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Stratigraphy, structure and geodynamic evolution of the Paleozoic rocks in the Cordillera del Viento (37º S latitude, Andes of Neuquén, Argentina)

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Abstract

The Pre-Andean Paleozoic substrate from the Cordillera del Viento anticline is a polyorogenic basement composed of two groups of preorogenic rocks with different stratigraphy and deformation. The oldest set consists of pre-Late Devonian metasedimentary rocks belonging to the Guaraco Norte Formation. The upper set is formed by the thick volcano-sedimentary sequence of the Carboniferous Andacollo Group. This group is composed from bottom to top of the silicic volcanic rocks of the Arroyo del Torreón Formation (early Carboniferous) and the marine sedimentary rocks of the Huaraco Formation (late Carboniferous) developed in an extensional basin. Both formations are locally separated by minor syn-extensional unconformities.

The relationship between the metamorphic rocks of the Guaraco Norte Formation and the volcano-sedimentary sequence of the Andacollo Group is not observed, but we inferred a major angular unconformity associated with the Late Devonian-early Carboniferous Chanic orogeny. The main Chanic structures are tight vertical and subvertical folds with slight W-WSW vergence, formed under low-grade metamorphic conditions, with the development of a pervasive axial-plane cleavage (S1), affected by a disjunctive crenulation cleavage (S2).

In the early Permian, during the San Rafael orogeny of the Gondwanan orogenic cycle, deformation occurred under very low-grade to non-metamorphic conditions. The main structures are thrusts and associated folds that are re-folded by the Cordillera del Viento anticline, related to the Andean orogeny. The WNW-oriented and SSW-vergent folds are associated with an incipient axial-plane cleavage in the pyroclastic rocks and pencil lineation in shales.

The pre-Andean Paleozoic basement rocks are intruded and unconformably covered by early Permian to Early Triassic? granitoids and silicic volcanic rocks from the Huingancó volcanic-plutonic Complex (equivalent to the Choiyoi Group), establishing the beginning of the Andean orogenic cycle in this region.

Keywords: Andes, Paleozoic, Tectonics, Chanic Orogeny, Cordillera del Viento

Resumen

El sustrato paleozoico pre-andino que aflora en el anticlinal de la Cordillera del Viento, es un basamento poliorogénico que está compuesto por dos conjuntos de rocas preorogénicas con estratigrafía y condiciones de deformación diferentes. El más antiguo tiene una edad devónica superior y está formado por las rocas metasedimentarias de la Formación Guaraco Norte, en tanto que el conjunto superior son las espesas acumulaciones volcano-sedimentarias carboníferas del Grupo Andacollo. Este grupo, integrado en su parte inferior por rocas volcánicas silíceas de la Formación Arroyo del Torreón (Carbonífero inferior) y hacia techo, por las sedimentitas clásticas marinas de la Formación Huaraco (Carbonífero superior) fue desarrollado en el marco de una cuenca extensional y pueden estar separadas localmente por discordancias menores de carácter sin-extensional.

Las relaciones entre las rocas metamórficas y la secuencia volcano-sedimentaria del Carbonífero no se observan, pero se infiere una discordancia mayor asociada con la orogenia Chánica, que tuvo lugar entre el Devónico Superior y el Carbonífero inferior. Las estructuras chánicas están asociadas a un metamorfismo de bajo grado y son pliegues apretados sub-verticales a verticales y con ligera vergencia al O-OSO que llevan asociados un clivaje penetrativo (S1) de rumbo N-S a NNO que está afectado por un clivaje subvertical más espaciado (S2).

En el Pérmico inferior, durante la orogenia San Rafael del ciclo orogénico Gondwánico, la deformación contraccional se produce en condiciones de metamorfismo de muy bajo grado o en ausencia de éste. Las estructuras principales son cabalgamientos y pliegues asociados que se encuentran plegados por el anticlinal ándico de la Cordillera del Viento. Los pliegues de rumbo ONO y vergencia al SSO llevan asociados un incipiente clivaje de plano axial en los contactos entre limolitas y volcanitas y lineación de tipo lápiz (pencil) en las lutitas.

Las rocas del basamento paleozoico pre-ándico están intruidas y cubiertas discordantemente por rocas volcánicas silíceas de edad Pérmico inferior a Triásico Inferior?, correspondientes al Complejo volcánico-plutónico Huingancó (equivalente al Grupo Choiyoi), unidad que marca el comienzo el ciclo orogénico Andino, en esta región.

Palabras clave: Andes, Paleozoico, Tectónica, Orogenia Chánica, Cordillera del Viento

1. Introduction

The Andean Paleozoic basement along the 37 ° S latitude, is well exposed in the Cordillera del Viento (CV; Fig. 1), a morphostructure developed during the Andean Orogeny. The CV is located between latitudes 36º45´S and 37º20´S and it is part of the Northern Neuquén Precordillera (*sensu* Ramos *et al*., 2011a). It is separated from the main cordillera by the Loncopué Trough, which has a width of 40km.

The CV is about 90 km long and 25 km wide, with a structural relief of almost 3,000 m, that reaches up to 4,707 m in areas with large Neogene magmatic edifices, such as the Cerro Domuyo, constituting the highest mountain in the Argentinean Patagonia. The CV forms a structural high that is associated with a large Andic N-S fold called the Cordillera del Viento Anticline (ACV) where Paleozoic and Mesozoic basement rocks of the Neuquén basin crop out. It is the western boundary and internal sector of the Chos Malal fold-and-thrust belt (Zapata and Folguera, 2005), which is the northern prolongation of the Agrio fold-and-thrust belt (Figs. 1 and 2).

The oldest rocks in the CV are low-grade metamorphic rocks of Upper Devonian age overlied by lower Carboniferous volcanic rocks with scarce sedimentary layers and upper Carboniferous clastic marine sediments. All these rocks are intruded by Permian granitoids and are unconformably covered by Permian to Lower Triassic? silicic volcanic rocks (Fig. 3).

The Paleozoic rocks show contractional and extensional structures that can be attributed to deformations during the Chanic, Gondwanan, and Andean orogenic cycles (see Ramos, 1988 and works cited therein). These cycles culminated in the Chanic (Late Devonian–early Carboniferous), San Rafael (late Carboniferous–early Permian) and Andean (Late Cretaceous–Present) orogenies, respectively. Major unconformities associated with these orogenies limit the stratigraphic record in the study zone. The uplift of the CV is related to the Andean orogeny during the Late Cretaceous.

The Paleozoic sequences of the CV show some similarities and they can be correlated with those of the Paleozoic outcrops located in the Cordillera Frontal of Mendoza, about 250 km further north, between 33º and 35º south latitude. Recent studies of the Cordón del Plata (Heredia *et al*., 2012) and Cordón del Carrizalito (García-Sansegundo *et al*., 2012) ranges described Paleozoic sedimentary series with similar ages, structures, and metamorphic grade to those described here that are likewise separated by two major Carboniferous and Permian unconformities.

A key characteristic of the CV, especially in the southern part of the studied area, is the presence of hydrothermal mineralizations, most of which are concentrated in the Andacollo Mining District (Fig. 3). This mining district is composed of the Andacollo and La Primavera gold-silver vein systems (Stoll, 1957; Danieli *et al*., 1999; Giacosa, 2011), as well as alluvial gold and alteration zones of porphyry copper-type, such as Los Maitenes–El Salvaje (Domínguez *et al*., 1984). The mineralizations formed during the Late Cretaceous to Paleocene magmatic phase (Franchini *et al*., 2003, Casé *et al*., 2008, Suárez and Etchart, 2008), are mainly controlled by older Paleozoic structures.

This work concerns about the Paleozoic structures formed during the pre- and synorogenic stages of the Chanic and Gondwanan cycles. Thus we characterize the Chanic structures and metamorphism of the Late Devonian and early Carboniferous, the extensional regime related to the Carboniferous basins development, as well as their later contractional deformation during the San Rafael (Gondwanan) orogeny, in early Permian times. We analyze the role of Paleozoic structures during the initial extensional stage and the later orogenic phase of the Andean cycle, and the way in which these structures affected previous ones. We also examine the way in which these structures controlled the architecture of this part of the Andes and the economic mineralizations. Finally, we discuss a geodynamic evolution model of this Andean region in the Late Paleozoic period in comparison with the neighboring areas to the north.

2. Stratigraphy

The arrangement of the Paleozoic outcrops in the CV is controlled by Andean tectonics, in a way that most of these rocks outcrop in the core of the Cordillera del Viento Anticline (CVA), very close to the Cordillera del Viento Fault (CVF; Fig. 3) and surrounded by Permian rocks. The metamorphic rocks are found as small, isolated outcrops in the northwest of the study area and in the vicinity of the CVF, making correlation sometimes difficult. Further north at 36º 15' S out of the study area, the location of two small outcrops of similar metamorphic rocks in the Varvarco Campos Lake (Zanettini, 2001), may represent the northern continuation of the CVF, suggesting a regional-scale magnitude for this fault.

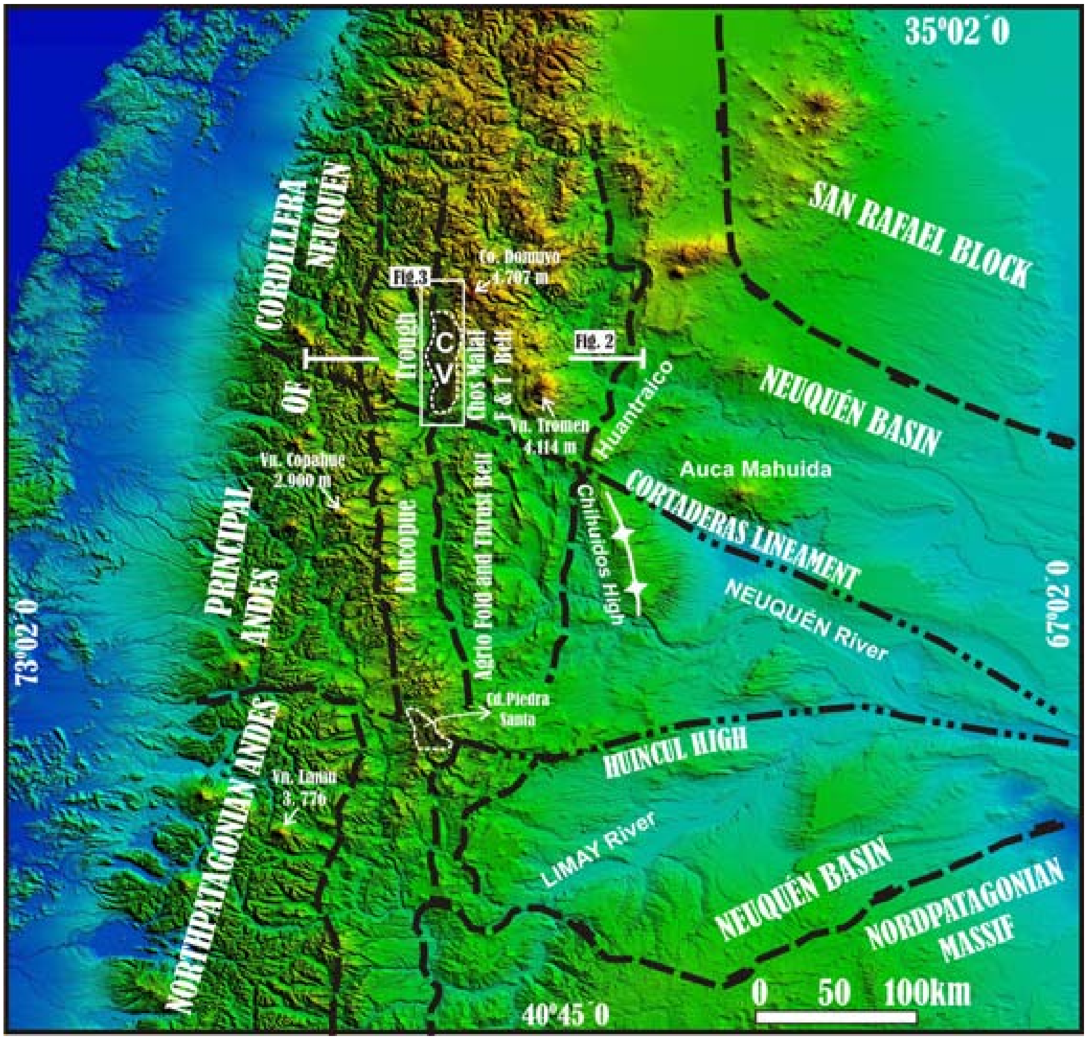

Fig. 1.- Geological location of the Cordillera del Viento. Note its location in the internal (western) sector of the Chos Malal fold-and-thrust belt and north of the Cortaderas lineament.

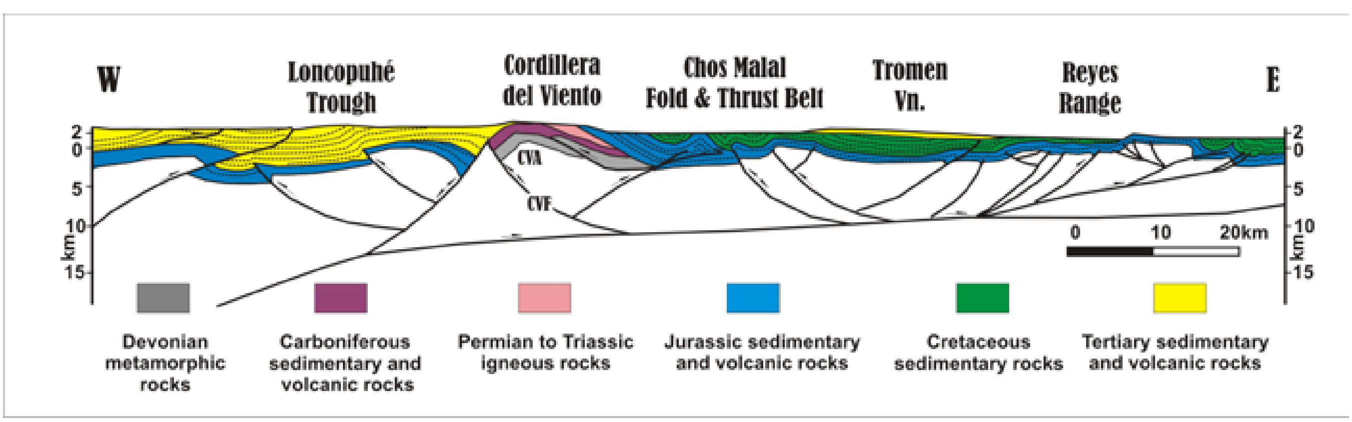

Fig. 2.- Regional structural cross-section showing the Cordillera del Viento and its relation to Loncopué Trough located to the west and Chos Malal fold-and-thrust belt to the east (modified from Zapata et al., 1999). Notice how the Paleogene volcanic rocks onlap the Cordillera del Viento Fault (CVF) and the western limb of the Cordillera del Viento Anticline (CVA). Location in figure 1.

The Carboniferous rocks occur as two large outcrops in the core of the CVA. The greatest of these outcrops is located close to the southern periclinal closure of this large anticline, near to the CVF (Figs. 2 and 3). In the core of the CVA, Permian granitoids intrude the Carboniferous rocks, while Permo-Mesozoic sequences of the Neuquén Basin appear on the shallow dipping eastern flank of the CVA (see Zöllner and Amos, 1973; Zanettini, 2001; Rovere *et al*. 2004). Upper Cretaceous and Paleogene granitoids also outcrop near to the CVF, whereas to the west, the extensive intraorogenic Eocene andesitic volcanism of the Cayanta Formation (Rapela and Llambías, 1985) covers the Loncopué Trough and the CVF (Fig. 3).

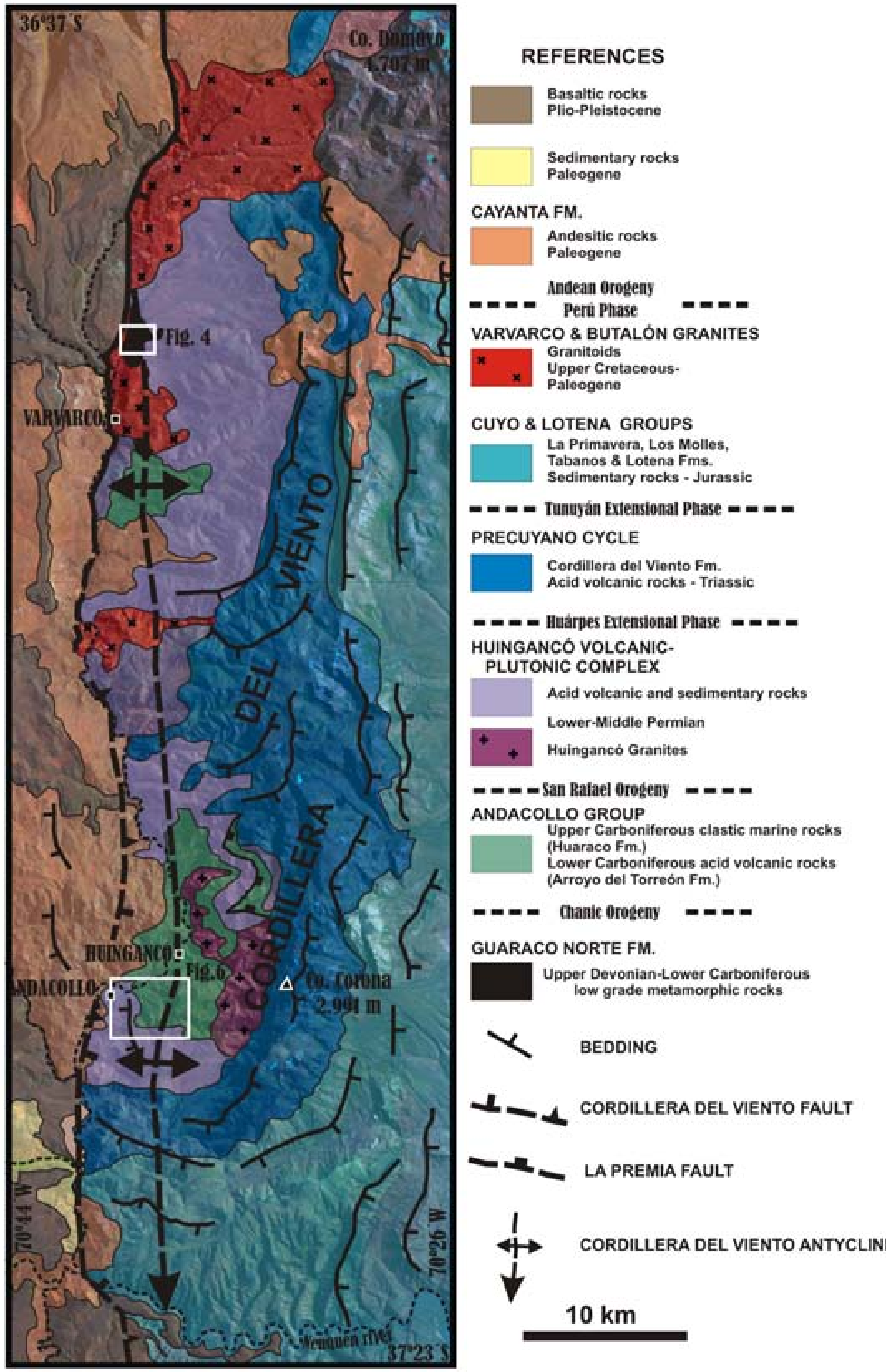

Fig. 3.- Geological map of the Cordillera del Viento (based on Stoll, 1957; Zöllner y Amos, 1973; Zanettini, 2001; Rovere *et al*., 2004; Llambías *et al*., 2007; Giacosa, 2011). Location in figure 1.

Since we did not observe the contact between the metamorphic rocks and the Carboniferous volcano-sedimentary rocks, we argue that the different structures and metamorphic grade suggest that such contact should correspond to a major unconformity, as is the case further north, along the Frontal Cordillera.

2.1. Upper Devonian metamorphic rocks.

The metamorphic rocks outcrop in the northwest of the CV (Figs. 3 and 4) and were grouped in the Guaraco Norte Formation (Zappettini *et al*., 1987) or Ectinita Guaraco Norte (Zanettini, 2001), composed of quartz-rich metasandstones

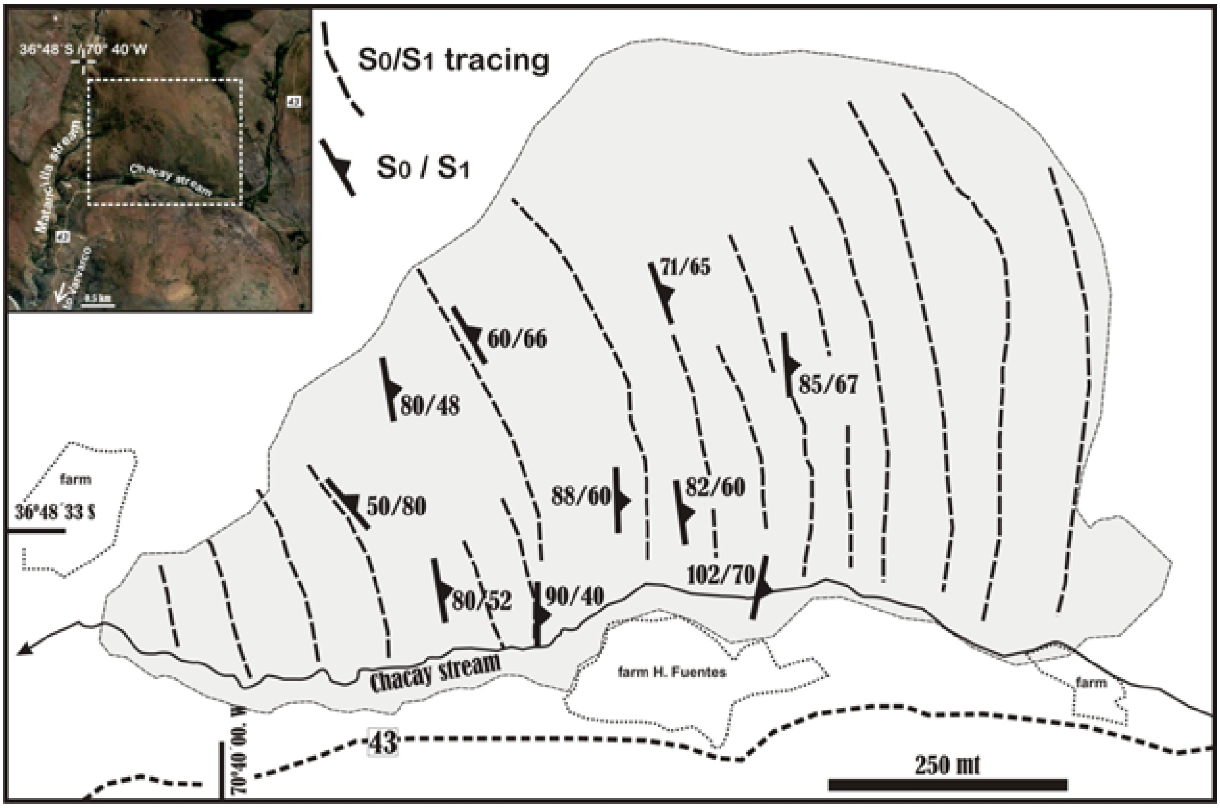

Fig. 4.- Geological map of the metamorphic rocks of the Guaraco Norte Formation in the Chacay stream (northwestern Cordillera del Viento). Location in figure 3.

and finely laminated quartzite layers and slates, cut by numerous quartz and granitic veins. The sedimentary protolith shows rhythmic alternation of sandstone and pelitic layers with small to medium cross-bedding. Recognized tractive layers (current ripples) correspond to dilute unidirectional flows developed under low-regime conditions (Fig. 5A). Paleoenvironmental conditions indicate deposition by traction-sedimentation in a subaqueous (deep?) environment.

Microscopic observations (Fig. 5B) show a foliation (S_1), characterized by biotite blasts and pressure-solution cleavage parallel to bedding (S_0) and syntectonic quartz veins (Fig 5C). The foliation (S_1 and S_0) is deformed by a disjunctive crenulation cleavage (S_2) whose planes are usually occupied by postectonic cm-scale granitic veins (Fig. 5D). The development of contact thermal metamorphic minerals, such as andalusite, biotite, diopside, and hornblende is related to the intrusion of Upper Cretaceous Varvarco granodiorite.

The chemical composition of the Guaraco Norte Formation corresponds to recycled, mature polycyclic sediment of mature continental provenance, pointing to a passive margin with minor inputs from magmatic rocks (Zappettini *et al*., 2012).

By correlation with similar rocks of the Cordillera Frontal, Bloque de San Rafael and Cordón de La Piedra Santa, the age of the Guaraco Norte Formation was attributed to Silurian-Early Devonian by Zappettini *et al*. (1987). Recent U-Pb SHRIMP dating of detrital zircons indicate zircons of magmatic origin are mainly Devonian and Ordovician and of a maximum depositional age of 374 Ma (Late Devonian; Zappettini *et al*., 2012**).** Considering that the Devonian–Carboniferous boundary is placed at 359 million years ago, and that deformation affecting similar rocks in the Frontal Cordillera has been dated in the Late Devonian-early Carboniferous (Heredia *et al*., 2012) and the metamorphism in Middle-Late Devonian (Wilner *et al*., 2011), the age of these rocks can be established as Upper Devonian (Fig. 6).

From the lithostratigraphic perspective, the Guaraco Norte Formation correlates with preorogenic metamorphic rocks, probably Devonian in age, that outcrop below the Carboniferous sediments in the Cordillera Frontal. More specifically, these rocks show several similarities with the Vallecitos beds of the Cordón del Plata (Heredia *et al*., 2012), which are also mainly sandy with quartzite layers (Fig. 6). Chanic synorogenic rocks, with early Carboniferous ages, are found further north, out of the CV (Heredia *et al*., 2012). These rocks form the Angualasto Group (Limarino and Césari, 1992) characterized by the presence of thick conglomeratic strata and syntectonic unconformities (Fig. 6).

Lithologically, the Guaraco Norte Formation can also be correlated with the 372 ± 18 Ma (K/Ar; Franzese, 1995) metamorphic basement exposed in the Cordón de la Piedra Santa, and the metamorphic rocks of <364 Ma of the Cuesta de Rahue (U-Pb SHRIMP Ramos *et al*., 2010), in the Southern Neuquén Precordillera (Fig. 1). However, the higher metamorphic grade of these rocks and the absence of discordant Carboniferous sediments make this correlation highly speculative.

2.2. Volcanic and sedimentary Carboniferous rocks

The Carboniferous rocks of the CV were grouped as “Andacollo Series” by Zöllner and Amos (1955), which was composed of three discordant units: the Lower Tuffs, the Huaraco Formation and the Upper Tuffs. Digregorio (1972) and Digregorio y Uliana (1980) grouped these units as the Andacollo Group, whereas Méndez *et al*. (1995) renamed the lower and upper tuffs as the Arroyo del Torreón and La Premia formations, respectively. Recently and based on magmatic and tectonic evidence, Llambías *et al*. (2007) revised the nature of the group and excluded the La Premia Forma-

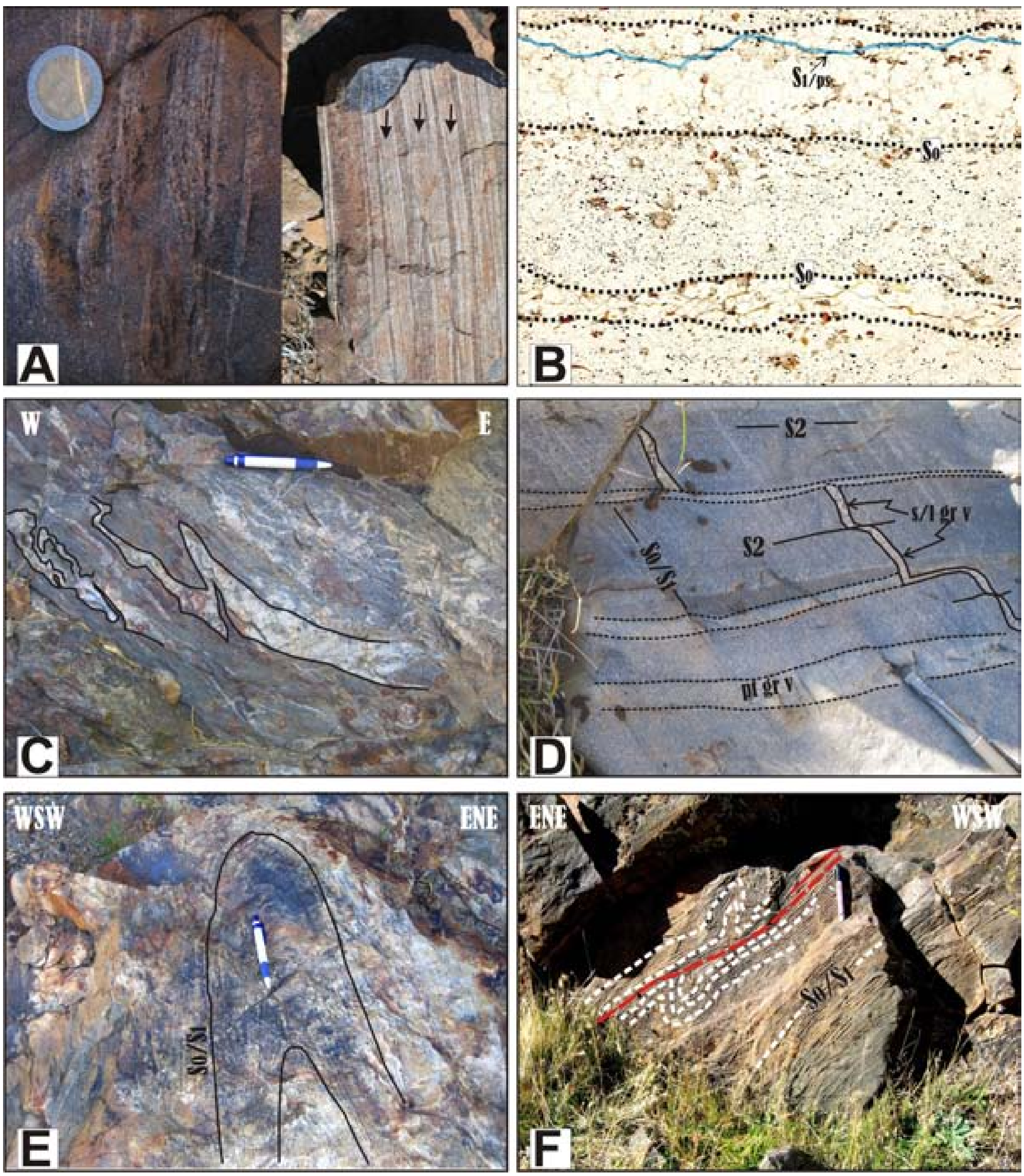

Fig. 5.- Structures in the Guaraco Norte Formation. A. - Sedimentary structures in quartz-rich metasandstones: light layers of sandstones rhythmically alternating with fine dark layers. Arrows show the direction of migration of current ripple marks. B. – Photomicrograph of metaquarzite. S_0 bedding and the development of parallel pressure solution cleavage (S_1/ps) and oriented blast of biotite. C. – W-vergence tight folds and tectonic transposition in sin-metamorphic quartz veins; D. - Cleavage (S_1), syn-to-late-tectonic granitic veins (s / l gr v) and post-tectonic granitic veins (pt v gr) intruded along a disjunctive cleavage with crenulations (S_2); E. - subvertical fold that deforms the cleavage (S_1); F. – WSW-vergence thrust and detachment folds in metasandstones that deform the cleavage (S_1).

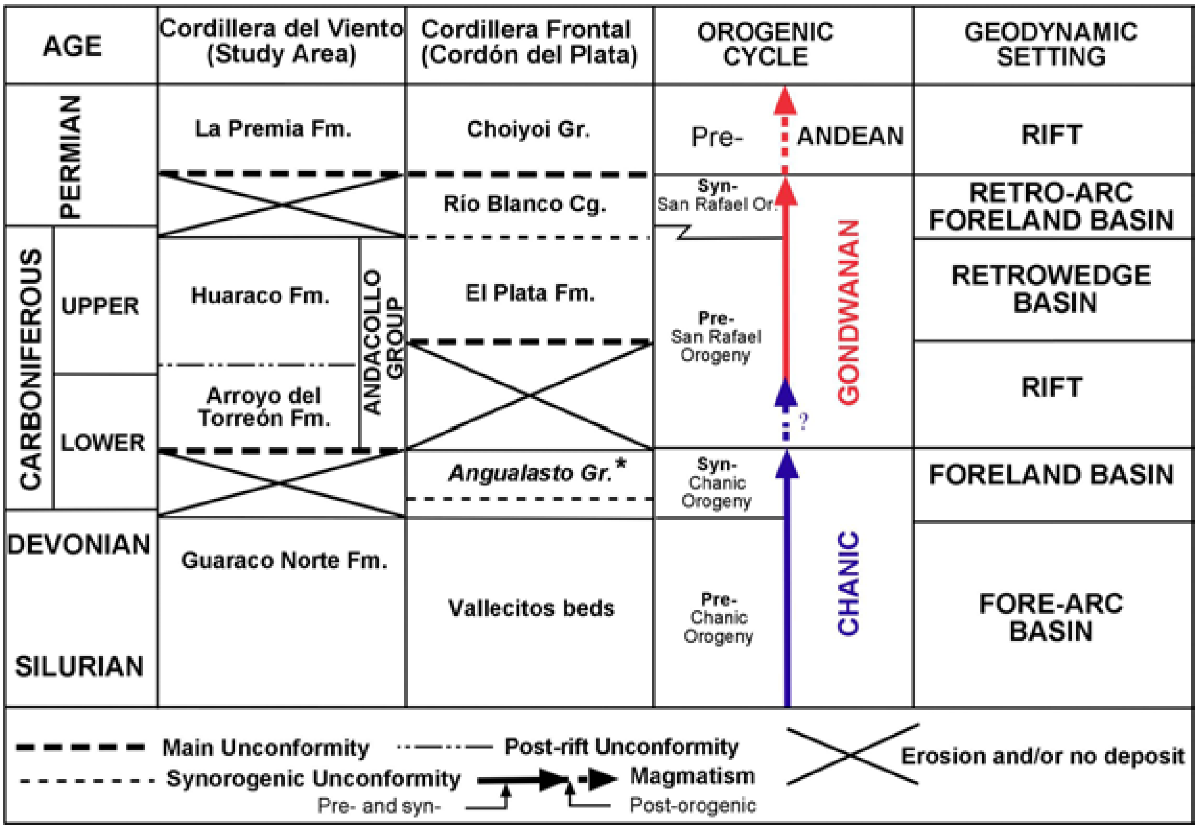

Fig. 6-. Geological correlation chart between the Cordillera del Viento and the Cordón del Plata in the Frontal Cordillera and their possible geodynamic settings (based on Heredia *et al*., 2012). *Defined in the Precordillera, doubtful presence in the Frontal Cordillera.

tion, adding it to the Huingancó volcanic-plutonic Complex. Thus, the Andacollo Group (Fig. 6) as we consider it in this paper, contains a lower unit, the Arroyo del Torreón Formation, consisting of silicic volcanic and subvolcanic rocks and an upper unit, the Huaraco Formation, composed of marine clastic sedimentary rocks (Figs. 3 and 7).

The Arroyo del Torreón Formation is made up of 1,200–1,800 m (Zöllner y Amos, 1973) of tuffs, ignimbrites, and rhyolite-dacite flows and domes (Fig. A,D) interbedded with clast-supported conglomerates with well-rounded clasts of up to 3 cm (Fig. 8E), sandstones, and black shales, that are more abundant toward the top and are very similar to those of the overlying Huaraco Formation. All volcanic rocks have significantly siliceous alteration (Fig. 8E).

Igneous zircons in rhyodacitic dome with fluidal texture, intruded in ignimbrites of the lower part of this formation were dated at 327.9 ± 2.0 Ma (U-Pb SHRIMP, Suárez *et al*., 2008). Furthermore, an interbedded rhyolite has been dated in 326 ± 3 Ma (U-Pb SHRIMP, Hervé *et al*., 2013), which allows us to assign an early Carboniferous age to the Arroyo del Torreón Formation.

Separated by a low angle angular unconformity, the Arroyo del Torreón Formation is covered by 700 m-thick Huaraco Formation. It starts with a conglomerate of volcanic and sedimentary clasts, but it is mainly composed of shale and dark green to black siltstones, which sometimes contain wave ripples (Fig. 9A). Towards the top, the sandstones and quartzite conglomerates are more abundant (eg. figure 9B,C; "Cuarcita Huaraco" Stoll, 1957). The conglomerate pebbles show a high degree of roundness with average maximum diameters of 2-3 cm. Suárez (2007) also mentioned intercalations of ignimbrites that are less thick and continuous than in the Arroyo del Torreón Formation.

The sediments of the Huaraco Formation represent a subaqueous depositional environment from deep-edge lutites, medium-depth siltstones with wave influence, and shallower quartzite sandstones and conglomerates. The high quartz content of the coarse lithofacies shows a good to very good compositional maturity. Based on brachiopods faunas, such as *Orbiculoidea* and *Spirifer* and *Rhacopteris* flora (Zöllner and Amos, 1955, 1973; Freytes, 1969), this formation has been attributed to the late Carboniferous period (Herrero Ducloux, 1946; Amos, 1972).

The Andacollo Group has a similar tectonostratigraphic position to those of the Gondwana preorogenic El Plata (Caminos, 1965) and Cerro Agua Negra (Polanski, 1970) formations of the Cordillera Frontal of Mendoza and San Juan, northern of the study area (Fig. 6). These units unconformably overlie the Chanic metamorphic series, dated between the late Neoproterozoic and Devonian, and they are also uncorformably covered by Permian volcanic series (Choiyoi Group) (Fig. 6). However, only the marine siliciclastic rocks of the Huaraco

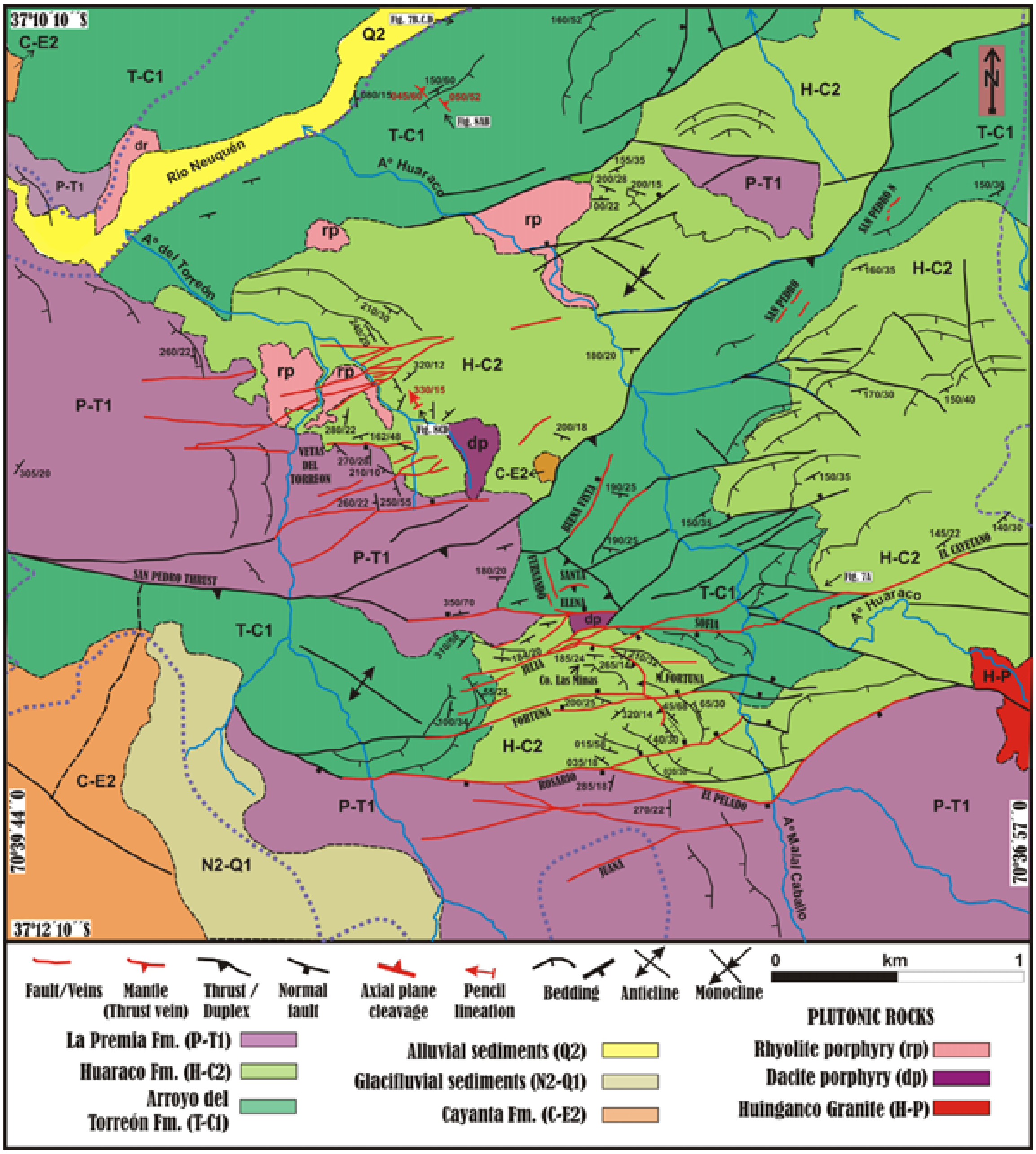

Fig. 7.- Geological map of the Cerro Las Minas area (Andacollo Mining District) in the southern Cordillera del Viento (based on Stoll, 1957; Giacosa, 2011). Location in Figure 3.

Formation and the top of the Arroyo del Torreón Formation are very similar (in facies) to the formations of the Cordillera Frontal described above, while the lower section has no lithological equivalent in the El Plata and Cerro Agua Negra formations. Again, there is no age similarity among these formations younger than late Carboniferous. All this suggests that the lower section mostly volcanic of the Arroyo del Torreón Formation would be unique to the CV (Fig. 6). Correlations are much more difficult to establish to the south, where Carboniferous rocks in the North Patagonian Andes have more deformation, metamorphism and igneous intrusions (García-Sansegundo *et al*., 2009). In the CV we did not observe synorogenic discordant sediments comparable to those of the San Ignacio Formation or equivalent to the Cordillera Frontal (Fig. 6), dated between the late Carboniferous and early Permian (Heredia *et al*., 2002, 2012; Busquets *et al*., 2005), probably because they were covered or eroded before the deposition of the sediments of the Andean cycle.

2.3. Permian to Lower Triassic? volcanic and plutonic rocks

Llambías *et al*. (2007) grouped the Permian to Early Triassic? igneous rocks of the CV into the Huingancó volcanic-plutonic Complex, composed of the Huingancó Granite and the ignimbrites of the La Premia Formation (Fig. 3). These rocks correlate with those of the Choiyoi Group that outcrop in the Andean Frontal Cordillera (Fig. 6) to the north of the CV, which unconformably overlie Chanic and Gondwanan rocks. The Huingancó Granite is a group of plutons ranging from granodiorites to monzogranites, with subvolcanic rhyolitic domes (Fig. 9E). The circular morphology of many of these plutons and their shallow emplacement, suggest that cauldron subsidence was the main intrusion mechanism (Suárez, 2007). The La Premia Formation consists mainly of dark silicic dacitic-rhyolitic ignimbrites (Fig. 9D), with subordinated conglomerates and sandstones, which according to Suárez (2007) are up to 1,000 m thick. In the Cerro Las Minas area, it is in contact with the Huaraco Formation by a normal fault (Rosario/El Pelado vein) and with the Arroyo del Torreón Formation by a thrust (Fig. 7). Plutons and ignimbrites are cogenetic, but there are nonconformity relationships of quartzite conglomerates of the La Premia Formation on the granites or rhyolitic domes, such as the outcrops found over Huaraco Creek. Besides these relationships, the general N–S trend of the La Premia Formation conglomerates and ignimbrites substantially differs from the more complex distribution of the Andacollo Group outcrops, due to their different deformation grade and the pronounced angular unconformity that separates them (e.g. Vetas del Torreón area, Fig. 7).

The synkynematic character of the magmatism with a crustal extensional (rift) regime (Fig. 6) similar to that proposed for the Choiyoi Group of the Cordillera Frontal (Heredia *et al.*, 2002) is genera*lly a*greed on.

The Huingancó Granite intrudes the Andacollo Group (Figs. 7 and 9E) and even the La Premia Formation. All these rocks are unconformably covered by Triassic volcanic rocks of the Cordillera del Viento Formation (Fig. 3). Radiometric datings indicate an early-middle Permian age for the Huingancó Granite: granodiorite pluton of 287 ± 9 Ma (K-Ar whole rock, Suárez and de la Cruz, 1997), biotite–perthite

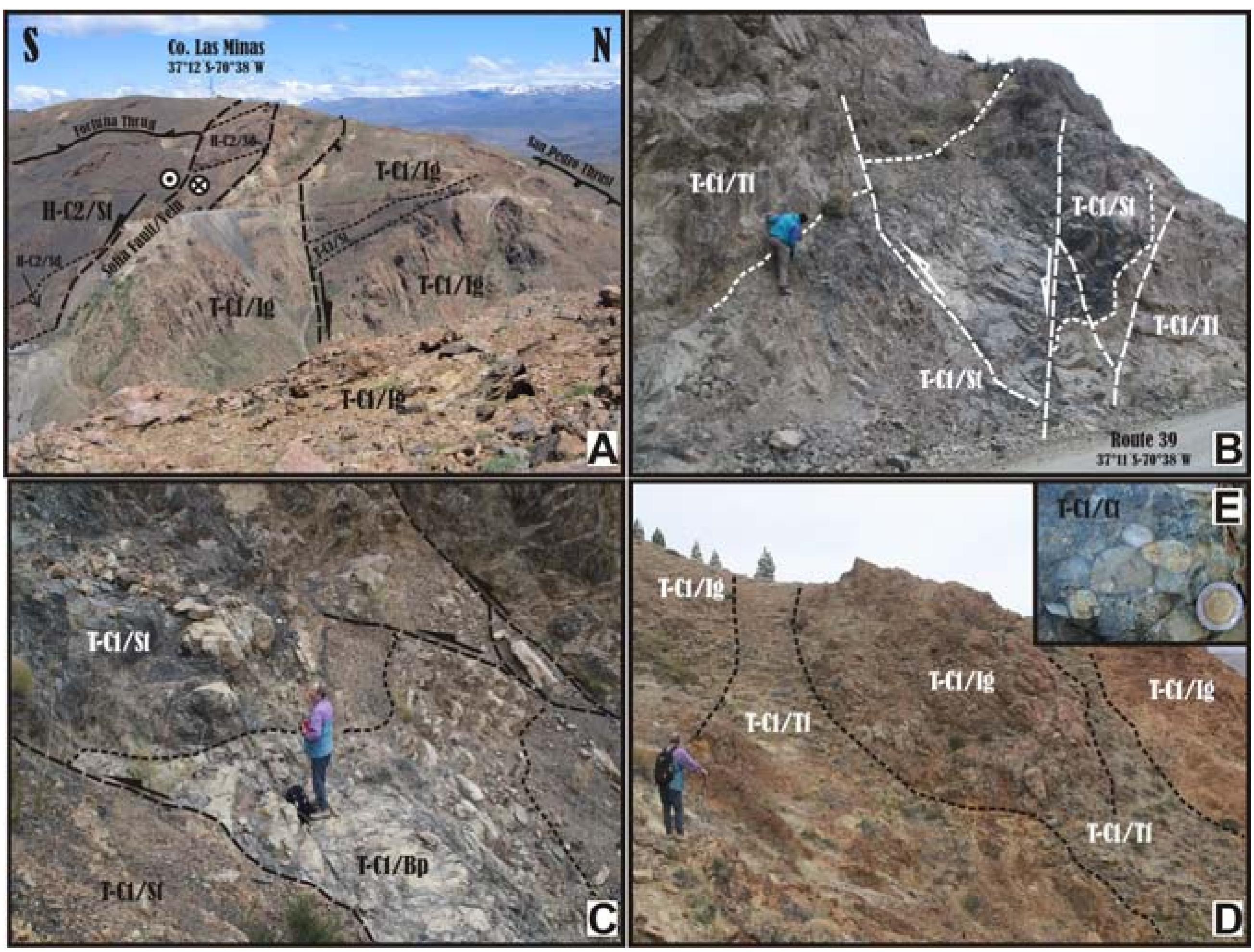

Fig. 8.- A.- Photography of the Cerro Las Minas. Note a wedge-shaped layer of shales interbedded between two ignimbrite flows in the hanging-wall of Carboniferous normal fault. To the left, Permian normal faults in shales and siltstones of the Huaraco Formation. Faults are mineralized and re-shearing during the Late Cretaceous; Manto Fortuna, a thin quartz-vein, was formed as a result of mineralization and thrusting during this time. To the right, the San Pedro thrust, a Carboniferous normal fault inverted during Andean orogeny. B. – Tuffs and shales of the Arroyo del Torreón Formation, shale deposits usually are wedge-shaped; C.- Brecha pipes and shales of the Arroyo del Torreón Formation and Andean thrusts; D.- Ignimbrites and tuffs of the Arroyo del Torreón Formation; E. - Silicic clasts in conglomerates of the Arroyo del Torreón Formation, and their typical silicious alteration. Key: Arroyo del Torreón Formation (T-C1), Huaraco Formation (H-C2); ignimbrites (Ig), tuffs (Tf).

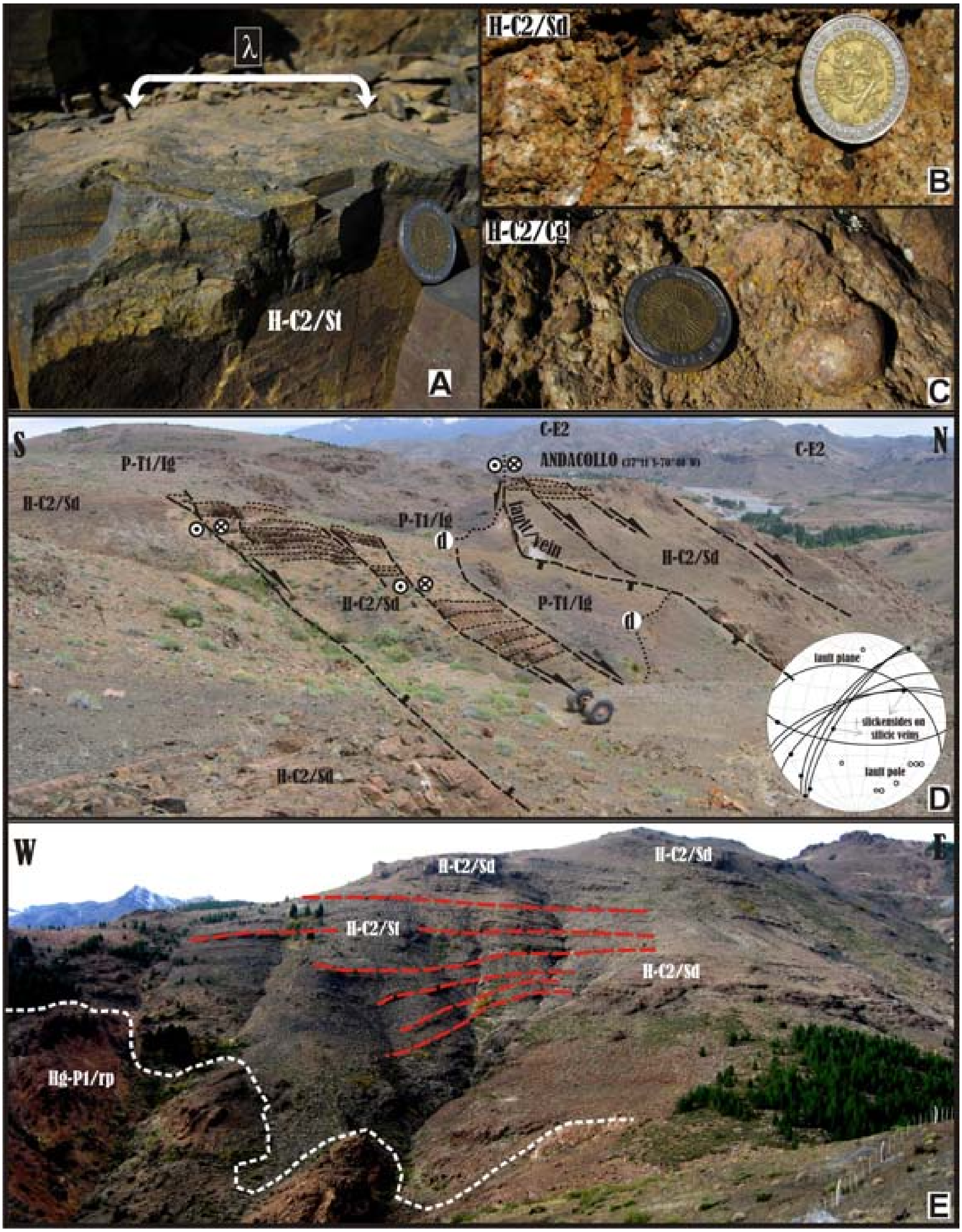

Fig. 9.- A. - Siltstones of the Huaraco Formation with symmetrical ripple marks preserved on bedding planes. λ = wavelength. B. - Thick and well-selected quartz sandstones of the Huaraco Formation (Cuarcita Huaraco, Stoll, 1957). C.- Well-rounded quartz clasts in conglomerates of the Huaraco Formation. D. - Normal faults of post-extensional regime associated with the San Rafael Phase. Sediments and ignimbrites of the La Premia Formation are unconformably deposited on the Huaraco Formation. Stereogram shows NE, ENE and E-O- normal faults and gentle lineations (striae on quartz veins) formed as re-shearing of normal faults during the Late Cretaceous transpressional deformation. Key: La Premia Formation (P-T1), Cayanta Formation (C-E2), angular unconformity (d). E. – synextensional-fan layers in the Huaraco Formation, intruded by a rhyolite dome as part of the Permian Huinganco volcanic-plutonic Complex (Hg-P1/rp).

granodiorite of 283 ± 2 Ma (U\Pb SHRIMP; Hervé *et al*., 2013) and rhyolite domes (Fig. 9 E) between 260 ± 10 Ma (Llambías, 1986) and 259 ± 18 Ma (JICA, 2001); while an ignimbrite from the base of the La Premia Formation gave an early Permian age of 282 ± 2 Ma (U-Pb zircon SHRIMP, Suárez *et al.,* 2008). Although all the available radiometric ages in the CV indicate a Permian age, based on regional correlations with the Choiyoi Group of nearby areas, the age of the complex can be extended to the Early Triassic (Llambías *et al*., 2007; Heredia *et al*., 2012).

3. Structure of Paleozoic rocks

The Paleozoic rocks of the CV were deformed during the Chanic (Neoproterozoic–early Carboniferous), Gondwanan (early Carboniferous–early Permian) and Andean (early Permian–Recent) orogenic cycles. These cycles ended during the Chanic (Late Devonian–early Carboniferous), San Rafael (late Carboniferous–early Permian) and Andean (Late Cretaceous–Cenozoic) orogenies respectively; this latter being responsible for the present relief of the CV. At this latitude of the Andes, the Chanic Orogeny is related to a Himalayan-type continental collision (Davis *et al*., 1999), whereas the two recent orogenies are related to non-collisional or Andean-type orogens (Ramos, 1988).

3.1. Structures of the Chanic cycle

During the Chanic cycle the compressive regime deformed the rocks of the Guaraco Norte Formation. The S_1 pervasive foliation and the S_2 disjunctive crenulation cleavage were formed under low-grade metamorphic conditions. Both, ductile deformation and associated metamorphism of greenschist facies (biotite zone) can be related to the Chanic orogeny.

To the north of Varvarco village, the cleavage (S_1) trending N–S to NNW and dipping E-50º–70º, is provided generally sub-parallel to bedding (S_0). At outcrop scale, the cleavage located on the normal limb of a W-vergent fold, is folded by vertical to W-vergent folds, of different scales (Fig. 5C and E). There are also numerous cm-scale folds of metamorphic quartz veins syntectonic with S_1 and syn- to post-kynematic thin granitic dykes (Fig. 5D). W-directed mesoscopic thrusts (post-S_1) detached from levels parallel to S_0=S_1 are also present (Fig. 5F).

3.2. Structures of the Gondwanan cycle

In the Carboniferous rocks, two sets of structures developed during different periods and under different conditions can be identified: synsedimentary normal faults synchronous with volcanic activity and thrusts and related folds corresponding to the early Permian San Rafael orogeny.

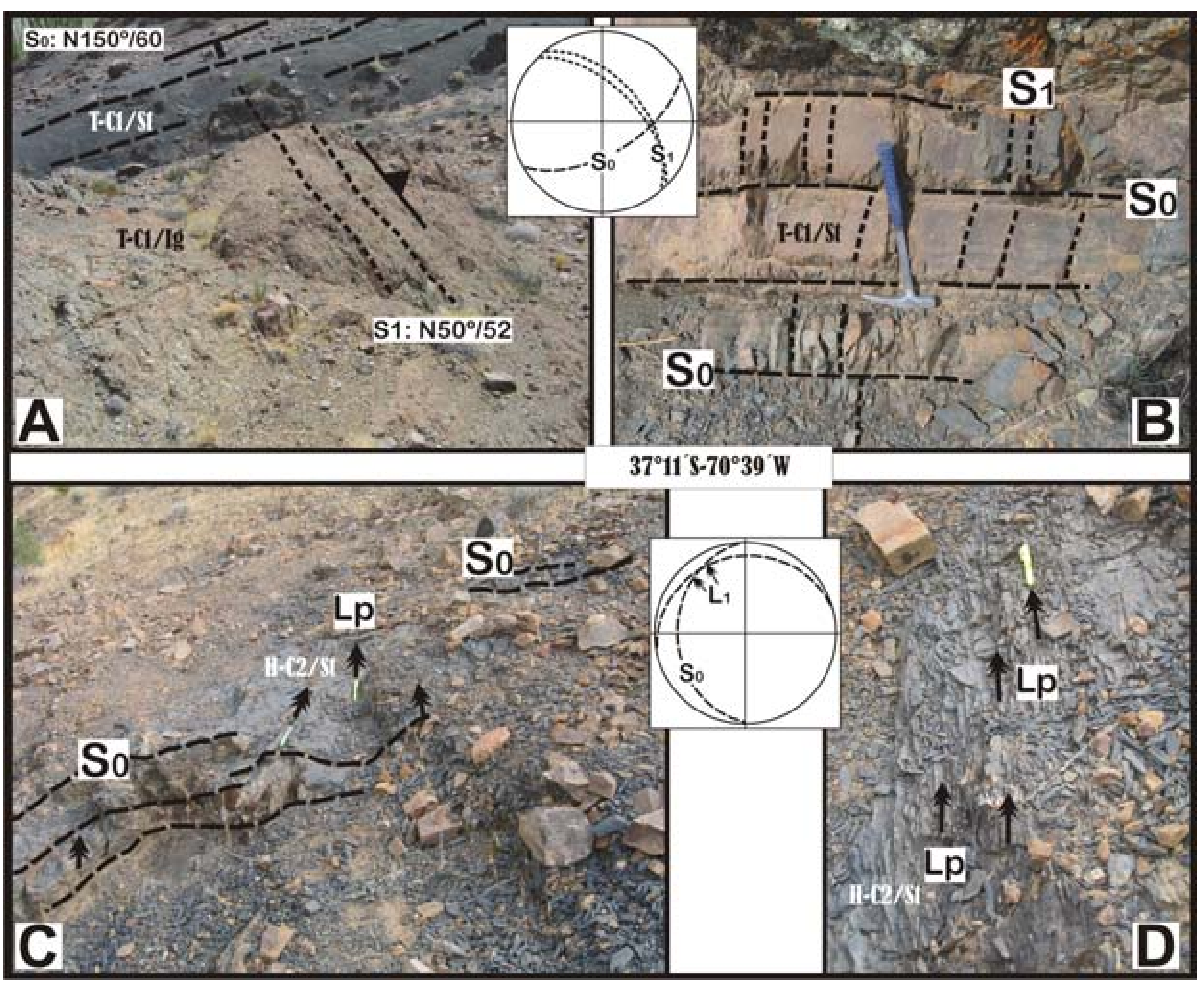

Fig. 10.- Carboniferous rocks with structures formed during the San Rafael Phase. A and B.- Stratification and axial plane cleavage in folded siltstone and ignimbrites of the Arroyo del Torreon Formation, C and D.- Stratification and pencil lineation in folded shales of the Huaraco Formation.

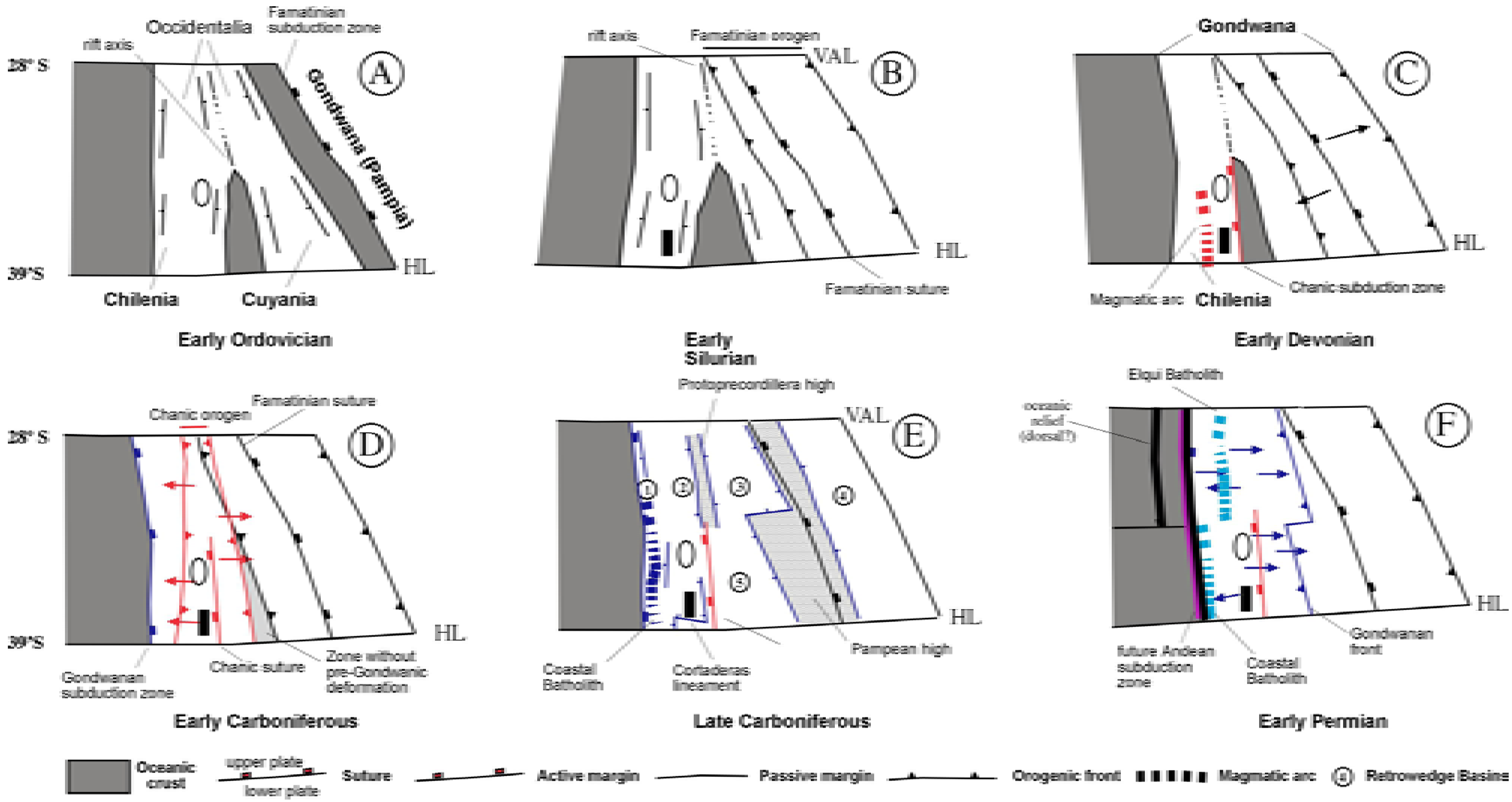

Fig. 11.- Paleozoic geodynamic model for the Andes and its foreland between 28° and 39° South latitude. Oval: Cordón del Plata, Cordón del Portillo y Cordón del Carrizalito in the Frontal Cordillera. Black box: Cordillera del Viento (study area). HL: Huincul High. VAL: Valle Ancho lineament. Retro-wedge basins: 1- Arrayan: 2- Río Blanco, 3- Paganzo, 4- Chaco-Paraná, 5- San Rafael. The red arrows (Chanic) and blue arrows (Gondwanic) show the vergence of the main structures.

Ramos *et al*. (2011b) date the end of the San Rafael orogeny in relation to the age of intrusion of the postorogenic Huingancó Granite, i.e. close to 287 Ma (early Permian).

In the northern CV, the extensional deformation is associated with N–S-trending faults and NNE–SSW to E–W-trending faults to the south, where shale strata with wedge geometry interbedded in ignimbrites are limited by normal faults (Fig. 8A). To the north of the Huaraco creek (Fig. 9E) we observed syn-extensional fans in the layers of sediments of the Huaraco Formation. In some localities a local unconformity, related to this extensional process, usually separates the Huaraco and Arroyo del Torreon formations (Fig. 6).

The compressive structures that deformed the Andacollo Group are thrusts and folds, developed in very low grade to non-metamorphic conditions. The most conspicuous structure is the San Pedro thrust that places rocks of the Arroyo del Torreón Formation on top of rocks of the Huaraco and La Premia Formation, showing a transport direction towards the SW. During Andean deformation, the thrust was folded in the periclinal zone of the CVA (Fig. 7; Giacosa, 2011).

The Arroyo del Torreón Formation depicts a rough axial plane cleavage (Fig. 10A and B); and its competent rocks such as ignimbrites and rhyolite domes are boudinaged (Fig. 8C and D), while the shales of the Huaraco Formation only depict pencil lineation in the fold hinge (Figs. 10C and D). As described by Stoll (1957), cleavage dips to the NE and is situated in a normal fold-limb position, whereas the pencil lineation plunges to the NW. If Andean structures are restored, particularly the CVA, the above described microstructures are related to the NW–SE-oriented and SW-vergent Paleozoic folds. All of these compressive structures are interpreted to be associated with the San Rafael orogenic phase that deformed the Carboniferous rocks of the Andean Cordillera between the late Carboniferous and early Permian.

3.3. Structures of the Andean cycle

The Permian to Lower Triassic? rocks in the CV are characterized by the presence of many normal faults associated with the development of an extensional basin that controlled volcanic deposition of the La Premia Formation, which affected the Pre-Andean basement. To the south of the CV, in the Andacollo Mining District, E–W to ENE–WSW-normal faults with bookshelf geometry deform the Huaraco and the La Premia formations (Figs. 7 and 9D). These faults were reactivated and mineralized during the Late Cretaceous to Paleogene as transtensive and transpressive zones (Fig. 8A) related to the onset of the Andean orogeny in this Andean sector (Giacosa, 2011).

In the northern part of the CV faults trend mainly N-S, while the E–W- to ENE–WSW-trending faults are interpreted to be transfer zones forming part of a generalized extensional system of N-oriented faults, which, as in the Cordillera Frontal, include other orientations (Heredia *et al*., 2012). Shallow faults of this extensional system have domino geometry, suggesting the presence of a listric basal detachment.

Some of these faults, such as those parallel to the Sofía vein/fault (Fig. 7), join the San Pedro thrust, so that they could be interpreted as extensional reactivations of the previous Gondwanan compressive structures, associated with the onset of the Andean orogenic cycle.

The CV is the western boundary of the Chos Malal fold-and-thrust belt, which constitutes the external sector of the Andean orogen at this latitude and it has a generalized eastern tectonic transport direction. In the CV, the Andean orogeny was mainly developed between the Late Cretaceous and the Miocene, although in other parts of the Andes it was characterized by the presence of several intraorogenic extensional periods, dominated by intense volcanic activity. The CVF and the CVA are the major Andean compressive structures associated with the current structural relief of the CV.

The CVF (Giacosa, 2011) corresponds roughly with the Andacollo/Loncopué fault system (Cobbold and Rossello, 2003; Fig. 2). The CVF was originally an E-dip normal fault that controlled the deposition of Permian-Triassic and Jurassic rocks, so the thickness of these rocks increases toward the east of the CVF. Vergani et al. (1995) note that since the Late Triassic rift stage until the Cuyo Group sedimentation, in Early Jurassic times, the westernmost depocenters of the Neuquén Basin were controlled by a N–S normal fault system, named Tres Chorros–Cordillera del Viento system (Tres Chorros extensional system), where the CVF would be one of its main structures.

During the Andean orogeny the Tres Chorros extensional system was inverted and the CVF became a reverse fault now, which uplifted Paleozoic rocks in the western edge of the Loncopué depression, forming the CVA. In depth, this fault merges with the W-diping basal Andean thrust (Fig. 2). The CVF is completely covered by Eocene volcanic rocks of the Cayanta Formation, that onlap until the CVA core (Figs. 3 and 7), suggesting a pre-Eocene age for the major tectonic activity in the CVA and CVF. Since the bedding of Cayanta Formation is W-slightly tilted (15-20º) we interpreted post-Eocene reactivations. In addition to the CVF, minor N–S thrusts as the named Manto Fortuna, are mineralized with Au-Ag (Figs. 7 and 8A).

The CVA (Zöllner and Amos, 1973), an asymmetric W-vergent S-plunging fold related to the CVF, is the most conspicuous structure in the study area. The periclinal termination of the CVA coincides with the Cortaderas lineament, a WNW-cortical structure (Cobbold and Rosello, 2003; Kay *et al*., 2006; Ramos and Kay, 2006; Zamora Valcarce *et al*., 2006; and others) that is the southern edge of the Chos Malal fold-and-thrust belt and the northern boundary of the Agrio fold-and-thrust belt (Fig. 1). At the southern edge of the CV, numerous E–W to ENE–WSW-normal Permian faults suggest an important transfer zone of the extensional system, which in turn points towards the formation of a N-dip blind lateral ramp with strike-slip components (Cortaderas lineament) during the Andean crustal shortening.

Faults/veins in the study area (Fig. 7) show evidence of an inverse-strike slip regime superimposed on normal faults (Fig. 8A and 9D). Au-Ag quartz veins with sub-horizontal striations are very common in the normal E-W Permian faults that affect the Huaraco and the La Premia formations, whereas mineralized thrusts (as Fortuna and Santa Elena) are recent N-trending structures.

Based on this analysis, we conclude that the Andean crustal shortening leads to N-S-faults, thrusts and associated folds, and W-E to WNW-strike slip structures. These latter would be lateral structures that control the N and S propagation of the Andean thrusts.

The main Andean (frontal and lateral) structures are mostly the result of reactivation of normal Permian faults (Permian extensional system). At the moment, assigning a precise age to the reactivation of the Permian faults during the Andean orogeny remains speculative. Several faults were inverted and mineralized in the Late Cretaceous period, when the CVA was forming associated with the CVF (Giacosa, 2011).

4. Discussion: geodynamic evolution and geotectonic framework

The descriptions and stratigraphic correlations presented in this work suggest that the Paleozoic rocks of the CV have characteristics similar to rocks of the same age that outcrop along the Andean Frontal Cordillera at latitudes 28º–39ºS. To the north and south of these latitudes, the geodynamic evolution, particularly from the Carboniferous, would be different (Ramos, 2009). At 39°S latitude, this change coincides with the Dorsal de Huincul (Mosquera *et al.,* 2011) which is located about 200 km south of the study area (Fig. 1).

The pre-Carboniferous rocks in the CV were deformed during the Chanic orogeny under low-grade metamorphic conditions, in a similar way to that described by Heredia *et al*. (2012) in the Cordón del Plata and by García-Sansegundo *et al*. (2012) in the Cordón del Carrizalito, located about 250 km north of the study area (oval area in figure 11).

In contrast, the Cordón del Portillo, located at an intermediate point between these two ranges (central part of oval in figure 11), shows evidence of high-grade metamorphic conditions and higher volume of granitic rocks, similar to the conditions in the northern part of the South Neuquén Precordillera, just south of the Dorsal de Huincul (Lucassen *et al*., 2004). However, the Chanic cycle is not well characterized south of latitude 39ºS, and accurate correlations are not possible.

Thus, the Carboniferous rocks of the CV have no evidence of metamorphism and are characterized by a group of structures resembling rocks of the same age in the Frontal Cordillera, where thrusts and associated folds are also predominant (Heredia *et al*., 2002; García-Sansegundo *et al*., 2012). In contrast, to the south of 39°S and especially at 41°S in the Northpatagonian Andes, Gondwanan deformation, metamorphism and magmatic activity increase considerably, with highly ductile structures (García-Sansegundo *et al*., 2009).

In the Frontal Cordillera, the onset of the Anden cycle takes place in the Permian, while in the Northpatagonian Andes and its foreland, the orogenic phase linked to the Gondwanan cycle extended throughout the Permian period and probably into the Triassic (von Gosen and Loske, 2004), so that the Andean cycle did not start until the Jurassic.

Thus, the geodynamic evolution of the Paleozoic rocks of the CV can be determined by comparison with that of the Andean Frontal Cordillera, characterized by Heredia *et al*. (2002). During most of the Paleozoic, this area of the Andes had a geodynamic evolution characterized by the accretion of terrains of variable size and allochthony at the margin of Gondwana. Between 28ºS and 39ºS latitude these terrains are represented by the Chilenia and Cuyania microcontinents (Fig. 11A), which may have been joined further north into a single continental mass labeled Occidentalia (Dalla Salda *et al*., 1992).

In the northern part and in the continuation of the southern oceanic zone, that separated Chilenia and Cuyania, an intracontinental rift with a thinned continental crust was formed (Fig 11A y B), resulting in a marine basin with passive margins on both sides (González-Menéndez *et al*., 2013). During the Ordovician, Cuyania joined to Gondwana, giving rise to the Famatinian orogeny, which did not affect the Chilenia Terrane (Frontal Cordillera) where the study area is located (Fig. 11B). In Silurian times, the Famatinian deformation ended because a new subduction zone was developed under the eastern margin of Chilenia (Fig 11B) (Davis *et al*., 1999) allowing the approach of this continent to the new margin of Gondwana and the development, during the Devonian, of a volcanic arc on the margin of Chilenia (Fig. 11C). In this context, the Guaraco Norte Formation can be interpreted as fore-arc basin deposits.

Alternatively, Zappettini *et al*. (2012) point out that this unit represents passive margin deposits predating the onset of the Gondwanan accretionary prism on the Chileean coast, during the early Carboniferous and extending to the first stages of accretion in a retro-wedge position (>326 and <374 million years). This interpretation is based on assigning a lower Carboniferous age to the metamorphic rocks and including them together with the Andacollo Group. This interpretation implies some uncertainty due to the lack of metamorphism in the Carboniferous rocks in the CV, while at this latitude the Gondwanan metamorphism is located farther west (Gondwanan accretionary prism) (Wilner *et al*., 2004, 2009). If these rocks are of Upper Devonian age, as we propose in this study, the Guaraco Norte Formation would be a preorogenic succession related to the Chanic cycle and separated from the Gondwanan succession by a major unconformity (Fig. 6).

Towards the end of the Devonian, the collision of Chilenia with Gondwana and the rift inversion of Occidentalia created the Chanic Cordillera. This cordillera is better developed to the south, where it presents quite wide internal zones. All the Chanic Cordillera shows a very characteristic double vergence (Fig. 11D), with a west-vergent branch developed on the eastern margin of Chilenia (Frontal Cordillera) and a generally east-vergent branch, developed on the western margin of Gondwana. This eastern branch is exposed in the Precordillera and San Rafael Block (Heredia *et al*., 2012). The low-grade metamorphism, the W-vergence of the structures, and the presence of syn- to late-orogenic magmatism, suggest that the CV was situated in the internal part of the western branch of the Chanic orogeny. Basins related to this collisional orogenic process are peripheral foreland basins and are preserved only on the eastern branch, as the early Carboniferous Agualasto Group. A new subduction began in the early Carboniferous (Rebolledo and Charrier, 1994) at the previous western margin of Chilenia, now amalgamated to Gondwana (Fig. 11E and D).

The Gondwanan cycle, represented in the CV by the Carboniferous Andacollo Group, begins after the Chanic orogeny. The first stage of this cycle (early Carboniferous) is dominated by a crustal extensional regime and the major silicic volcanism of the Arroyo del Torreón Formation, coeval with marine deposits. In the late Carboniferous, during the subsequent deposition of the Huaraco Formation, the extension is attenuated and therefore volcanism and sedimentary thickness variability decrease.

The extensional regime during deposition of the Andacollo Group was linked to the presence of an attenuated crust (Ramos *et al*., 2011b), where volcanism *ca*328 Ma is older than the Cordillera de la Costa Batholith Fig. 11E) at these latitudes (Glodny *et al*., 2008; Wilner *et al*., 2009).

The Gondwanan subduction in late Carboniferous times developed a first magmatic arc (Coastal Batholith in figure 11E) and a retro-wedge preorogenic basin (Fig. 6) where the Andacollo Group is deposited. Zappettini *et al.* (2012) argue that the retro-wedge basin is associated with the early stages of the frontal accretionary prism that currently outcrops in the Chilean coastline.

The retro-wedge extensional basin was highly compartmentalized by structural highs (Fig. 11 E) such as the Protoprecordillera, which is a remnant of the Chanic Cordillera (Heredia *et al.*, 2012). The Andacollo Group basin may have been similar to the Río Blanco basin in the Frontal Cordillera (location 2 in figure 11E), where the Cerro Agua Negra Formation and its equivalent to the south, the El Plata Formation, were deposited. However, these formations show much less volcanic intercalation, probably because the northern extensional regime was less developed.

To the north of the CV, since late Carboniferous to early Permian, a change from an extensional to a compressional tectonic regime, interpreted to be linked to a flat-slab subduction (García-Sansegundo *et al*., this volume) resulted in the San Rafael orogeny (Fig. 11F)). The flat subduction produced a rapid eastward migration of the deformation and the magmatic arc (Elqui Batholith in figure 11F). The orogeny reached the middle Permian due to the subsequent collision of an oceanic relief with the Gondwana margin (García-Sansegundo *et al*., this volume).

However, at the CV latitude, the magmatic arc does not migrate to the east and the Coastal Batholith was still active up to Permian times (Parada *et al*., 1999; Hervé *et al*., 2007). These facts are interpreted as a consequence of the non-development of a shallow flat subduction at this latitude, which is probably related to the arrival, at the trench, of an older and denser oceanic crust than in the northern segment. Furthermore, Ramos *et al*. (2011b) date the end of the San Rafael Orogeny in relation to the age of intrusion of the postorogenic Huinganco Granite, i.e. close to 287-282 Ma (early Permian). Therefore, the Gondwanan deformation in the CV was mainly developed in early Permian times.

During this non-collisional orogenic process, pre-arc and retroarc foreland basins were developed. The pre-arc basins outcrop near the Chilean coast (see García-Sansegundo *et al*., this volume) and the retroarc basins are mostly preserved in the Andes of Argentina (Busquets *et al*., 2005), both on the Frontal Cordillera as well as on the Precordillera, characterized respectively by San Ignacio and Del Salto formations, which have no equivalent in the CV. According to Heredia *et al*. (2012), the ancient Chanic reliefs of the Protoprecordilera disappeared (Fig. 11F), as a consequence of the formation of a retroarc foreland basin inside Gondwana.

In the CV, W-vergent structures, such as the San Pedro thrust and associated folds, suggest the existence of a retrovergent Gondwanan thrust system. The Gondwanan orogenic belt can be considered an Andean-type orogene, where most of the deformation occurs under non-metamorphic conditions, such as metamorphism only developed close to the trench, in the accretionary prism ((Rebolledo and Charrier, 1994, Wilner *et al*., 2004, 2009). After the San Rafael orogeny a new subduction zone starts (the present one) and the Andean orogenic cycle begins. This zone, located at the western edge o South America, is very close to the ancient Gondwanan subduction (Fig. 11F).

In the early Permian, and as part of an extensional tectonic regime associated with the collapse of the Gondwanan orogen, the Andean Orogenic Cycle began, characterized in the CV by the post-tectonic intrusion of the Huingancó Granite associated with the volcano-sedimentary rocks of the La Premia Formation. In the CV, preorogenic sequences continued until the Jurassic, with two other extensional phases (Huarpes and Tunuyán phases) separated by unconformities (Llambías *et al*., 2007). Preorogenic deposits filled the Neuquén Basin until the Cretaceous. The Andean orogeny during the Late Cretaceous is associated with a further decrease of the angle of the subducted slab.

5. Conclusions

The Paleozoic rocks of the CV have structures of at least three orogenic cycles; the Chanic and Gondwanan during the Paleozoic and the Andean cycle developed mostly during the

Mesozoic and Cenozoic. Each cycle was separated by major unconformities separating rocks with different deformations and metamorphism.

In the Chanic cycle, Upper Devonian low-grade metamorphic rocks of the Guaraco Norte Formation were deformed during the Chanic orogeny in the Late Devonian to early Carboniferous. Conspicuous structures are the two cleavages associated with the W-vergent folds, thrusts and granitic and pressure solution-quartz veins.

In the CV, the early to late Carboniferous Andacollo Group is part of the Gondwanan cycle; during its preorogenic stage volcano-sedimentary rocks were deposited and deformed by syn-sedimentary normal faulting, where synextensional unconformities are associated to block tilting during half-graben development. Synorogenic non-metamorphic compressive deformation during the San Rafael orogeny (early Permian) leads to NW-trending folds and associated thrusts with SW vergences, which are retro-vergent structures in the Gondwanan orogen context.

The Andean cycle in the region occupies a broad span of time from its initial early Permian preorogenic extensional stages, starting with plutonic and volcanic acidic rocks of the Huingancó volcanic-plutonic Complex and the La Premia Formation.

In the study area, the extensional regime continued in the Late Triassic, represented by the acidic volcanic rocks of the Pre-Cuyano cycle, through the Jurassic marine sediments of the Cuyo and Lotena groups, until Lower Cretaceous sediments that outcrop close to the study sector.

The Andean Orogeny produces the uplift of the CV as part of the western internal sector of the E-vergent Chos Malal fold-and-thrust belt and it is associated with the Late Cretaceous plutonic arc. The main Andean (frontal and lateral) structures are mostly the result of the reactivation of the Permian extensional system. Major structures related to this orogeny in the CV are W-retrovergent CV Fault and the related asymmetric CV Anticline. Dates suggest that the silicic Ag-Au hydrothermal veins, developed under a transpressive regime during the Late Cretaceous–Paleogene magmatic phase, were mainly controlled by Permian E-W normal transfer faults. Possibly, these faults also controlled the southern end of the CV as lateral (strike-slip) faults of the Andean thrust and fold belt.

The rocks and the Paleozoic structures of the CV show many similarities with those located in the Cordillera Frontal of the Andes between 28° and 39° S latitude. In this context, and considering the more recent published data, we propose a new geodynamic evolution model for the Paleozoic of the CV, in the context of the proto-Pacific margin of Gondwana at this latitude.

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