.

The main structures related to Neopaleozoic Gondwanan deformation in the Cordón del Plata range are NNE-trending ESE-vergent reverse faults: the Cerro Arenal and Cerro Médanos faults. The Cerro Arenal fault was reactivated during the Andean orogeny in the Blanco river area, where affects Triassic intrusives (Fig. 2), diminishing its Cenozoic offset to the south. The Cerro Médanos fault corresponds to a Gondwanan reactivated structure at the El Plata peak latitude, while southwards, it only presents an Andean movement. On the other hand the Hoyada fault, that affects late Carboniferous rocks, is unconformably covered by the Choiyoi Group. To the west, Heredia *et al*. (2012) described several east-vergent Paleozoic thrusts, which are grouped here into the El Plata fault system (Figs. 4, B-D). It consists of three east-vergent Gondwanan thrusts and an associated backthrust (Fig. 4E), which involve the previously deformed Devonian Vallecitos beds and late Carboniferous strata, being unconformably covered by the Choiyoi Group.

In the central domain, the most important Gondwanan fault is the west-vergent Bonilla fault. Von Gosen (1995) documented the Neopaleozoic movement of this structure, pointing out that this structure uplifts the Cambro-Ordovician rocks on top of the late Carboniferous sediments and it is unconformably covered by the Permo-Triassic volcanics, north of the study area. To the south, close to the Mendoza river, the Bonilla fault was reactivated during Andean times. The Cenozoic Burro fault, which belongs to the Bonilla fault system, presents a Permian movement in its northern segment, while southwards it was reactivated together with the Bonilla fault. At the latitude of cross-section 1, both faults affect the Permo-Triassic volcanics (Fig. 3).

In the eastern domain, several structures present evidence of Permian deformation. The reactivation of the Chanic Villavicencio fault during the Permian is registered by shear fractures affecting the Upper Paleozoic sediments but not the Permo-Triassic volcanics. A splay of this structure, the Cerro Pelado fault, also has evidence of Permian movement.

In the Yaretas area (Fig. 1), the Rincón fault system consists of a series of NNE trending thrust faults and fault propagation folds, unconformably covered by the Permo-Triassic volcanics. These structures have been interpreted as representing a Permian thin-skinned fold-and-thrust belt with detachment within the Lower Paleozoic sedimentary rocks (Giambiagi *et al*., 2011).

The Paleozoic fold-and-thrust belt has been forward modelled with the 2D Move software (Fig. 5B) back stripping the Choiyoi Group volcanic rocks and the Triassic sedimentary rocks to a horizontal position. The cross-section 1 (Fig. 5B) shows the Permian (Gondwanan) uplift of the western and central domains, with east- and westward vergences respectively. The cross-section 2 represents the Gondwanan uplift of the Cordón del Plata range with an eastward vergence.

4.3. Andean deformation.

In the studied location, the area comprising the Precordillera and Frontal Cordillera can be structurally divided into western, central and eastern domains, separated by the La Carrera fault system and the Villavicencio fault respectively (Figs. 2 and 3). The western domain corresponds to the Cordón del Plata range characterized by east-vergent reverse faults crossed by sinistral strike-slip faults with NW orientation. The reverse faults have been traditionally grouped into the La Carrera fault system and were recognized as responsible for the Andean uplift of this range in late Cenozoic (Caminos, 1965; Polanski, 1972; Cortés, 1993; Folguera *et al*., 2004), which reaches an altitude of 6,100 m in the El Plata mount. This fault system involves the pre-Carboniferous metamorphic rocks and it is composed by several N to NNE-

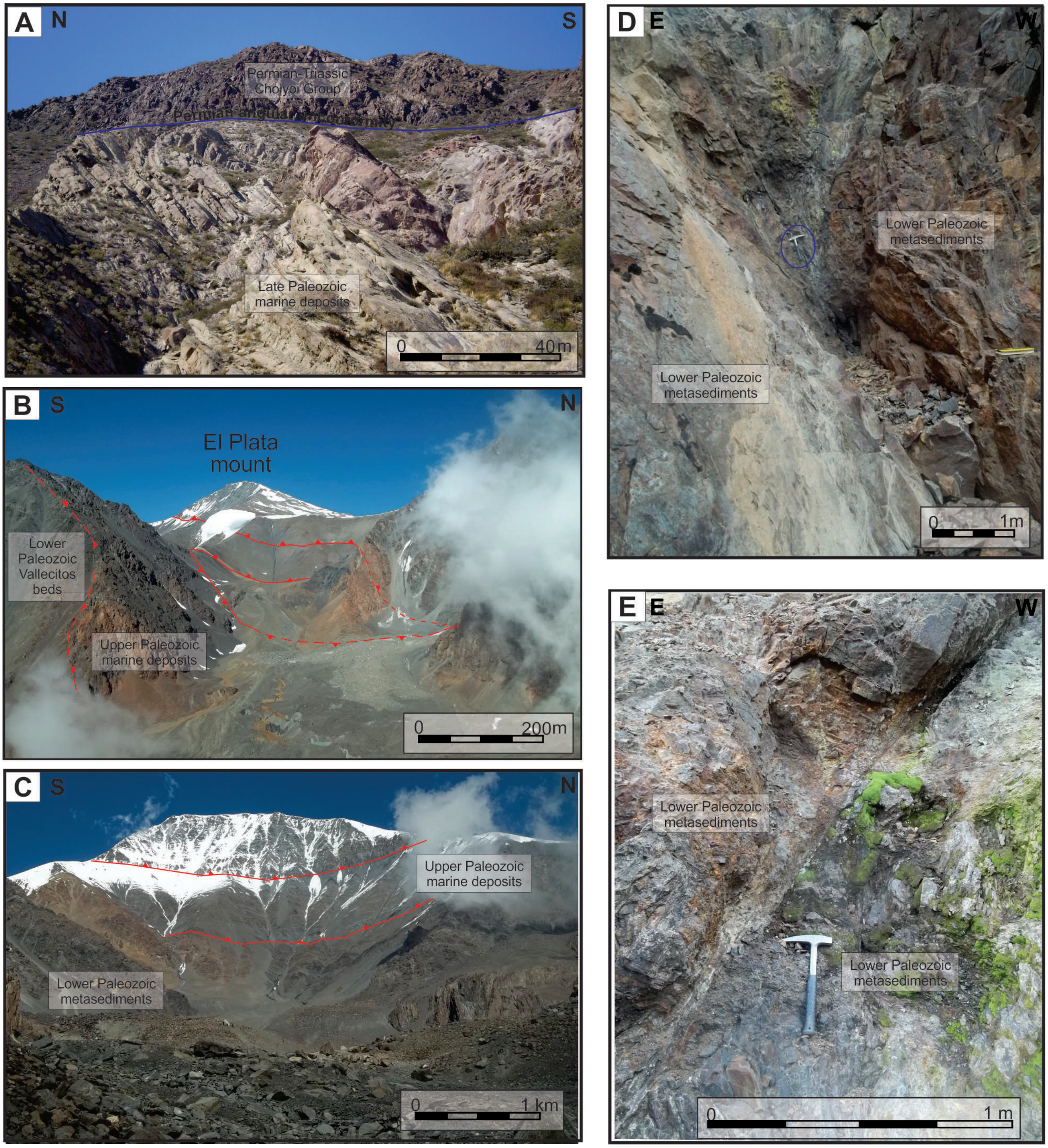

Fig. 4.- A) Angular unconformity of Early Permian, between Permo-Triassic Choiyoi Group and late Carboniferous marine deposits of the El Plata Formation. B) Gondwanan thrust faults of the El Plata fault system in the Rincón de Vallecitos glaciar valley (Cordón del Plata range) affecting different members of the El Plata Formation C) Gondwanan thrust –not reactivated– of the El Plata fault system in the Angostura valley (Cordón del Plata range). The contact between the Vallecitos beds and El Plata Formation is a Gondwanan (late Carboniferous) normal fault, reactivated in the Permian times (San Rafael Orogeny). D) Detail of the easternmost of the faults of the El Plata system, Piedra Grande fault, affecting the Silurian-Devonian Vallecitos beds metasedimentary rocks. E) Detail of the back-thrust of the El Plata fault system, repeating the Silurian-Devonian Vallecitos metamorphic rocks.

trending faults, which are from west to east, Cerro Arenal, Hoyada, Cerro Médanos, and El Salto faults (Figs. 2 and 3). The NW-oriented strike-slip faults have been interpreted as inherited Late Permian to Middle Triassic rift-related normal faults (Giambiagi and Martínez, 2008).

The Cerro Arenal fault has been traditionally assigned to the westernmost of these foreland-directed structures (Caminos, 1965; Folguera *et al*., 2004; Casa *et al*., 2010). It is a N-S to NNE trending reverse fault, placing the Carboniferous to Permian black shales on top of the Permo-Triassic volcanic rocks in its northern segment, and a Triassic intrusive over the Lower Paleozoic metamorphic rocks in the south (Fig. 6A). The Hoyada fault presents Cenozoic movement only in its northernmost segment. To the south, it places a thin sheet

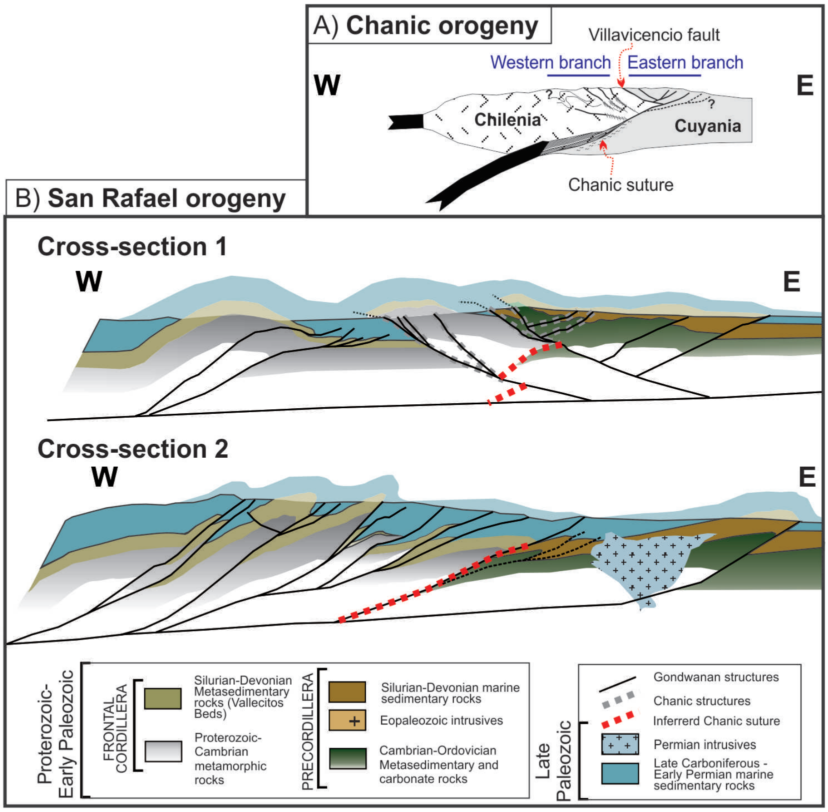

Fig. 5.- A) Conceptual model for the geotectonic context of the Chanic orogeny, based on the reconstruction of the Gondwanan deformation along cross-section 1 (Fig. 3). B) Reconstruction of the Gondwanan late Carboniferous-Early Permian fold-and-thrust belt by back stripping the base of the Permo-Triassic volcanics and Triassic rift-related sediments to their horizontal depositional line, using in the cross sections shown in Fig. 3. Cross-section 1 suggests the existence of a dual vergence thrust system, probably influenced by the Late-Devonian-early Carboniferous (Chanic) structural grain. In cross-section 2, the Proto-Frontal Cordillera has a predominantly eastward vergence in the Gondwanan structures, with an incipient development of a Proto-Precordillera.

of the Lower Paleozoic phyllites over the Carboniferous sequences, but it is unconformably covered by the Permo-Triassic volcanics, indicating a Permian age without subsequent reactivation. Towards the east, a major sheet of Carboniferous marine deposits has been placed over the Neogene synorogenic deposits by activity along the Cerro Médanos fault (Figs. 6A and 6B). This fault runs with a NNE trend north of La Polcura creek and has a N-S trend south of it. Its change in trend is related to the presence of the Cerro Médanos granitoid. To the south, it continues with the NNE trend. The easternmost structure of the La Carrera fault system, the El Salto fault, affects the Neogene synorogenic deposits and shows evidence of Quaternary activity (Fauqué et al., 2000; Folguera *et al*., 2004; Borgnia, 2004; Casa *et al*., 2010).

The main structures of the central domain correspond to the west-vergent Bonilla fault system, which is composed by a series of N-S striking reverse faults affecting the Lower Paleozoic metamorphic rocks, the Upper Paleozoic sedimentary rocks, and the Permo-Triassic volcanics (Fig. 7A). The Bonilla fault places Lower Paleozoic metasedimentary rocks on top of the Upper Paleozoic strata and Permo-Triassic volcanics, being continuous for more than 30 km. Another structure that conforms this system corresponds to the a NNE-trending west-vergent Burro fault, which uplift the Lower Paleozoic

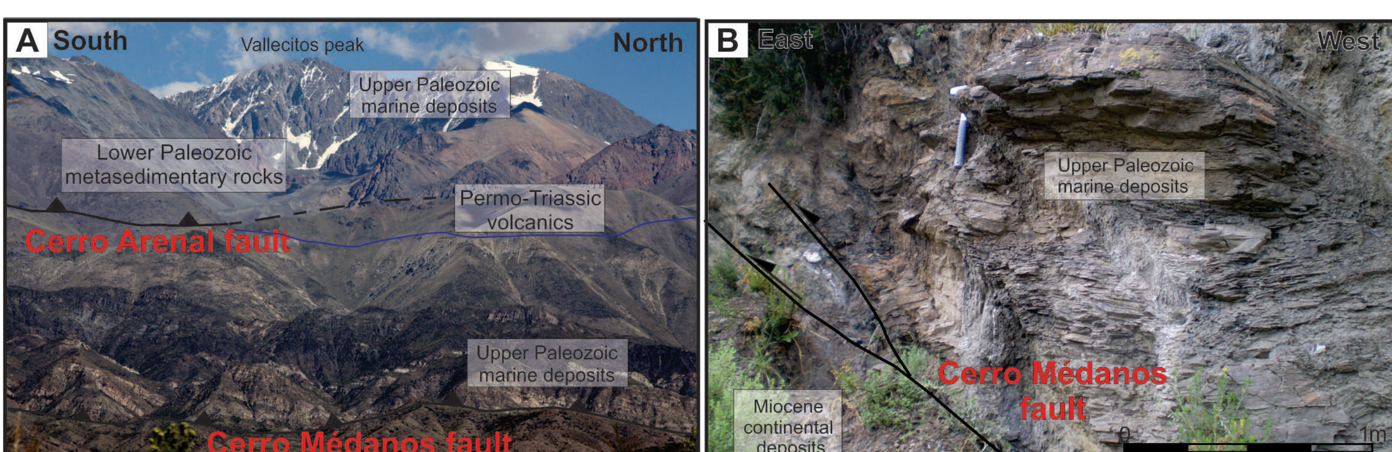

Fig. 6.- A) Photograph looking west of the main Andine structures of the La Carrera fault system, eastern slope of the Cordón del Plata range. B) Detailed of the Cerro Médanos fault uplifting marine sedimentary rocks of the upper Carboniferous (El Plata Formation) on top of the Miocene synorogenic units.

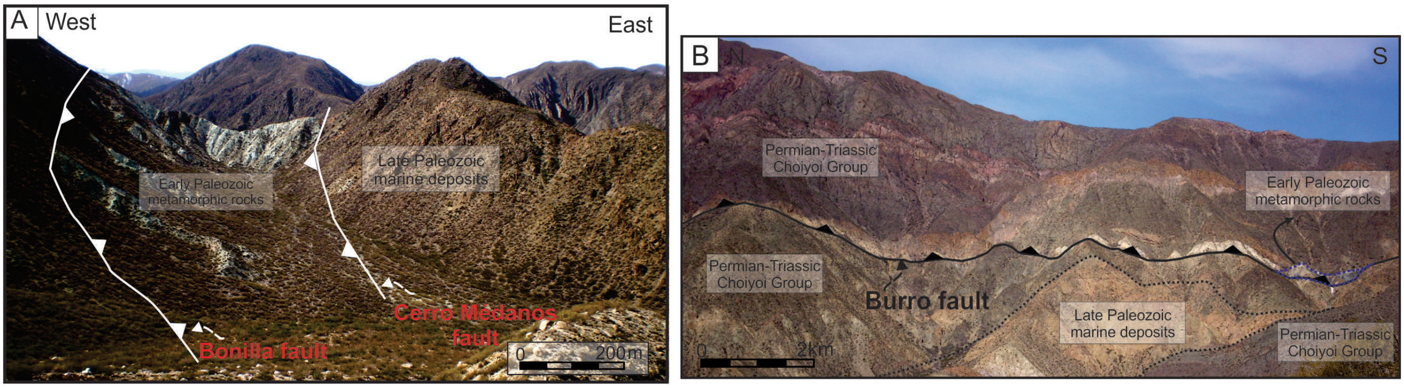

Fig. 7.- A) The Bonilla west-vergent fault and the Cerro Médanos east-vergent fault, uplifting low grade metamorphic rocks of late Paleozoic age on to Permo-Triassic volcanics and late Carboniferous siliciclastic rocks respectively. B) The Burro west-vergent fault, belonging to the Bonilla fault system, uplifting a thin sheet of Lower Paleozoic metasedimentary rocks over Permo-Triassic volcanics of the Choiyoi Group.

low-grade metamorphic rocks on top of the Upper Paleozoic marine strata (Fig. 7B).

The eastern domain is affected by NNE-trending reverse faults, some of them affecting the Permo-Triassic volcanics, and some of them unconformably covered by these rocks. The main structures in this domain are the Villavicencio, Cerro Pelado (Fig. 8A), Yaretas and La Cal faults. These faults have decreasing displacements along strike to the south and die into the Carreras fault system of the Frontal Cordillera (Fig. 2). As a consequence, the shortening on the eastern Precordillera is progressively replaced to the south by movement on the La Carrera fault system. In this manner, the Potrerillos area is interpreted to be a displacement transfer zone formed by sinistral strike-slip faults.

The Villavicencio fault marks the limit between central and eastern domains. Its Cenozoic movement can be inferred close to the Mendoza river, where it affects the Permo-Triassic rocks. To the east, the Cerro Pelado and Yaretas faults uplift the Lower Paleozoic sedimentary rocks on top of Upper Paleozoic and Permo-Triassic rocks. Further east, the Del Toro (Fig. 8B) and San Isidro faults run parallel to the Yaretas fault, and uplift the Lower Paleozoic sediments on top of the Triassic sediments.

5. Geotectonic context of the Chanic deformation

We interpret that the Villavicencio fault corresponds to a west-vergent Chanic backthrust fault, deeply rooted into the inferred west dipping Chanic suture (Fig. 5A). This structure with evidences of Gondwanan and Andean reactivations puts in contact rocks with different pre-Carboniferous stratigraphy (different paleogeographic positions), metamorphic grade, and deformation. We propose that the Bonilla Group was deposited, together with the same age rocks of the Frontal Cordillera, on the outer margin of the Chilenia terrane, while the rest of Paleozoic rocks of the Precordillera, presently located eastwards of the Villavicencio fault, were deposited in the western margin of the Cuyania terrane.

In this context, the Chanic orogen contains two branches. The western branch was developed on Chilenia, nowadays located in the Frontal Cordillera (Cordón del Plata) and the western Precordillera (west of the Villavicencio fault). The eastern branch was developed on Cuyania, located in the eastern Precordillera. These Chanic branches should be separated by a Chanic suture, westward tilted, whose inferred location is shown in Figure 5A. This suture shows opposite structural vergences, to the west in the western branch and to the east in

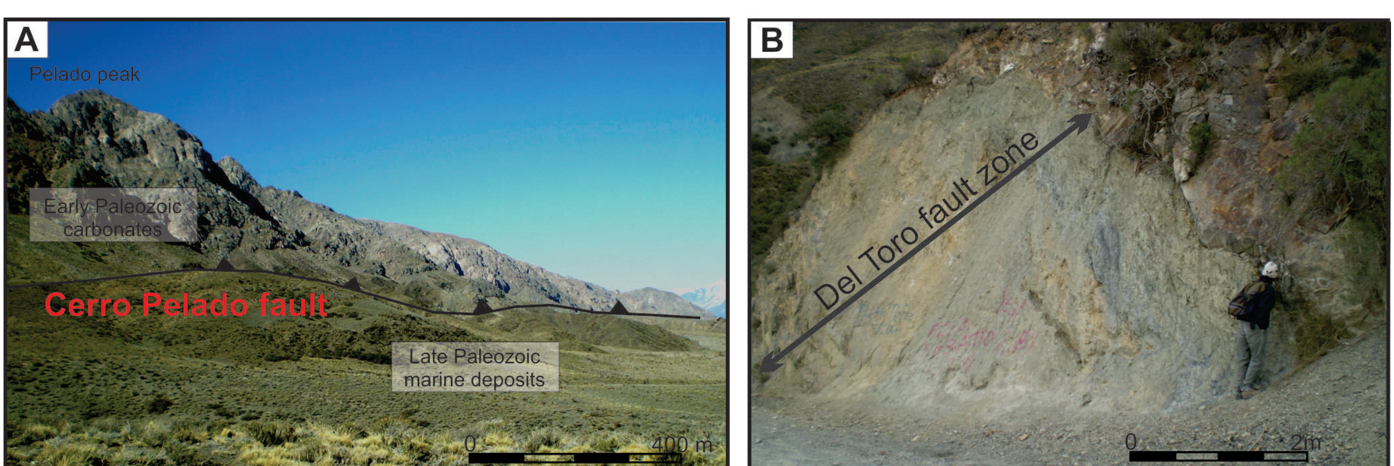

Fig. 8.- A) Two major Gondwanan faults reactivated during the Andean compression: Cerro Pelado Gondwanic brittle thrust (A) and Del Toro Gondwanic and Chanic (more ductile) fault (B).

the eastern branch (Heredia *et al*., 2012). The internal zones of this orogen, that occupy most of the study area, are located close to the boundary between the Precordillera and Frontal Cordillera morphostructural units.

6. Discussion: The role of pre-existing faults on the Andean deformational evolution

It is now well-established that pre-existing major faults form planes of mechanical weaknesses within the upper crust and can strongly influence the structural evolution of orogenic belts (Watterson, 1975; White *et al*., 1986; Holdsworth *et al*., 1997). Structural reactivation of faults occurs when displacements are repeatedly focused along well-defined, pre-existing features such as faults or shear zones (Holdsworth *et al*., 1997). Theoretical, experimental and microstructural studies have shown that there are numerous fault and shear zone processes which may lead to weakening of pre-existing structures (Handy, 1989; Rutter *et al*., 2001).

The deformation of the eastern morphostructural units of the Central Andes between 32°20´ and 33°20´S is strongly influenced by pre-Andean structures, especially those developed during the Chanic and the San Rafael orogenies. On one hand, the ancient Chanic suture (Fig. 5A) and the eastern branch of the Chanic Orogen have controlled the position of the east-vergent Gondwanan thrusts of the Cordón del Plata and Precordillera.

On the other hand, the Southern Precordillera and the Cordón del Plata show reactivation of some of the late Paleozoic Gondwanan structures that conform a fold- thrust belt, with distinct characteristics north and south of 33°S. The northern sector of the Gondwanan belt corresponds to a bivergent system, while the southern sector had a notable east vergence. These features are also observed in the Andean deformation. Field evidence for the interaction of the systems that bound the Frontal Cordillera and Precordillera are well exposed along the Quebrada de la Polcura and Quebrada del Medio areas (see box in figure 2). This 10 km wide area marks the limit between the Frontal Cordillera and the western sector of the Precordillera. In this zone, structures of both ranges overlapped in space and time, such that east-vergent faults cut west-vergent faults and viceversa. The kinematic evolution of the two opposing vergence systems is schematically illustrated in figure 9. Detailed mapping and structural analyses of both systems have revealed that deformation in the pre-existing, late Paleozoic, east-vergent La Carrera fault system occurred synchronously with reactivation of the Gondwanan west-vergent Bonilla fault system. After that, the reactivation of east-vergent structures of the Precordillera took place. This suggests that the eastern Frontal Cordillera and the western Precordillera uplifted and deformed synchronically. The reactivation of these pre-existing structures was related to the kinematic evolution of the mountain belt (i.e. the relationship between the stress state and the strain of the South American plate, which resulted in the uplift of the Andes), controlled in

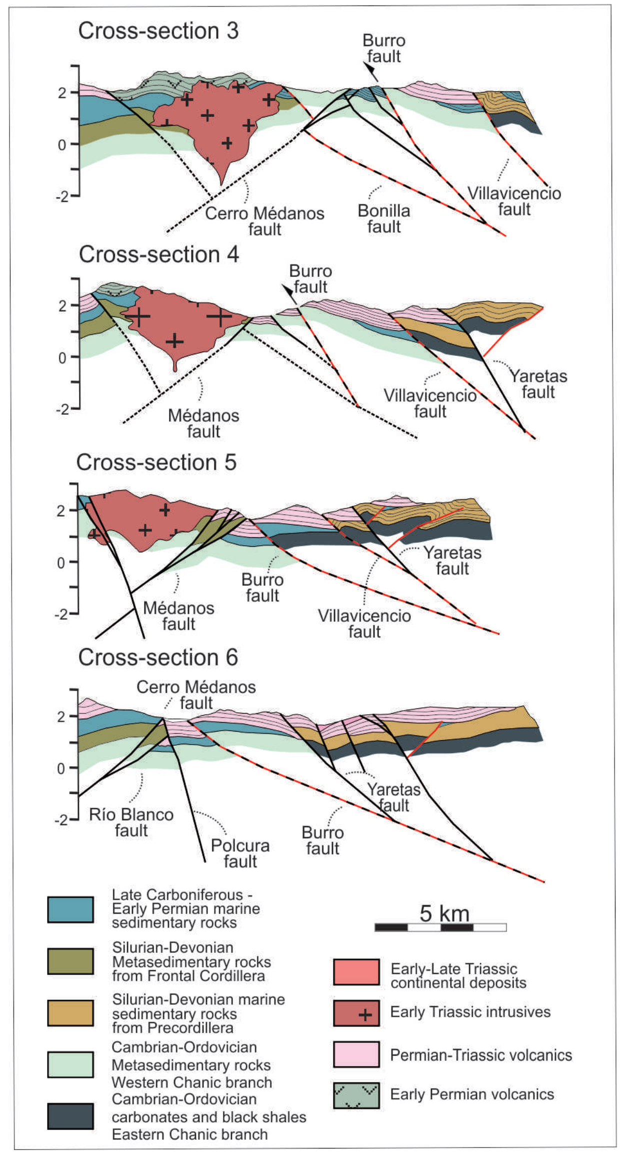

Fig. 9.- Schematic cross-sections 3 to 6 of the Quebrada La Polcura and Quebrada del Medio areas (see location in Fig. 2). Field evidence show cross-cutting relationship between the La Carrera fault system of the Cordón del Plata range – Cerro Médanos and Río Blanco faults- and the Bonilla fault system of the western sector of the Precordillera – Bonilla and Burro faults. The Cerro Médanos thrust cuts the Bonilla fault but it is cut by the Burro fault.

this area by the late Miocene development of the Pampean flat-slab (Ramos *et al*., 2002). Once the kinematic conditions for reactivation were met, the faults became active irrespective of the vergence of the structures. This led to the complex interaction of east- and west-vergent faults shown in figure 9.

The reactivation of Gondwanan faults with dips to the east during the Andean orogeny explains why west-vergent structures developed in a strongly east-vergent mountain range such as the Andes. We propose that the geometry of the Andean thrust front was strongly controlled by basement-rooted reverse faults inherited from the late Carboniferous-Lower Permian San Rafael orogeny, which in turn have been controlled by Chanic structures. The influence of the pre-existing late Paleozoic structures on the geometry and kinematics of the Andean orogenic wedge is emphasized by the southward sharp disappearance of the Precordillera, which reflects along-strike variations of the structural style of the Paleozoic faults.

7. Conclusions

The geometry of the Andean eastern ranges at the latitudes 32-33°S was strongly controlled by orientation of basement-rooted reverse faults inherited from the compressive phase of the Gondwanan cycle (Early Permian), known as San Rafael orogeny, and to a lesser extent by the reactivation of Chanic structures (Late Devonian-early Carboniferous).

The Chanic structures show a generalized western vergence in the Frontal Cordillera and western Precordillera (western branch of the Chanic orogen) and an eastern vergence in the eastern Precordillera (eastern branch of the Chanic orogen). The Chanic deformation was developed in metamorphic conditions, which reached high degree conditions in some localities of the easternmost part of the Frontal Cordillera (Guarguaraz Complex). We propose the presence of a west-dipping suture zone located between both branches of the Chanic orogen (Fig. 8).

The Chanic Villavicencio fault put in contact rocks with different Chanic paleogeographic position, metamorphic grade, and vergence. This fault is inferred to be rooted into the Chanic suture. In this context, the Bonilla Group was deposited in the outer margin of Chilenia and can be correlated with the Lower Paleozoic rocks of the Frontal Cordillera.

The Gondwanan structures show a generalized eastern vergence in the Frontal Cordillera, while the western sector of the Precordillera shows west-vergence. The Gondwanan deformation was developed without metamorphism, in brittle conditions, very similar to the Andean deformation.

Although the Andean deformation is Cenozoic, most of this deformation in the Cordón del Plata range and the Southern Precordillera affected to Paleozoic rocks. Therefore, the main Andean structures are due to reactivation of pre-existing Gondwanan thrusts, which can be superimposed to Chanic ductile thrusts. Evidence for this can be found in the La Carrera fault system, responsible for the uplift of the Cordón del Plata range during the late Cenozoic (Neogene), and in the Bonilla fault system, responsible for the uplift of western Precordillera at the latitude of the Uspallata city.

Our data suggest that the double verging character of the Andean Precordillera fold-and-thrust belt is mainly the result of the reactivation of San Rafael structures that belonged to a previous fold-and-thrust belt, with distinct characteristics north and south of 33°S. The northern sector of the belt corresponds to a bivergent system, while the southern sector has a notable eastward vergence.

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