Review of the polyorogenic Paleozoic basement of the Argentinean North Patagonian Andes: age, correlations, tectonostratigraphic interpretation and geodynamic evolution

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The presence of metamorphic rocks along the North Patagonian Andes is well known. All these metamorphic rocks are intruded by plutonic igneous rocks of Devonian, Carboniferous and Permian ages. The geographic localization of these rocks in the same geological province led to a first approach to grouping them under the same lithostratigraphic unit (Colohuincul Complex). Later studies, based on geological mapping and geochronological, structural and petrological data, gave an account of the differences among these rocks. The main distinction is that these metamorphic rocks were affected by two dissimilar Paleozoic tectono-metamorphic events. The oldest one is related to a lower Palaeozoic orogenic event (Famatinian orogeny) and the other one to an upper Palaeozoic event (Gondwanan orogeny). For this reason, it is necessary to distinguish and group the metamorphic rocks from the North Patagonian Andes basement in two different tectonostratigraphic units: the Colohuincul Complex (Cambrian-Ordovician) and the Cushamen Complex (middle Silurian-early Carboniferous) in order to better understand the geodynamic evolution of the Gondwana southwestern margin during the Paleozoic.

Keywords: Famatinian orogeny; Gondwanan orogeny; Paleozoic metamorphisms; Geodynamic evolution; North Patagonian Andes.

Introduction

The basement of the North Patagonian Andes is constituted by Paleozoic igneous and metamorphic rocks covered and intruded by Mesozoic and Cenozoic rocks related to the Andean cycle, at the end of which the current Andes was formed. This basement crops out discontinuously between 39° and 42° S latitude, mainly in the surroundings of the localities of Aluminé, San Martín de los Andes, Bariloche and El Maitén (Fig. 1). These outcrops are conditioned by the presence of major structures (thrust and/or anticlines) related to the Andean Orogeny, the compressive event that represents the end of the Andean Cycle.

Our recent research (Serra-Varela et al., 2016; 2019), including mapping, structural studies, and new radiometric ages of the basement rocks, suggests that this basement, usually grouped in a single lithostratigraphic unit, was greatly affected by two Paleozoic orogenic cycles, showing different tectonothermal and tectonostratigraphic evolutions.

The aim of this paper is to recognize the Paleozoic orogenic cycles that affected the North Patagonian Andes, distinguishing the pre-orogenic and synorogenic events (sedimentary, metamorphic and igneous) of each cycle. In order to do this, the igneous and metamorphic rocks of the early Paleozoic Colohuincul Complex will be redefined first, evaluating their possible correlations with other basement units of the North Patagonian and extra Andean region. The more abundant upper Paleozoic metamorphic rocks, known as the Cushamen Formation in the Patagonia territory and redefined here as the Cushamen Complex, will be considered to verify the difference between the geodynamic evolution and their belonging to a more recent orogenic cycle. Finally, based on a multidisciplinary work where the abundant previous structural, stratigraphic-sedimentological, petrological (both igneous and metamorphic) and geochronological data have been jointly studied, an integrated model for the geodynamic evolution during the Paleozoic is proposed.

Previous works and geological setting of the North Patagonian Andes basement

The isolated outcrops of the North Patagonian Andes basement rocks look quite similar in terms of lithologies and metamorphic grade and therefore, based on these characteristics, it is not possible to make a clear distinction among different lithostratigraphic units. For this reason, in previous works, the metamorphic basement of this Andean region was differentiated considering its protolith (sedimentary or igneous), geographic location or deformation style, distinguishing three main lithostratigraphic units: the Colohuincul Complex and Cushamen Formation, mostly metasedimentary, and the Huechulafquen Formation, mostly igneous or metaigneous.

Turner (1965) first defined the Colohuincul and Huechulafquen Formations in basement rocks found between the Lácar and Huechulafquen lakes. The Colohuincul Formation was defined as low-grade metamorphic rocks of Precambrian and Paleozoic age, while the Huechulafquen Formation was defined as granitic and migmatic rocks of Permian ages.

Afterwards, many authors (Caminos and Llambías 1984, Dessanti 1972, González Díaz and Nullo 1980) grouped the metamorphic rocks cropping out in the North Patagonian Andes between Aluminé and Bariloche and located north of 41º S (Fig. 1) as part of the Colohuincul Formation, and the metamorphic rocks located south of 41° S latitude as part of the Cushamen Formation (Volkheimer 1964).

Dalla Salda *et al*. (1991) re-defined the Colohuincul Formation as Colohuincul Complex, formed by medium to high-grade metamorphic rocks that cropped out in the North Patagonian Andes, and used the Cushamen Formation term for the metamorphic rocks located out of the Andean Cordillera, both with Precambrian to Palaeozoic ages. This criterion was also used in the subsequent regional geological mapping (1:250.000 scale) of the SEGEMAR (Cucchi and Leanza 2006, Escosteguy *et al.* 2013, Giacosa and Heredia 2001).

Characterization of the igneous-metamorphic basement rocks in the North Patagonian Andes

In this section, the lithostratigraphic units that constitute the igneous-metamorphic basement of the North Patagonian Andes will be described and correlated with others of the Andean sector and nearby areas. From oldest to most recent, the metamorphic units are the Colohuincul Complex (Cambrian- Middle Ordovician) and the Cushamen Complex (middle Silurian-lower Carboniferous) (Fig. 1). Moreover, the plutonic rocks (Devonian to Carboniferous) that intrude these units will be described separately.

Colohuincul Complex

Since the rocks from the Colohuincul Complex are scarce and little known, a more detailed description will be made with respect to their lithological and metamorphic characteristics in the locality where the complex was defined. These outcrops are located between the Curruhue and Lácar lakes, near the San Martín de los Andes village, in different hillsides including the Colohuincul Peak (2.165 m), which gives name to the unit (Fig. 1 and 2). The metamorphic rocks from the Colohuincul Complex mainly have a sedimentary protolith with minor igneous intercalations, being formed by schists, granofels, gneisses and migmatites. These metamorphic rocks are found as roof pendants in the Devonian plutonic rocks (Serra-Varela *et al.* 2019, 2016). Jurassic-Cretaceous igneous rocks intruding the Colohuincul complex were also recognized in this area. All these rocks are covered by Cenozoic volcanic materials (Escosteguy and Franchi 2010) (Fig. 3).

Metasedimentary rocks

The metasedimentary sequence shows granulometric and compositional differences that are seen as an S_0 foliation. Schists cropping out on both sides of the Lácar Lake are black with a well-developed lepidoblastic texture mainly defined by biotite and sillimanite crystals (Fig. 4a-b). The metamorphic association that defines this lithology is Qtz + Pl + Bt + Crd + Sil + Ilm ± Kfs (Mineral abbreviations according to Siivola and Schmid 2007). In some cases, plagioclase forms rims surrounding cordierite crystals (Fig. 4b-c). Cuspate areas of quartz are found distributed in grain boundaries and rounded crystals of biotite are present in larger crystals of quartz and plagioclase (Fig. 4c). All these microstructures are identified as indicators of a former presence of melt in the rocks. Coronas can be explained as back-reactions between peritectic grains and cooling melt (Brown 2002, Vernon 2011) while rounded biotites are interpreted as reacting minerals in melting reactions (Vernon 2011). In addition, postectonic muscovite porphyroblasts with symplectitic rims of quartz are common. These porphyroblasts can be related to a later rehydration stage between metamorphic minerals and aqueous fluids produced by migmatization (Brown 2002, Sawyer 2008, White *et al*. 2005).

Granofels are light grey, fine-grained with a predominant granoblastic texture (Fig. 4d). The foliation is incipient in these rocks due to the minority of micaceous minerals. The granofels paragenesis is defined by Qtz + Pl + Bt + Crd ± Sil ± Kfs. As schists, postectonic muscovite porphyroblasts are commonly found.

Migmatites are common in the area and partial melting microstructures found in non-migmatic rocks make them suitable for their protolith in a prograde path. Migmatites can be classified as metatexites and diatexites. Diatexites can be divided into schlieren and schollen types. In metatexites, mesosomes are defined by a second generation of biotites of bigger sizes than those of the paleosomes and are enriched in accessory minerals. Melanosomes are fine-grained and have similar textural and mineralogical characteristics as schists and granofels (Fig. 4e).

Leucosomes are white and medium-grained. They are composed of Qtz + Kfs + Pl + Bt. In schollen diatexites, muscovite is also present and the feldspar is microcline (Fig. 4f). Common accessory minerals are zircons and apatites. Mirmequites lobes are found in leucosomes that are projected into the feldspar (Fig. 4f). This microstructure has been recognized as a product of partial melting by Hasalová *et al*. (2008). In schlieren diatexites, schlierens are composed of biotite and ilmenites and are arranged in the form of a flow banding (Fig. 5a). They present polygonal granoblastic textures where large crystals of quartz, that are in optical continuity with lobate edges, can be found and can be interpreted as pockets of melt trapped in the rock in the form of microleucosomes (Vernon 2011).

Recent U-Pb dating of detrital zircons shed light on the maximum deposition ages for the protoliths of the Colohuincul Complex metamorphic rocks. Serra-Varela *et al*. (2019) defined a late Cambrian maximum sedimentation age (ca. 501 Ma) for the San Martín de los Andes protoliths. For equivalent rocks outcropping at the same latitude in Chile, Hervé et al. (2018) dated a schist boulder with medium-grade metamorphism similar to that in San Martín de los Andes with a maximum sedimentation age of ca. 460 Ma (Middle Ordovician, Darriwilian; Fig. 1).

Some authors (see Dalla Salda *et al*. 1991 and citations therein) have proposed Precambrian ages for the Colohuincul Complex, although these ages have not been confirmed in the most recent studies. However, since the basal part of this unit is unknown, Neoproterozoic ages for the Colohuincul Complex should not be totally excluded. This age is suggested by Heredia *et al*. (2016, 2018) in comparison with pre-Gondwanan lithostratigraphic units of the Andean Frontal Cordillera, located somewhat further north.

Metaigneous rocks

Metamorphic rocks from igneous protoliths are scarce in the Colohuincul Complex in the San Martin de los Andes area and can be classified as amphibolites. They were only found in two small different outcrops. In both, amphibolites are found as sheet-like intrusions with sharp contacts parallel to the regional foliation of the metasedimentary rocks.

One of the outcrops is located at the base of the Colorado hill where the rocks are grey and fine-grained with porphyroblasts included in a granoblastic matrix. The metamorphic association of this outcrop is defined by Bt + Am + Pl + Qtz + Grt. Garnet is found as porphyroblasts with sizes up to 3 mm (Fig. 5b). Amphiboles are zoned with colourless cores and green rims that can be identified as cummingtonite-grunerite and hornblende, respectively (Fig. 5c). Apatite is abundant in this sample.

The second outcrop is located on the East side of the Curruhuinca hill. This rock is green and medium-grained with a porphyroblastic texture. Garnet porphyroblasts are syntectonic of the rock main foliation. These porphyroblasts reach up to 4 mm in diameter with abundant inclusions of quartz and biotite. The matrix of the rock is composed of Bt + Am + Pl + Qtz. There are plagioclase crystals larger than the ones in the matrix, showing a compositional zoning with altered cores and clear unaltered rims (Fig. 5d). These crystals could be interpreted as relictic phenocrysts from the original igneous protolith. Zircons and apatites are found as accessory minerals.

Characteristics and age of the metamorphism

The metamorphism affecting the Colohuincul Complex in its type locality has been described by Dalla Salda *et al.* (1991) as an upper Precambrian metamorphic event dated by whole rock Rb-Sr. However, an anatectic granite has been recently dated back to ca. 434 Ma (Serra-Varela et al., 2019), suggesting that peak metamorphic conditions would be early-middle Silurian. Moreover, all the metamorphic rocks are intruded by plutonic rocks of ca. 400 Ma (Hervé *et al*., 2016, Pankhurst *et al.* 2006, Varela *et al.* 2005), where the Colohuincul Complex appears as xenoliths (Fig. 2 and 3), confirming a pre-Devonian age for the metamorphic rocks.

Age and characteristics of the deformation

The rocks of the Colohuincul Complex developed up to three tectonic foliations where the main one is defined as a regional S_2 cleavage, which contains the peak metamorphic assemblage. This foliation is marked by the orientation of biotite and sillimanite crystals in the metasedimentary unit (Fig. 4b). S_1 foliation can be recognized in some thin sections where it appears as relictic microfolds and polygonal arcs defined by small crystals of graphite and biotite. S_0, S_1 and S_2 are usually subparallel (Fig. 6).

S_2 foliation is found with different orientations mostly because it is affected by a posterior folding stage that produces crenulations, and finally, S_3 spaced crenulation cleavage is characterized by a low-grade mineral association related to the dissolution in the limbs and concentration of opaque minerals parallel to the cleavage plane. The folds related to the S_2 foliation (F_2) are isoclinal and they are rarely found, showing axes that plunge from NW to SE. The F_3 folds vary from open to tight with axes oriented from N-S to NW-SE and varied plunge showing SW vergence in some cases (Fig. 6). Leucosomes from metatexites are found parallel to the S_2 foliation and are subsequently affected by F_3 folds. Since the anatectic event has been dated at ca. 434 Ma (Serra-Varela *et al*. 2019) and leucosomes are syn-post S_2 foliation, it can be interpreted that the first two deformational events have occurred in the late Ordovician–early Silurian. Since the Devonian granitoids cut the three tectonic fabrics of the metamorphic rocks, the third deformation that affects the migmatites should be posterior to 434 Ma and prior to 400 Ma. Finally, there are faults and thrusts affecting the metamorphic rocks with associated open folds (F_4) that are also deforming the Mesozoic-Cenozoic lithostratigraphic units of the area, thus they are probably associated with the Andean Orogeny (Fig. 6).

Regional correlations

Metamorphic rocks with similar maximum sedimentation ages to the ones in San Martín de los Andes (Cambrian-Middle Ordovician) can be found in a large basement outcrop of Bariloche where three samples present maximum sedimentation ages of 500, 485 and 470 Ma (Hervé *et al.* 2018; Fig. 1) but these metamorphic rocks seem not to register a Silurian metamorphic event.

García-Sansegundo et al. (2009) interpreted a late Carboniferous-early Permian age for the metamorphism of these rocks, based on the presence, in this area, of co-deformed foliated intrusive rocks with crystallization ages of ca. 323-310 Ma and post-orogenic granitoids of ca. 295 Ma (Pankhurst *et al.* 2006). In the same area, Martínez *et al.* (2012) found two groups of U-Th-Pb ages in monazites of 391 and 350 Ma, which were attributed to prograde and retrograde metamorphisms, respectively, and Hervé *et al.* (2018) described metamorphic zircon rims of 330-260 Ma and 376-290 Ma (Fig. 1). According to these data, in the Bariloche area, the Colohuincul Complex does not register the characteristic early Paleozoic metamorphism as in its type locality, but it does register subsequent events developed in late Paleozoic times which will be described later. The end of this tectonometamorphic event has been dated at 305-296 Ma (late Carboniferous-early Permian), in the Chilean Coast and the North Patagonian Andes, by Willner *et al.* (2004) and Oriolo *et al.* (2019), respectively.

Other rocks with maximum sedimentation Cambrian ages are present in the central and eastern part of the Patagonia but they were affected by older tectono-metamorphic events than the ones found in the North Patagonian Andes. While the maximum sedimentation age for the protoliths in the North Patagonian Andes is constrained to upper Cambrian – Lower Ordovician, the sedimentation ages for the eastern part of the Patagonia are restricted to lower Cambrian ages (González *et al.* 2018, Greco *et al.* 2017, Pankhurst *et al.* 2006, Rapalini *et al.* 2013) with a metamorphic event that ends in early Ordovician ages (Greco *et al*. 2017, Pankhurst *et al*. 2006) which can be correlated with de Ross orogeny of the Patagonia, as Ramos and Naipauer (2014) stated.

The Cushamen Complex

The Cushamen Complex was originally defined as the Cushamen Formation (Volkheimer 1964). However, owing to its high complexity, due to its great lithological variety, strong deformation and metamorphism, the authors of this paper suggest denominating this lithostratigraphic unit as a Complex, in the same manner Dalla Salda *et al*. (1991) renamed the Colohuincul Formation of Turner (1965). This lithostratigraphic unit comprises medium to high-grade metamorphic rocks from sedimentary and igneous protoliths. Outcrops associated with the Cushamen Complex have been described between 40° and 43° S, being the most representative ones those located in the surroundings of Cushamen (type locality), Piedra del Águila, Gastre and Río Chico villages, all located in the extra-Andean region but not far from the Andean front range (Fig. 1).

Lithological characterization and age

The metamorphic rocks of the Cushamen Complex are gneises, metadiamictites, metavulcanites, schists with garnet and sillimanite and occasional staurolite, and migmatites (Cerredo 1997, Cerredo and López De Luchi 1998, 2010, Dalla Salda *et al*. 1994, Duhart *et al*. 2002, Giacosa *et al.* 2004, Volkheimer 1964).

According to Lopez de Luchi *et al.* (2010), major element chemical data point to an active continental margin as a probable setting for the sedimentary protoliths of the Cushamen Complex with compositional signatures, suggesting their provenance from felsic plutonic and volcanic detritus as well as recycled mature polycyclic quartzose detritus. For these authors, the metagranitoids are calc-alkaline, peraluminous Bt-tonalites to Ms (± Bt ±Grt)-granites to leucogranites with metavulcanites, dikes and layers (sills and/or lava flows) of dacitic to basaltic composition.

Geochronological analyses of the Cushamen Complex suggested a maximum sedimentation age for the sedimentary protolith between lower Carboniferous (ca. 335 Ma; Hervé *et al*. 2005) and Silurian (ca. 440 Ma; Hervé *et al*. 2018, Pankhurst *et al*. 2006) (Fig. 1). However, the oldest sedimentation age cannot be earlier than a Famatinian metamorphism (peak at ca. 434 Ma) and deformation that affected the Colohuincul Complex until Wenlock. Therefore, the oldest sedimentation age of this lithostratigraphic unit must be middle Silurian, and the more recent early Carboniferous.

Characteristics and age of the metamorphism

These metamorphic rocks are affected by a green schist-amphibolite facies metamorphism reaching, at least, a part of the Cushamen Complex under high grade conditions, marked by the presence of migmatites near Piedra del Águila and Rio Chico (Cerredo 1997, Varela *et al*. 2005). The first geochronological analyses proposed that the metamorphic event affecting the Cushamen Complex could be assigned to middle - late Proterozoic (Linares *et al*. 1988). Afterwards, Ostera *et al*. (2001) assigned a Devonian metamorphic age to a Precambrian protolith of the Cushamen Complex.

However, Lopez de Luchi *et al*. (2010) proposed that part of the Cushamen Complex underwent a late Devonian metamorphic event (ca. 370 Ma). Moreover, an age between ca. 380 and 360 Ma (Middle-late Devonian) was determined by Lucassen *et al*. (2004) for the metamorphic peak associated with a local migmatization (Fig. 1).

In the area of El Maitén, Pankhurst *et al*. (2006) described one main metamorphic peak between 360-380 Ma and a subordinated one affecting the Cushamen Complex between 330-340 Ma (Fig. 1).

In the Bariloche Area, García-Sansegundo *et al.* (2009) described a late Carboniferous-early Permian regional metamorphism, developed under low to intermediate pressure conditions, superimposed on a previous high-pressure metamorphism. This high-pressure metamorphism, along with an associated foliation, is only preserved in garnets and albite crystals.

According to the data previously exposed, two metamorphic events affected the Cushamen Complex, the first one in Middle-late Devonian - early Carboniferous times and the last one in the late Carboniferous-early Permian.

Age and characteristics of the deformation

In the extra-Andean zone, next to the North-Patagonian Andes (Limay-Collón Curá river junction), Serra-Varela *et al*. (2018) describe schists with up to three tectonic foliations and migmatites that were mobilized in favour of an S_2 foliation. These metamorphic rocks are intruded by small granitic plutons and dikes of *ca*. 348 Ma in age (Varela *et al*. 2005), which only show one foliation, related to discrete N-S ductile shear zones that were later folded.

In the Río Chico area, García-Sansegundo *et al*. (2008) have recognized an S_2 crenulation cleavage in the Cushamen Complex, where S_1 is preserved as polygonal arcs within the microlithons of the S_2 regional foliation (Fig. 7). These two tectonic foliations were also recognized in nearby areas of the extra-Andean region by Giacosa *et al*. (2004 and cited therein). The high-grade metamorphic paragenesis is associated with this S_2 pervasive foliation and the related folds show an N-S trend and eastern vergence (Figs. 7 and 8).

In this area, Giacosa *et al*. (2004) described the presence of a first metamorphic event related to a contact metamorphism followed by a regional metamorphism in amphibolite conditions. The regional event shows a clockwise P-T path that reached the metamorphic peak during an intermediate decompressive stage (Cerredo 1997).

In the North-Patagonian Andes, this event is post-dated at ca. 295-272 Ma (Varela *et al*. 2005, Pankhurst *et al*. 2006) by the intrusion of late- and post-tectonic granitoids which contain xenoliths of a foliated Cushamen Complex (von Gosen 2009). This deformation can be correlated with the Gondwanan orogeny of García-Sansegundo *et al*. (2009) and Heredia *et al*. (2016, 2019). This last and pervasive Gondwanan deformational event would obliterate the structures related to previous Gondwanan metamorphic events, Devonian and Carboniferous (Lucassen *et al*. 2004, Pankhurst *et al*. 2006, Lopez de Luchi *et al*. 2010, Martínez *et al*. 2012, Hervé *et al*. 2018, among others), which are preserved in zircons, titanites and monazites with some related tectonic foliations preserved in garnets and albites (García-Sansegundo *et al*. 2009).

Although the basement rocks from the Bariloche area were considered as part of the Colohuincul Complex, their deformation and metamorphism correspond to the last Gondwanan orogenic event. Thus, García-Sansegundo *et al*. (2009) described up to three foliations affecting both these rocks and the Upper Carboniferous and lower Permian granites that intrude them. The two most modern tectonic (S_2 and S_3) foliations affect the Upper Carboniferous syn-orogenic (S-type) granites of ca. 323-310 Ma but do not affect the post-orogenic lower Permian granitoids of ca. 295 Ma (Pankhurst *et al*. 2006). The main structures of the area correspond to the D2 deformation episode. Those structures are represented by a regional schistosity (S_2) associated with NW–SE trending and NE-verging folds. D2 structures are folded by upright open folds (D3) with an associated crenulation cleavage. The vergence of the D2 structures could indicate the foreland location of this orogeny to the NE part of the study area. D2–D3 developed under regional intermediate - low pressure metamorphic conditions. The transition from high pressure to intermediate pressure metamorphic conditions can be related to the emplacement of crustal scale thrusts during D2. High temperature conditions were reached during D2–D3 episodes, as evidenced by a regional migmatization and the intrusion of Upper Carboniferous to Permian syn- to post-orogenic S-type granitoids. The S_2 and S_3 foliations can be correlated with the two tectonic foliations found in the Rio Chico area, supporting the same deformational style.

In the extra-Andean sector, several authors described shear zones after the regional metamorphic event (Cerredo and López De Luchi 1998, von Gossen 2003, von Gossen and Loske 2004, among others). This last tectono-metamorphic event is related to mylonitic rocks affecting the metamorphic rocks of the Cushamen Complex and the plutonic rocks of lower Permian age or younger ones that intrude them (Varela *et al.* 2005, Pankhurst *et al.* 2006). This event can be correlated with the transpressive deformation of the subduction-related Tabarin orogeny, late Permian-Triassic in age (Heredia *et al.* 2016), which marks the ending of the Tabarin orogenic cycle (Fig. 9). The main structures developed during this orogeny in Patagonia are sinistral shear zones (Coira *et al.* 1975, Nullo 1978, Proserpio, 1978, Volkheimer and Lage, 1981, among others), which, in some cases, reactivated previous Gondwanan structures. The Tabarin orogenic cycle is related to the subduction developed under Pangea after the accretion of Western Antarctica to Gondwana at the end of the Gondwanan cycle (Heredia *et al.* 2016, 2018) (Fig. 11). In Patagonia, the pre-orogenic early-Permian sequences of the Tabarin cycle (e.g. the Golondrina Formation, Fig. 9), rest unconformably over the Famatinian and Gondwanan basement, mainly outcropping in the southern part of the extra-Andean Patagonia. The retroarc synorogenic series of the Tabarin cycle, defined in the Antarctic Peninsula (Heredia *et al.* 2016), have not been recognized so far in the Patagonian territory.

García-Sansegundo *et al*. (2008) proposed that inverse faults with an N-S to NNW-SSE trend related to the Andean Cenozoic deformation in the North Patagonian Andes were formed by the reactivation of more ductile Gondwanan structures with the same trends and tectonic transport.

Regional correlations

The oldest part of the protoliths of the Cushamen Complex can be equivalent in age to the Sierra Grande Formation of the North-Patagonian Massif (Fig. 9). This formation presents a Silurian-Devonian age (Wenlock at the base, ca. 433-427 Ma.) based on fossil records (Manceñido and Damborenea 1984, Müller 1965), in agreement with a detrital zircon analysis which depicts a maximum sedimentation age for this unit at ca. 428 Ma. (Uriz *et al.* 2011). The Sierra Grande Formation is a siliciclastic succession composed of sandstones, shales and scarce conglomerates with some intercalations of basic volcanic rocks. This formation unconformably lies over lower Paleozoic metamorphic rocks deformed by the Famatinian orogeny (late Ordovician-middle Silurian) and Ross orogeny (late Cambrian –early Ordovician) of the Patagonia.

The upper part of the Cushamen Complex (Fig. 9) can also be correlated to the Esquel Formation (as described by Cucchi (1980)), (Fig. 10a), and its equivalents of the Tepuel Group basal part (Page *et al.* 1984), all of them litostratigraphic units Upper Devonian- Lower Carboniferous in age, according to Hervé *et al.* (2005) and Carrizo and Azcuy (2000) (ca. 373 Ma detrital zircons at the base and Lower Carboniferous floras at the top of the sequence).

Both the Sierra Grande and Esquel Formations have been described as part of non- to low-grade metamorphic areas of the Gondwanan orogen, where their stratigraphic characteristics are very well preserved, unlike the equivalent Cushamen Complex that could represent outcrops in the innermost parts of this orogen.

The correlation between the Pampa de Tepuel Formation (middle part of the Tepuel Group) and the Cushamen Complex, as Marcos *et al*. (2017) have proposed, is arguable for us on the grounds that: (i) the Upper Carboniferous Pampa de Tepuel Formation (Fig. 10b) and its equivalents rest on the oldest Palaeozoic lithostratigraphic units with an angular unconformity; (ii) in this formation but especially in the upper part of the Tepuel Group (Mojon de Hierro Formation of Upper Carboniferous-lower Permian age), the presence of abundant and thick conglomeratic intercalations (Figs. 10c and 10d), with almost no volcanic rocks, and rapid changes in facies and thickness seem to indicate the synorogenic deposition of these formations; (iii) this indicates that these formations wouldn´t reach high-grade metamorphic conditions like the pre-orogenic (pre-collisional) successions (as the Cushamen Complex, Esquel Formation, etc).

The Paleozoic igneous rocks

The presence of Mesozoic to Cenozoic igneous rocks along the North Patagonian Andes, particularly studied south of 40° S latitude (Aragón *et al.* 2011, Castro *et al*. 2011, Hervé *et al*. 2007, Pankhurst *et al*. 1999), is well known. North of this latitude, plutonic igneous rocks have been mostly assigned to the Huechulafquen Formation of late Paleozoic-early Mesozoic age (Cucchi and Leanza 2006, Turner 1965), correlated to the Permian-Triassic Choiyoi magmatism (Llambías and Sato 2011).

Later geochronological studies of outcrops assigned to the Huechulafquen Formation, north of 39° 10´S, showed that most of these rocks presented ages between 111 and 65 Ma (Latorre *et al.* 2001, Lucassen *et al.* 2004, Urraza *et al.* 2011), reassigning these outcrops to the Paso de Icalma Granodiorite (Cucchi and Leanza 2006) of Cretaceous age (Fig. 2).

However, the igneous rocks between 38° 50´and 39° 10´S have been constrained between 306 and 209 Ma (Fig. 2; Hervé *et al*. 2018, Latorre *et al*. 2001, Lucassen *et al*. 2004, Varela *et al*. 1994). This group of ages shows that, at least, a part of the plutonic igneous rocks from the northern part of the Patagonian Andes records a late Paleozoic– early Mesozoic magmatism, as first assigned by Turner (1965) for the Huechulafquen Formation.

Likewise, the rocks assigned to the Huechulafquen Formation near the San Martín de los Andes region (just north of 40º S) turned up to be older than expected, recording a Devonian plutonic event between 420 and 374 Ma (U-Pb SHRIMP in zircons; Hervé *et al*. 2016, Pankhurst *et al*. 2006, Varela *et al*. 2005) (Fig. 2).

South of 40º S, Pankhurst *et al.* (2006) described four late Palaeozoic plutonic events in the North-Patagonian territory, being the three oldest ones related to the Gondwanan cycle and the youngest one with the Tabarin cycle, which reached the Triassic. According to these authors, the oldest late Paleozoic magmatic event has been dated between 401 and 371 Ma (Devonian), the intermediate one has two pulses, one in 330-323 Ma (Lower Carboniferous) and another one in 320-310 Ma (late Carboniferous), and the youngest one in 295-257 Ma (Permian) (Fig. 1). Only this last plutonic event can be correlated with the Huechulafquen Formation. These plutonic igneous rocks intruding the Colohuincul and Cushamen metamorphic complexes are composed of I-Type and S-type granitoids (Pankhurst *et al*. 2006). The granitoids form two separate alignments with NNW-SSE trends so that the Devonian alignment seems to be located more to the east than the early Carboniferous alignment (Fig. 1), while the Upper Carboniferous and Permian igneous rocks have a more irregular distribution. The igneous events described by Pankhurst *et al.* (2006) will be considered but, since the

Permian igneous rocks are mostly post-Gondwanan (the last Palaeozoic orogenic phase), they will not be explained in this work.

Devonian plutonic igneous rocks

Devonian plutonic igneous rocks can be well recognised in the San Martín de los Andes area represented by granodiorites, tonalites, granites and gabbros, being the former the most abundant lithological type (Serra-Varela *et al*. 2019). The contacts between these rocks are transitional. In this area, the Devonian plutonic rocks crosscut the cleavages of the Colohuincul Complex, developed during the Famatinian orogeny (Serra-Varela *et al*. 2019), which appears as roof-pendants and foliated xenoliths into the plutonic rocks. In the San Martín de los Andes area, the Devonian plutonic rocks are affected by spaced ductile-brittle shear zones developed under low-grade metamorphic conditions during the Gondwanan orogeny. The general trend of these Gondwanan structures is NNW-SSE dipping WSW. These shear zones have widths up to tens of meters (Serra-Varela *et al*. 2019).

Varela *et al*. (2015) described the granites and granodiorites as sub-alkaline, calcalkaline peraluminous rocks and they related these granitoids to a subduction zone (I-type granitoids) with minor components of continental crust.

Carboniferous plutonic igneous rocks

The Carboniferous plutonic rocks are well exposed in the surroundings of Bariloche, Cushamen and Piedra del Águila. Varela *et al*. (2005) described the Carboniferous plutonic rocks as I-type granites and monzogranites with calcalkalines, peraluminous to metaluminous signatures. In the tectonic discrimination plots, they show a continental arc signature evolving to post-collisional arcs. As regards Pankhurst *et al*. (2006), they differentiated two types of granitoids within the Carboniferous rocks, an I-type and an S-type belt. The I-type comprises the igneous rocks of Lower Carboniferous age (323-330 Ma) while the S-type igneous rocks present Upper Carboniferous ages (310–320 Ma).

The I-type rocks are foliated metaluminous hornblende-biotite granitoids with a low abundance of lithophile trace elements and rare earth element (REE) patterns, typical of Andine type calcalkaline arc rocks. Furthermore, positive εNdt values (+0.1 to +2.8) and low initial $^{87}Sr/^{86}Sr$ (0.7034–0.7046) indicate a long-term light-REE depleted source such as the upper mantle (Pankhurst *et al.* 2006). These I-type igneous rocks should represent the western migration (retraction to the trench) of the Devonian magmatic arc. This arc migration precedes the collisional event of the Gondwanan orogeny.

The S-type granitoids are scarcer than those of the I-type. These granitoids are garnet-bearing deformed peraluminous leucogranites with high SiO_2 contents, with negative εNdt values (−5.0 to −6.0) and relatively high initial $^{87}Sr/^{86}Sr$ (0.7078–0.7098), indicating an upper crustal melting (Pankhurst *et al*. 2006) that could have been produced by crustal thickening during the collisional stage of the Gondwanan orogeny (Fig. 9).

Discussion

Tectonostratigraphic interpretation of the Colohuincul Complex

Considering the deformation, metamorphism and age of the Colohuincul Complex, it can be interpreted that the protoliths of these metamorphic rocks are associated with the pre-orogenic succession of the Patagonian Famatinian orogenic cycle, developed in the passive margin of the Western Patagonia microcontinent, according to Heredia *et al*. (2016, 2018), where the main structures show N-S to NNW-

SSE orientations and a W to SW vergence (Fig 11). The synorogenic succession of this orogenic cycle should be of a similar age to the Famatinian orogeny in this sector: late Ordovician to middle Silurian (Wenlock). However, there is no record of this synorogenic succession, probably due to the high erosion level of the Famatinian Cordillera in Patagonia.

Taking into consideration that the metamorphic rocks from Bariloche can be correlated to the Colohuincul Complex of San Martin de los Andes with respect to their age and lithology, it could be said that these rocks represent a pre-orogenic succession of the Famatinian orogenic cycle that did not register the tectono-metamorphic event related to the end of the Famatinian cycle. It can be interpreted that the late Paleozoic (Gondwanan) metamorphic events that affected this sequence could have obliterated the evidence of the early Palaeozoic Famatinian event or even that the Famatinian event did not affect these rocks. This might be possible if these rocks would have been located in the foreland or in the external western branch of the Famatinian orogen where it did not propagate or was developed under non-metamorphic conditions, respectively. Later, these rocks were included in the hinterland of the Gondwanan orogen (6 in Fig. 11), where they were tectonically transported to the NE and away to the Gondwanan suture (see García-Sansegundo *et al.* 2009). This event would have located these rocks closer to their equivalents in the hinterland of the Famatinian belt.

Tectonostratigraphic interpretation of the Cushamen Complex

As was previously described, the Cushamen Complex presents a wide range of sedimentation ages for its protoliths ranging from Silurian to early Carboniferous. Moreover, the metamorphism associated with these rocks is related to Devonian, early Carboniferous and late Carboniferous-early Permian events. This deformation and metamorphism could be related to the Gondwanan cycle in Patagonia (Heredia *et al.*

2016, 2019) (Fig. 9). These authors divided the Gondwanan cycle into two parts, the first one being an Andean–type subduction related margin (Devonian-early Carboniferous) that later turned into a collisional margin (late Carboniferous– early Permian) (Fig. 9).

In this context, the intense deformation and metamorphism of the Cushamen Complex could be associated with a pre-orogenic succession of the Gondwanan cycle. However, the development of the Gondwanan orogeny in an active subduction margin would allocate the upper part of the strongly deformed Cushamen Complex to a syn-orogenic sequence, related to an Andean type orogen (Fig. 9). The late Devonian and early Carboniferous ages of the metamorphic climax related to this orogenic event imply that the Esquel Formation and its equivalents, correlated with the upper part of the Cushamen Complex, represent a pre-collisional synorogenic succession that would not be affected by a high-grade metamorphism.

The oldest part of the Cushamen complex, equivalent in age to the Sierra Grande Formation, could have been deposited close to the volcanic arc, while the eastern position of the Sierra Grande Formation would have been placed in the back-arc basin, but further from the volcanic arc.

In the Bariloche area, the Gondwanan deformation is much more intense and the metamorphic rocks register the peak of their metamorphism in the late Carboniferous, in an event of high pressure followed by decompression that ends in early Permian times (García-Sansegundo *et al*. 2009). This metamorphism would be associated with the collisional orogenic event of the Gondwanan orogeny (Fig. 9).

Only the Pampa de Tepuel Formation and the rest of the Tepuel Group (Upper Carboniferous-lower Permian), which unconformably cover the oldest Gondwanan sequences (Silurian to early Carboniferous), are similar in age to the main collisional deformation event of the Gondwanan orogeny (late Carboniferous-early Permian) and could be related to the synorogenic infill of a Gondwanan peripheral foreland basin (Fig. 9).

Integrated geodynamic evolution

The basement metamorphic rocks from the North Patagonian Andes record two main Paleozoic tectono-metamorphic events, in lower Paleozoic and upper Paleozoic times. These events coincide with two orogenic cycles further recognized in the Patagonia by Heredia *et al.* (2016, 2018) and Serra-Varela *et al.* (2019): the Famatinian and Gondwanan cycles (Fig. 9 and 11). Other constrains on the geodynamic evolution proposed by these authors are presented in this work.

The first tectono-metamorphic event resulted in the metamorphic rocks of the Colohuincul Complex, being the oldest one found in the North Patagonian Andes. This is reflected in the age of the metamorphic peak (Silurian, Wenlock) associated with a partial melting event. This orogenic event is described by Heredia *et al.* (2016) as a collisional event, which is the result of the accretion of the Western Patagonia continental fragment to Gondwana, giving place to the Patagonian Famatinian orogeny (Figs 9 and 12). This orogeny was developed in late Ordovician-middle Silurian (Wenlock) times (Serra-Varela *et al.* 2019) and it affected a pre-orogenic sequence constituted by the Cambrian-Ordovician protoliths of the Colohuincul Complex, deposited on the passive western and eastern margins of Western Patagonia (Heredia *et al*. 2016) (Fig. 12a). The main structures of the Patagonian Famatinian Orogeny are located in the middle part of the Patagonia and show a N-S to NW-SSE trending (Fig. 11). These structures characterize a double vergence collisional orogen with a well-developed hinterland. The location of the suture is uncertain, but it should be located in the middle of the internal zones of this orogen, where the structural vergence changes

(Fig. 11). The high-grade metamorphism of the Colohuincul Complex was developed in the western branch hinterland of the Famatinian orogenic belt (with W/SW structural vergence, Fig. 11). Conversely, near the western margin of Western Patagonia, the Famatinian orogen foreland would be located where the Colohuincul Complex was slightly deformed or not deformed at all, under very low grade to non-metamorphic conditions (Fig. 12b).

To the north of the Huincul lineament (Fig. 11), the Famatinian orogen ends later, close to the Silurian-Devonian limit (Mulcahy *et al.* 2011), so this lineament must have constituted a major tectonic boundary in early Paleozoic times.

In Patagonia, the Famatinian orogeny probably ended because a subduction began in the new margin of Gondwana (ancient western margin of Western Patagonia) where the oldest rocks of the Cushamen Complex and the Sierra Grande Formation were being deposited, being this last formation located further eastwards and away from the volcanic arc (Fig. 12c). In this subduction context, the less deformed rocks of the ancient Colohuincul Complex (Cambrian-Silurian) and the Chilean Western Series (Devonian-Carboniferous) were introduced in the subduction zone (Fig 12c) from the upper Silurian to late Carboniferous, where both reached high pressure conditions in late Carboniferous times (Willner *et al.* 2004).

During Devonian times, this subduction resulted in a large magmatic arc with exposures of plutonic rocks not only in the San Martín de los Andes region, but also in the North Patagonian Massif, near Gastre and Colan Conhué (Pankhurst *et al.* 2006). This magmatic arc produced a metamorphism in the rocks located in different sites. The plutonic igneous rocks of this arc were intruded in the already metamorphosed Famatinian basement (Colohuincul Complex) from San Martín de los Andes, where they appear as roof pendants over the Devonian granitoids. In this scenario, the

Devonian metamorphism that characterizes the Cushamen Complex of the Andean and extra-Andean regions was developed. The metamorphism shows a prograde path recorded in monazite, titanite and zircon rims, with ages between 380 Ma and 360 Ma (late Devonian) (Pankhurst *et al.* 2006, Lucassen *et al,* 2004, Martínez *et al*. 2012, Hervé *et al.* 2018). This metamorphism is contemporary with a compressive deformation related to an Andean-type orogen (Fig. 9), the subduction-related Gondwanan orogen (Heredia *et al.* 2018, 2016), and with the sedimentation of the upper part of the Cushamen Complex and the basal part of the Esquel Formation, its non-metamorphic equivalent. Thus, the base of the Esquel Formation is an unconformity that would represent the beginning of the Gondwanan syn-orogenic sedimentation in a retroarc foreland basin, located in the current Argentinean Andes.

During the early Carboniferous, the magmatic arc migrated to the west and, related to this arc, a new metamorphic event was developed with ages between 330 and 320 Ma (Pankhurst *et al.* 2006) (Fig. 12). The migration of the magmatic arc and the change to a compressive stage in the tectonic regime could be related to the arrival of an oceanic relief in the trench (Chaitenia island arc as described by Hervé *et al.* 2016). During this time, the upper part of the Esquel and Cushamen lithostratigraphic units was deposited in the back-arc (Fig. 12), while the Chilean Eastern and Western series were deposited in the fore-arc (Hervé *et al*. 2013, Willner *et al*. 2004).

In the Cuyanan Sector (Heredia *et al.,*2016, 2018), located to the north of the study area (north of 38º S) and the Huincul lineament (HL in Fig. 11), the collisional Chanic orogeny was developed in Late Devonian-early Carboniferous times (Heredia *et al.* 2018). In this sector, the orogenic event is related to the accretion of the Chilenia microcontinent to Gondwana (Ramos *et al.* 1986, 1988). However, some authors interpret that the Chanic orogeny has also developed south of the Huincul lineament

(Patagonian Sector from Heredia *et al.* 2016, 2018), mostly based on metamorphic ages and paleomagnetic data (Martínez *et al.* 2012, Tomezzoli, 2012, among others) although no structural data or characteristic features of a collisional orogen have been described for this period of time in Patagonia. In this sense, and in agreement with Heredia *et al.* (2016, 2018), the Huincul lineament should represent the southern limit of Chilenia and the Chanic orogen.

In the late Carboniferous, the collision of a new continental fragment with the Gondwana margin (Western Antarctica according to Heredia *et al.* (2016) gave rise to the Gondwanan collisional orogen, which reached the early Permian. This orogen, which shows a NW-SE trend in northern Patagonia, turns in an E-W direction in southern Patagonia, resulting in its arcuate shape (Fig. 11). The Gondwanan collisional orogen also shows the characteristic double vergence of this orogenic type, developing a wide and NE vergent branch in the Patagonian territory (Gondwana) and a narrower and SE vergent branch that has the best outcrops in the Antarctic Peninsula (West Antarctica). (Figure 11).

The strong deformation associated with this orogenic event obliterated or masked the subduction-related structures and produced the exhumation and tectonic transportation of high pressure-low temperature units of the ancient Gondwanan accretionary prism hundreds of kilometres to the NE, far from the Gondwana margin (García-Sansegundo *et al.* 2009) (6 in Fig. 11 and Fig 12). The Gondwanan orogen in the North Patagonian Andes is part of the hinterland of this orogen eastern branch (Fig. 11), which has a generalized tectonic vergence to the NE (Heredia *et al.* 2016).

The metamorphic rocks from Bariloche reached the metamorphic high pressure - low temperature peak in late Carboniferous times (Willner *et al.* 2004). The S_2 pervasive foliation was developed in intermediate – low pressure conditions and was associated with large crustal ductile thrusts, the same ones that exhumed and transported the high pressure – low temperature accretionary units to the E (García-Sansegundo *et al*. 2009) (Fig. 12). The peak of this metamorphism was reached at the end of the development of the S_2 regional foliation and coincided with a regional migmatization and the intrusion of late Carboniferous S-type granitoids in late Carboniferous times (320-310 Ma).

Outside the Bariloche area, this metamorphic event related to the Gondwanan collisional orogen would have occurred under low-grade conditions, developing more discrete ductile thrusts. This would reinforce the proposal of Serra-Varela *et al.* (2019) that the Famatinian metamorphic rocks (Colohuincul Complex) from San Martín de los Andes might have been exhumed to shallow levels of the crust in this period of time.

Contemporaneously with the development of the collisional Gondwanan orogeny, the upper part of the Tepuel Group (Pampa de Tepuel, Mojón del Hierro and other related formations) was deposited in a peripheral foreland basin. This syn-orogenic sedimentation would rest in angular disconformity on the older rocks, including the Esquel Formation and the Famatinian basement. The conglomerates of the basal part of the Pampa de Tepuel Formation incorporated clasts and boulders of plutonic rocks from the Gondwanan magmatic arc, indicating its subaerial exposure.

The post-orogenic granites, of ca. 295 Ma, mark the end of the Gondwanan orogeny in the study area (Pankhurst *et al*. 2006, Heredia *et al.* 2016).

To the north of the Huincul lineament, the late Carboniferous-early Permian Gondwanan orogen, also named San Rafael orogeny (Ramos 1988), is a subduction-related orogenic event. This implies that the Western Antarctica terrane would end to the north of this structure (Heredia *et al*. 2016, Fig. 11).

This lineament has also been interpreted as a suture that would represent the collisional zone between the Patagonia terrane and Gondwana (e.g. Ramos 1984; 2008). Other authors like Pankhurst *et al.* (2006) suggest the collision of the Deseado terrane took place in late Carboniferous times producing a NNW-SSE and double-vergence orogenic belt in the middle of the Patagonian territory, although they do not indicate evidence of the related suture or show the approximate geometry of the orogen. These interpretations are not consistent with the data provided for the Gondwanan orogen in this work or in those of Heredia et al. (2016, 2018), in terms of trend, vergences of structures, migration of the synorogenic depocenters and location of the hinterland and magmatic arcs. These data allow the reconstruction of a very wide and time-dilated Gondwanan orogen (Late Devonian-early Permian), whose western branch (developed in Gondwana) propagated beyond the northern limits of Patagonia (Fig. 11). In our opinion, the Huincul lineament is an early Paleozoic tectonic limit (Famatinian) reactivated during the late Paleozoic Gondwanan orogen, while the SE vergences located close to the Deseado massif by Pankhurst *et al.* (2006) could be related to back-thrusts, developed in the internal parts of the Gondwanan fold and thrust belt.

Use of terms Colohuincul and Cushamen

The use of the names Colohuincul Complex or Cushamen Complex should be made with restrictions in the Argentinean North Patagonian Andes and surrounding areas. The adscription of basement rocks to one of these lithoestratigraphic units should not be only based on its deformational and metamorphic characteristics or its geographical location.

The name Colohuincul Complex should be used to name the preorogenic and pre-Silurian succession, mainly metasedimentary, of the Famatinian cycle. Since the protoliths of the Colohuincul Complex were deposited in different passive margins of the same crustal fragment, the opposite margin to the Famatinian collision may not show evidence of the previously mentioned collision and only record tectonometamorphic events related to the subsequent Gondwanan collision. This absence of early Paleozoic Famatinian deformations occurs in the Bariloche area (Bariloche nappe from García-Sansegundo *et al.*, 2009) and also in the Patagonian Chilean territory located south of 38º S (Tavera 1979), where Silurian rocks are only affected by Gondwanan tectono-metamorphic events (Hervé 1988). This fact could indicate that the western foreland of the Famatinian Patagonian Orogen might be located in the Chilean Patagonia (Fig. 12).

The name Cushamen Complex should be used to name the metasedimentary and metaigneous pre-collisional succession of the Gondwanan cycle, of middle Silurian-early Carboniferous age. This succession was deposited in a subduction active margin, probably close to the volcanic arc, which was later included in the hinterland of the Gondwanan collisional orogen. Thereby, the Cushamen Complex shows evidence of several tectonometamorphic events related to the Gondwanan subduction and collisional orogens. With respect to the equivalents of the Cushamen Complex in Chilean territory, the Western and Eastern Series can be recognised as such.

In the low-grade and non-metamorphic zones of the Gondwanan orogenic belt in Argentinean territory, the name Sierra Grande Formation should be used to describe the pre-orogenic Middle Silurian-Devonian sequence of the Gondwanan cycle, and the name Esquel Formation should be used to describe the syn-orogenic sequences related to the Gondwanan subduction, developed in late Devonian-lower Carboniferous times. Since these formations do not crop out together, the basal part of the Esquel Formation could be partially equivalent in age to the Sierra Grande Formation, cropping out in the eastern part of the Patagonia outside the Andean sector. Additionally, it should be considered that the Cushamen Complex is the metamorphic equivalent of both formations.

Conclusions

Based on the previous data, the following concluding remarks can be made:

1. Two main Paleozoic orogenic events represented in the North Patagonian Andes led to the formation of the pre-Andean basement metamorphic rocks and the plutonic rocks hosted in them. These orogenic events marked the ending of the Famatinian and Gondwanan cycles, as interpreted by Heredia (2016, 2019), mainly developed in early (Cambrian- middle Silurian) and Upper Paleozoic (middle Silurian-early Permian) times, respectively.

2. The Cambrian-Middle Ordovician sedimentation, represented in the Colohuincul Complex in the North Patagonian Andes, would represent the pre-orogenic sequences of the Famatinian cycle. The synorogenic succession should present ages ranging from late Ordovician to middle Silurian (Wenlock). However, there is no record of this last succession, probably due to the high erosion level of the Famatinian Cordillera in Patagonia.

3. A Silurian (Llandovery/Wenlock, ca. 434 Ma.) tectono-metamorphic event is responsible for the high-grade metamorphic rocks from San Martín de los Andes that reached partial melting conditions.

4. Some outcrops of the Colohuicul Complex, such as the ones in the Bariloche area, did not register Famatinian tectonometamorphic events. This could be explained if these rocks were formed in the western foreland of the Famatinian orogenic belt.

5. The existence of a significant Paleozoic tectonic boundary at the current location of the Huincul lineament is justified by: (i) the earliest end of the Famatinian

orogen, (ii) the westernmost location of the Famatinian suture, iii) the absence of Chanic structures, (iv) the presence of a large Devonian-Lower Carboniferous magmatic arc, and (v) the presence of a Gondwanan collision orogen in the Patagonian sector. This tectonic limit was active during most of the Paleozoic, until the lower Permian, with later reactivations during the Andean cycle.

6. The pre-orogenic sequences of the Gondwanan cycle in the Patagonia present a middle Silurian-Middle Devonian age.

7. A Devonian magmatic arc was well developed in the surroundings of the San Martín de los Andes area, forming a NNW-SSE alignment for this belt at southern latitudes. This magmatic arc is composed of I-type granitoids related to an Andean-type subduction. This magmatic belt intrudes the Lower Paleozoic high-grade metamorphic rocks from the San Martín de los Andes area. Later, a Carboniferous magmatic arc, with a similar trend, was developed further west.

8. The first stage of the Gondwanan orogeny would have developed in an active subduction margin where the pre-orogenic sequence of this stage is represented by the oldest part of the Cushamen Complex, in a position close to the volcanic arc. Furthermore, the contemporaneous sedimentation of the Sierra Grande Formation would be placed in a back-arc position, further from the volcanic arc.

9. The metamorphism recorded in the Cushamen Complex shows a prograde path beginning at 380 Ma (late Devonian) and 340 Ma (Lower Carboniferous). These first metamorphic events would be contemporary with the compressive deformation related to an Andean-type orogen and with the development of related contemporary magmatic arcs.

10. The upper part of the Cushamen Complex can be correlated to the Upper Devonian- Lower Carboniferous Esquel Formation, a non-metamorphic to very low-grade unit located in the foreland region.

11. In late Carboniferous times, the collision of a new continental fragment with the Gondwana margin, Western Antarctica according to Heredia *et al*. (2016), gave rise to the Gondwanan collisional orogen, which reached the early Permian (post-orogenic intrusions at ca. 295-272 Ma). The strong deformation associated with this orogenic event mostly obliterated the subduction-related structures and produced the exhumation and tectonic transportation of high pressure – low temperature units of the ancient Gondwanan accretionary prism hundreds of kilometres to the NE, far from the Gondwana margin. The related regional metamorphism shows a retrograde path, developed under intermediate – low pressure conditions. At that moment, S-type granitoids (ca. 320-310 Ma) were intruded.

12. The Pampa de Tepuel Formation and the rest of the Tepuel Group (Upper Carboniferous-lower Permian) unconformably cover the oldest Gondwanan sequences (Silurian to Carboniferous), present similar ages to the main collisional deformation event of the Gondwanan collisional orogeny (late Carboniferous-early Permian) and, therefore, would represent the synorogenic infill of a Gondwanan peripheral foreland basin.

13. The lithostratigraphic units from the North Patagonian Andes and surrounding areas should be named with caution. The authors of this work propose that the name Colohuincul Complex should be used for preorogenic sequences with their associated metamorphism of the Famatinian cycle (late Ordovician - middle Silurian in age). Moreover, the name Cushamen Complex should be used to name the preorogenic and synorogenic sucessions with their associated metamorphism related to the

Gondwanan cycle (middle Silurian-early Permian in age). The Tepuel Group represents the synorogenic sequence of the Gondwanan cycle and the name Esquel Formation (Devonian-Lower Carboniferous),a formation located at the base of this group which is equivalent to the upper part of the Cushamen Complex, should be used for low-grade or non-metamorphic synorogenic sequences related to the Andean-type orogen of this cycle. Finally, the names Pampa de Tepuel and Mojón del Hierro Formations of the upper Tepuel Group (late Carboniferous-early Permian) can be used to separate the non-metamorphic synorogenic sequences of the Gondwanan collisional orogen.

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Fig. 1: Geographic location of the geochronological dating of metamorphic and plutonic igneous rocks. Crystallization ages are coloured according to the period of time: Devonian (orange), Carboniferous (light blue) and Permian (red). Ages according to [1]Pankhurst *et al*. (2006), [2]Varela *et al*. (2005), [3]Hervé *et al*. (2005), [4]Hervé *et al*. (2018), [5]Martínez *et al*. (2012), [6]Lucassen *et al*. (2004), [7]Hervé *et al*. (2016), [8]Serra-Varela *et al.* (2019).

Fig. 2: Geological sketch map showing the location of the plutonic igneous rocks between the Aluminé and Lácar Lakes.

Fig. 3: Geological sketch map of the area located near San Martín de los Andes village in the surroundings of the Lácar Lake, showing the distribution of the main lithological units. Location in Figure 1.

Fig. 4: Field photographs and photomicrographs showing the metasedimentary rocks from the Colohuincul Complex. Mineral abbreviations according to Siivola and Schmidt (2007). a) Field photograph of schists. In dashed line S_2 foliation. b) Main metamorphic assemblage in schists Qtz + Pl + Bt + Crd + Sil + Ilm defining the crenulated S_2 foliation (dotted line). c) Photomicrograph with ¼ wave mica plate showing different melt microstructures. In the bottom left corner, cordierite with plagioclase rims. Pink arrow: quartz film along grain boundaries. Top left corner: plagioclase crystal with round quartz inclusions. Green arrows: rounded biotite crystals as inclusions in quartz. d) Photomicrograph of general granoblastic texture in granofels. e) Field photography of a stromatic structure in a metatexite. f) Photomicrograph of a leucosome showing mirmequite lobes (Mrm) between quartz and feldspar.

Fig. 5: Field photographs and photomicrographs showing the schlieren migmatite and amphibolites from the Colohuincul Complex. a) Schlieren diatexites with flow banding structure. b) Photomicrograph of a garnet porphyroblast with quartz and ilmenite inclusions in a matrix of Qtz + Pl + Bt + Anf. c) Details of the amphiboles with cummingtonite-grunerite cores and hornblende rims. d) Photomicrography of a garnet porphyroblast in association with biotite, plagioclase and quartz. At the bottom right corner: plagioclase crystal with zonation evidenced by altered core and clearer rims. In dotted line S_2 foliation.

Fig. 6: Geological sketch map showing the different structures recognized in the Colohuincul Complex from the San Martín de los Andes area, represented in steoreographic nets. Location in Figure 3.

Fig. 7: Field photographs from the Rio Chico area. a) S_2 foliation related to a Gondwanan thrust that affects the Cushamen Complex. b) Field aspect of a sill of an acid igneous rock into the Cushamen Complex, which outcrops in the subvertical-reverse limb of an F2 fold (see Fig. 8 for location). c). Details of the sill, which is affected by the S2 subhorizontal foliation. The east to the right.

Fig. 8: Geological map and cross sections of the Cushamen Complex in the Río Chico area. Modified from García-Sansegundo *et al*. (2008). Location in Figure 1.

Fig. 9: Proposal for the correlation between different geological events in the North Patagonian Andes. The asterisks mark the lithostratigraphic units that only outcrop in the extra-Andean Patagonia.

Fig. 10: Characteristics of rocks related to the Gondwanan cycle in the North Patagonian Andes and surrounding areas. a) Gondwanan thrust affecting the Esquel Formation (lower Tepuel Group) in non-metamorphic conditions. The eastern side of Cerro de la Cruz, surroundings of Esquel village. b) Details of the Pampa de Tepuel Formation (middle Tepuel Group), showing glacial dropstones. c) Thick conglomeratic intercalation located in the upper part of the Tepuel Group (Mojón de Hierro Formation). d) Detailed view of Fig. 10c (location in this Fig.), showing a great boulder of granite intercalated at the base of the conglomerates. All photographs are oriented with the east to the right.

Fig. 11: Geological sketches showing main geotectonic features in the Paleozoic basement in the Patagonian Sector for late Permian times, based on Heredia *et al*. (2016, 2018). Main Gondwanan rocks outcrops (late Carboniferous – early Permian): 1- Eastern Andes metamorphic complex. 2- Tecka-Tepuel, 3- Southern San Rafael, 4- Claromecó. In the Gondwanan suture, the little black rectangles mark the upper plate. HL- Huincul lineament. High pressure metamorphic rocks related to the Gondwanan basal accretionary prism (Western Series and equivalents) emplaced over the fore-arc basin (Eastern Series): 5- Puerto Mont-Chiloé, 6- Bariloche. Gondwanan magmatic arcs: PA- Gondwanan magmatic arc of the Patagonian Sector (late Silurian-late

Carboniferous). In the Southwestern margin of Pangea, the triangles mark the position of the Tabarin subduction.

Fig 12: Geodynamic sketch on the evolution of the southwestern Gondwana margin, preserved in the North Patagonian Andes and their foreland. A- Early Ordovician: Famatinian subduction, B- Middle Silurian: Famatinian orogeny. C- Early Devonian: Gondwanan subduction. D- Early Carboniferous: subduction Gondwanan orogeny. E- Early Permian: collisional Gondwanan orogeny. Colohuincul Complex outcrops: Western Patagonia margins: [1] San Martín de los Andes area, [2] Bariloche area; [3]Gondwana margin (unknown, probably eroded).

- Two main Paleozoic orogenic events can be recognized in the North Patagonian Andes
- The first one took place in the Early Paleozoic while the other in the Late Paleozoic
- Only the Colohuincul Complex is affected by the Early Paleozoic orogenic event
- Cushamen Complex is affected by the Late Paleozoic orogenic event.
- Tepuel Group represents the synorogenic succession of the Late Paleozoic event.

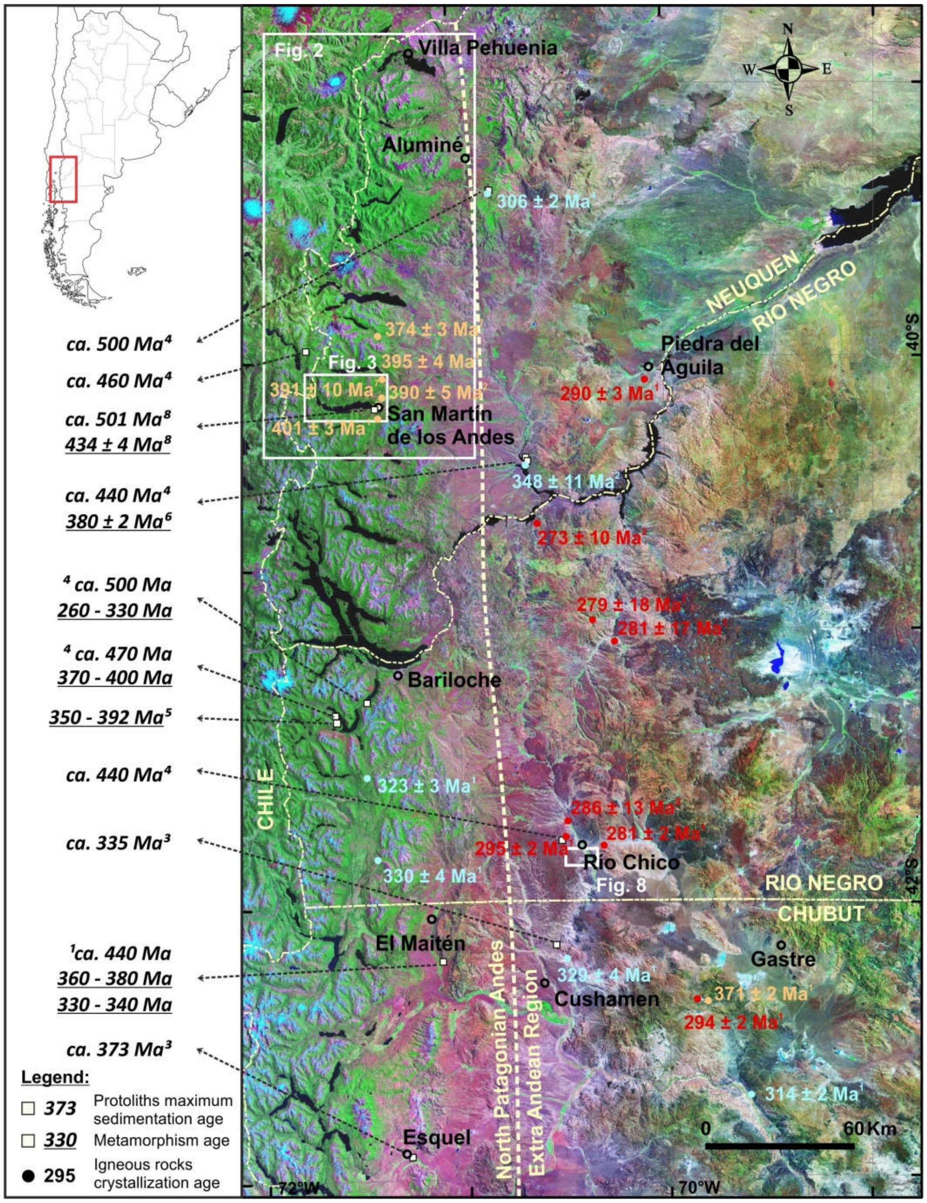

Fig. 1: Geographic location of the geochronological dating of metamorphic and plutonic igneous rocks. Crystallization ages are coloured according to the period of time: Devonian (orange), Carboniferous (light blue) and Permian (red). Ages according to ¹Pankhurst et al. (2006), ²Varela et al. (2005), ³Hervé et al. (2005), ⁴Hervé et al. (2018), ⁵Martínez et al. (2012), ⁶Lucassen et al. (2004), ⁷Hervé et al. (2016), ⁸Serra-Varela et al. (2019).

186x239mm (300 x 300 DPI)

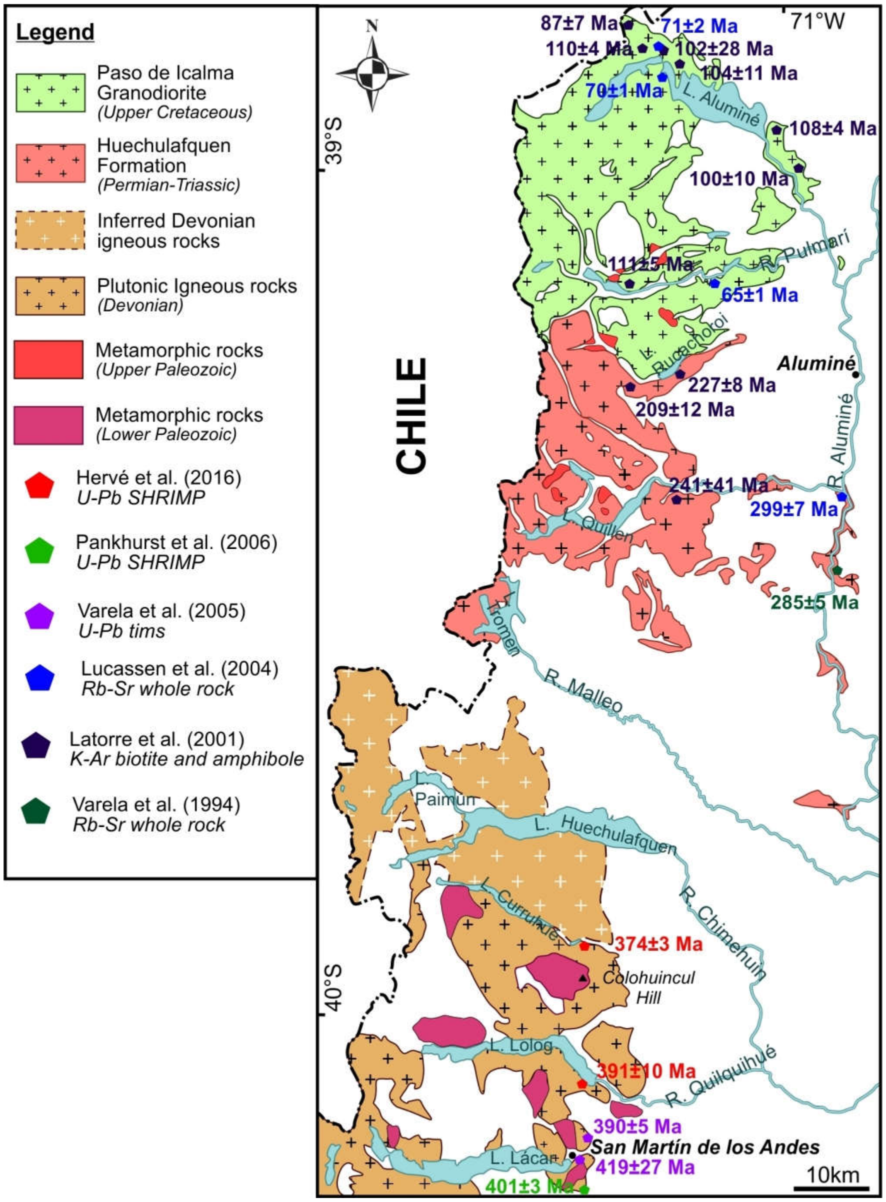

Fig. 2: Geological sketch map showing the location of the plutonic igneous rocks between the Aluminé and Lácar Lakes. Location in Figure 1

140x190mm (300 x 300 DPI)

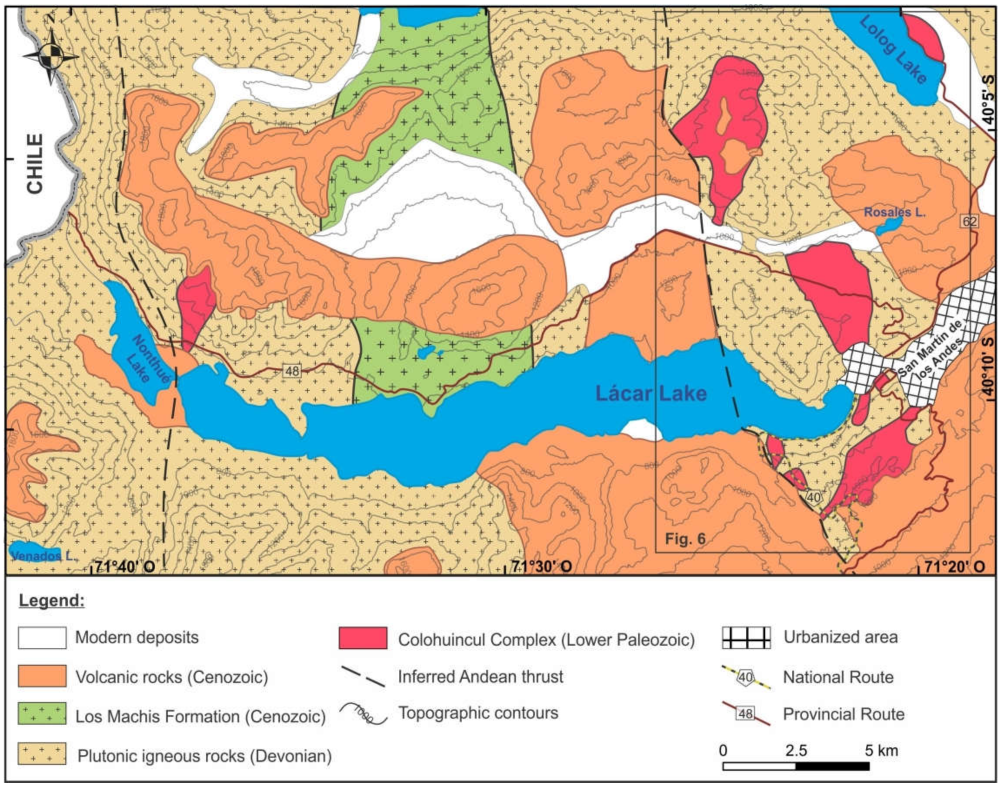

Fig. 3: Geological sketch map of the area located near San Martín de los Andes village in the surroundings of the Lácar Lake, showing the distribution of the main lithological units. Location in Figure 1.

239x187mm (300 x 300 DPI)

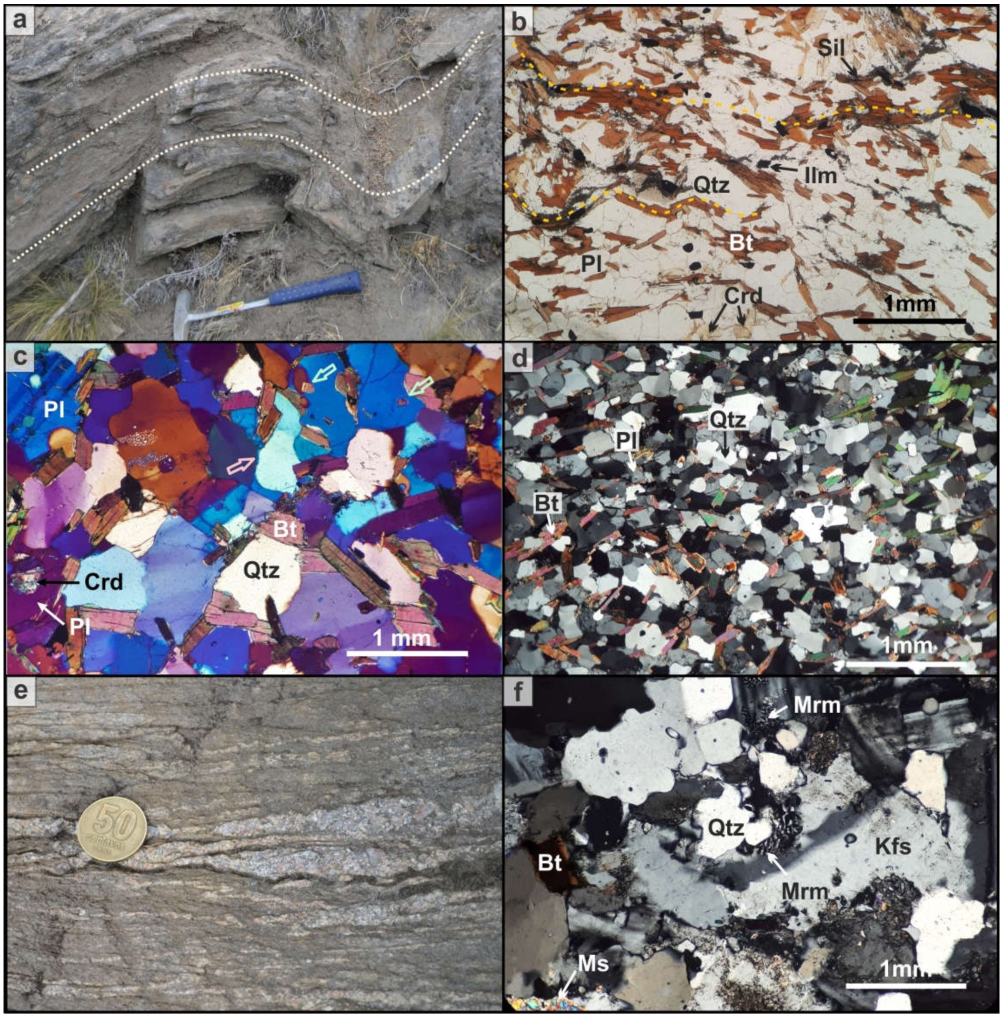

Fig. 4: Field photographs and photomicrographs showing the metasedimentary rocks from the Colohuincul Complex. Mineral abbreviations according to Siivola and Schmidt (2007). a) Field photograph of schists. In dashed line S2 foliation. b) Main metamorphic assemblage in schists Qtz + Pl + Bt + Crd + Sil + Ilm defining the crenulated S2 foliation (dotted line). c) Photomicrograph with ¼ wave mica plate showing different melt microstructures. In the bottom left corner, cordierite with plagioclase rims. Pink arrow: quartz film along grain boundaries. Top left corner: plagioclase crystal with round quartz inclusions. Green arrows: rounded biotite crystals as inclusions in quartz. d) Photomicrograph of general granoblastic texture in granofels. e) Field photography of a stromatic structure in a metatexite. f) Photomicrograph of a leucosome showing mirmequite lobes (Mrm) between quartz and feldspar.

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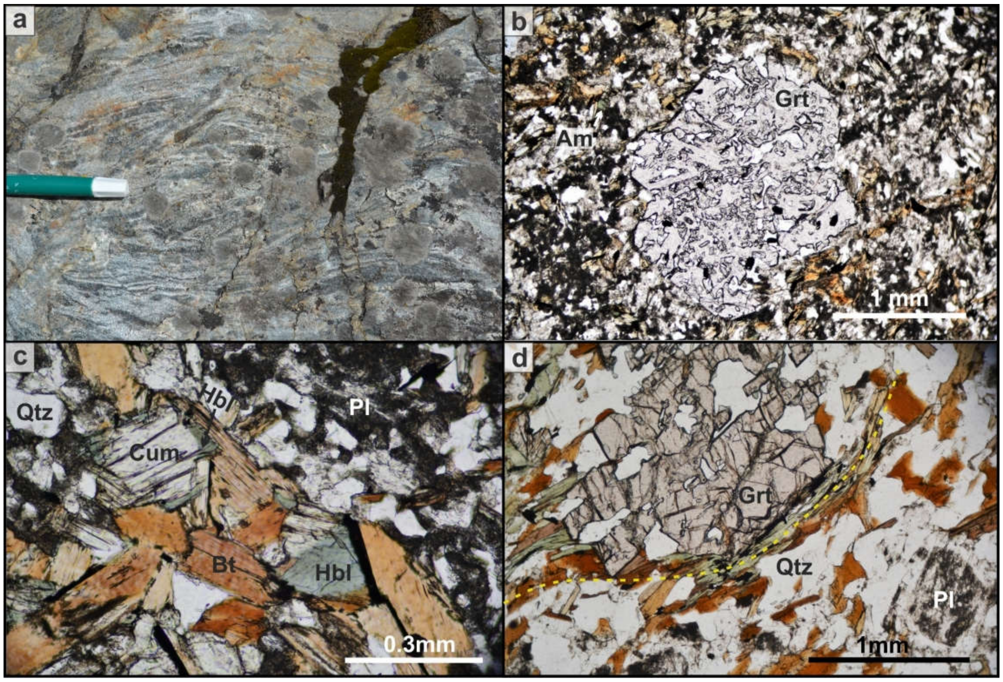

Fig. 5: Field photographs and photomicrographs showing the schlieren migmatite and amphibolites from the Colohuincul Complex. a) Schlieren diatexites with flow banding structure. b) Photomicrograph of a garnet porphyroblast with quartz and ilmenite inclusions in a matrix of Qtz + Pl + Bt + Anf. c) Details of the amphiboles with cummingtonite-grunerite cores and hornblende rims. d) Photomicrography of a garnet porphyroblast in association with biotite, plagioclase and quartz. At the bottom right corner: plagioclase crystal with zonation evidenced by altered core and clearer rims. In dotted line S2 foliation.

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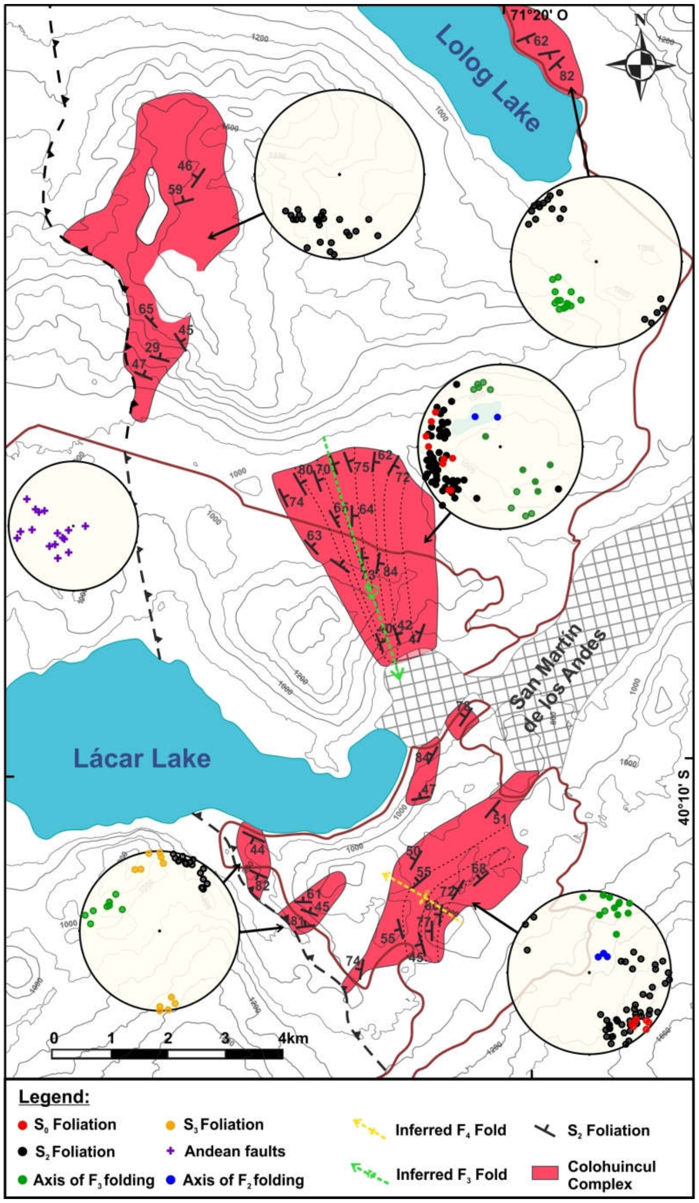

Fig. 6: Geological sketch map showing the different structures recognized in the Colohuincul Complex from the San Martín de los Andes area, represented in steoreographic nets. Location in Figure 3

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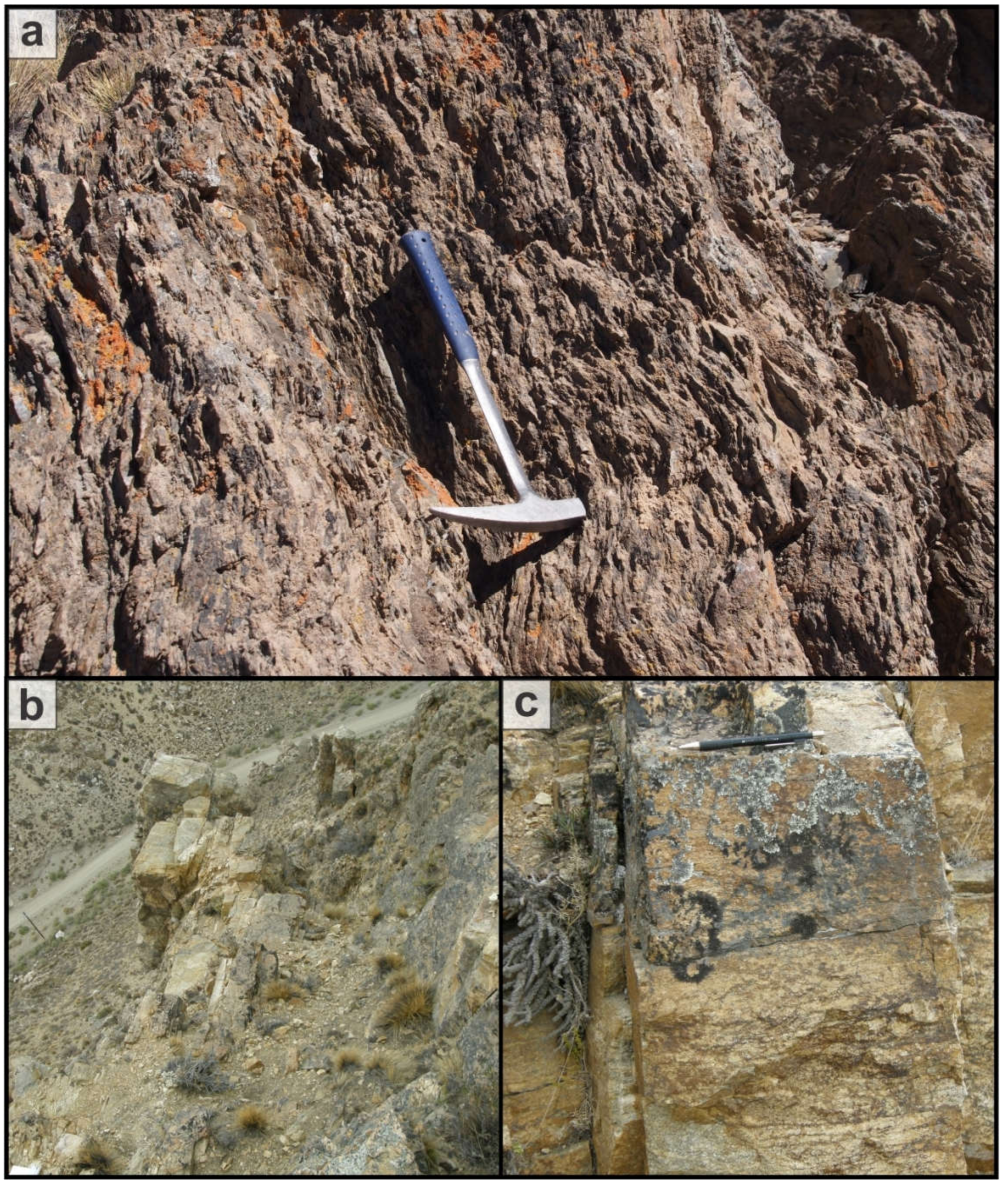

Fig. 7: Field photographs from the Rio Chico area. a) S2 foliation related to a Gondwanan thrust that affects the Cushamen Complex. b) Field aspect of a sill of an acid igneous rock into the Cushamen Complex, which outcrops in the subvertical-reverse limb of an F2 fold (see Fig. 8 for location). c). Details of the sill, which is affected by the S2 subhorizontal foliation. The east to the right.

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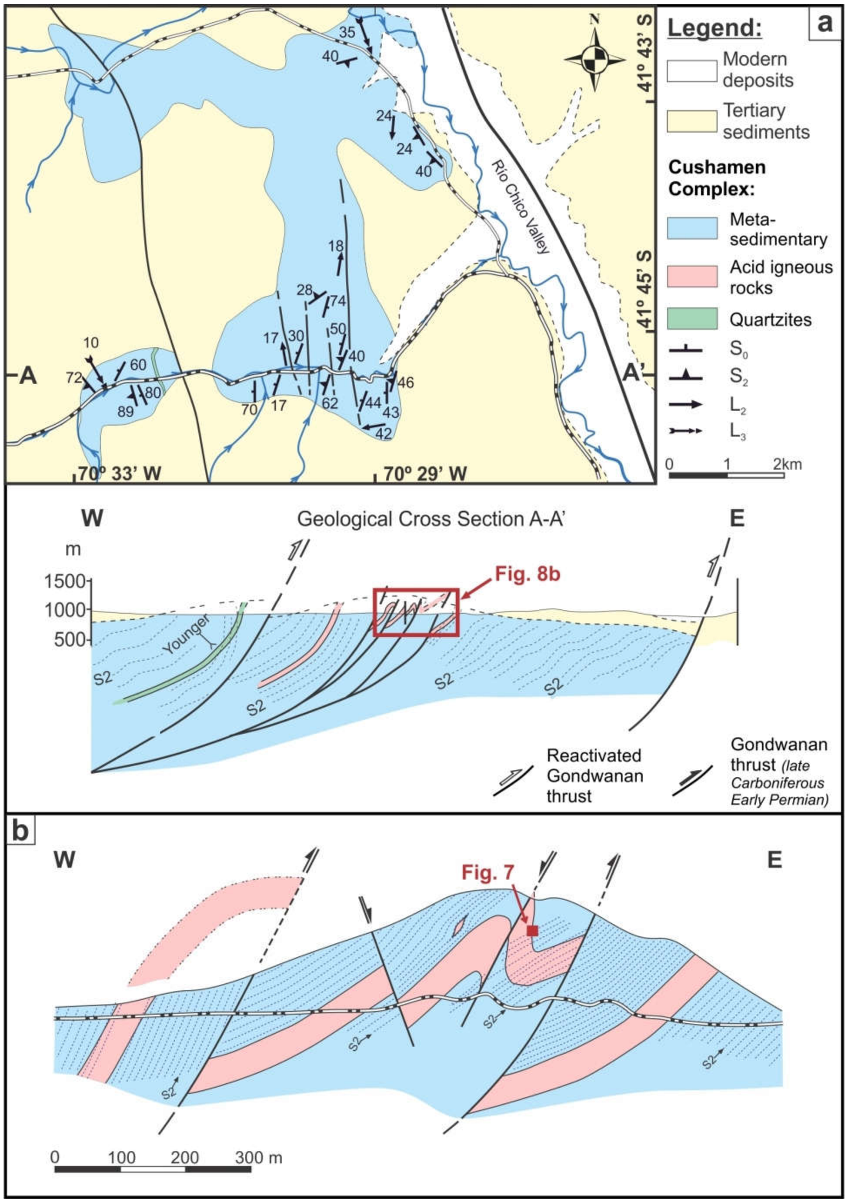

Fig. 8: Geological map and cross sections of the Cushamen Complex in the Río Chico area. Modified from García-Sansegundo et al. (2008). Location in Figure 1.

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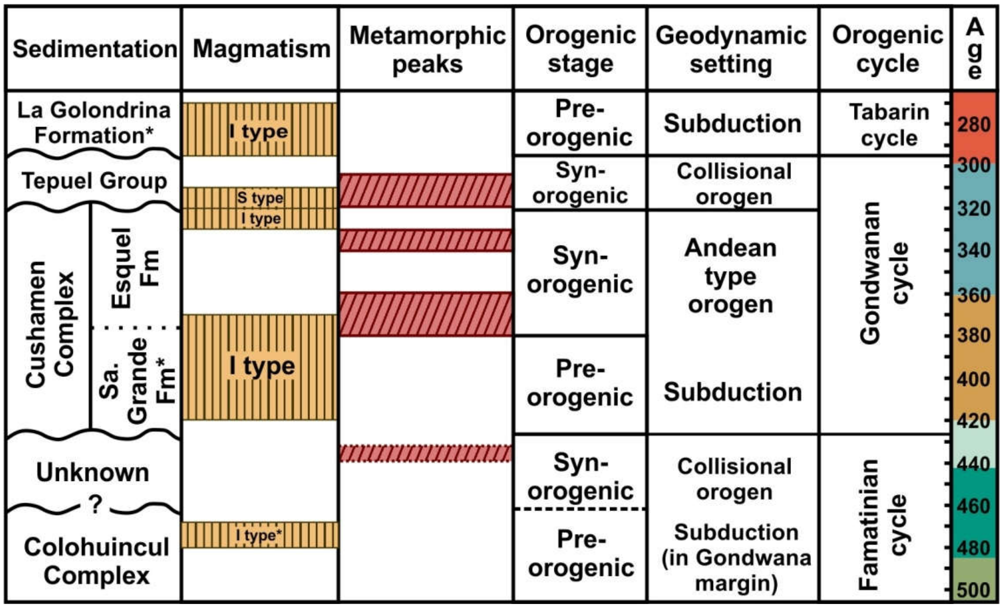

Fig. 9: Proposal for the correlation between different geological events in the North Patagonian Andes. The asterisks mark the lithostratigraphic units that only outcrop in the extra-Andean Patagonia.

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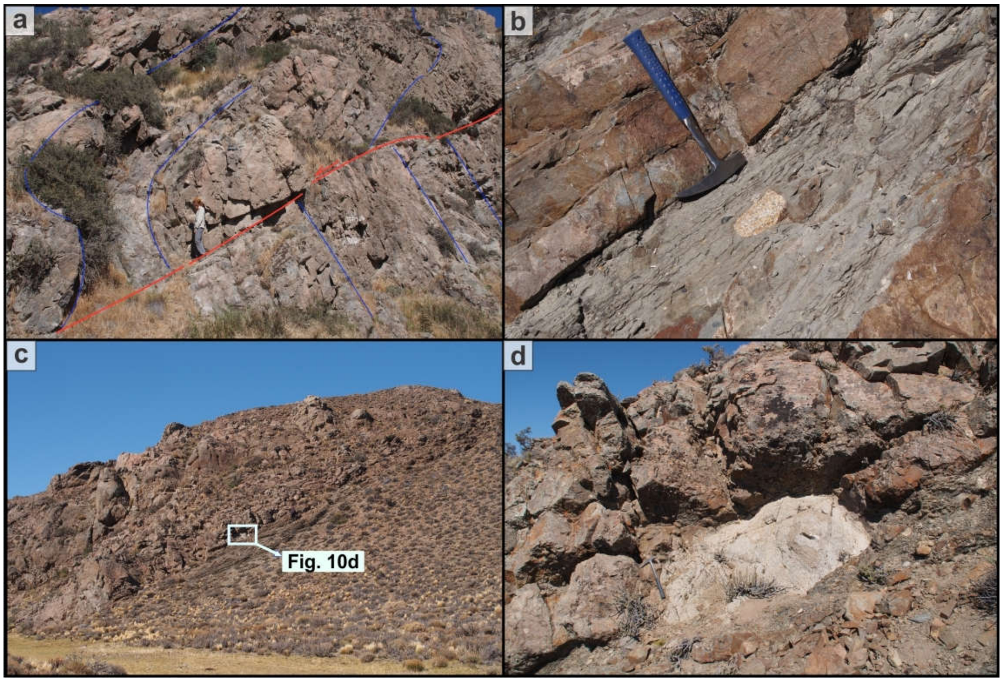

Fig. 10: Characteristics of rocks related to the Gondwanan cycle in the North Patagonian Andes and surrounding areas. a) Gondwanan thrust affecting the Esquel Formation (lower Tepuel Group) in non-metamorphic conditions. The eastern side of Cerro de la Cruz, surroundings of Esquel village. b) Details of the Pampa de Tepuel Formation (middle Tepuel Group), showing glacial dropstones. c) Thick conglomeratic intercalation located in the upper part of the Tepuel Group (Mojón de Hierro Formation). d) Detailed view of Fig. 10c (location in this Fig.), showing a great boulder of granite intercalated at the base of the conglomerates. All photographs are oriented with the east to the right.

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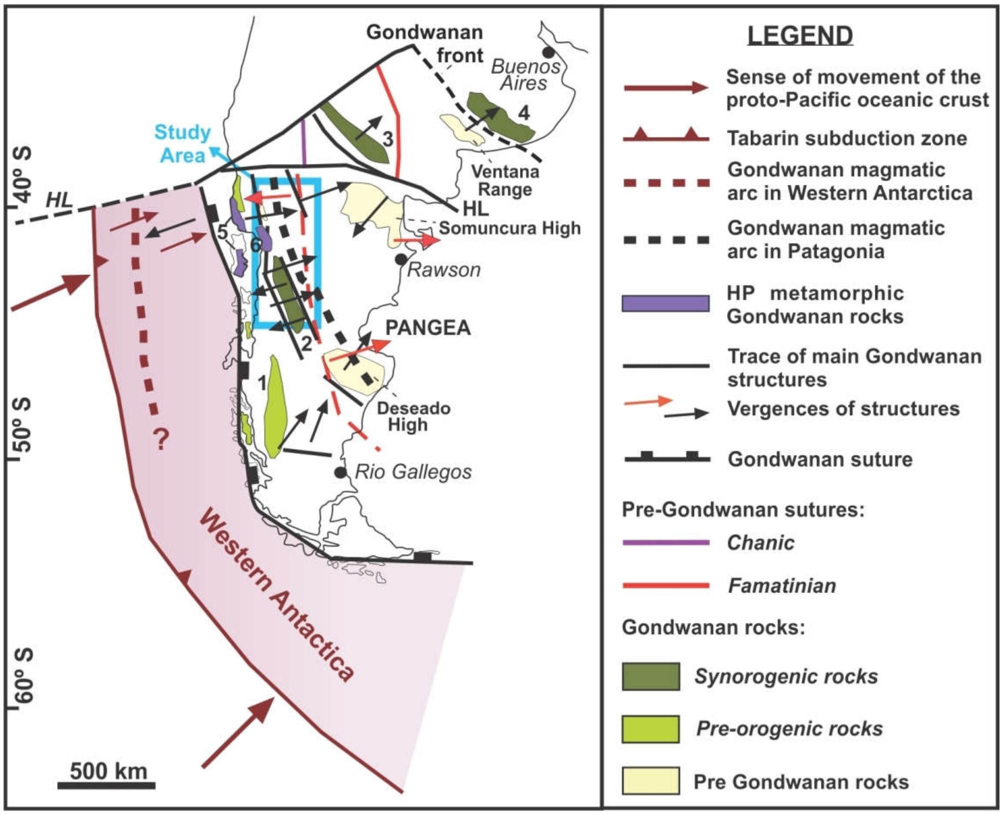

Fig. 11: Geological sketches showing main geotectonic features in the Paleozoic basement in the Patagonian Sector for late Permian times, based on Heredia et al. (2016, 2018). Main Gondwanan rocks outcrops (late Carboniferous – early Permian): 1- Eastern Andes metamorphic complex. 2- Tecka-Tepuel, 3- Southern San Rafael, 4- Claromecó. In the Gondwanan suture, the little black rectangles mark the upper plate. HL- Huincul lineament. High pressure metamorphic rocks related to the Gondwanan basal accretionary prism (Western Series and equivalents) emplaced over the fore-arc basin (Eastern Series): 5- Puerto Mont-Chiloé, 6- Bariloche. Gondwanan magmatic arcs: PA- Gondwanan magmatic arc of the Patagonian Sector (late Silurian-late Carboniferous). In the Southwestern margin of Pangea, the triangles mark the position of the Tabarin subduction.

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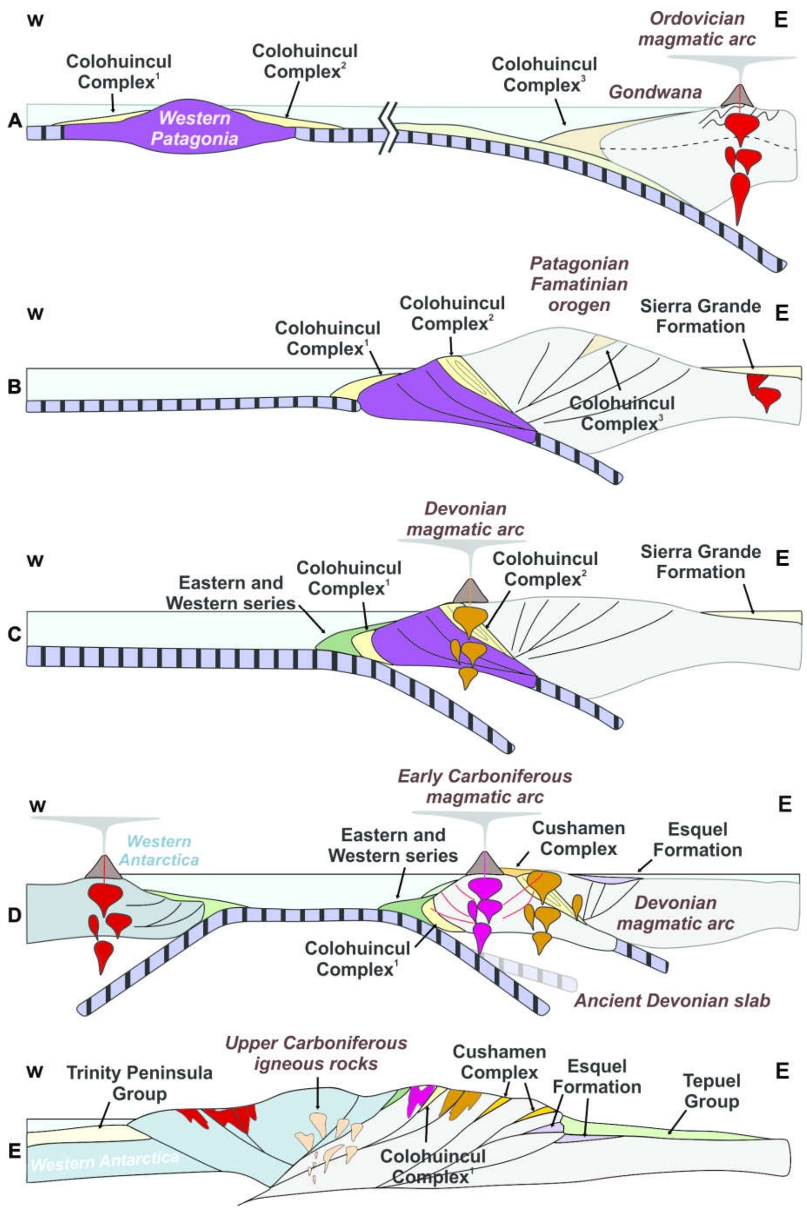

Fig 12: Geodynamic sketch on the evolution of the southwestern Gondwana margin, preserved in the North Patagonian Andes and their foreland. A- Early Ordovician: Famatinian subduction, B- Middle Silurian: Famatinian orogeny. C- Early Devonian: Gondwanan subduction. D- Early Carboniferous: subduction Gondwanan orogeny. E- Early Permian: collisional Gondwanan orogeny. Colohuincul Complex outcrops: Western Patagonia margins: ^{1} San Martín de los Andes area, ^{2} Bariloche area; ^{3}Gondwana margin (unknown, probably eroded).

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