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Polyorogenic structure of the San Rafael Block, Mendoza, Argentina: New data for the interpretation of the Chanic Orogen

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ABSTRACT

The Paleozoic pre-Carboniferous rocks of the San Rafael Block, located to the east of the Los Reyunos Gondwanan Thrust, show Chanic structures (Late Devonian–early Carboniferous) with east vergence, which were generated in the absence of metamorphism. This Paleozoic succession is unconformably located on the basement of Cuyania. The rocks, located to the west of the Los Reyunos Thrust, were deformed by two fold episodes, the first and main (D1) west verging, developed under low to very low-grade metamorphic conditions, and the second (D2) east verging and mainly developed near Los Reyunos Reservoir. Therefore, the Los Reyunos Thrust must be considered a reactivation of a Chanic structure during the Gondwanan Orogeny (late Carboniferous–early Permian). The ancient Chanic thrust could be responsible for the overlay of the hinterland of the western branch of the Chanic Orogen on the foreland of its eastern branch, at the end of the collision between the Cuyania and Chilenia subplates. The results of this work have been related to those of nearby areas located to the north and west, which has allowed the elaboration of a model that explains the characteristics of the Chanic Orogen in this area. During the Carboniferous, the Los Reyunos Thrust was reactivated as a normal fault, facilitating the sedimentation of carboniferous rocks thousands of meters thick in its hanging wall and later, during the Gondwanan deformation, it underwent a tectonic inversion. During the Andean cycle, the Permian–Triassic beds of the Choiyoi Group were deposited in relation to NW–SE trending normal faults, giving rise to rollover structures. Finally, during the Cenozoic, Andean compression gave rise to the formation of an open antiform, in whose core is the Mesoproterozoic–Paleozoic basement of the San Rafael Block.

1. Introduction

The Paleozoic basement of the Andes in the Cuyo Sector is located between 28 and 38°S latitude, limited to the north and south by the Valle Ancho (Ramos, 1999) and Huincul (Ploszkiewicz et al., 1984) lineaments, respectively (Fig. 1). In this sector, the Paleozoic rocks are grouped into four tectonostratigraphic units: (i) Pampean ranges, to the NE; (ii) Precordillera, to the north; (iii) Frontal Cordillera, to the west; and (iv) San Rafael Block, where the present study is carried out, to the south (Fig. 1). Keller (1999) considered the San Rafael Block to be the southern extension of the Precordillera. The San Rafael Block groups a set of outcrops of Paleozoic rocks located south of the Mendoza Province (Argentina) and close to the Andes Mountains, in Frontal Cordillera, and to the south of the Precordillera (Fig. 1) (Heredia et al., 2016). According to Heredia et al. (2016, 2018a, 2018b), the Paleozoic rocks of the Cuyo Sector were involved in three Paleozoic orogenic cycles that developed in the SW margin of Gondwana and concluded with the orogens: Famatinian (Middle Ordovician–Silurian), Chanic (Late Devonian–early Carboniferous), and Gondwanan (late Carboniferous–Lower Permian). The first two orogenies were collisional and the third non-collisional. The non-collisional Gondwanan Orogeny was related to the subduction of the paleo-Pacific plate. The Paleozoic rocks of the Cuyo Sector show a heterogeneous distribution of deformation and metamorphism generated during these three Paleozoic orogenies (Heredia et al., 2018b). Thus, pre- and syn-collisional Famatinian structures developed between the Middle Ordovician and late Silurian (Aceñolaza and Toselli, 1973; Astini et al., 1995; Ramos et al., 1996; Mulcahy et al., 2011; Heredia et al., 2016), which affect the Pampean

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Fig. 1. Map of Cuyo Sector (Heredia et al., 2016, 2018a), limited by the Valle Ancho and Huincul lineaments, and location of the study area. Proterozoic and Paleozoic rocks are colored in mauve.

ranges and the northeastern part of the Precordillera. Pre- and syn-collisional Chanic deformation is recognized in the western part of the Precordillera, Frontal Cordillera, and San Rafael Block, between the Late Devonian and early Carboniferous (Ramos, 1986). Finally, the Gondwanan deformation took place between the late Carboniferous and the lower Permian (Alonso et al., 2005, 2014; Ramos and Folguera, 2009; Cingolani and Ramos, 2017) and affected the rocks of the Precordillera, Frontal Cordillera, and San Rafael Block (Fig. 1). In addition to the structures developed during the Paleozoic, the entire Cuyo Sector was affected by structures related to the Andean Orogeny that took place in this area during the Cenozoic.

The oldest rocks of the San Rafael Block are found in small outcrops belonging to the Cerro de la Ventana Formation and the Nihuil Mafic Unit, from the Mesoproterozoic (ca. 1.2 Ga, Rb–Sr, Sm–Nd, Pb–Pb and U–Pb; Criado Roque, 1972; Cingolani et al., 2017a), on which the Paleozoic lies unconformably (Fig. 2a). The Mesoproterozoic rocks correspond to a metamorphosed plutonic–volcanic complex with little sedimentary protolith. The rocks mainly have a calc-alkaline affinity and are tonalites, gabbros, and diorites that grade to amphibolites and granodioritic–dioritic orthogneisses, with abundant angular enclaves of microgranitoids. The isotopic characteristics and age of these rocks are typical of the Cuyania basement (Cingolani et al., 2017a).

The pre-Andean Paleozoic rocks are grouped into two sets separated by an unconformity: (i) the El Imperial Formation (Carboniferous–Permian), and (ii) the Ordovician–Devonian series (Fig. 2a). All Paleozoic rocks were deformed by Gondwanan structures, although pre-Carboniferous rocks show earlier structures, generated under different metamorphic conditions. The pre-Carboniferous rocks of the La Horqueta Formation located in the northwestern part of the San Rafael Block (Fig. 2a) were affected by Chanic structures developed in low to very low-grade Devonian metamorphism (ca 371–379 Ma; Tickyj et al., 2001; 2017) (Fig. 2a and b). The rest of the pre-Carboniferous units of the San Rafael Block present Chanic structures generated in non-metamorphic conditions (Farias et al., 2016). Finally, the lithological group formed by the Mesoproterozoic and Paleozoic constitutes the basement of the Andes, on which the Permian–Mesozoic and Cenozoic cover unconformably rests, represented at its base by the

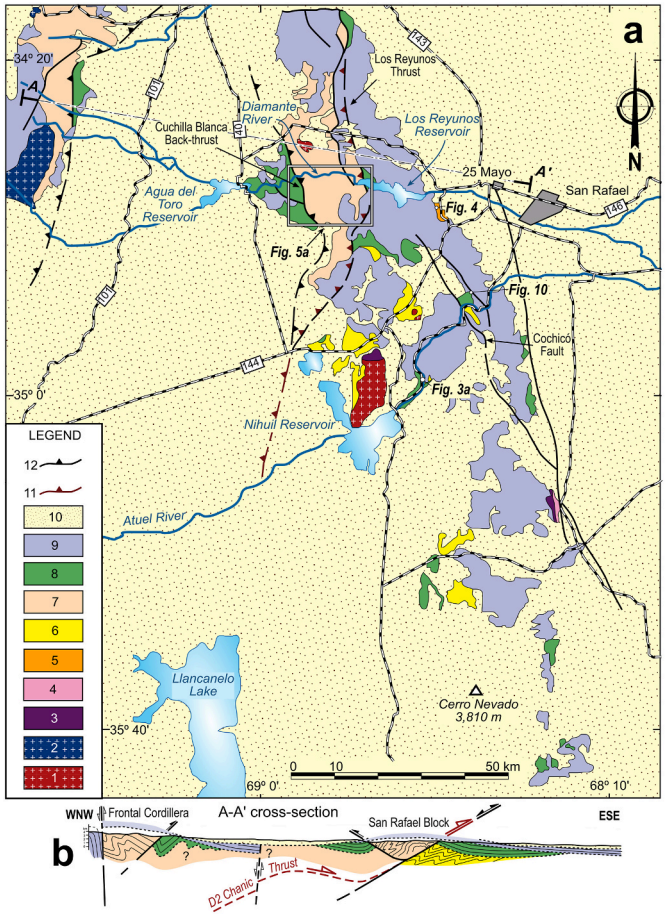

Fig. 2. a. Geological sketch of the San Rafael Block. (1) Paleozoic A-Type granitoids of the western margin of the Cuyania subplate: El Nihuil dolerites (Upper Ordovician–lower Silurian) and Rodeo de la Bordalesa tonalites (Lower Devonian); (2) I-Type granitoids of the eastern margin of the Chilenia subplate (Lower–Middle Devonian) and S-Type granitoids (early Carboniferous); (3) Ventana Formation (Mesoproterozoic); (4) Ponón Trehué Formation; (5) Pavón Formation; (6) Rio Seco de los Castaños Formation; (7) La Horqueta Formation; (8) El Imperial Formation and equivalents in the Frontal Cordillera (El Plata Formation); (9) Choiyoi Group; (10) Miocene–Pleistocene; (11) D2 Chanic thrust (the black trace indicates the reactivation during the Gondwanan deformation); (12) Gondwanan thrust. Modified of Sepúlveda et al. (2007a, 2007b) and Cingolani (2017). Location of Figs. 3A, 4 and 5a, 10 and the A–A' geological cross section. Location shown in Fig. 1b **b.** Geological cross section A–A' between Cordón del Carrizalito and the Veinticinco de Mayo village. The western end of the cross section, belonging to the Cordón del Carrizalito (Frontal Cordillera), from García-Sansegundo et al. (2014b).

Permian–Triassic Choiyoi Group.

In the San Rafael Block, the presence and characteristics of mentioned Paleozoic orogens were still not well defined, so it was difficult to establish precise correlations between this unit and the Precordillera. The aim of this work is to characterize the structures developed in the San Rafael Block and to analyze and interpret, within this structural context, the causes of the stratigraphic and metamorphic differences existing in the pre-Carboniferous rocks. The structure of the isolated outcrops of Ordovician–Devonian rocks of the entire San Rafael Block has been studied, as well as, in detail, those that affect the pre-Carboniferous rocks that crop out to the north and south of the Diamante River, between the Los Reyunos and Agua del Toro reservoirs. To carry out this study, these structures have been analyzed at all scales, and detailed geological sections and microstructure studies have been prepared. The results of this work have been related to those of nearby areas located to the North (Precordillera) and to the West (Frontal

Cordillera), which has allowed the elaboration of a model that explains the characteristics of the Chanic Orogen in this area.

2. Lithological units

In the San Rafael Block, the Paleozoic rocks rest unconformably on the intensely deformed Mesoproterozoic, which constitutes the basement of the Cuyania subplate (Cingolani and Ramos, 2017; Heredia et al., 2018b). In the Paleozoic rocks, two lithological assemblages of marine origin, separated by an angular unconformity, can be distinguished: the Ordovician–Devonian and the Carboniferous–Permian, which represent the pre-orogenic successions of the Chanic and Gondwanan cycles, respectively (Fig. 3a).

The upper Permian-Triassic rocks, with continental origin and numerous volcanic intercalations, rest unconformably on the pre-Gondwanan units (Fig. 3b), and represent the pre-orogenic succession of the Andean cycle. Above, the slightly deformed Andean continental synorogenic sequences of Cenozoic are also discordant (Fig. 2).

2.1. Pre-Carboniferous Paleozoic succession

The Pre-Carboniferous Paleozoic rocks occur in isolated outcrops, so it is not possible to develop a continuous and representative stratigraphic column for the area. In any case, four formations are distinguished whose main characteristics are the following:

2.1.1. Ponón Trehué Formation (Bordonaro et al., 1996; Abre et al., 2011)

The Ponón Trehué Formation corresponds to a small outcrop of limestone and dolomite, located to the south of the San Rafael Block, and lies unconformably on the Mesoproterozoic rocks of the Cerro de la Ventana Formation (Fig. 2a). These limestones are about 260 m thick and were deposited on a shallow to deep carbonate platform. This formation has been dated as Early–Middle Ordovician through various fossil faunas. Recently, based on conodonts, its upper limit has been placed in the Middle–Upper Ordovician (Heredia, 2006; Heredia and Mestre, 2017).

2.1.2. Pavón Formation (Cuerda and Cingolani, 1998; Cingolani et al., 2003)

Described in a small outcrop 1.5 km SE of the Veinticinco de Mayo village (Fig. 2a), the Pavón Formation consists of a massive green-reddish-gray sandstones, wackes, quartz sandstones, siltstones, and shales (Fig. 4) with remains of Ordovician graptolites. The Pavón Formation has an average thickness of about 700 m in the San Rafael Block (Manassero et al., 1999), deposited in a turbidite sand-rich ramp, which in its upper part was dated as Late Ordovician (Abre et al., 2017b). The rocks of this formation show deeper facies than those of the Ponón Trehué Formation, and contain olistoliths of this last formation (Heredia and Mestre, 2017) as well as from the Mesoproterozoic basement of Cuyania.

2.1.3. Río Seco de los Castaños Formation (González Díaz, 1972, 1981)

This formation is found in small outcrops located to the south of the study area and to the north of the Nihuil Reservoir (Fig. 2a). It is made up of sandstones and shales with greenish and grayish tones, with remains of acritarchs and plants that indicate a possible late Silurian–Early Devonian age (Manassero et al., 2009; Cingolani et al., 2017d). The minimum thickness of this formation is 2000 m.

2.1.4. La Horqueta Formation

Dessanti (1956) called the "La Horqueta Series" the pre-Carboniferous siliciclastic rocks of the San Rafael Block. But it was González Díaz (1972) who separated the Río Seco de los Castaños Formation from the La Horqueta Formation, deformed under low-grade to very low-grade metamorphic conditions (Tickyj et al., 2017). The outcrops of La Horqueta Formation are limited to the east by the Los Reyunos Thrust, which places it over the El Imperial Formation (Carboniferous), and extends westwards to the Cuchilla Blanca Back thrust (Figs. 2b and 5), where again it comes into contact with the El Imperial Formation. In the westernmost sectors, the La Horqueta Formation is made up of an alternance of quartzites in meter-scale beds and slates, while in the eastern part, near the Los Reyunos Reservoir, it is made up of coarse-grained white quartzites in layers of centimeter to decimeter scale, alternating with thin layers (millimeter to centimeter) of slates. The thickness of this formation is difficult to specify due to the intense deformation, although it can be estimated at several thousand meters. In the sandy layers, sedimentary structures are frequently recognized (such as graded bedding) that allow knowing the polarity of the succession. No fossil remains have been found in the rocks here considered to belong to the La Horqueta Formation, so their age is undetermined. However, detrital zircons have been analyzed that allow us to estimate a maximum age of sedimentation from the Silurian to the lower Devonian for this formation (Cingolani et al., 2008; Tickyj et al., 2017).

2.2. Pre-carboniferous igneous rocks

Intruding in the pre-Carboniferous Paleozoic succession, a set of

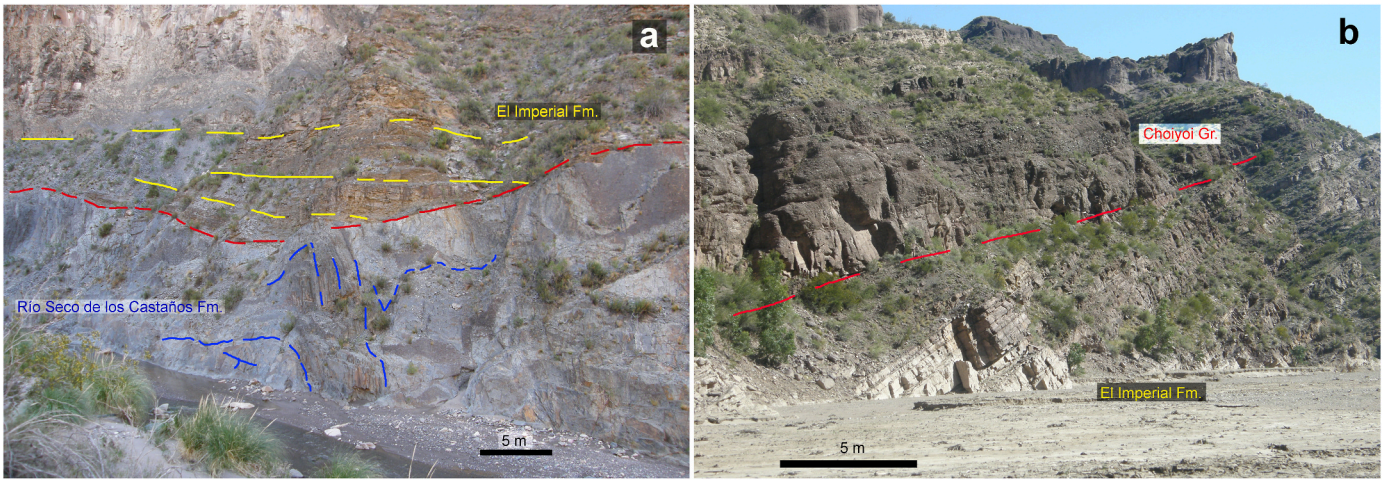

Fig. 3. El Imperial Formation. **a.** Angular unconformity of the El Imperial Formation over the sandstones and shales of the Río Seco de los Castaños Formation (looking NW). Location shown in Fig. 2 **b.** Angular unconformity of the Choiyoi Group on the El Imperial Formation (looking NW). Location shown in Fig. 5a.

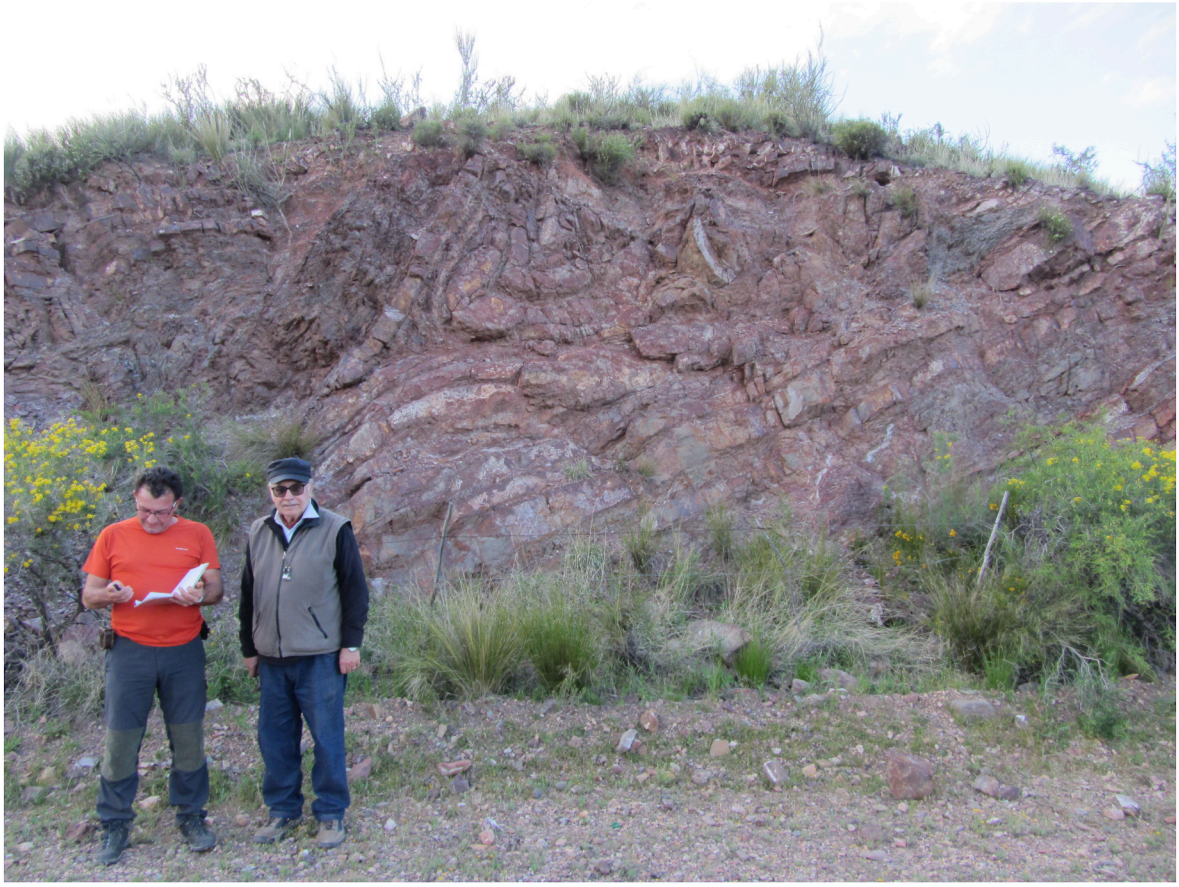

Fig. 4. East-verging folds developed in the Pavón Formation (looking NW). Location shown in Fig. 2.

igneous bodies of basic to intermediate nature crops out:

2.2.1. *El Nihuil Dolerites (Cingolani et al., 2017c)*

These rocks are located to the north of the reservoir of the same name, intruding the Ventana Formation (Mesoproterozoic) (Fig. 2a). This unit is constituted by a set of dikes and sills of porphyritic dolerites of tholeiitic signature with ages between the Late Ordovician and early Silurian (448.5 ± 10 and 434.2 ± 10 Ma; Cingolani et al., 2017c).

2.2.2. *Rodeo de la Bordalesa Tonalites (González Díaz, 1981)*

These rocks consist of two small calc-alkaline signature tonalitic bodies (Cingolani et al., 2017b), which intrude the Río Seco de los Castaños Formation to the NE of the Nihuil Dolerites (Fig. 2a) and are Early Devonian in age (401 ± 3 Ma; Cingolani et al., 2003).

2.3. *Carboniferous–Permian succession*

El Imperial Formation (Dessanti, 1956; González Díaz, 1972; Sepúlveda et al., 2007a). This is the only unit of the Carboniferous and Permian succession. It is found in small outcrops distributed throughout the study area, although it is best represented in the surroundings of the Los Reyunos and Agua del Toro reservoirs (Fig. 2a). The El Imperial Formation is made up of conglomerates, sandstones (sometimes feldspathic), micaceous quartzites, siltstones, and shales and can reach 2300 m in thickness within the San Rafael Block (Espejo et al., 1996). The lower part of this unit presents glaciomarine facies of the distal platform, which gradually pass to the proximal and deltaic fan front, while in the upper levels it presents fluvial, deltaic, and shallow marine facies (Espejo, 1990). Based on the flora and fauna studied, the age of this unit is late early Carboniferous–early Permian (Late Mississippian–Cisuralian) (Azcuy and Gutiérrez, 1985; Sabattini et al., 1991; Azcuy et al., 1993; Henry et al., 2014).

In the Frontal Cordillera the El Plata Formation (Caminos, 1965) crops out, which is equivalent to the El Imperial Formation and exceeds 6500 m in thickness (Azcuy et al., 1999). In the NW corner of Fig. 2a, the El Plata Formation crops out, where it was mapped by García-Sansegundo et al. (2014b).

2.4. *Permian-Triassic succession*

Choiyoi Group (Groeber, 1947). In the lower part of the Choiyoi Group there is the Cochicó Group (Dessanti and Caminos, 1967), formed by a varied set of continental, volcanic and volcano-sedimentary units. The Cochicó Group, over 1000 m thick, is post-Gondwanan and its basal part has been dated as Permian (Kleiman and Japas, 2009). The Cochicó rocks are calc-alkaline to alkaline, dacitic or andesitic volcanic and hypoabyssal rocks, which are more acidic at the top and can be rhyolitic (Kleiman and Japas, 2009). The age of this set of rocks is Permian–-Triassic (Groeber, 1947; Rolleri and Criado, 1969), between ca. 281.4 ± 2.5 Ma (Rocha-Campos et al., 2011) and 241 ± 10 Ma (Valencio et al., 1975). This group constitutes the beginning of the pre-orogenic sequence of the Andean cycle, deposited in a pre-orogenic extensional context.

2.5. ***Cenozoic Succession***

This unit includes the Miocene sandstones of the Aisol Formation and the Pliocene conglomerates, sandstones, shales, and tuffs of the Río Seco del Zapallo Formation (González Díaz, 1972). This succession almost always appears subhorizontal, lies discordantly on the previously described units, and constitutes the synorogenic sequence deposited at the end of the Andean Orogeny, which is currently active.

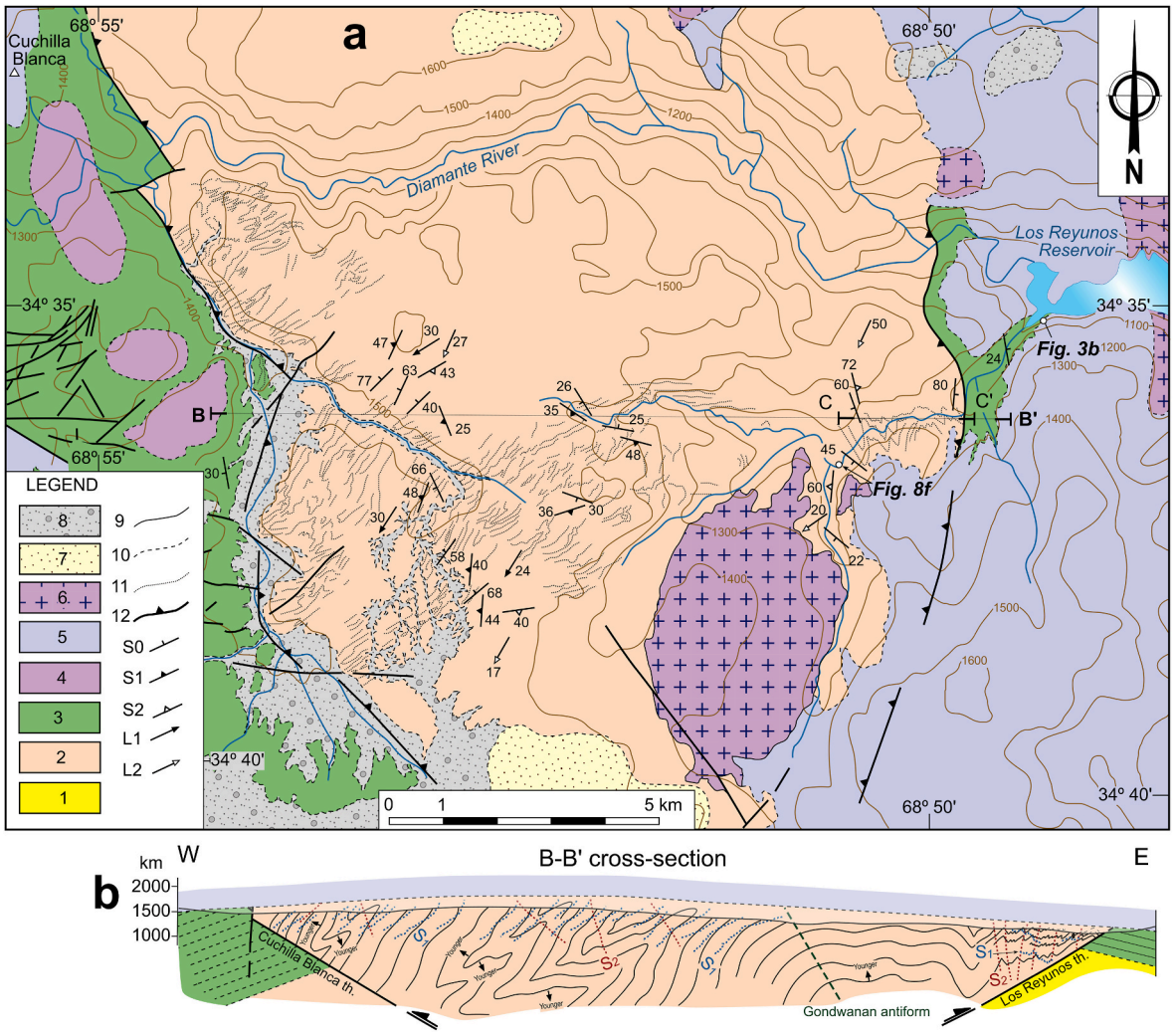

Fig. 5. a. Geological map of the area south of the Diamante River, between the Los Reyunos Reservoir and the Sierra de la Cuchilla Blanca. B–B' geological cross section of this figure and C–C' detailed geological cross section of Fig. 7. (1) Río Seco de los Castaños Formation (only indicated in B–B' geological cross section); (2) La Horqueta Formation; (3) El Imperial Formation; (4) Cerro Las Yeguas Formation, (5) Choiyoi Group; (6) Hypoabyssal intrusive rocks of El Portillo Group; (7) Pleistocene; (8) Quaternary; (9) intrusive limit; (10) unconformable limit; (11) trace beds; (12) Gondwanan thrust. Location shown in Fig. 2. **b.** B–B' geological cross section showing the characteristics of the structures that deform the La Horqueta and El Imperial formations.

3. Structure

In the San Rafael Block, structures related to three orogenic cycles are recognized: (1) Andean structures, which jointly deform the Permian–Cenozoic cover and the Paleozoic–Mesoproterozoic basement; (2) Gondwanan structures, developed under non-metamorphic conditions, which deform Carboniferous and pre-Carboniferous rocks, but which overlain by the Permian–Mesozoic unconformable cover; and (3) structures sometimes accompanied by metamorphism dated as Devonian (ca. 371–379 Ma, Tickyj et al., 2001), which only affect pre-Carboniferous rocks, so they must be Chanic.

3.1. Chanic structures

Two structural domains can be distinguished in the pre-Carboniferous Paleozoic rocks of the San Rafael Block: (1) structures corresponding to Chanic folds developed in the absence of metamorphism that affect the pre- Carboniferous Paleozoic formations located to the east of the Los Reyunos Thrust, and (2) structures characterized by Chanic structures generated in low to very low-grade metamorphic conditions that only affect the La Horqueta Formation and that develop to the western part of the Los Reyunos Thrust (Figs. 2 and 5).

3.1.1. Chanic structures developed under non-metamorphic conditions

In the San Rafael Block, the Ponón Trehué, Pavón, and Río Seco de los Castaños formations are affected by N–S trending folds, verging to the east, which when developed on alternating sandstones and shale show chevron-type geometries and low angles between limbs (<50°) (Fig. 4). Locally, these folds are associated with a rough cleavage.

3.1.2. Chanic structures developed under low to very low-grade metamorphic conditions

Rocks of the La Horqueta Formation, located to the north and south of the Diamante River, between the Sierra de la Cuchilla Blanca and the Los Reyunos Reservoir (Figs. 2 and 5), are deformed by two Chanic deformation episodes (D1 and D2). These structures are represented by folds with oblique directions, associated with two generalized tectonic foliations (S_1 and S_2) that, as will be seen later, developed under greenschist facies metamorphic conditions. The characteristics of both episodes of deformation are as follows:

D1 Chanic structures. These structures consist of asymmetric tight to isoclinal folds, with thickened hinges and an associated and generalized tectonic foliation (S_1). The trend and plunge of these folds is variable

because they are deformed by later Chanic and Gondwanan structures (Fig. 6). However, in the surroundings of the Los Reyunos Reservoir, where the Gondwanan folds are poorly developed, it is possible to reconstruct D1 structures by retrodeformation of D2 Chanic structures. The calculated trend in this area of the D1 folds is N 170°E and plunge to the south (Fig. 6A). The general vergence of the D1 structures is to the west, which can be confirmed by the good examples of the relationships between S_0 and S_1 (Figs. 7 and 8). Near the Los Reyunos Reservoir, the D1 structures are intensely deformed by the D2 folds, despite good examples of small-scale D1 folds (Fig. 7.1 and 8b). Further west, the D1 folds have been deduced from the relationships between S_0 and S_1 since, although the D2 structures are not very penetrative, the Gondwanan deformation has overturned the D1 folds (facing-down folds, western part of Fig. 5b). A slaty cleavage (S_1) is associated with the D1 folds, which is the most penetrating foliation in the area and is characterized by the lattice-preferred orientation of synkinematic chlorite-muscovite blasts (Fig. 9).

D2 Chanic structures. These structures are characterized by folds from centimeter to hectometer scale. Due to the superimposition of the Gondwanan structures, the strike of the D2 structures varies between NE–SW and NW–SE (Fig. 6). In the surroundings of the Los Reyunos Reservoir, where the effect of the Gondwanan deformation on the previous structures is less, the direction of the D2 folds is N 200°E, with a dip of 35° towards the SW (Fig. 6A). The D2 folds are vergent to the east, although to the west they are straight or tilted westwards due to superimposed Gondwanan deformation (Fig. 5b). These folds present an interlimb angle of around 70° (Fig. 7.3, 7.5 and 8a, 8c), although locally they can become isoclinal (Fig. 7.2 and 8d) and are associated with crenulation cleavage S_2 (Figs. 7 and 8).

The obliquity between the D1 and D2 fold systems is greater than 30°

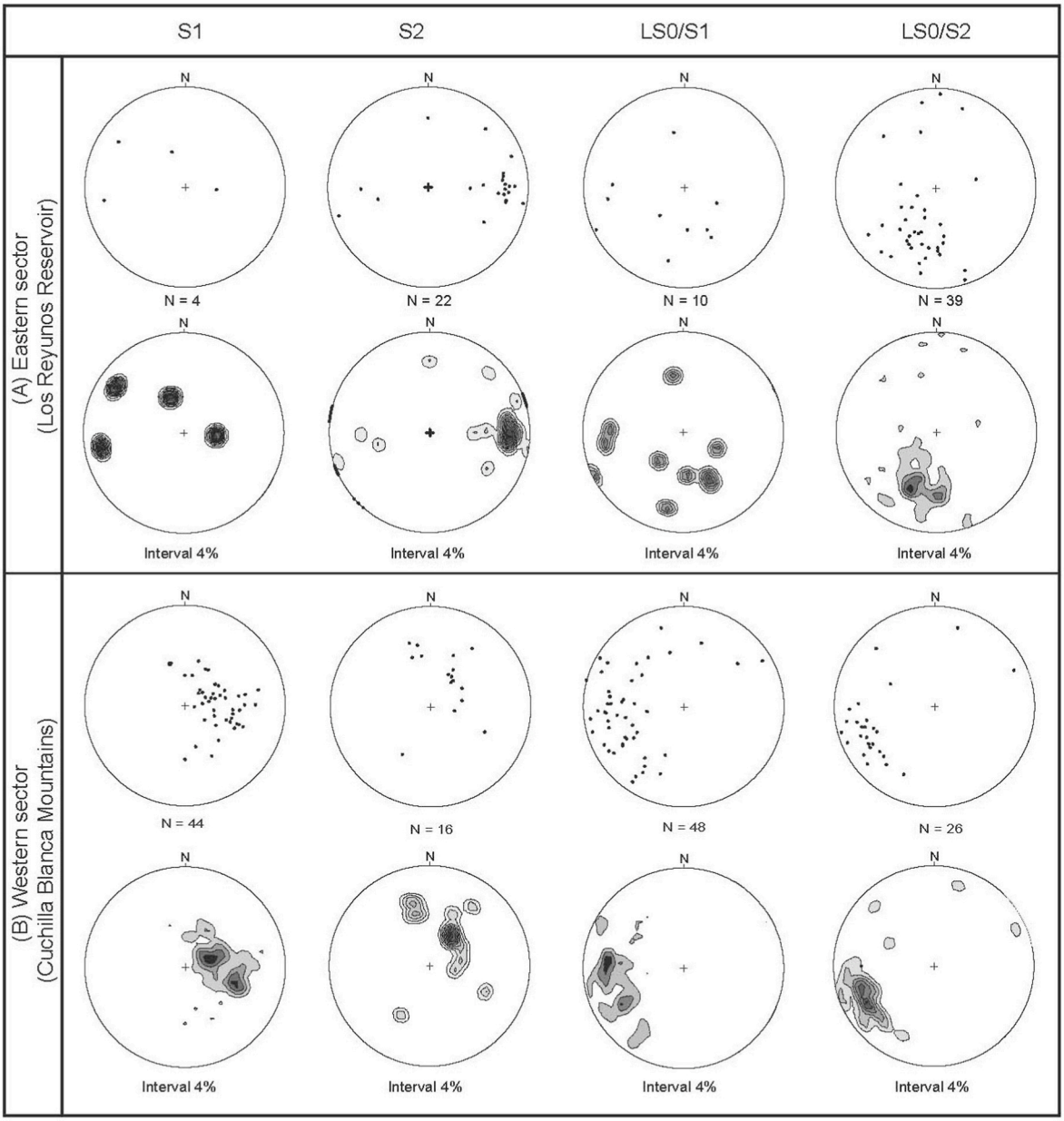

Fig. 6. Stereograms showing the position of the Chanic structures that deform the La Horqueta Formation between the Los Reyunos and Cuchilla Blanca thrusts. A. Poles of the S_1, S_2 foliations and the L_1, L_2 lineation near the Los Reyunos Reservoir, where the Chanic structures approximately maintain their original position, as they are not rotated by the effect of the Gondwanan deformation. B. Poles of the S_1, S_2 foliations and the L_1, L_2 lineation, in the western sector, near Cuchilla Blanca Ranges, where the Chanic structures are folded by the antiform associated with the Gondwanan Cuchilla Blanca Back thrust.

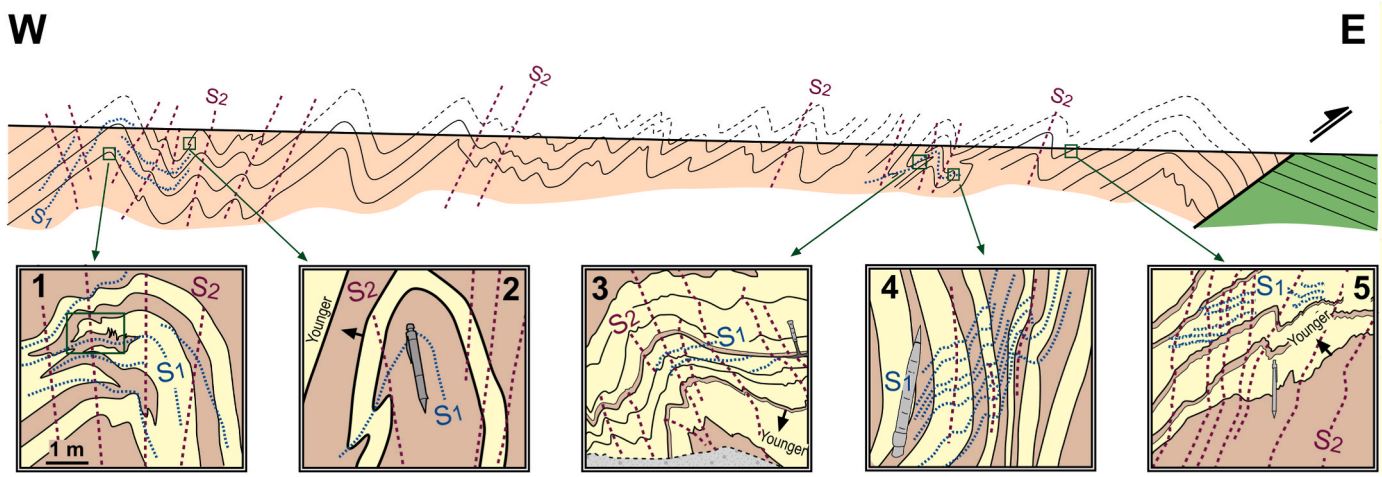

Fig. 7. Detailed geological cross section of the area located to the west of the Los Reyunos Reservoir showing the style of the structures that deform the La Horqueta Formation. Location shown in Fig. 5. Schemes from 1 to 5 show details of the structures in different parts of the geological cross section: **(1)** D1 Chanic folds deformed in the hinge zone of a D2 fold (the diagram corresponds to Fig. 8b). **(2)** D2 Chanic antiform, with a D1 fold on its western limb (the scheme corresponds to Fig. 8d). **(3)** D2 Chanic folds, with the associated incipient S_2 crenulation cleavage, deforming the reverse limb of a fold D1 (scheme corresponds to Fig. 8c, in which the polarity of the layers and the angle of cut between S_0/S_1 confirm the west vergence of D1 structures). **(4)** Area of a D1 fold close to the hinge zone, where the S_0 is subvertical and the S_1 subhorizontal, affected by folds D2 (scheme corresponds to Fig. 8e). When the D2 structures develop on the subvertical S_0, a flattening occurs perpendicular to the layers, while the S_1, in favorable position, is folded by the D2 structures. Examples of overlapping structures of this type have been described in the Coastal Cordillera of Chile and in the Pyrenean Axial Zone (Spain, France) (García-Sansegundo, 1992; García-Sansegundo et al., 2014a, 2014c). **(5)** D2 Chanic folds with the associated S_2, deforming S_1 (scheme corresponds to Fig. 8a, in which the polarity of the layers indicates that this outcrop corresponds to the normal limb of a west-verging D1 fold).

(Fig. 8f), which causes the dispersion of the D1 structures and gives rise to complex fold interference figures of type 2 and 3 (Ramsay, 1967).

The tectonic foliation associated with the D2 folds results from the microfolding of the S_1 and corresponds to a rough crenulation cleavage (S_2), defined by anastomosed domains in which the iron oxides and scarce and incipient muscovite blasts are concentrated, separating a few microlithons in which the folded S_1 is observed (Fig. 9). In the vicinity of the Los Reyunos Reservoir, there is a good development of the S_2, which, however, is not observed to the west, where the S_2 foliation is not very penetrative or was not generated. This irregular distribution of the D2 deformation can be related to a Chanic shear zone located in the vicinity of the Los Reyunos Reservoir, in relation to which the D2 structures were generated (Fig. 2b).

3.2. Gondwanan structures

The Gondwanan structures are NNW–SSE trending thrusts, developed in the absence of metamorphism, and which jointly affect the pre-Carboniferous series and the El Imperial Formation. One of the best-developed structures of this type is the east-directed Los Reyunos Thrust, located to the west of the Los Reyunos Reservoir, which dips 30° to the west and produces the overthrust of the La Horqueta Formation on the El Imperial Formation (Fig. 5). No Gondwanan folds associated with this thrust have been observed. To the east of the Agua del Toro Reservoir (Fig. 2a), the Back thrust of the Cuchilla Blanca also produces the overthrust of the La Horqueta Formation on the Imperial Formation. This structure dips 30° to the east and, in the hanging wall, a large antiform develops that produces the westward tilting of the D1 Chanic structures and the verticalization or inversion of the D2 Chanic structures that affect the La Horqueta Formation (Fig. 5). In contrast, the Cuchilla Blanca Back thrust is associated with ENE–WSW trending tear faults (Fig. 5a). The unconformable character of the Choiyoi Group (Fig. 5) confirms the Gondwanan age of these structures.

3.3. Andean structures

In the geological sections of Figs. 2b and 5b, the main Andean structure of the San Rafael Block is an open antiform, which deforms the Choiyoi Group, and in whose core the basement rocks crop out. In contrast, normal, subvertical, NNW–SSE faults are recognized, affecting the Choiyoi Group, whose beds sometimes have associated rollovers (Fig. 10). Some of these faults also affect the Cenozoic succession (Cochicó Fault in Fig. 2a), being in this case faults related to the Permian–Mesozoic extension that were later reactivated during the Cenozoic compression.

4. Discussion

In the study area, solid evidence has been found that allows us to deduce the age of the structures observed. Thus, the pre-Carboniferous succession is affected by structures and metamorphism dated as Devonian (Tickyj, 2011; Tickyj et al., 2017) that are not developed in the Carboniferous rocks of the El Imperial Formation, so they must be interpreted accordingly with the Chanic Orogeny. In contrast, both the El Imperial Formation and the pre-Carboniferous succession are deformed by NNW–SSE trending thrusts with opposite vergences, between which there is an antiform. The Permian–Cenozoic unconformable cover postdates these structures, so they must be considered as developed during the Gondwanan Orogeny. Rollover-type folds, associated with NW–SE trending normal Permian syn-sedimentary faults (Fig. 10), affect the Choiyoi Group. Finally, the Paleozoic basement rocks of the San Rafael Block are located in the core of an open Andean antiform, depicted by the beds of the Permian–Mesozoic cover (Figs. 2b and 5b).

The pre-Carboniferous Paleozoic rocks of the San Rafael Block represent the pre-orogenic sequence of the Chanic cycle, deposited for the most part on the western passive continental margin of the Cuyania subplate in an extensional context (Kury, 1993; Keller, 1999; Alonso et al., 2008; Heredia et al., 2016; Cingolani and Ramos, 2017 and citations therein). Syn-orogenic sediments related to the Chanic Orogeny do not crop out in the San Rafael Block, although they can be observed in the Precordillera, where they are represented by the Angualasto Group (Limarino et al., 2006; Heredia et al., 2012; Colombo et al., 2014). Due to their age and facies, many of the pre-Carboniferous units of the San

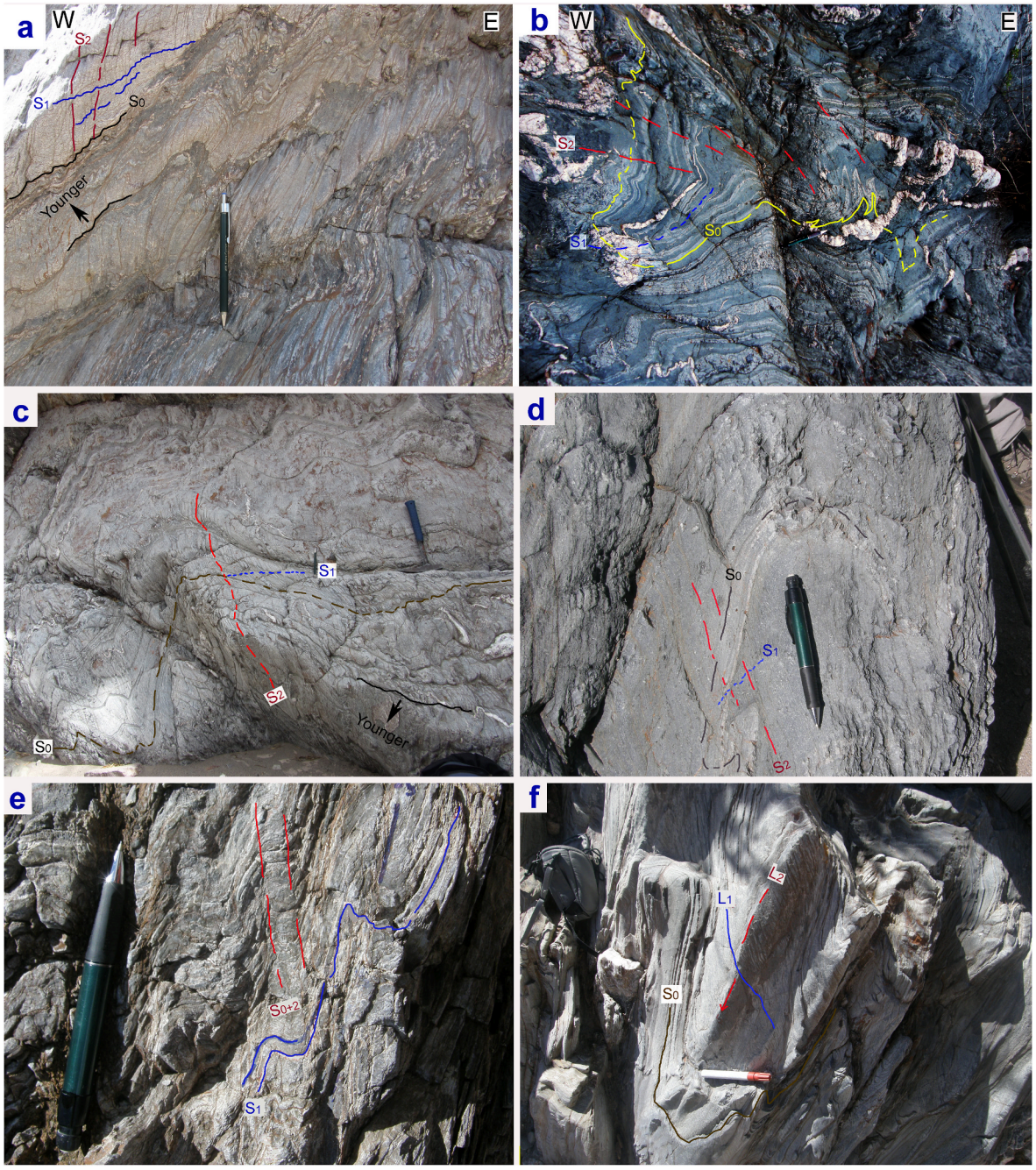

Fig. 8. Aspect of the Chanic structures that deform the La Horqueta Formation. In all photos west is to the left. **a.** D2 Chanic folds, with the associated S_2 deforming S_1 (photo corresponds to scheme 5 of Fig. 7). **b.** D1 Chanic folds, deformed by D2 folds (photo corresponds to scheme 1 of Fig. 7). **c.** D2 Chanic folds with the associated S_2 deforming the reverse limb of a D1 fold (photo corresponds to scheme 3 of Fig. 7). **d** D2 Chanic antiform, with a D1 fold on its west limb (photo corresponds to scheme 2 of Fig. 7). **e.** Area close to the hinge zone of a D1 fold deformed by D2 structures (photo corresponds to scheme 4 of Fig. 7). **f.** D2 Chanic fold with its hinge strongly dipping, deforming the intersection lineation L1. This example allows us to know the angle formed by the direction of structures D1 and D2 (situation shown in Fig. 5a).

Rafael Block have notable similarities with series from the Precordillera. Thus, the Ponón Trehué Formation can be correlated with the San Juan Limestone, which widely crops out in the Central and Eastern Precordillera (Bordonaro, 1980, 1999). The Pavón Formation has turbidite characteristics and contains Ordovician graptolites (Manassero et al., 1999; Cingolani et al., 2003), which allows it to be correlated with some units described in the Precordillera. The Los Sombreros (Benedetto and Vaccari, 1992), Empozada (Harrington and Leanza, 1957), and Alcaparrosa (Amos et al., 1971; Aparicio and Cuerda, 1976; Kerlleñevich and Cuerda, 1986; Schauer et al., 1987) are units comparable to the Pavón Formation. The Pavón Formation, and those equivalent in age to the Precordillera, can be interpreted as the distal and deep facies of the Ponón Trehué Formation. In this sense, Alonso et al. (2008) indicated in the Los Sombreros Formation (Upper Ordovician) the presence of olistoliths and calcareous conglomerates from the carbonate platform, represented by the San Juan Limestone. Similarly, Heredia (2006) cited deep facies in the upper part of the Ponón Trehué Formation, which reinforces the correlation between the Los Sombreros and Pavón formations. Regarding the Río Seco de los Castaños Formation, it can be correlated with the Villavicencio Formations (Harrington, 1941;

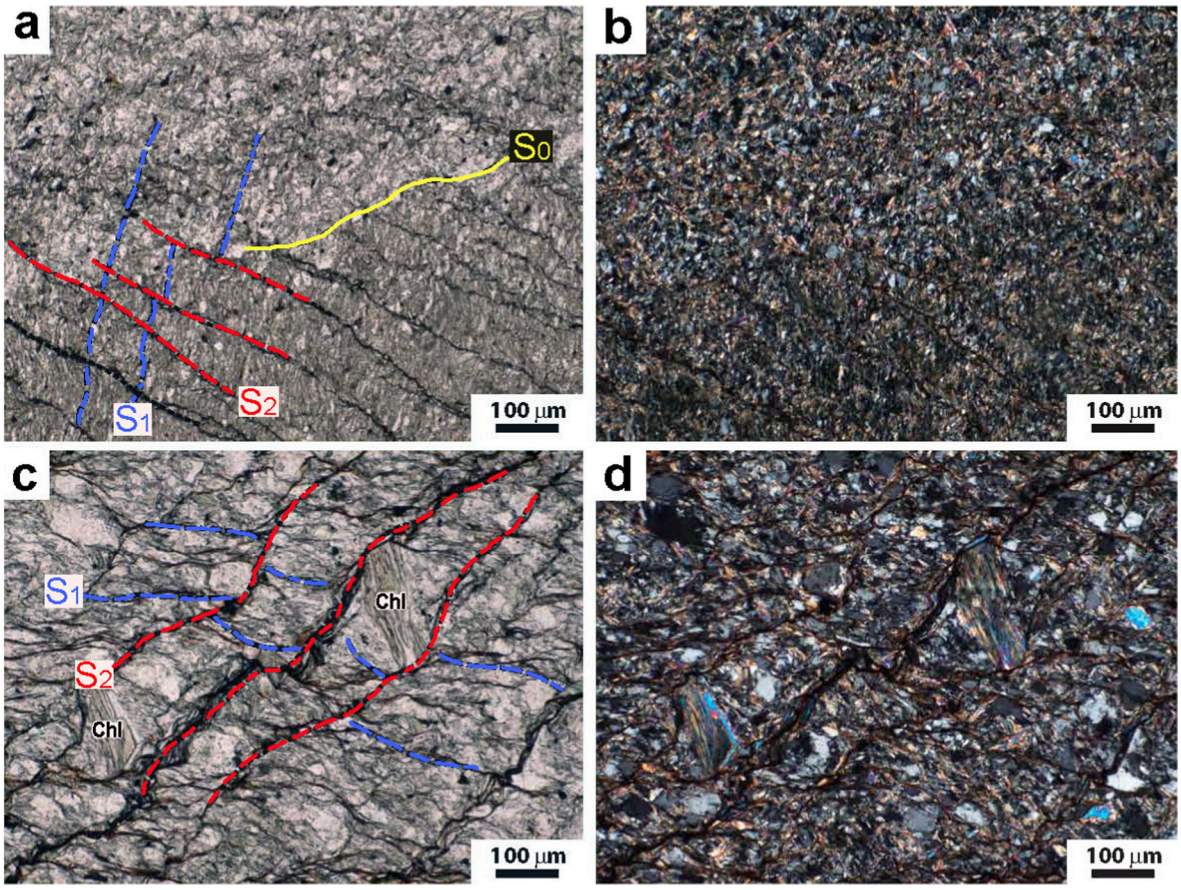

Fig. 9. Microscopic aspect of the Chanic tectonic foliations, developed in the layers of the La Horqueta Formation, under low to very low metamorphic conditions. **a, b.** Images with plane-polarized light and crossed polars of a section where you can see the contact (S_0) between a level of very fine-grained sandstones and slates, and the two Chanic tectonic foliations: S_1 corresponds to a penetrative slaty cleavage and S_2 to a rough crenulation cleavage. **c, d.** Plane-polarized light and cross-polarized light images of a medium-fine grained meta-sandstone with syn-kinematic blasts with S_1, surrounded by S_2 that appears as an anastomosed crenulation cleavage. Notice the syn-S_1 chlorite (Chl) blasts controlling the thickness of the S_2 microlithons.

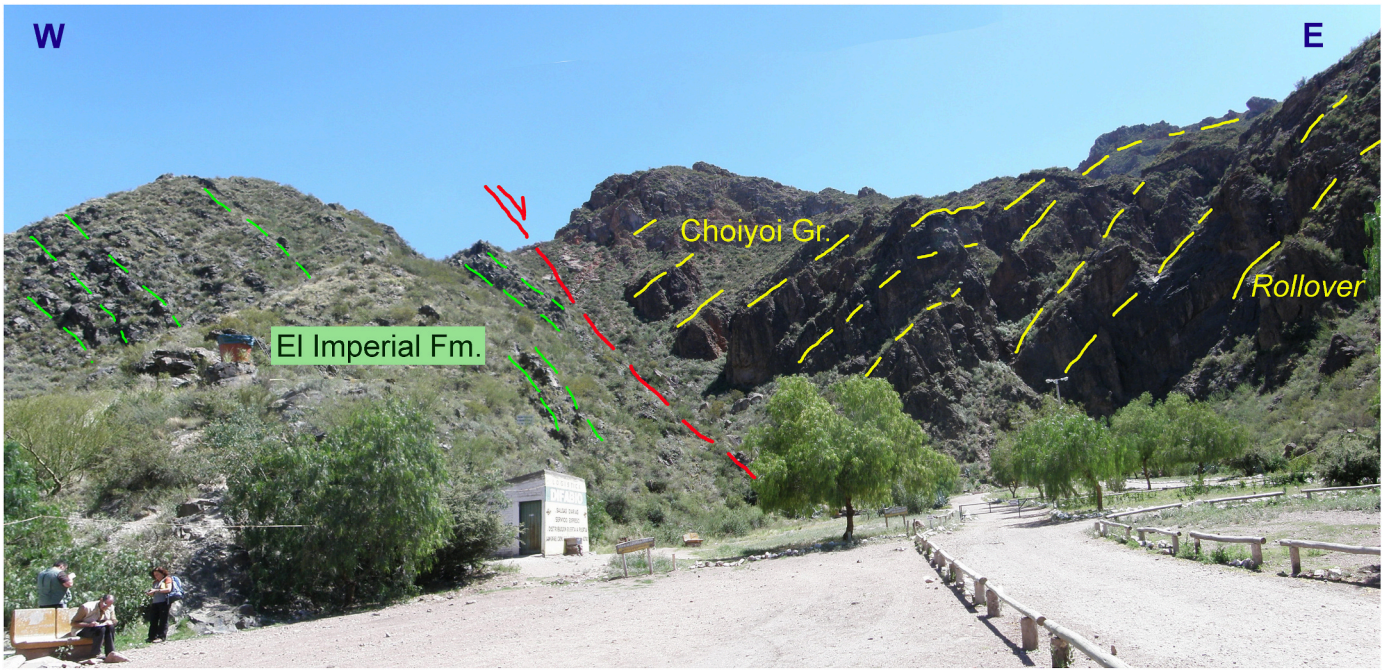

Fig. 10. Normal fault trending NW–SE affecting the El Imperial Formation and the Choiyoi Group. Notice that a fault-related rollover develops in the layers of the Choiyoi Group. Location shown in Fig. 2a.

Guerstein et al., 1965; Sessarego, 1988; Baldis and Peralta, 1999) and Punta Negra, of the Southern and Central Precordillera respectively. These units were deposited in a prograding deltaic system, from a shallow external marine platform to deep turbidite systems (Bustos and Astini, 1997).

The La Horqueta Formation, located in the western part of the study area, shows stratigraphic characteristics similar to those of the Vallecitos Layers, a turbidite sequence located in the Frontal Cordillera (Cordón del Plata) and attributed to the Devonian (Heredia et al., 2012). The La Horqueta and Río Seco de los Castaños formations, of similar ages, show age patterns of U–Pb in detrital zircons suggesting that the contributions come mainly from Mesoproterozoic rocks, belonging, according to Abre et al. (2017a) and Tickyj et al. (2017), to the Cuyania basement. However, the Río Seco de los Castaños Formation shows different amounts of detrital zircon ages than the La Horqueta Formation (Abre et al., 2017a), indicating that, although the geochemical nature of the basement is the same, the source areas were different. Thus, based on the work of Heredia et al. (2012), La Horqueta Formation and the Vallecitos Layers represent a turbiditic succession deposited on the eastern margin of the Chilenia sub-plate. In contrast, the Río Seco de los Castaños Formation, and the equivalent units of the Precordillera, were deposited on the passive western margin of the Cuyania sub-plate (Keller, 1999; Heredia et al., 2018b). The existing connection north of the Precordillera between the Chilenia and Cuyania sub-plates (Chi–Cu Terrane, according to Heredia et al., 2018b) can explain their coincident geochemical nature. As will be seen later, the current proximity between both units can be related to the Chanic Orogeny, developed during the Upper Devonian–lower Carboniferous.

The El Imperial Formation rests unconformably on the pre-Carboniferous lithostratigraphic units of the San Rafael Block (deformed during the Chanic Orogeny). Thus, the El Imperial Formation represents the pre-orogenic sequence of the Gondwanan cycle and its sedimentation occurred in a retro-wedge or retro-arc basin, located on a margin with active subduction (Heredia et al., 2016). This formation can be correlated with part of the Precordillera Paganzo Group (Guandacol, Tupe, and equivalent formations; Limarino and Spalletti, 2006; Henry et al., 2014 and citations therein). The El Imperial Formation is deformed by structures related to the Gondwanan Orogeny (upper Carboniferous–lower Permian). In the San Rafael Block, the syn-orogenic Gondwanan sediments have not been recognized, which crop out in the Precordillera and correspond to the upper part of the Paganzo Group (Patquia Formation and equivalent, of early Permian age) (Limarino et al., 2006; Colombo et al., 2014). In the Frontal Cordillera, corresponding to an innermost part of the Gondwanan Orogen, syn-orogenic sedimentation began in the upper Carboniferous (Busquets et al., 2005, 2013a, 2013b).

The basic pre-Carboniferous igneous rocks of the San Rafael Block are related to the extensional process that took place between the Ediacaran and Lower Devonian due to the separation of the Cuyania and Chilenia sub-plates (Davis et al., 1999; López and Gregori, 2004; González-Menéndez et al., 2013; Heredia et al., 2016; Cingolani et al., 2017c). Thus, the El Nihuil Dolerites, from the Upper Ordovician–lower Silurian, correspond to intrusions of the westernmost part of the thinned Cuyania margin. In contrast, the Rodeo de la Bordalesa Tonalites, from the Lower Devonian, represent intrusions located further east (Cingolani et al., 2017b), where the crust was thicker. From the Devonian, the Chilenia margin became active, so that the igneous rocks located in this subplate are related to a subduction process that concluded with the Chanic Orogeny (Heredia et al., 2016, 2018b; Dahlquist et al., 2021) (Fig. 2a).

In relation to the structure, in the pre-Carboniferous rocks of the San Rafael Block there is an uneven development of Chanic deformation. Thus, in the La Horqueta Formation, two fold systems with associated tectonic foliations were generated under low to very low-grade metamorphic conditions, the first and better developed verging west and the second verging east. In contrast, in the rest of the pre-Carboniferous rocks, the Chanic structures consist of a system of east-verging folds, developed in non-metamorphic conditions. Together with the stratigraphic characteristics of the Ponón Trehué, Pavón, and Río Seco de los Castaños formations, the Chanic structures indicate that the area is located in the foreland of the eastern branch of the Chanic Orogen. However, the stratigraphic characteristics of the La Horqueta Formation, the vergence of the main Chanic structures that deform it (D1), and the metamorphic conditions under which they developed indicate that this part of the San Rafael Block corresponds to the hinterland of the western branch of the Chanic Orogen. Therefore, we suggest that there must be a structure that brought these two parts of the Chanic Orogen together. In this sense, the La Horqueta Formation is deformed by D2 Chanic structures that have an uneven development. Thus, while in the area of the Los Reyunos Reservoir, the D2 structures are well developed with a marked vergence to the east, in more western sectors (near the Cerro de la Cuchilla Blanca, Fig. 5a), these structures are less developed and are less penetrative. This allows us to suggest that the Los Reyunos Gondwanan Thrust corresponds to the reactivation of an important previous Chanic structure, contemporaneous with the D2 deformation and responsible for the superimposition of the hinterland of the western branch of the Chanic Orogen over the foreland of the eastern branch.

Taking into account the data provided by García-Sansegundo et al. (2014b, 2016) on the characteristics of the Chanic structures of various areas of the Frontal Cordillera, an approximation to the geometry of the Chanic orogenic belt between this tectonostratigraphic unit and the San Rafael Block can be proposed, which is synthesized in Fig. 11. In the Frontal Cordillera, the Chanic orogenic belt presents a marked vergence of its structures towards the west, as corresponds to its position in the western branch of this orogen. In its hinterland, near the surface, thinned parts of the basement of the Chilenia sub-plate crop out, represented by the Las Yaretas Gneisses (Ramos and Basei, 1997). The age of this basement is between 1.4 and 1.7 Ga (U–Pb ID–TIMS ages; Basei et al., 1998) (Fig. 11). Also in the hinterland of the western branch of the Chanic Orogen, rocks were deformed under HP–LT conditions, related to the Chanic subduction, which lasted until the Middle Devonian (Willner et al., 2011). These outcrops constitute the Guarguaraz Complex (López and Gregori, 2004), which was exhumed and emplaced on the Chilenia margin during the Chanic Orogeny (Fig. 11). Dismembered ophiolitic fragments crop out to the east, emplaced over Cuyania, belonging to the ocean that separated both sub-plates and representing the suture of the Chanic Orogen (Davis et al., 1999; Heredia et al., 2018b). These ophiolitic fragments have ages between the Ediacaran and the Late Ordovician (Davis et al., 2000) and appear mainly in the southern part of the Western Precordillera, to the N of the San Rafael Block. No evidence of the suture zone has been found in the study area, so we suggest that it is located in deep areas, in the lower part of the hanging wall of the Los Reyunos Chanic Thrust (Fig. 11). After the Chanic Orogeny, its extensional collapse occurred (Heredia et al., 2012, 2018b), which could be related to a reactivation of the Los Reyunos Thrust as a normal fault. The extension produced by this fault facilitated the deposit of the El Imperial Formation and its equivalents in the Frontal Cordillera (El Plata Formation) in its hanging wall, where thicknesses greater than 6000 m were reached. Subsequently, this normal fault underwent a tectonic inversion during the Gondwanan Orogeny, giving rise to the current Los Reyunos Thrust (Fig. 11).

5. Conclusions

The main conclusions of this work are the following:

1. The pre-Carboniferous Paleozoic Ponón Trehué, Pavón, and Río Seco de los Castaños formations of the San Rafael Block have similarities with units of the Precordillera. However, the La Horqueta Formation, of the same age as the Río Seco de los Castaños Formation, is similar to the Vallecitos Layers that crop out in the Frontal Cordillera (Cordón del Plata).

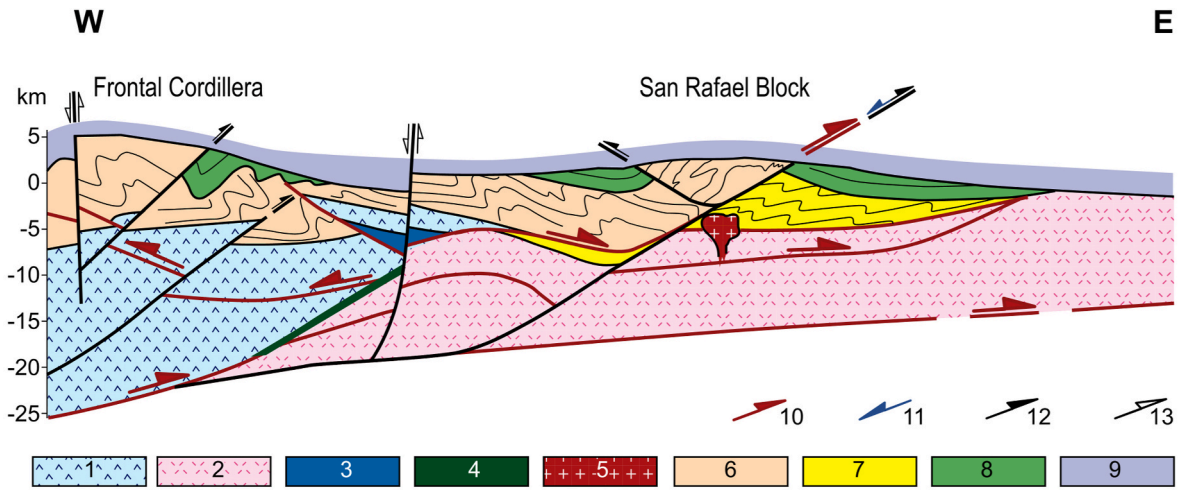

Fig. 11. Schematic showing the reconstruction of the Chanic Orogen in the San Rafael Block transect, based on Figs. 5b and 10. The in-depth interpretation of the structures is based on Rodríguez-Fernández et al. (1997). (1) Chilenia basement; (2) Cuyania basement; (3) Accretionary wedge (Guarguaraz Complex); (4) Suture: ophiolites (Ediacaran–Late Ordovician); (5) Paleozoic pre-Carboniferous granitoids; (6) Pre-orogenic Chilenian cover rocks; (7) Pre-orogenic Chanic rocks of Cuyania (Ordovician–Late Devonian); (8) Carboniferous rocks; (9) Andean cover (Permian–Cenozoic); (10) Chanic thrust; (11) Possible Gondwanan normal fault; (12) Gondwanan thrust; (13) Andean faults.

2. The Chanic structures that deform the pre-Carboniferous Paleozoic Ponón Trehué, Pavón, and Río Seco de los Castaños formations consist of N–S trending folds, verging to the east, developed in non-metamorphic conditions. On the contrary, the La Horqueta Formation is affected by Chanic structures developed under low to very low-grade metamorphic conditions, consisting in two system folds (D1 and D2). The D1 fold system is the main one; it has a direction N 170°E, vergence to the west, and is associated with a slaty cleavage (S_1). The D2 system is well developed near the Los Reyunos Reservoir, it has a direction N 200°E, and vergence to the east.
3. We suggets that the Ponón Trehué, Pavón and Río Seco de los Castaños stratigraphic units and the Chanic structures that deform them belong to the foreland of the eastern branch of the Chanic Orogen. On the contrary, the La Horqueta Formation and the D1 structures that deform it correspond to the hinterland of the western branch of the same orogen.
4. The approach of the two branches of the Chanic Orogen is interpreted here as due to a thrust of crustal scale (Los Reyunos Thrust), east-directed, during the D2 Chanic episode, which overthrust the La Horqueta Formation on the non-metamorphic pre-Carboniferous units of the San Rafael Block.
5. The Chanic suture zone in the San Rafael Block is sheltered by the Los Reyunos Chanic Thrust. This thrust was subsequently reactivated during the Gondwanan cycle, first as a normal fault, conditioning the deposition of the Carboniferous series (Gondwanan pre-orogenic succession) and then as a Gondwanan thrust, that partially preserved the displacement of the normal fault.

CRediT authorship contribution statement

J. García-Sansegundo: Investigation, Conceptualization, Funding acquisition, Methodology, Validation, Writing – original draft, Writing – review & editing. **P. Farias:** Investigation, Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **A. Rubio-Ordoñez:** Investigation, Conceptualization, Methodology, Validation, Writing – original draft. **P. Clariana:** Investigation, Conceptualization, Methodology, Validation, Writing – original draft. **C. Cingolani:** Investigation, Conceptualization, Methodology, Validation, Writing – original draft. **N. Heredia:** Investigation, Conceptualization, Funding acquisition, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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