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Structure of the Andean Palaeozoic basement in the Chilean coast at 31º 30' S: Geodynamic evolution of a subduction margin

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Abstract

The Palaeozoic basement outcropping to the north of Los Vilos is formed by (i) the Choapa Metamorphic Complex (ChMC) made of metabasites (amphibolites and retrogressed eclogites), fine-grained gneisses, schists and quartz-schists, and (ii) the meta-sedimentary and sedimentary rocks of the Arrayán and Huentelauquén formations respectively. Near Huentelauquén (31º 30' S), the ChMC has been affected by three deformation episodes related with the Gondwanan orogenic episode. The first episode (D1) is represented by a foliation (S1) formed under HP-LT metamorphic conditions and preserved in syn-D2 garnet and albite porphyroblasts. A generalised crenulation cleavage (S2) was developed under pressure decreasing conditions during the second deformation episode (D2). This episode is responsible for the exhumation of the ChMC, which took place through an east-directed reverse fault system that thrusts the ChMC over the Arrayán Formation, producing more than 20 km shortening. The third deformation episode (D3) is represented by a west-verging kilometre-scale anticline, with a thrust in its reverse limb (Las Caldas thrust). Minor folds and crenulations are also associated with D3. D3 structures affect the ChMC and the Arrayán Formation and are responsible for the overturning of the D2 thrusts. The Huentelauquén Formation, late Carboniferous – Permian in age, is the latest unit deformed by Gondwanan structures. The characterisation of the structure and its relation to metamorphism in the study area, lead to propose a geodynamic model related with an Andean type non-collisional orogenic process, for the Gondwanan orogenic episode of the Andes at this latitude.

Keywords: Gondwanan structure, tectono-metamorphic evolution, Choapa Metamorphic Complex, Chile, system thrust

Resumen

El basamento Paleozoico que aflora al norte de Los Vilos está constituido por (i) el Complejo Metamórfico de Choapa (CMCh), formado por esquistos, cuarzo esquistos, gneises de grano fino y metabasitas (anfibolitas y retroeclogitas) y (ii) rocas metasedimentarias y sedimentarias de las formaciones Arrayán y Huentelauquén respectivamente. En los alrededores de Huentelauquén (31º 30' S), las rocas del CMCh han sido afectadas por tres fases de deformación (D1, D2, D3), relacionadas con el episodio orogénico Gondwánico. Las estructuras D1 están representadas por una foliación tectónica (S1), que se desarrolló bajo condiciones metamórficas de AP-BT y que está preservada en porfiroblastos de granate y albita, crecidos durante el segundo episodio de deformación. Durante la fase de deformación D2 se produce una bajada de la presión y se desarrolla la foliación regional S2. La foliación S2 es contemporánea con el emplazamiento de un dúplex de cabalgamientos dirigidos hacia el este que exhuman el CMCh y lo sitúan sobre las series epimetamórficas de la Formación Arrayán. El acortamiento que producen las estructuras D2 es superior a 20 km. La tercera fase de deformación está representada por pliegues y crenulaciones asociados a un antiforme de escala kilométrica, vergente al oeste, al que se asocia un cabalgamiento dirigido en esa misma dirección (cabalgamiento de Las Caldas). Estas estructuras D3 son las responsables de la inversión de los cabalgamiento D2 de la zona estudiada. La Formación Huentelauquén, del Carbonífero superior – Pérmico, es la unidad más moderna afectada por estructuras Gondwánicas. El análisis de la estructura y su relación con el metamorfismo en la zona estudiada permiten proponer un modelo geodinámico ligado a un proceso orogénico no-colisional, de tipo Andino, para el episodio orogénico Gondwánico de los Andes a esta latitud.

Palabras clave: Estructura gondwánica, evolución tectono-metamórfica, Complejo Metamórfico de Choapa, Chile, sistema de cabalgamientos

1. Introduction

In the Chilean coast, the existence of rock suites that formed part of a Palaeozoic accretionary prism during subduction of the palaeo-Pacific plate is accepted since the works of Hervé (1988), Hervé *et al*. (1988) and Irwin *et al*. (1988). These rocks are exposed in several discontinuous outcrops from the Península de Mejillones (23º S latitude, see Fig. 1b), in northern Chile, to the Los Vilos area, located at 32º S latitude (Fig. 1a). Further south, the Palaeozoic accretionary complex is exposed almost continuously from the Pichilemu area to the Taitao peninsula (Hervé *et al*., 2007) (Fig. 1b). In the study area, these rocks were deformed during the Gondwanan orogenic episode (San Rafael orogeny) (Ramos, 1988), that took place in late Carboniferous – mid Permian times and have been also involved in the Andean orogeny. In the Huentelauquén region (Fig. 1a), north of Los Vilos (30º – 31º latitude S), Palaeozoic basement rocks were studied by Rebolledo (1987), Godoy and Charrier (1991) and Rebolledo and Charrier (1994), who proposed a late Carboniferous – Permian age for the accretionary process. New data have been recently reported on the metamorphic processes that affected these rocks and the chronology of their evolution (Willner, 2005; Willner *et al*., 2008, 2012). The detailed study of the structure, microstructure and metamorphism of these rocks has permitted us to construct a geological cross-section and to establish their tectono-metamorphic evolution. This study also led to fit the study area in a new proposal of geodynamic evolution model for the Gondwanan orogenic episode at this latitude.

2. Lithologies

The rocks cropping out in the Punta Claditas area can be included in two main lithologic groups, separated by thrusts and deformed under different metamorphic conditions: the Choapa Metamorphic Complex (ChMC) and the three metasedimentary units included in what we will name Arrayán basin. This basin, Devonian – Permian in age, hosted the Agua Dulce Metaturbidites (Rebolledo and Charrier, 1994), the sedimentary rocks of the Arrayán Formation, locally Puerto Manso Formation (Rivano and Sepúlveda, 1991), and the Huentelauquén Formation (Muñoz Cristi, 1942). All these rocks have been deformed during the subduction-accretion process developed in the Gondwana – Chilenia continental margin during the early Carboniferous – mid Permian (Figs. 1a and 2).

2.1. Choapa Metamorphic Complex (ChMC)

This group of rocks consists of three main lithologies: (i) a monotonous sequence of schists and quartz-schists; (ii) fine-grained gneisses with intercalations or boudins of schists and metabasites; and (iii) metabasites which, in the vicinity of the gneisses, contain boudins of fine-grained gneisses and schists. These three rock units are separated by tectonic contacts, show a similar tectono-metamorphic evolution (Fig. 2) and have been affected by structures developed during three superimposed deformation events (D1, D2, D3).

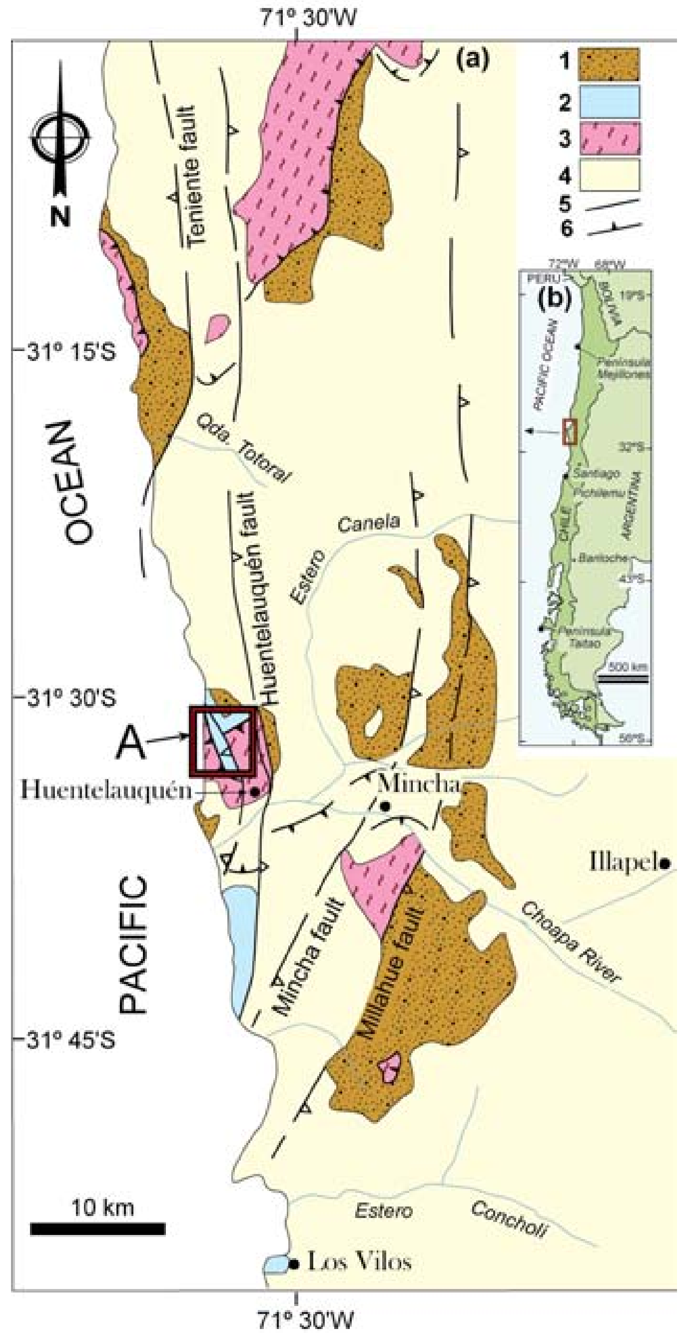

Fig. 1.- (a) Geological map of the Chile coast between 31º 00’ and 31º 35’ S, based on Rebolledo and Charrier (1994). (A) Location of the geological map of figure 2. (1) Huentelauquén Formation, (2) Arrayán Formation, (3) Choapa Metamorphic Complex, (4) Mesozoic and Cenozoic rocks, (5) fault, (6) thrust. (b) Map of Chile with study area location.

The **schists and quartz-schists** (Esquistos Grises de Punta Claditas and Esquistos Grises de la Gruta, after Rebolledo and Charrier, 1994) consist of quartz, white-mica, chlorite, albite and garnet (Grt1±Grt2), with tourmaline, epidote, apa-

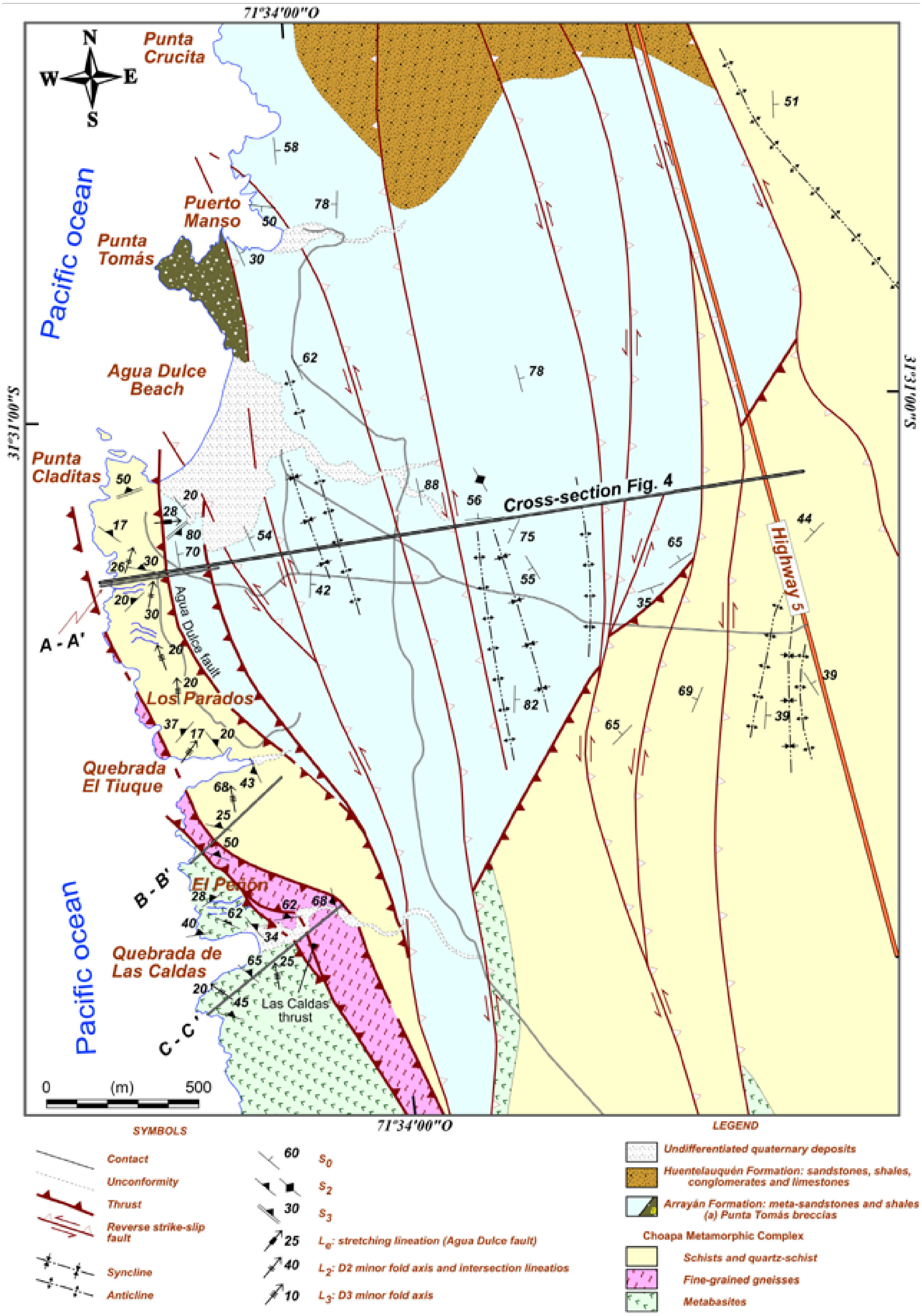

Fig. 2.- Geological map of the study area (see location in Fig. 1). Modified after Rebolledo and Charrier (1994), Ring *et al*. (2012). A-A' corresponds to the geological cross-section of western part of Fig. 4, further detailed in Fig. 8b. B-B' corresponds to the geological cross-sections of Fig. 8a, and C-C' to the geological cross-section of Fig. 5a.

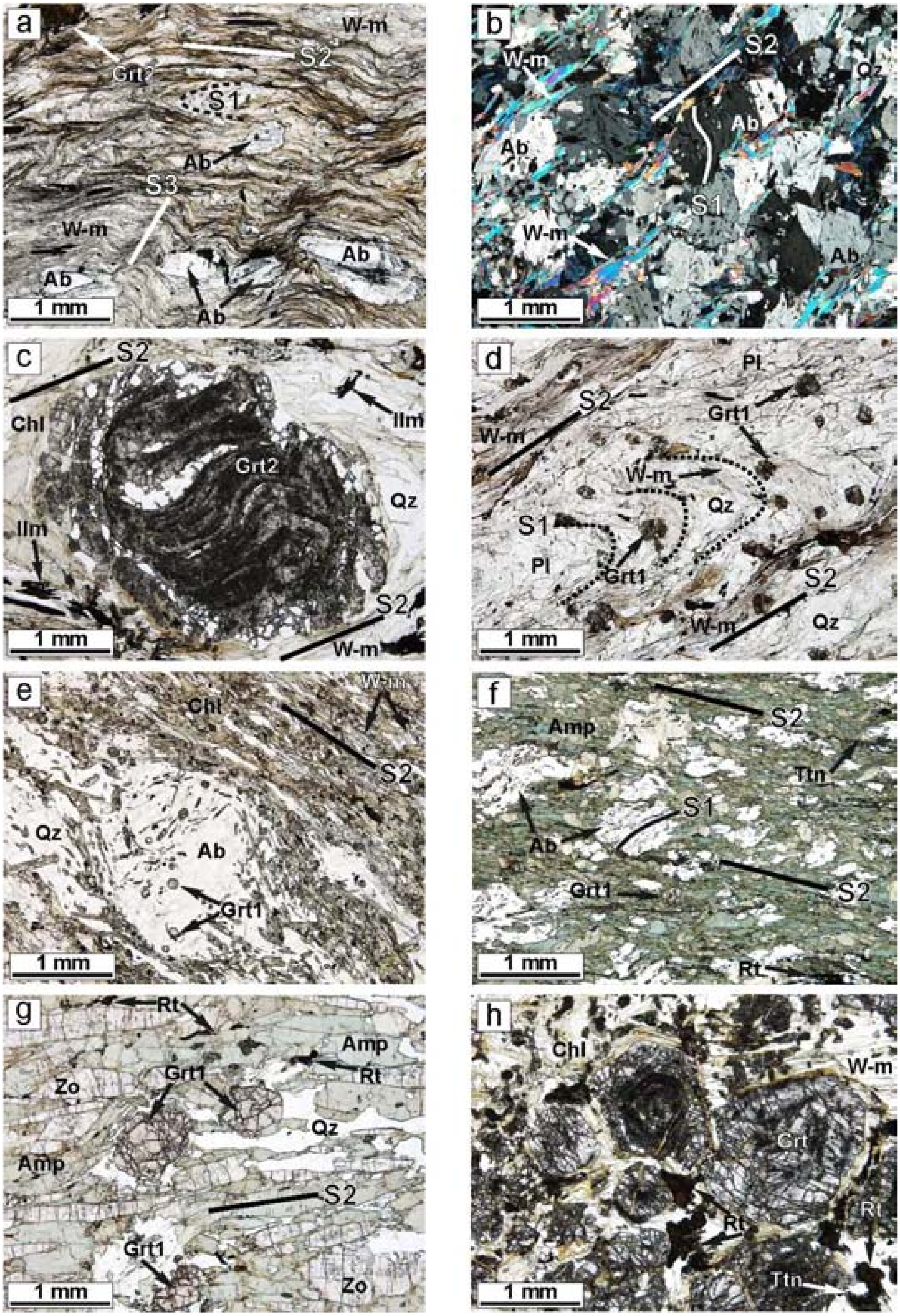

Fig. 3.- Microstructure and petrographic aspects of the ChMC: (a) Aspect of the S2 regional foliation defined by white-mica (W-m) in schists with Ab and Grt porphyroblasts folded by S3 crenulation. The S1 is preserved in the S2 microlithons (plane polarised light). Location at coordinates: 31º 31' 23" S, 71º 34' 30" W. (b) Schists with S2 regional foliation defined by white-mica (W-m) and Ab porphyroblasts with S1 internal foliation (crossed polars). Location at coordinates: 31º 31' 36" S, 71º 34' 25" W. (c) Schists with Grt porphyroblasts (Grt2) showing helicitic microstructure (S1 foliation) (plane polarised light). Location at coordinates: 31º 31' 46" S, 71º 34' 24" W. (d) S2 regional foliation and S1 folded, both defined by white-mica, and small garnets (Grt1) in fine-grained gneisses (plane polarised light). Location at coordinates: 31º 31' 47" S, 71º 34' 23" W. (e) Ab porphyroblasts with Grt1 inclusions in schists (plane polarised light). Location at coordinates: 31º 31' 53" S, 71º 34' 21" W. (f) Amphibolites with S2 regional foliation (Amp, Ep, Rt, and Ttn) and pre-S2 garnet (Grt1). The internal foliation (S1) is preserved in Ab porphyroblasts (plane polarised light). Location at coordinates: 31º 31' 56" S, 71º 34' 15" W. (g) Pre-S2 garnet (Grt1) and S2 regional foliation (Amp, Zo, Rt, Qz) in amphibolites (plane polarised light). Location at coordinates: 31º 32' 00" S, 71º 34' 17" W. (h) Retrogressed eclogite with garnet, white-mica, and Rt with Ttn outer rims (plane polarised light). Location at coordinates: 31º 31' 46" S, 71º 34' 24" W.

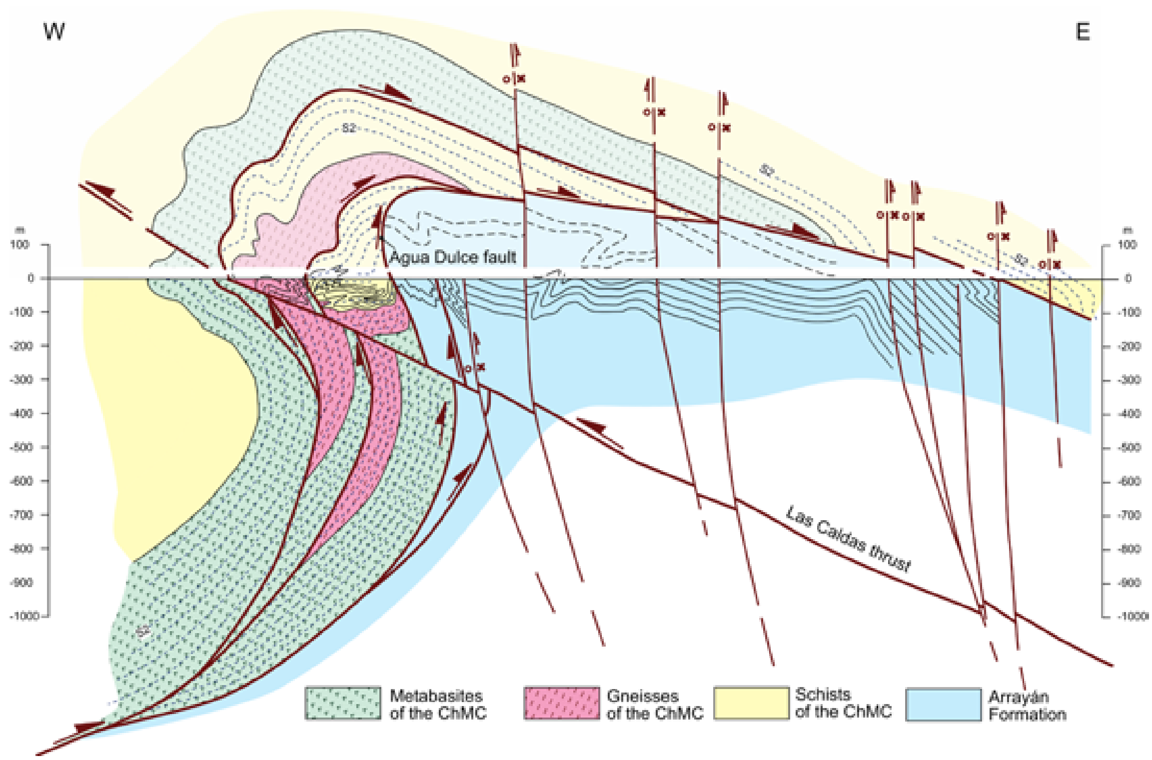

Fig. 4.- Geological cross-section of the study area. For location see figure. 2.

tite, zircon, titanite, ilmenite and rutile as accessory minerals. The regional foliation is mostly a schistosity (S2) defined by the alternance of quartz and chlorite+white-mica bands (Fig. 3a). The composition of the white-mica is muscovite to phengite (Willner *et al*., 2012). Albite (Ab) and Grt2 (mineral abbreviations from Whitney and Evans, 2010) are porphyroblasts mainly syn-kinematic with the S2 and frequently helicitic, including a previous foliation (S1) (Figs. 3b, 3c). In the Ab porphyroblasts, an internal foliation (S1) is defined by graphite inclusion trails, and sparsely oriented inclusions of Rt, Ilm, Ttn, Ep ± Tur ± Qz ± white-mica. The S1 is also preserved in S2 microlithons and polygonal arcs defined by white-mica. Most of the Grt2 porphyroblasts appear as chloritised pseudomorphs but retain an internal foliation (S1) of graphitic inclusion trails or opaque minerals.

This group of rocks includes the "Filitas de La Quebrada Poleo" (Rebolledo and Charrier, 1994), that crop out to the east of the studied region and are in fault contact with the Huentelauquén Formation to the west.

The fine-grained **gneisses** have been included in the "Esquistos de Punta Claditas" by Rebolledo and Charrier (1994). Most of these gneisses are formed by re-crystallised polygonal aggregates of Pl and Qz (triple junctions at 120º) and white-mica+chlorite bands defining the S2 foliation and also the folded S1. Like the schists, the gneisses are characterised by the abundance of syn-S2 albite and garnet (Grt2) porphyroblasts. Internal foliation (S1) in Ab porphyroblasts is defined by graphitic inclusion trails and opaque minerals. Most of the Grt2 porphyroblasts are chloritised but preserve the S1 defined by opaque mineral or rutile inclusions. These rocks can show abundant crystals of Ep and of Rt partially retrograded to Ilm or Ttn. Other accessory minerals are the same as in the schists.

In some gneisses, and in the previously described schists, there are also small idiomorphic or subidiomorphic garnets (Fig. 3d) showing two or more stages of growth indicated by the arrangement of inclusions. These garnets (Grt1) formed previous to the Ab porphyroblasts, in which they appear as inclusions (Fig. 3e), and are pre-kinematic with the regional foliation (S2).

The **metabasites**, included in the "Esquistos Verdes de Maintencillo" by Rebolledo and Charrier (1994), show a wide compositional and textural variety. However, most of the studied metabasites are nematoblastic amphibolites, consisting of Amp, Ep, Rt, Chl, Qz ± Grt ± white-mica ± Cb and Ilm ± Ttn after Rt. These rocks show a main foliation corresponding to the regional S2 defined by the dimensional preferred orientation of Amp, Ep, Rt, Ttn and Chl. The S1 foliation can be seen deformed by centimetre-scale D2 folds. These amphibolites are characterised by a remarkable development of syn-kinematic Ab porphyroblasts parallel to the regional S2 foliation. This Ab porphyroblasts exhibit an internal foliation (S1) (Fig. 3f), in some cases folded, and defined by oriented inclusions of Rt, Ttn, Grt, Amp and Ep. The garnets usually host numerous inclusions of epidote, are pre-kinematic with the regional foliation (S2) and previous to the Ab porphyroblasts, in which they are included. In some metabasites both Amp and Grt are totally chloritised, which results in schists consisting mainly of Chl, Ab, Ep, Ttn ± white-mica ± Cb. Other metabasites are nematoblastic amphibolites composed by Amp, Zo, Grt, Qz, Rt and Ttn. Prismatic Amp and Zo are arranged in parallel defining the regional foliation (S2) (Fig. 3g). The Grt is pre-kinematic respect to the S2 and rich in inclusions of Ep+Qz. Associated with both types of amphibolites there are lenses of rocks that are interpreted as retrogressed eclogites. These rocks consist of Grt (up to 35%), Zo, white-mica, Chl, Qz and Rt variably transformed into Ilm ± Ttn. The garnets reveal a complex history with two or more episodes of concentric growth or rotational movements indicated by the arrangement of inclusions (Fig. 3h).

The schists and gneisses of the ChMC were described as a set of greywackes and/or arkoses resulting from erosion of a volcanic arc, and the metabasites as oceanic ridge tholeiitic basalts, all of them affected by successive processes of low-grade regional metamorphism (Rebolledo, 1987). Rebolledo and Charrier (1994) regarded the above described schists and gneisses as the metamorphic equivalent to the Arrayán Formation (Devonian – early Carboniferous) according to Muñoz Cristi (1942), Cecioni (1962, 1974) and Bernardes de Oliveira and Roesler (1980). However, U-Pb age determinations on detrital zircons from the schists of the ChMC yielded a 308 Ma maximum age for the protoliths of these rocks (late Carboniferous – Permian) (Willner *et al*., 2008), which is quite close to the age of the Huentelauquén Formation.

2.2. The Arrayán basin

To facilitate the description of the geodynamic evolution model for the Gondwanan orogenic episode to be discussed later, it is necessary to define the basin in which the stratigraphic units, Devonian to Permian in age, were deposited (Arrayán and Huentelauquén formations). The Arrayán Formation, *sensu* Rivano and Sepúlveda (1991), includes similar deposits exposed in the coastal area of north central Chile, which were formerly named Puerto Manso (in the study region), Arrayán (south of the Choapa river outlet), and Los Vilos (near the south of the city of Los Vilos) formations (Muñoz Cristi, 1942). In the study region, it consists of sandstones alternating with gray, black and green shales interpreted as a turbiditic succession deposited in a medial to distal submarine fan, with a western to north-western source determined on the basis of palaeocurrent indicators (Muñoz Cristi, 1942; Cecioni, 1962, 1974; Charrier, 1977; Rebolledo, 1987; Rivano and Sepúlveda, 1991; Rebolledo and Charrier, 1994). Based on fossil remains, this formation has been assigned to the Devonian – early Carboniferous (Muñoz Cristi, 1942; Cecioni, 1962, 1974; Bernardes de Oliveira and Roesler, 1980). The maximum depositional age obtained for this formation is 343 Ma (U-Pb dating of detrital zircons) (Willner *et al*., 2012).

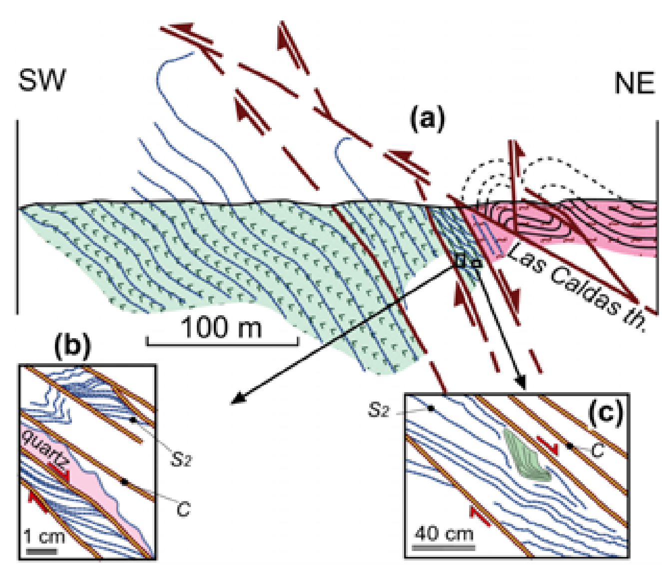

Fig. 5.- (a) Detailed geological cross-section of the Las Caldas River, (C-C' in figure 2). (b) S-C mylonites in the shear zone at the base of the metabasites of the ChMC, that allow deduce that the hanging-wall down. (c) Shear zone, showing folds developed in competent levels of the metabasites of the ChMC, with thickened hinges and strongly stretched limbs, which can even disappear.

The Agua Dulce Metaturbidites are in all aspects similar to the Arrayán Formation, except for their higher-grade metamorphism. For this reason we prefer to include them within the Arrayán Formation. This view is shared by Willner *et al*. (2012) based on the maximum depositional age of 337 Ma (U-Pb dating of detrital zircons) for the Agua Dulce Metaturbidites (Willner *et al*., 2008), which is similar to that obtained for the Arrayán Formation in the study region. These metaturbidites consist of an alternance of shales and sandstones, interpreted as turbidites from a distal to middle part of a submarine fan (Rebolledo and Charrier, 1994). The Agua Dulce Metaturbidites pass gradually into a broken-formation (mélange type 1 of Cowan, 1985) (Fig. 2), which is unconformably covered by the Punta Tomás breccia, possibly Triassic in age.

The exposures of the Huentelauquén Formation in the northern part of the study area (Muñoz Cristi, 1942; Rebolledo and Charrier, 1994) consist mainly of gray and black shales, including encrinitic levels. East of the study area, the Huentelauquén Formation is formed by an alternance of sandstones, shales, limestones and conglomerates made of up to 60-70% rhyolite and leucogranite pebbles (Rebolledo and Charrier, 1994; Willner *et al*., 2008). These deposits accumulated in a shallow and restricted environment with deltaic and carbonate facies (Mundaca *et al*., 1979; Rivano and Sepúlveda, 1983 Charrier *et al*., 2007; Méndez-Bedia *et al*., 2009). The age of the Huentelauquén Formation has been dated on the base of its fossiliferous content as late Carboniferous – early Permian (Sundt, 1897; Groeber, 1922; Fuenzalida, 1940; Muñoz Cristi, 1942, 1968; Minato and Tazawa, 1977; Mundaca *et al*., 1979; Thiele and Hervé, 1984; Díaz-Martínez *et al*., 2000). This age is consistent with the maximum deposition age of this formation (~303 Ma) obtained on magmatic zircons in leucogranite/rhyolite conglomerate pebbles (Willner *et al*., 2008), and is very similar to that obtained using the same method by these authors for the schists and quartz-schists of the ChMC.

The Arrayán Formation was deposited in a pre-orogenic stage of the Arrayán retro-wedge basin (Willner *et al*., 2012),

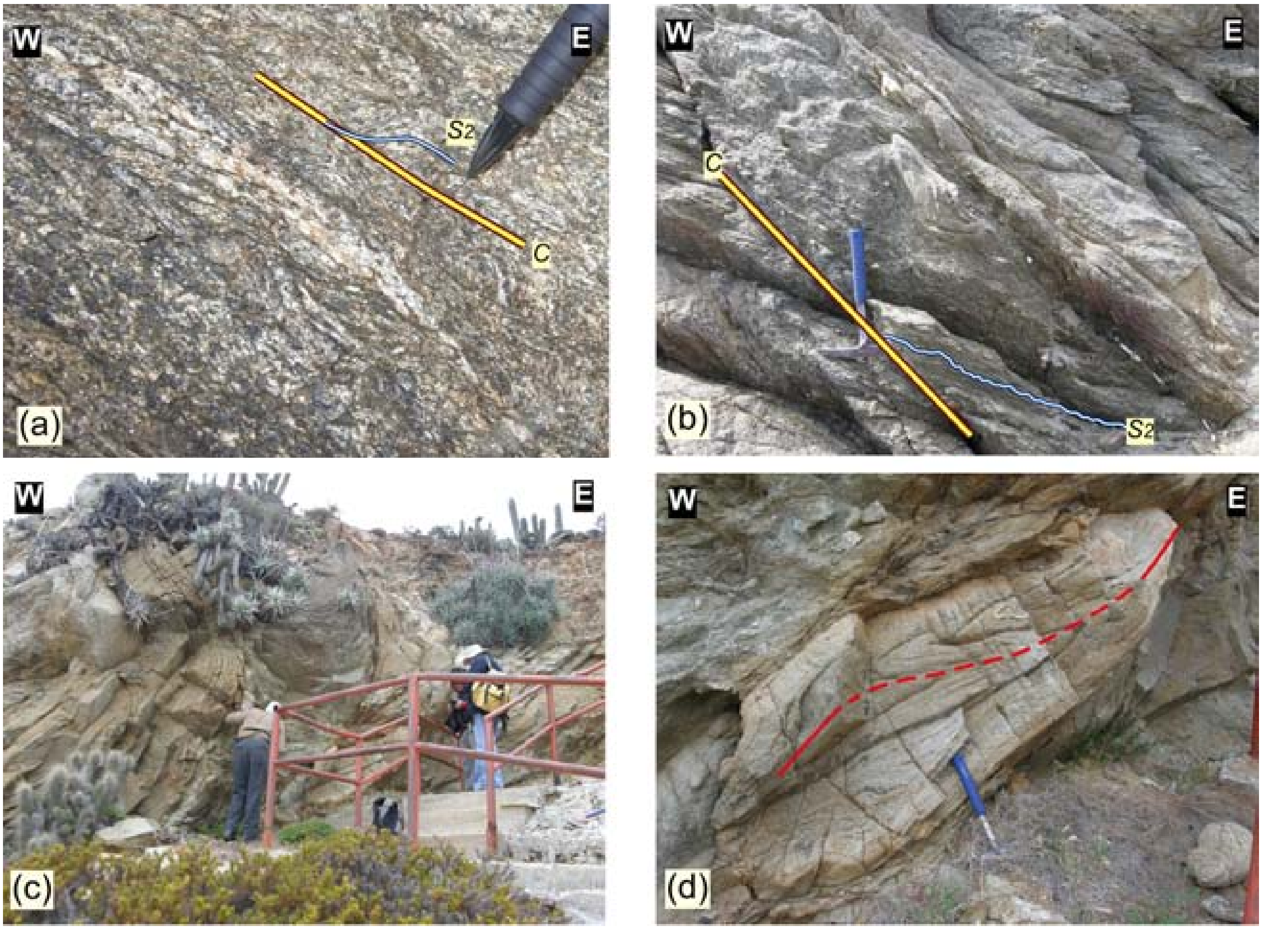

Fig. 6.- Photographs of the Las Caldas River. (a) S-C mylonites of the figure 5b. (b) Shear zone of the figure 5c. (c) West-verging D3 fold associated to the hanging-wall of the Las Caldas thrust. (d) Shear zone showing west-verging sheath tight folds associated with the Las Caldas thrust (red curved line: hinge fold). Location at coordinates (a) and (b): 31º 31' 55" S, 71º 34' 16" W; (c) and (d): 31º 31' 58" S, 71º 34' 12" W.

which to the east of the study area shows shallow marine platform facies. On its behalf, the syn-orogenic Huentelauquén Formation formed during the deformation stage of the Arrayán basin, coinciding with the Gondwanan compressive deformation (San Rafael orogenic phase) (Charrier *et al*., 2007). The magmatic arc represented by the Elqui superunit of the Elqui – Limarí batholith developed to the east of the eastern platform deposits.

2.3. Igneous rocks

In this area, igneous rocks are represented by abundant, mostly E-W orientated, andesitic dykes 2 to >10 m thick and possible Jurassic in age, that cross-cut structures developed in the ChMC (Berg and Charrier, 1987). According to these authors, the dykes host granitic xenoliths of late Carboniferous age. This age is similar to that of the Santo Domingo Complex in the Coastal batholith (Parada *et al*., 1999, 2007) that outcrops further south between 31-34 ºS latitude. This could attest to the presence of intrusive rocks, similar in age to those of the Coastal batholith, underlying the current outcrops of ChMC.

3. Structure

As previously described, the regional foliation is a schistosity (S2) developed in the rocks of the ChMC, in which different evidences of a previous S1 cleavage can be observed. At microscopic scale the Ab porphyroblasts show syn-S2 growth, but at the outcrop scale a direction of preferred stretching lineations has not been observed. The S2 corresponds to the S4 foliation described in the schists and quartz schists ("Esquistos Grises de Punta Claditas" unit) and the S2 foliation described in the metabasites ("Esquistos Verdes de Maitencillo" unit) by Rebolledo and Charrier (1994). The number of foliations described by these authors in each of these units was based on a geometric analysis. For this reason, the number of foliations resulting from superposed deformations detected in the quartz-rich lithologies is greater than in the amphibole schists, which contain almost no quartz. Our own analysis is based mostly on mineralogical criteria that allow a better geodynamic approach to the interpretation of the ChMC.

The Arrayán Formation and the three lithological units of the ChMC previously described are bounded by tectonic contacts consisting of faults dipping NE with an apparently normal component of displacement. Associated to these faults there are mylonites and, locally, foliated cataclasites. According to the kinematic criteria these faults have been interpreted as east-directed inverted thrusts that caused the superposition of three thrust sheets, which we named, from west to east: upper, intermediate and lower thrust sheet. thrusts separating these sheets form a kilometre-scale duplex in which the floor-thrust is the Agua Dulce fault (Figs. 2, 4) that overlaps the ChMC on the turbiditic Arrayán Formation. This thrust-sequence is folded by a kilometre-scale west-vergent antiform that produces its inversion and the tectonic window; in which the Arrayán Formation is exposed. The reverse limb of this fold is affected by a west-directed thrust (Las Caldas thrust) (Figs. 2, 4) and the normal limb is cut by Andean vertical faults.

3.1. Upper thrust sheet

This thrust sheet crops out in the Quebrada de Las Caldas (southern part of the study area), and also in the eastern part of the study area, next to Highway 5 (Fig. 2). The floor thrust of this sheet can be seen in the Quebrada de Las Caldas, putting in contact the metabasites of the ChMC over the fine-grained gneisses of the same unit (Fig. 5a). A 40º NE dipping ductile shear zone, more than 20 m thick and associated to the thrust, developed in the metabasites in this locality. In the more ductile levels of the metabasites within the shear zone, there are folds with thickened hinges and extremely, often disrupted, stretched limbs (Figs. 5c, 6b). Kinematic criteria in the gneisses show the descent of the hanging-wall, so the fault appears like a normal fault (Figs. 5b, 6a). However, the fact that the metabasites are located in the foot-wall of the fault must be interpreted in the sense that, actually, it consists of a thrust which has been overturned by a younger west-vergent structure.

The geological cross-section shows that the basal thrust of the upper thrust-sheet is in a normal position in the eastern part of the study area (Fig. 4). Thus, in the vicinity of Highway 5, the La Gruta Schists (Rebolledo and Charrier, 1994) are overthrusting the Arrayán Formation. In this area, the La Gruta Schists show tectonic foliations and folds belonging to the three deformation episodes (D1, D2, D3) defined in the study area. D1 structures correspond to S1 cleavage that, within quartzitic beds, appears crenulated by D2 millimetre-scale folds, which in turn have been folded by D3 centimetre- to metre-scale folds (Fig. 7).

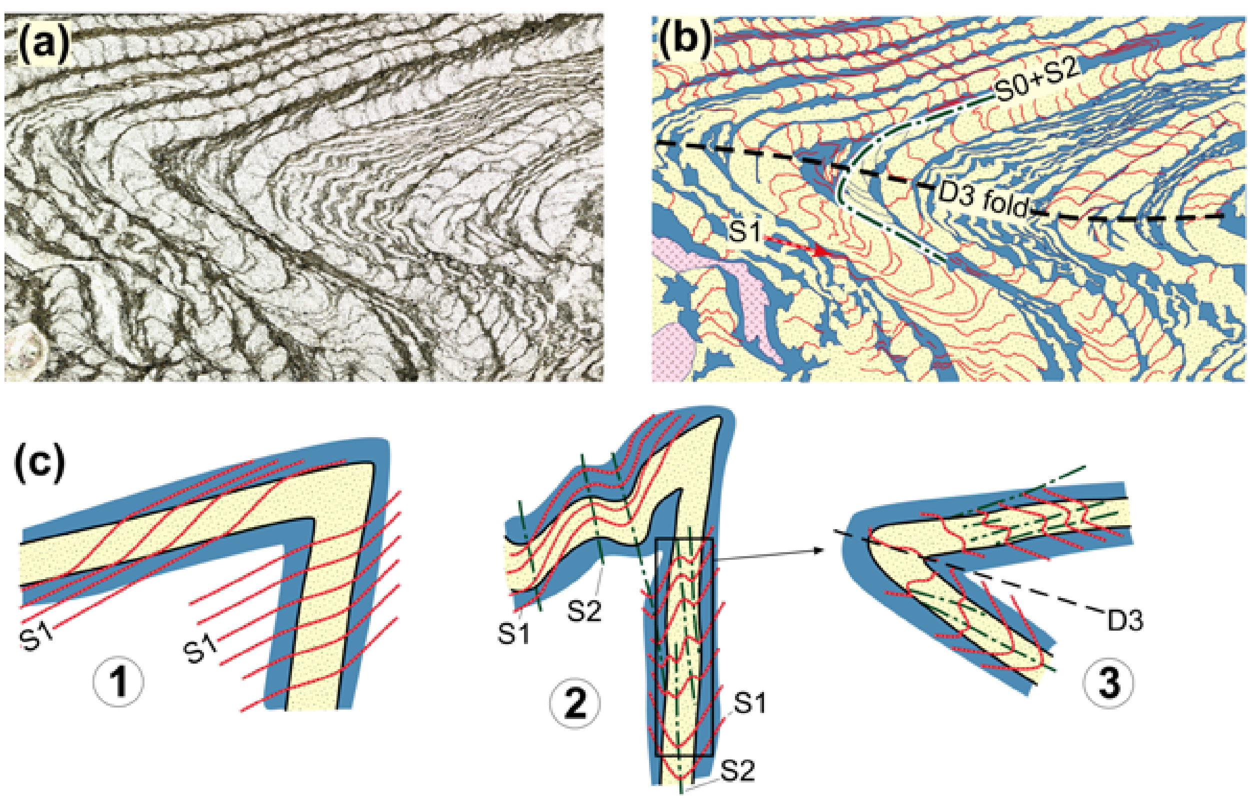

Fig. 7.- Superimposed deformations observed in the La Gruta Schists. (a) Microscopic photograph of the La Gruta Schists. Location at coordinates 31º 31' 20" S, 71º 33' 20" W. (b) Scheme of the photograph 6a. (c) Explanation of the structures observed in the La Gruta Schists: *1*. D1 fold with S1 associated and refracted in competent levels. In the short limb S0 is subvertical and, therefore, perpendicular with respect to main shortening direction. *2*. D2 folds developed in the normal and short limbs of the D1 fold. The S1 appears folded in the short limb of the D1 fold, and the S0 is unfolded due to its perpendicular attitude with respect to the main shortening direction and undergoes a bedding-perpendicular flattening (in this case, S0 and S2 remain sub-parallel). *3*. The D2 short limb is folded by a west-verging D3 structure. Similar cases to the described here been observed for instance in relation to the Variscan structure of the Axial zone of the Pyrenees, Spain (García-Sansegundo, 1992; García-Sansegundo *et al,* 2014b).

The frontal part of this thrust sheet extends 20 km to the east of the study area, close to the Millahue fault (Fig. 1a) where the easternmost outcrops of the ChMC schists are exposed. According to this we estimate a tectonic displacement over 20 km for this thrust.

3.2. Intermediate thrust sheet

In the El Peñón area, the intermediate thrust sheet crops out underneath the upper thrust sheet. This sheet consists of gneisses, schist and quartz-schists of the ChMC (Fig. 8a). The basal thrust of this sheet is associated with a 10 m thick ductile shear zone that includes chunks of metabasites (Figs. 8a, 9a). This basal thrust, like the basal thrust of the upper sheet, is rooted in the metabasites of the ChMC. The tectonic displacement associated with this structure deduced from the cross-section is approximately 700 m (Fig. 4).

3.3. Lower thrust sheet

The lower thrust sheet of this duplex is exposed in the Punta Claditas area, where the schists and quartz-schists of the ChMC overthrust the Arrayán Formation. The basal thrust of this sheet is the Agua Dulce fault (Figs. 4, 8b), that can be observed in the south-western end of the Agua Dulce beach. A shear zone of about 10 m thick is associated to this fault, mainly constituted by foliated cataclasites and mylonites (Fig. 8c). The tail of this thrust is not exposed, therefore the tectonic displacement cannot be deduced, although its magnitude is certainly kilometric.

In this thrust sheet, structures associated to the three previously mentioned deformation episodes (D1, D2, D3) can be recognised in the schists and quartz-schists alternations of the ChMC. Foliation S1 is deformed by isoclinal, metric D2 folds with an associated S2 (Fig. 9b). Finally, the S2 foliation is folded by D3 structures, which can be related with the last Gondwanan deformation episode (Fig. 4).

3.4. West-vergent structures

As previously mentioned, west-vergent structures can be observed in the study area, which are responsible for the inversion of the east-directed duplex previously described. Such structures are the kilometre-scale antiform that folds the previously described sheets and the Las Caldas thrust, developed in its reversed frontal limb (Fig. 4). This southwest-directed thrust can be observed in the Quebrada de Las Caldas, dipping 30º to the NE. A shear zone 2 m thick is associated to this struc-

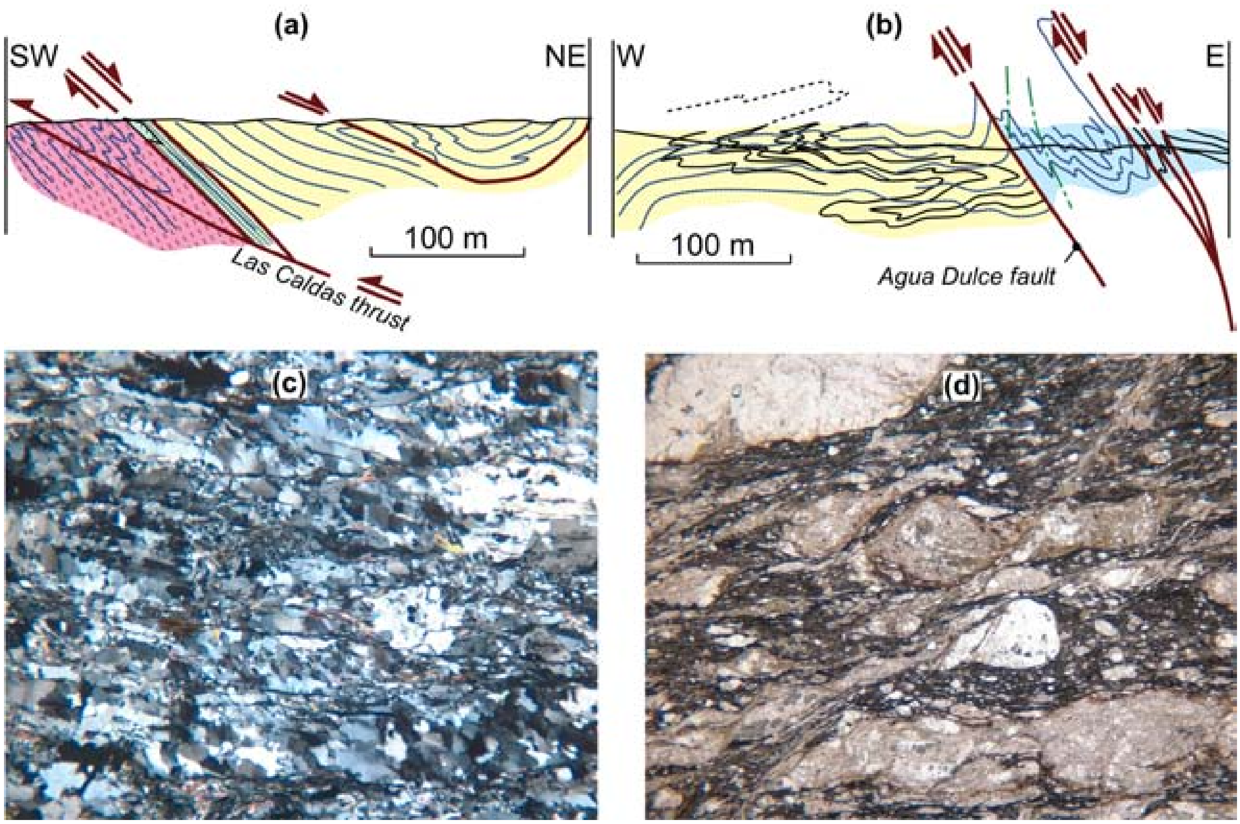

Fig. 8.- Detailed geological cross-section of the (a) El Peñón area (B-B' in Fig. 2), and (b) Punta Claditas zone (A-A´ in Fig. 2). (c) Mylonites developed in relation to the basal thrust of the Upper thrust sheet (Agua Dulce fault). The oblique foliation in quartz indicates sinistral sense of shear. North-east to the left. Undulose extinction and lobate contacts of quartz grains point to low-grade metamorphic conditions during mylonitisation (crossed polars). Location at coordinates 31º 31' 20" S, 71º 34' 30" W. (d) Foliated cataclasites associated to a N-S Andean fault, close to the Highway 5 (location at coordinates 31º 31' 20" S, 71º 33' 17" W). Several kinematic criteria (trails, P-foliation and R1 shear) indicate a sinistral sense of shear. East to the left (plane polarised light).

ture. In this shear zone, the fine-grained gneisses are deformed by isoclinal sheath folds (Fig. 6d). In the hanging wall of this thrust, the gneisses are affected by a metre-scale fold trending NW-SE and vergent to the SW (Fig. 6c). This fold is interpreted as a hanging wall ramp of this thrust. The displacement of the Las Caldas thrust is about 100 m (Fig. 4). The normal limb of this fold is cut by Andean vertical faults, with sinistral-reverse displacement (Rebolledo and Charrier, 1994; Ring et al., 2012) and associated foliated cataclasites (Fig. 8d).

The retro-vergent D3 structures must have formed because of the difficulty of the propagation of the deformation to the east. This could be explained by the existence of a buttress or rigid obstacle that prevented the progression of thrusting towards the foreland (probably the plutonic rocks of Elqui superunit of the Elqui – Limarí batholith).

4. Tectono-metamorphic evolution of the Choapa Metamorphic Complex

The rocks of the ChMC have been exposed to different P-T metamorphic conditions during the Gondwanan orogenic episode. Godoy and Charrier (1991) estimated pressure conditions of >5 kbar according to the composition and zoning patterns of amphibole and garnet. Subsequently, Willner (2005) indicated that these rocks underwent a HP-LT metamorphism, and Richter *et al*. (2007) considered them as a basal accretionary complex, similar to the one exposed further south, between 34º 32´ S and 40º 57´ S, along the Chilean coast (Willner *et al*., 2004; Willner, 2005). Recently, Willner *et al*. (2012) established the P-T conditions reached during HP-LT metamorphism in the ChMC, the age of the metamorphic peak, and the onset of exhumation based on K-Ar ages obtained in white-micas.

The crystallisation-deformation relationships and mineral parageneses observed in the schists, gneisses, and metabasites of the ChMC allowed us to advance the tectono-metamorphic evolution during the HP-LT subduction – related metamorphism and later retrogression to greenschists-facies conditions. These processes occurred between 307 and 274 Ma (late Carboniferous – early Permian) (Willner *et al*., 2012). In the schists and fine-grained gneisses, the absence of biotite and the occurrence instead of phengite-rich muscovite coexisting with Grt is a characteristic feature of rocks affected by HP-LT subduction-related metamorphism (Bucher and Frey, 2002). This phengite-rich muscovite forms the microlithons and polygonal arcs (S1) preserved in the S2 regional foliation. On the other hand, minerals defining the internal foliation within the syn-S2 albite porphyroblasts in the schists, leucogneisses and metabasites (graphitic inclusions trails ± Rt ± Ilm ± Ep ± Grt1 ± white-mica) represent a high-pressure relict assemblage in rocks that underwent significant further retrogression and total destabilisation of previous high-P minerals (Arenas *et al*., 1995; Rubio Pascual *et al*., 2002). Garnet (Grt2) and albite porphyroblasts are mainly syn-kinematic with the regional (S2) foliation. In the schists, garnets show a zonal growth characterised by enrichment in Fe, Mg, as well as an increase in the X_{Mg} ratio towards the borders, coupled with a decrease in Ca and Mn (Willner *et al*., 2012). This zoned pattern, as described by Willner *et al*. (2004) for the metamorphic complex located south of 34º S in the Chilean coast and García-Sansegundo *et al*. (2009; 2014a) in the Argentine Andes at 41º S, indicates a temperature rise and pressure drop during garnet growth. The widespread development of Ab porphyroblasts in schists, fine-grained gneisses and metabasites, points to a pervasive metamorphic retrogression of the previous HP minerals in a decompressive tectonic context (Jamieson and O'Beirne-Ryan, 1991; Arenas *et al*., 1995). The growth of Ab porphyroblasts could result from destabilisation of jadeite through reactions such as Jd + Qz = Ab, or paragonite, present in some rocks of ChMC (Willner *et al*., 2012). In the metabasites, Ab porphyroblasts can also represent pseudomorphs after lawsonite, given the abundance of Ca-rich minerals included. Maximum conditions of P and T obtained by Willner *et al*. (2012) for this first stage of high-P metamorphism, in the schists (Grt, Qz, white-mica, Chl, Ep, Rt) of Quebrada Las Caldas, are

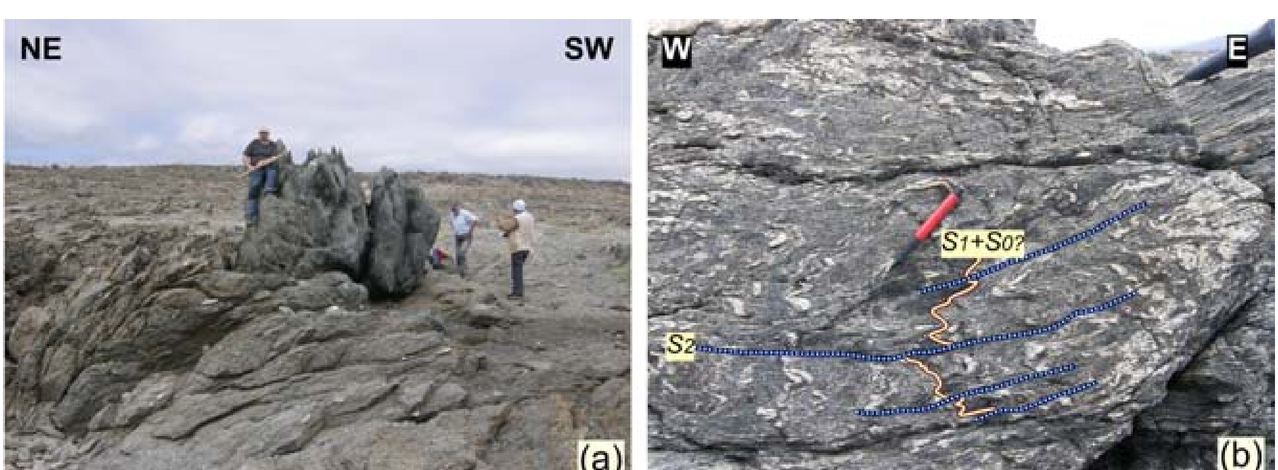

Fig. 9.- Photographs of the (a) boudin in the metabasites of the ChMC in El Peñón area, and (b) D2 recumbent folds in the Punta Claditas zone. Location at coordinates (a) 31º 31' 47" S, 71º 34' 23" W; (b) 31º 31' 17" S, 71º 34' 31" W.

ca. 11-13 kbar and 570-585 ºC. In metabasites without Grt (Amp, white-mica, Ep, Pl, Chl, Rt) the same authors obtained maximum P-T conditions of 6-9 kbar and 500-570 ºC. The peak of the HP-LT metamorphism would have taken place around 279±3 Ma (early Permian) (Willner *et al*., 2012). The destabilisation of previous HP minerals and growth of Ab and Grt2 porphyroblasts, indicate a pressure drop occurred during development of the regional (S2) foliation. This regional foliation must be related with the emplacement of east-directed thrusts that caused the exhumation, metamorphic retrogression to greenschist-facies conditions and the overlap of the ChMC on no- or low grade metamorphic units. Such exhumation process would have started at ~274 Ma and must have come to its end before ~260 Ma (Willner *et al*., 2012).

The S3 crenulation cleavage was formed under no- or low grade metamorphic conditions. The D3 deformation episode carries an incipient development of biotite from chlorite, indicating a slight increase in temperature. The D3 microstructures are related with the major west-vergent fold (Fig. 3). The exhumation of the rocks of the ChMC continued at a slower rate during the Mesozoic associated with the Andean cycle. The Gondwanan deformation and metamorphism are also post-dated by the latest Permian? – Triassic sequences (Rebolledo and Charrier, 1994; Charrier *et al*., 2007).

5. Geodynamic Model

A new model is presented in the next paragraphs to explain the evolution of the western Gondwana margin in central Chile and western central Argentina during Devonian to mid Permian times. This is based on: (i) the structural data and the analysis of the tectono-metamorphic relationships in the Palaeozoic rocks, (ii) the ages and geochemical signature of the Gondwanan magmatism and metamorphism, and (iii) the palaeogeographic distribution and characteristics of the sedimentary basins associated with the Gondwanan orogenic episode (Mpodozis and Ramos, 1990; Ramos, 1988; Rebolledo and Charrier, 1994) (Fig. 10). At this latitude, the Palaeozoic accretionary processes that occurred in the ancient southwestern margin of Gondwana start with the Cuyania collision

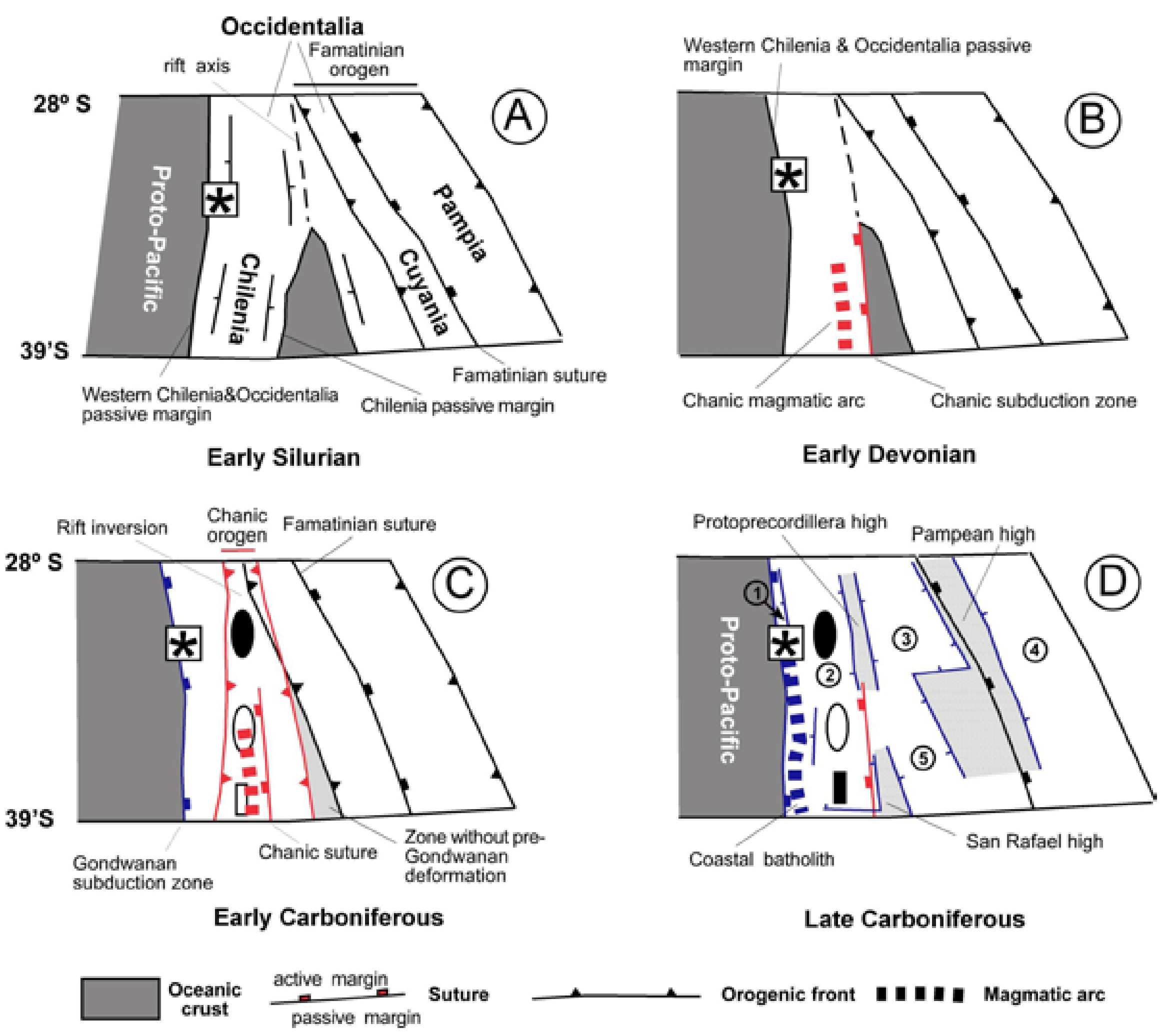

Fig. 10.- Sketch of the palaeogeographic evolution of the Gondwana margin, between 28° and 39° S latitude, before the Permian period (San Rafael orogeny). Asterisc: study area. Main Carboniferous basins: (1) Arrayán, (2) Río Blanco, (3) Paganzo, (4) Chaco – Paraná, (5) San Rafael. Location of the main Palaeozoic outcrops of the Andean Frontal Cordillera: Sierra de Castaño and Cordón de Colangüil (black oval). Cordón del Plata, Cordón del Portillo and Cordón del Carrizalito (white oval). Cordillera del Viento (black box).

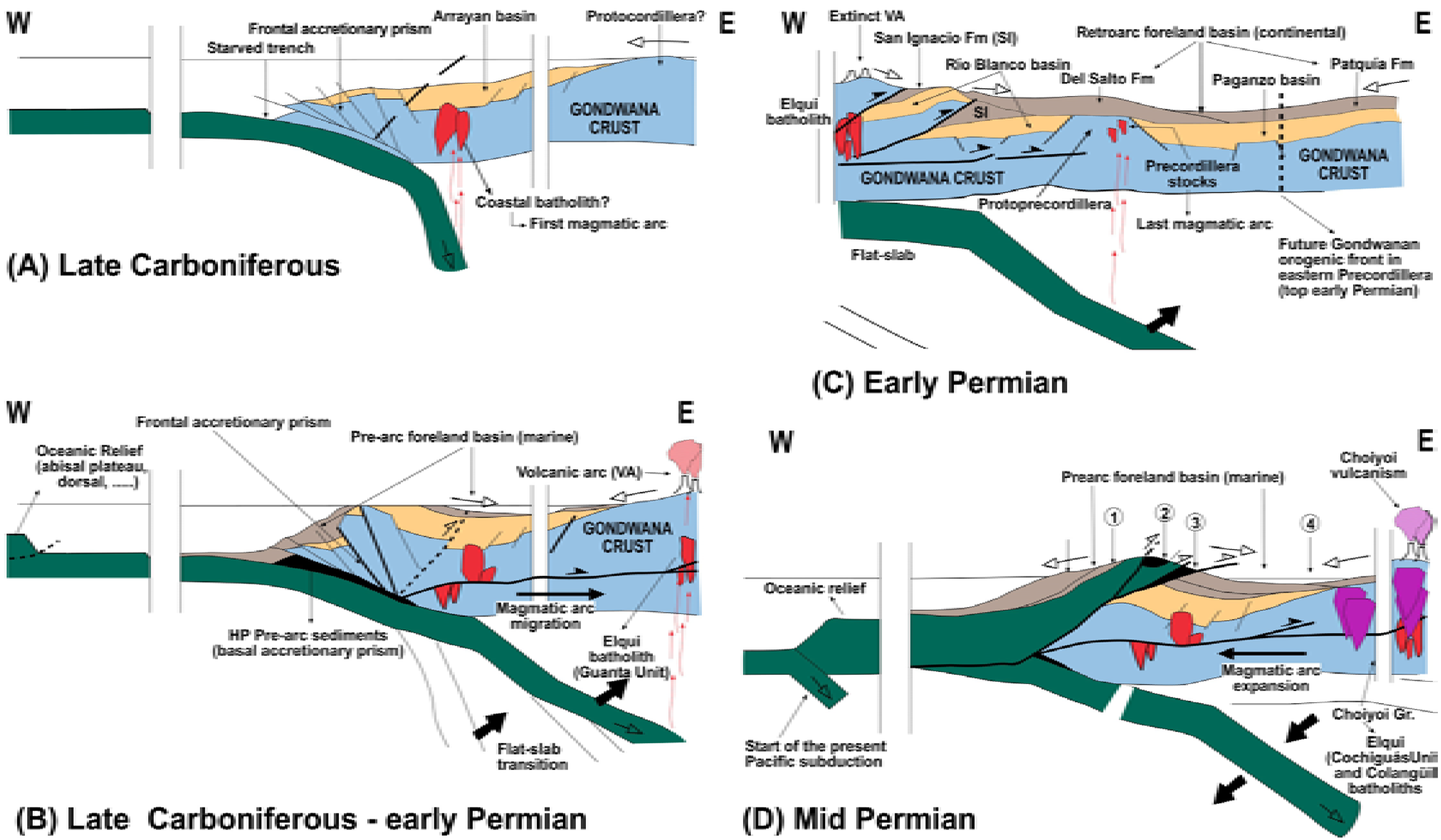

Fig. 11.- Geodynamic model for the Gondwanan episode in the Andes at 31º S latitude. (A) Palaeo-Pacific steep subduction. (B) Start of the flat-slab stage and beginning of the San Rafael orogeny. (C) End of the flat-slab stage. (D) Collision of an oceanic relief, slab roll-back and ending of the San Rafael orogeny. Present location of: 1) Huentelauquén coast, 2) Las Caldas Quebrada, 3) Mincha, 4) Illapel.

to Gondwana (old Pampia terrane), causing to Famatinian orogeny in Ordovician times (Fig. 10) and ended with the late Carboniferous – mid Permian San Rafael orogenic phase (Fig. 11b-d).

During the Palaeozoic, until Late Devonian times, the study sector of the Chilean coast was located on the western or rear border of the Chilenia terrane, which was positioned to the west of Gondwana and partially separated from this continent to the N (Fig. 10a and b) (Dalla Salda *et al*., 1992). At that time, Lower to Middle Devonian deposits were accumulating in a subsident marine platform on the rear (western) side of Chilenia – Occidentalia (Fig. 10a and b). Final docking of Chilenia to the Gondwana margin took place in Late Devonian – early Carboniferous times (Fig. 10c), producing the Chanic orogeny (Ramos, 1988) (Fig. 10c). After that, subduction began under the formerly passive western margin of Chilenia (Fig. 10c) and the accretionary complex began to grow, gradually forming a ridge that emerged above sea level leading to the creation of a retro-wedge basin separated from the oceanic trench (Fig. 11). This new basin, the Arrayán basin (Fig 10d and 11a), hosted the turbiditic series of the Arrayán Formation (Agua Dulce Metaturbidites and Puerto Manso formations) on its western side and platform deposits on its eastern side, which at the latitude of the study area are the Las Placetas beds (Reutter, 1974) and the Hurtado Formation (Mpodozis and Cornejo, 1988).

The continuous early Devonian to early Carboniferous sedimentation in the Arrayán basin (Charrier *et al*., 2007) demonstrates that the Chanic deformation did not affect the western passive margin of the Chilenia – Occidentalia terrane (Fig 10c). After the Chilenia – Gondwana collision, a new subduction process started at the western margin of Gondwana in the early Carboniferous (old Chilenia passive margin). Associated with this subduction, a first plutonic arc was developed (Fig. 11a) to the west of the former Chanic arc (Fig 10b-d) and close to the Gondwanan subduction zone (Fig. 10d). This new arc has a similar chronologic position that the Coastal batholith (Fig. 10d) exposed south of the study area, and yielded ages comprised between the late Carboniferous and early Permian (Hervé *et al*., 1988; Mpodozis and Kay, 1990; Parada, 1990; Parada *et al*., 2007) (Fig. 11a). Westwards of this plutonic arc, the Arrayán basin developed in a retro-wedge subsident basin. The scarcity or absence of late Carboniferous series in the accretionary prism (schists and quartz-schists of the ChMC), can be understood by the highly subsident character of the Arrayán basin that trapped the sediments and hindered their transport to the trench (Figs. 10d and 11a). Eastwards of the Arrayán basin, a shallow marine basin (Río Blanco basin) and a continental basin (Paganzo basin) were developed (Fig. 11c) (Limarino and Spalletti, 2006; Limarino *et al*., 2006). The sediments of these basins are respectively preserved in the Argentine Andean Frontal Cordillera and in the Precordillera (2 and 3 in figure 10d) and its main source area was located to the east, in the western Sierras Pampeanas (Spalletti *et al*., 2012) (Pampean high in Fig. 10d). These basins were partially separated in relation to a horst formed in the pre-Gondwanan basement (Protoprecordillera in figure 10d and 11c), which is an old remain of the Chanic orogen (Limarino and Spalletti, 2006; Limarino *et al*., 2006; Heredia *et al*., 2012) (Fig. 10c and d). That horst could be the local source area for the sediments of the Río Blanco and Paganzo basins.

The lack of late Carboniferous rocks in most of the Andean High Cordillera hinders the establishment of whether the Arrayán and Río Blanco basins were connected or not in this period. According to Spalletti *et al*. (2012), the lack of volcanogenic sediments suggests that the Río Blanco basin was open towards a proto-Pacific ocean (Fig. 10d), located to the west rather than being separated from it by a volcanic arc, as previously suggested by several authors. We consider that a discontinuous tectonic high (similar to the Protoprecordillera) could have existed between both basins, but without volcanic activity at this time (Protocordillera high in Fig. 11a). This tectonic high could have been submarine and/or subaerial, but in both cases the connection between the Paganzo and Arrayán basins must been maintained.

From the late Carboniferous to the mid Permian took place the San Rafael orogeny, in which the deformation spread from the accretion prism (in the study area) towards the east, reaching in Argentina the eastern Precordillera (Figs. 11b and c). At this time, while the subducted oceanic crust was getting younger, the plate was progressively rising up, passing to a flat-slab subduction (Ramos and Folguera, 2009). This interpretation permits to explain the rapid displacement of the deformation front towards the east in this period. At the same time, the magmatism migrated to the east, allowing the building of a new magmatic arc, the Elqui superunit of the Elqui – Limarí batholith (Fig. 11b), in early Permian times (~285 Ma) (Pankhurst *et al*., 1996). This is the age of the oldest intrusive superunit of this batholith: the Guanta unit (Nasi *et al*., 1985) that exhibits foliated fabrics and mid-crustal emplacement conditions (Sial *et al*., 1999). Extrusive rocks of Permian age, associated with the Elqui magmatic arc, covered the shallow marine deposits on the east side of the Arrayán pre-orogenic basin (Charrier *et al*., 2007).

The compressive deformation resulted in the uplift of both the acretionary prism and the western segment of the Arrayán basin, whose emerged portions were affected by erosion and supplied sediments to the oceanic trench (Fig. 11b). Part of these sediments entered in the subduction zone, reaching HP metamorphic conditions, while another portion resulted in the Huentelauquén Formation, deposited on a pre-arc foreland basin. With the eastward progression of the deformation, the tectonic setting to the east of the Elqui – Limarí batholith changed into a continental retroarc foreland basin. This basin, developed on top of the previous Río Blanco basin, hosted the San Ignacio Formation (Fig 11c). Due to its syn-orogenic character and its proximity to the volcanic arc associated with the Elqui – Limarí batholith, the San Ignacio Formation rest unconformably on the Cerro Agua Negra Formation (Río Blanco basin) and contains abundant interbedded volcanic rocks (Busquets *et al*., 2005, 2013a, b). Evidence of Permian magmatic activity in the Argentine Precordillera and Sierras Pampeanas can be also related with the latest stage of the flat-slab subduction process and indicates the maximum east migration of the arc (Ramos and Folguera, 2009). The lithospheric flexure linked to the development of the retroarc foreland basin also migrates to the east, producing the downfall of the ancient Protoprecordillera relief simultaneously with the deposition of the Del Salto Formation (Fig. 11c).

At the end of early Permian the main compressive process stopped in the eastern orogenic front and remained concentrated close to the oceanic trench until the middle Permian, ending before late Permian times. East-directed crustal thrusts developed, producing the exhumation of both the basal accretionary wedge and a part of the oceanic crust, as well as the thrusting of the ChMC units over the no- or low grade metamorphic Arrayán and Huentelauquén formations (Fig. 11d). This obduction process, possibly caused by the arrival at the subduction zone of some oceanic relief (guyots chain, oceanic ridge, oceanic plateau, etc.), that was unable to enter in the subduction zone (X terrane of Mpodozis and Kay, 1990), implied exhumation and retrograde metamorphism of the rocks of the ChMC (Fig. 11d).

The blocking of the subduction during the middle Permian may have produced the formation of a roll-back in the subducted slab which increased their inclination. This could be the cause for the significant changes described for this period in the configuration of the San Rafael orogen: (i) the migration to the west of the syn-orogenic basins and the deformation, which concentrated in the hinterland of the orogen (upper part of the Huentelauquén Formation); (ii) to the east, in the foreland, the orogeny was now completed and extension began that gave rise to very subsident sedimentary basins in which deposited unconformably the volcanic, sedimentary and volcano-sedimentary series of the Choiyoi Group. This intense volcanic activity was accompanied to the east of the study region by the intrusion of a large number of plutons in upper crustal levels (e. g. the Cochiguás unit of the Elqui – Limarí batholith and the Colangüil batholith, ~276-246 Ma, see Parada *et al*., 2007). Accumulation of the extrusive equivalents of the mentioned plutonic activity, the Choiyoi Group, remained active until late Triassic at this latitude (see Heredia *et al*., 2002, and literature therein). The Gondwanan orogenic episode ended in middle Permian times, giving way to the development of new tectonic conditions that ended with resumption of subduction in the current South American continental margin, which was fully active in Jurassic times and remained so until present.

6. Conclusions

-The rocks exposed in the Huentelauquén – Punta Claditas area can be grouped in two main units of different lithologies, separated by thrusts and deformed under different metamorphic conditions during the San Rafael orogen: the Arrayán basin deposits and the Choapa Metamorphic Complex (ChMC).

-The Arrayán basin hosted in its western side two sedimentary formations: the pre-orogenic and partially meta-sedimentary Arrayán Formation (Devonian – Carboniferous) and the syn-orogenic Huentelauquén Formation (late Carboniferous – middle Permian).

-The marine sediments of the Arrayán basin (>3000 m) began to accumulate in later Devonian times over a continental platform on the rear side of the Chilenia terrane. The deposition continued once the accretionary wedge was already developed and formed an outer ridge that separated a retrowedge basin (Arrayán basin) from the open sea.

-The ChMC (Carboniferous – Permian) consists of three units, namely schists, fine-grained gneisses and metabasites (amphibolites and retrogressed eclogites), separated by tectonic contacts. These units show a similar tectono-metamorphic history and depict structures developed during three consecutive deformation events (D1, D2, D3).

-In the ChMC, the crystallisation-deformation relationships indicate that HP-LT metamorphism was associated with the first episode of deformation (D1).

-The retrogression of HP metamorphic parageneses to greenschists-facies conditions occurs in relation to the exhumation of the ChMC. This process took place during the D2 deformation episode by the emplacement of east-directed thrusts, in connection with which different types of fault rocks were generated. The shear deformation during D2 led to the development of the regional foliation S2.

-The D3 deformation episode occurred under no- or low grade metamorphic conditions and is represented by the west-verging kilometre-scale anticline, and its associated thrust (Las Caldas thrust).

-A new geodynamic model is proposed to explain the evolution of the Gondwanan orogenic episode at 31º S in relation to the subduction zone developed in the south-western margin of Gondwana during early Carboniferous to middle Permian times. In late Carboniferous times, deformation and magmatism associated to this non-collisional orogeny began to migrate rapidly to the east, in relation with the flat-slab developed during most of the early Permian. At the end of the early Permian, an oceanic relief arrived to the trench, and due to the difficulty to enter in the subduction zone, an important deformation developed circumscribed to the continental margin. This deformation led to the exhumation of the accretional basal prism in the middle Permian, and to the obduction of a part of the subducted palaeo-Pacific oceanic crust onto the Gondwana continental margin.

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