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The Cuesta de Rahue Basement Inlier (Southern Neuquén Precordillera, Argentina): A Devonian to Triassic polyphase orogenic record in northern Patagonia

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Abstract

New geological, structural, microstructural, and K-Ar biotite and illite geochronological data of igneous-metamorphic rocks exposed in the Cuesta de Rahue Basement Inlier are presented to reconstruct the Late Palaeozoic to Mesozoic tectonometamorphic and magmatic history of northwestern Patagonia. This block comprises a medium-grade metasedimentary sequence (Cuesta de Rahue Metamorphic Complex), Late Carboniferous granitoids and a low-grade metavolcano-sedimentary unit (Arroyo Coloco Metamorphic Complex). The Cuesta de Rahue Metamorphic Complex was deposited during the middle Palaeozoic and underwent Devonian low-pressure regional metamorphism, succeeded by the intrusion of granitoids at ca. 300 Ma. On the other hand, the Arroyo Coloco Metamorphic Complex record deformation and metamorphism at epizonal conditions (> 300 °C), constrained at ca. 232-199 Ma by K-Ar and XRD illite data. The Cuesta de Rahue Basement Inlier thus records a protracted orogenic evolution, recording Devonian metamorphism, Late Carboniferous-Permian Gondwanide tectonomagmatic processes, and Late Triassic deformation and

metamorphism. Afterwards, this block was also affected by Mesozoic normal faulting and, finally, by Miocene-Pliocene Andean deformation. The latter was intimately related to reactivation of inherited basement fabrics, favouring a transpressional deformation regime.

Coupled metamorphic and magmatic processes in convergent margins are the main triggers of continental crust growth, which ultimately leads to stabilization of continents (Ernst 2010). In southwestern Gondwana, these processes are well-recorded along the proto-Pacific margin, which underwent protracted Palaeozoic to Mesozoic subduction. In northern Patagonia (southern Argentina and Chile), this complex orogenic evolution is documented by high- to low-grade regional and high-pressure/low-temperature metamorphism, calc-alkaline arc-related magmatism and sedimentary basins (e.g., Varela *et al*. 2005, 2015; Pankhurst *et al*. 2006; Hervé *et al*. 2008, 2013; Suárez *et al*. 2019; Navarrete *et al*. 2019; Oriolo *et al.* 2019).

In particular, middle to late Palaeozoic tectonometamorphic and magmatic events, culminating with the Late Carboniferous-Permian Gondwanide Orogeny, controlled the early orogenic construction of northwestern Patagonia between the North Patagonian Andes and the western North Patagonian Massif (Fig. 1a; e.g., Varela *et al.* 2005, 2015; Pankhurst *et al.* 2006; Ramos 2008; García-Sansegundo *et al.* 2009; Martínez *et al.* 2012; García *et al.* 2018; Oriolo *et al*. 2019; Renda *et al*. 2019; Serra-Varela *et al*. 2018, 2021; Gregori *et al*. 2020; Marcos *et al.* 2020; Rapela *et al.* 2021). However, the Palaeozoic record north of 40 °S is limited to scarce basement inliers (Cingolani *et al.* 2011 and references therein), where detailed geological, structural, petrological and geochronological studies are scarce (Franzese 1993, 1995; Zappettini *et al.* 2012; Giacosa *et al.* 2014; Urraza *et al*. 2015). This region is particularly relevant, not only to disentangle the complex Palaeozoic evolution of Patagonia but also to compare it with the tectonic history of regions located further north, such as the San Rafael Block and the Cordillera Frontal (e.g., Kleiman & Japas 2009; Heredia *et al.* 2012; García-Sansegundo *et al.* 2014; Sato *et al.* 2015).

Though the evolution of the igneous-metamorphic basement of northwestern Patagonia has classically been considered as the result of Palaeozoic orogenic processes, recent contributions also highlighted the existence of Mesozoic tectonometamorphic events (Suárez & González 2018; Oriolo *et al*. 2019; Urraza *et al*. 2019; Sosa *et al*. 2020). Their tectonic significance and spatial distribution are, however, still uncertain. Nevertheless, they might have played a major role in the pre-Andean crustal evolution of the region, as coeval tectonothermal events are also documented in adjacent areas (Castro *et al*. 2011; Martínez Dopico *et al*. 2017; Zaffarana *et al*. 2017; Riley *et al.* 2020; Suárez *et al*. 2021).

Located in the Southern Neuquén Precordillera, Argentina (Figs. 1a, b), the Cuesta de Rahue Basement Inlier represents a key exposure of the igneous-metamorphic basement of northwestern Patagonia. It has been considered a basement block made up of low-grade metasedimentary rocks (Turner 1965; Cingolani *et al*. 2011), though Hervé *et al*. (2018) also identified Pennsylvanian granitic dykes. Nevertheless, robust constraints on the evolution of this area are nearly absent, being only limited to scarce U-Pb zircon data (Ramos *et al*. 2010; Hervé *et al*. 2018). For these reasons, we present detailed geological, structural, microstructural, and K-Ar biotite and illite geochronological data of igneous-metamorphic rocks exposed in the Cuesta de Rahue Basement Inlier, in order to reconstruct its tectonometamorphic and magmatic history. Data are also compared with those of adjacent basement blocks, providing regional insights into the evolution of northwestern Patagonia in the context of the Palaeozoic-Mesozoic orogenic construction of southwestern Gondwana.

Regional setting

The Cuesta de Rahue Basement Inlier is located in the Southern Neuquén Precordillera (Argentina), which is exposed between the North Patagonian Cordillera, the Neuquén Basin and the North Patagonian Massif (Fig. 1). The Southern Neuquén Precordillera constitutes a morphostructural unit characterized by west-verging Andean deformation resulting from positive inversion of Mesozoic extensional structures (García-Morabito *et al*. 2011; Ramos *et al*. 2011). In the study area, basement exhumation has been attributed to deformation along the NNW-SSE-striking Rahue Fault (Fig. 2).

Basement rocks of the Cuesta de Rahue Basement Inlier have commonly been assigned to the Colohuincul Formation, comprising schists and phyllites (Turner 1965; Cingolani *et al.* 2011). Alternatively, Franzese (1993, 1995) correlated these rocks with low-grade metasedimentary sequences of the Piedra Santa Complex, exposed immediately to the east (Fig. 2). U-Pb SHRIMP detrital zircon data of schists of the Cuesta de Rahue Basement Inlier suggest a maximum depositional age of ca. 500-480 Ma, based on scarce Early Palaeozoic grains (Ramos *et al*. 2010; Hervé *et al*. 2018). In addition, Hervé *et al.* (2018) reported a U-Pb SHRIMP zircon age (weighted average) of 306 ± 2 Ma for the crystallization of an undeformed granodiorite dyke, thus constraining the minimum age for sedimentation and subsequent metamorphism.

On the other hand, basement rocks at the Cuesta de Rahue are covered by Mesozoic volcano-sedimentary sequences of the Neuquén Basin (Cucchi *et al.* 2005). Miocene-Pliocene volcanoclastic deposits and basalts are exposed in the area as well (Fig. 2; García-Morabito *et al*. 2011).

Methodology

Field mapping and structural analysis were applied in the Cuesta de Rahue Basement Inlier (Fig. 2), where samples were also collected for microstructural and geochronological analysis. Statistical analysis of structural data was carried out using Stereonet 10.0.6 and FaultKin 7.5 (Marrett & Allmendinger 1990; Allmendinger *et al.* 2013; Cardozo & Allmendinger 2013). In the case of kinematic data of the Rahue Fault, striae, P and R structures were used for calculations (see Japas *et al.* 2013 and references therein).

On the other hand, two samples (RA 22-18 and RA 32-18) of phyllites were collected for K-Ar and XRD fine-fraction analysis, which was carried out at the Geoscience Centre of the Georg-August-Universität Göttingen. One sample (AB-2) of biotite schists was also obtained for K-Ar biotite geochronology at the Centro de Pesquisas Geocronologicas of the Universidade de São Paulo. Analytical procedures are detailed in Supplementary Material 1.

Results

Lithological units

Based on geological mapping, three basement units were recognized in the study area (Fig. 2). Intercalations of low-grade phyllites, metasandstones, felsic metavolcanic/metavolcaniclastic rocks and dacitic-andesitic metavolcanic breccias are exposed in the footwall of the Rahue Fault. This sequence, defined as the Arroyo Coloco Metamorphic Complex (*nom. nov.*), was first recognized herein. On the other hand, paragneisses, schists and subordinate metasandstones are present in the hanging wall of the

Rahue Fault and correspond to metasedimentary sequences previously assigned to the Colohuincul Formation or the Piedra Santa Complex (Turner 1965; Franzese 1993, 1995; Cingolani *et al.* 2011). However, due to differences in their age and metamorphic grade, they are herein assigned to the Cuesta de Rahue Metamorphic Complex (*nom. nov*.).

Metasedimentary rocks of the Cuesta de Rahue Metamorphic Complex are intruded by the Pennsylvanian Cuesta de Rahue Granodiorite, from which felsic dykes derived further north. In the southern area, schists recording contact metamorphism and minor hornfels sensu strictu are dominant due to pluton emplacement (Fig. 3a). They commonly exhibit biotite porphyroblasts, though andalusite porphyroblasts are also locally observed. To the north, evidence of contact metamorphism is not observed and schists are intercalated with paragneisses. Biotite and andalusite are observed in some cases, exhibiting shape-preferred orientation that defines a stretching lineation (Fig. 3b).

The Cuesta de Rahue pluton corresponds to a biotite-bearing granodiorite, which intrudes metasedimentary rocks of the hanging wall and cross-cuts their folded metamorphic foliation (Fig. 3c). Xenoliths of wall-rock are also observed. To the north of the contact, granitic and pegmatitic dykes that derive from the pluton are observed, suggesting that they represent felsic apophyses of the latter.

On the other hand, the Arroyo Coloco Metamorphic Complex footwall is characterized by low-grade intercalations of phyllites, metasandstones and subordinate metavolcanic/metavolcanoclastic rocks (Fig. 3d), which show no evidence of intrusive magmatism and contact metamorphism. This evidence suggests that this low-grade sequence is not only different from metasedimentary rocks of the hanging wall but also that it was not intruded by late Palaeozoic magmas (see Discussion).

Microstructures

Paragneisses and schists of the Cuesta de Rahue Metamorphic Complex are made up of biotite + quartz + plagioclase ± andalusite ± cordierite ± muscovite. The metamorphic foliation S_1 is observed as either a gneissic layering or a continuous/disjunctive schistosity. Synkinematic porphyroblasts of biotite ± andalusite exhibit strain shadows of S_1 planes, defined by lepidoblastic biotite and muscovite, and granoblastic quartz and plagioclase (Fig. 4a). Cordierite is occasionally present as well in the matrix (Fig.4b), whereas tourmaline, titanite and zircon are common accessory minerals. A mylonitic overprint is locally recorded in schists, as documented by bookshelf and anti-bookshelf biotite porphyroclasts, shear bands and mica fish. The mylonitic foliation lies parallel to S_1 and is commonly associated with localized development of retrograde fine-grained white mica + chlorite aggregates in the matrix and microboudinage of biotite porphyroclasts (Fig. 4c).

The Cuesta de Rahue Granodiorite is equigranular and comprises quartz, plagioclase, K-feldspar, biotite and subordinate hornblende (Fig. 4d). Myrmekites are present and fine-grained white mica, chlorite and epidote represent secondary minerals. Deformation is nearly absent, being only documented by local chessboard extinction in quartz.

Metamorphic rocks of the Arroyo Coloco Complex are mainly constituted of quartz + plagioclase + white mica + chlorite + K-feldspar (possibly of detrital origin), whereas the matrix of the volcanic metabreccias are made up of plagioclase (likely of volcanic origin) + chlorite + pumpellyite + opaque minerals + clay minerals (Figs. 4e, f). Pre- to synkinematic porphyroblasts of opaque minerals and chlorite stacks are frequent, particularly in phyllites.

In the latter, the metamorphic foliation S_1 is essentially observed as a continuous cleavage, whereas a disjunctive or continuous schistosity is recorded in coarser-grained lithologies.

Structure

Metasedimentary rocks of the Cuesta de Rahue Metamorphic Complex are characterized by a S_1 metamorphic foliation, though relics of S_0 bedding planes are observed as well (Fig. 5). S_1 represents an axial plane foliation of F_1 folds affecting S_0 planes. Both S_0 and S_1 strike mainly WNW-ESE, with moderate dip towards NNE. A stretching lineation L_1 defined by shape-preferred orientation of biotite and subordinate andalusite is associated with S_1, exhibiting moderate plunge towards NW. Locally, L_1 is affected by F_1 folds, which are overturned, close to isoclinal and show gently NNW- to NW-plunging axis, with dominant vergence towards S-SSW. In contrast, the orientation of felsic dykes intruding metasedimentary rocks strike is dominated by NE-SW strike with moderate to steep dip towards SE (Fig. 3e).

On the other hand, the S_1 metamorphic foliation of the Arroyo Coloco Metamorphic Complex is also subparallel to S_0 bedding planes, being both characterized by WNW-ENE strike and moderate to steeply dip towards SSW (Fig. 5). A stretching lineation L_1 defined by fine-grained white mica is observed in some cases in S_1 planes, showing moderate plunge from dominantly NE to SW orientations, as it is affected by F_1 folds. These folds are typically overturned and show vergence towards the NNE, with moderately to gently plunging axes towards W-NW. Locally, phyllites exhibit minor ENE-verging F_2 kink folds.

Finally, metamorphic fabrics are overprinted by brittle structures. In the first place, minor normal faults striking NW-SE to W-E crosscut schists and paragneisses. Local crenulation associated with normal faulting is observed in schists, which develop F_2 kink drag folds. The Rahue Fault, which strikes NNW-SSE and shows gently to moderate dip towards the ENE, overprints all aforementioned features. Kinematic data from this major fault and associated minor faults reveal reverse dextral kinematics, suggesting a dextral transpressional deformation regime (Fig. 6).

K-Ar and XRD illite data

Sample AB-2 of biotite schists of the Cuesta de Rahue Metamorphic Complex yielded a K-Ar age of 368.4 ± 4.8 Ma (Table 1). Due to the medium-grade conditions inferred based on the presence of andalusite ± cordierite and the relatively lower closure temperature expected for Ar diffusion in biotite (Harrison *et al*. 1985; Grove & Harrison 1996), this age is interpreted to represent cooling shortly after regional metamorphism. The relatively low K_2O content may either indicate biotite partial alteration or the presence of impurities, even though that none of them were microscopically observed. Since geochronological data and regional correlations (see *Late Palaeozoic tectonometamorphic and magmatic evolution*) further support a Devonian age, the K-Ar age is therefore considered as a rough minimum estimate for the timing of metamorphism.

On the other hand, samples RA 22-18 and RA 32-18 of phyllites of the Arroyo Coloco Metamorphic Complex yielded nearly comparable K-Ar and XRD results. In the case of sample RA 22-18, ages of 231.6 ± 3.5 and 210.4 ± 4.1 Ma were obtained for fractions of < 2 and < 0.2 µm, respectively, whereas sample RA 32-18 showed ages of 215.4 ± 4.6 and 199.4 ± 3.7 Ma for these grain size fractions. On the other hand, the Kübler Index is < 0.240 for all studied fine fractions (Table 2), indicating epizonal conditions (> ca. 300 °C) for illite growth. Similarities between air dry and glycolated Kübler Index values allow ruling out the presence of mixed layer clays, which could potentially affect K-Ar ages. The ages of the <2 µm fractions are interpreted to constrain the timing of peak metamorphism or cooling shortly afterwards, whereas ages of the fractions <0.2 µm reflect later illite growth under retrograde conditions, documented by higher Kübler Index values. The estimated epizonal conditions (> ca. 300 °C), which are comparable to slightly higher than closure temperatures for Ar diffusion in fine-grained white mica (Wemmer & Ahrendt 1997; Oriolo *et al.* 2018; Süssenberger *et al.* 2018), indicate that ages constrain the timing of a low-grade metamorphic event associated with ductile deformation during the Upper Triassic for the Arroyo Coloco Metamorphic Complex.

Discussion

Basement stratigraphy

Previous contributions have considered basement rocks of the Cuesta de Rahue Basement Inlier as equivalents of low-grade rocks of the Colohuincul Formation or the Piedra Santa Complex (Turner 1965; Franzese 1993, 1995; Cingolani *et al.* 2011). The Colohuincul Formation mainly comprises phyllites and schists in its type locality (Turner 1965), where geochronological constraints are absent. However, different authors assigned contrasting ages between the early and late Palaeozoic for deposition of the Colohuincul Formation/Complex based on U-Pb detrital zircon data, further supported by ages of metamorphism and intrusive magmatism (e.g., Dalla Salda *et al.* 1991; Cingolani *et al.* 2020; Serra-Varela *et al*. 2020). On the other hand, schists and phyllites of the Piedra Santa Complex yielded late Devonian to Carboniferous whole-rock K-Ar ages (Franzese 1993, 1995), suggesting middle to late Palaeozoic metamorphism and early Palaeozoic protolith deposition.

In contrast, new evidence indicates the presence of two metasedimentary sequences at the Cuesta de Rahue Basement Inlier. The first sequence comprises medium-grade paragneisses, schists and metasandstones, intruded by a granodioritic pluton and cogenetic dykes that locally generate contact metamorphism. U-Pb SHRIMP detrital zircon data of schists of the Cuesta de Rahue Basement Inlier suggest a maximum depositional age of ca. 500-480 Ma for this unit (Ramos *et al*. 2010; Hervé *et al*. 2018), whereas the K-Ar biotite age of 368.4 ± 4.8 Ma constrains the timing of cooling shortly after Devonian regional metamorphism. The latter is also in line with the U-Pb SHRIMP zircon age (weighted average) of 306 ± 2 Ma for an undeformed granodioritic dyke. Therefore, a Middle Ordovician to Late Devonian age is inferred for the timing of deposition of sedimentary protoliths. Due to the lack of spatial continuity of outcrops and differences with the Colohuincul and Piedra Santa complexes, this unit is thus defined as the Cuesta de Rahue Metamorphic Complex. Though correlations with adjacent metasedimentary sequences is possible, further analytical data are required, for which a local name is therefore preferred herein.

In a similar way, low-grade metavolcano-sedimentary sequences of the Cuesta de Rahue Basement Inlier are defined as the Arroyo Coloco Metamorphic Complex, which records Late Triassic metamorphism (see K-Ar and XRD illite data). A pre-Late Triassic deposition age is thus inferred for the protolith, which may be equivalent to Carboniferous metavolcano-sedimentary sequences of the Andacollo Group of the Cordillera del Viento at the Northern Neuquén Precordillera (Danieli *et al*. 2011; Zappettini *et al*. 2012; Cisterna Riba 2022). Alternatively, the Arroyo Coloco Metamorphic Complex may be comparable to Permian to Triassic metavolcano-sedimentary sequences in northwestern Patagonia (García and González 2019; Restelli *et al.* 2022). Nevertheless, further geochronological data are required to establish regional correlations.

Late Palaeozoic tectonometamorphic and magmatic evolution

The tectonometamorphic and magmatic record of northwestern Patagonia are mainly associated with Devonian and Late Carboniferous-Early Permian orogenic events (e.g., Varela *et al.* 2005, 2015; Pankhurst et al. 2006; Martínez *et al.* 2012; Oriolo *et al*. 2019; Renda *et al*. 2019, 2020; Gregori *et al*. 2020; Marcos *et al.* 2020; Serra-Varela *et al*. 2020, 2021; Rapela *et al*. 2021), which are separated by a magmatic lull (Renda *et al*. 2021). Both events seem to be recorded along the Southern Neuquén Precordillera and the Sañicó High, though robust geochronological and structural constraints are still scarce (Franzese 1993, 1995; Lucassen *et al*. 2004; García *et al*. 2018; Hervé *et al*. 2018).

Mineralogical, structural and microstructural data of the Cuesta de Rahue Metamorphic Complex suggests low-pressure medium-grade regional metamorphism, as indicated by the presence of synkinematic biotite and andalusite porphyroblasts with subordinate cordierite in the matrix. These rocks are associated with WNW-ESE- to NW-SE-striking fabrics, which might have resulted from inclined transpression, according to the orientation of foliations, lineations and folds (sensu Jones *et al*. 2004). As previously exposed, the timing of metamorphism and deformation is constrained at ca. 368 Ma by K-Ar biotite data, and can thus be attributed to late Devonian tectonometamorphic events recorded in adjacent areas (Fig. 7a; Franzese 1995; Lucassen *et al*. 2004; Varela *et al*. 2005; Rapela *et al*. 2021). This correlation is further supported by low-pressure medium-grade conditions estimated for the Cuesta de Rahue Metamorphic Complex, which is in line with comparable low-pressure medium- to high-grade conditions of Devonian metamorphism (Martínez *et al*. 2012; Serra-Varela *et al*. 2018). This low-pressure metamorphism was associated with the development of a Devonian magmatic arc related to a retreating accretionary orogen (Rapela *et al*. 2021 and references therein).

On the other hand, the Gondwanide record is supported by the presence of the late Pennsylvanian Cuesta de Rahue Granodiorite and coeval dykes. Coeval late Pensylvanian magmatism were reported for granitic intrusions of the Chachil Plutonic Complex (Romero et al. 2019) and the N-S-striking Coastal Batholith located further northwest in Chile (Deckart *et al*. 2014), indicating that the study area represents the transitional zone between the latter and the Paleozoic Central Patagonian Igneous-Metamorphic Belt (Fig. 7b; Renda *et al*. 2019). In the latter, Late Carboniferous to Early Permian granitoids with arc affinity are widespread (Varela *et al*. 2005, 2015; Pankhurst *et al*. 2006; Renda *et al*. 2019, 2021).

Finally, deposition of volcano-sedimentary protoliths of the Arroyo Coloco Complex prior to the Upper Triassic (see *Basement stratigraphy*). They may be coeval with

Carboniferous metavolcano-sedimentary sequences of the Andacollo Group (Danieli *et al*. 2011; Zappettini *et al.* 2012; Cisterna Riba 2022) or volcano-sedimentary sequences of the Cordillera del Viento Formation, exposed to the north in the Northern Neuquén Precordillera, where Early Permian granitoids are also present (Llambías *et al.* 2007; Hervé *et al*. 2013). These sequences may thus represent the southernmost exposures of the Choiyoi magmatism, ubiquitously recorded in the San Rafael Block further north (e.g., Kleiman and Japas 2009; Rocha-Campos *et al.* 2011; Sato *et al*. 2015).

Triassic metamorphism and deformation

In addition to Middle to Late Paleozoic tectonometamorphic processes, K-Ar illite data of the Arroyo Coloco Metamorphic Complex demonstrate the existence of Late Triassic low-grade metamorphism and NNE-vergent deformation in the Southern Neuquén Precordillera, characterized by WNW-ESE regional metamorphic fabrics. Likewise, the Rb-Sr whole-rock analysis (Cingolani *et al.* 1991) of the Cuesta de Rahue Granodiorite yielded a recalculated age of 230 ± 15 Ma (2σ, $^{87}Sr/^{86}Sr_0 = 0.70694 \pm 0.00024$), thus providing a rough constraint for the Late Triassic regional tectonothermal event in the hanging wall.

Comparable Late Triassic low-grade metamorphism and deformation associated with NW-SE deformational fabrics were also reported along the western North Patagonian Massif (von Gosen and Loske, 2004; Zaffarana *et al*. 2017; González *et al.* 2021). In this region, U-Pb LA-ICP-MS zircon overgrowth data constrain the timing of this tectonometamorphic event at 226.7 ± 4.4 Ma (González et al. 2021), though widespread nearly coeval Late Triassic magmatism at ca. 222-213 Ma is present as well (Rapela *et al.* 2005; Zaffarana *et al.*

2014; Lagorio *et al*. 2015). Further northeast, Gregori *et al*. (2016) reported slightly younger ages of ca. 206-193 Ma for the timing of shearing along a NW-SE-striking mylonitic belt, according to U-Pb zircon ages obtained in the protolith and post-mylonitic intrusions. To the southeast, Navarrete *et al*. (2019) reported Late Triassic folding in the eastern Deseado Massif, which is constrained at ca. 220-207 Ma by U-Pb zircon ages of pre- and post-folding magmatic units. Middle to late Triassic deformation of mélange sequences is also widespread along the Pacific coast in Chile (Kato and Godoy, 2015).

Likewise, Late Triassic metamorphism was reported to the west of the study area in the North Patagonian Andes, as revealed by a ^{40}Ar/^{39}Ar amphibole isochrone age of 212.7 ± 9.6 Ma in an amphibolite with MORB composition (Urraza *et al*. 2019). These rocks also recorded a counterclockwise path from ca. 1.9-3.9 kbar and 677-745 ºC to P-T conditions of ca. 6.4 kbar and 723 ºC (Urraza *et al*. 2019). Assuming pure volume diffusion, the ^{40}Ar/^{39}Ar age can be correlated with the latter conditions, indicating regional medium-grade metamorphism.

The existence of a regional low- to medium-grade metamorphic event in northwestern Patagonia, which postdates Early Triassic extensional tectonics, has also been documented in southern Patagonia and the Antarctic Peninsula, where they were attributed to the Chonide/Peninsula orogenic event (Hervé *et al*. 2008; Suárez *et al*. 2019; Riley *et al*. 2020). Late Triassic deformation and magmatism in southwesternmost Gondwana have been linked to crustal shortening during flat-slab subduction, which promoted inland migration of arc magmatism (Navarrete *et al*. 2019; Suárez *et al*. 2019, 2021). In this context, Late Triassic deformation and metamorphism associated with coeval magmatism in northwestern Patagonia are attributed to a NNW-SSE to NW-SE transpressional belt (Fig. 7c; Kato and

Godoy, 2015; Zaffarana *et al*. 2017; Navarrete *et al*. 2019), which resulted from oblique flat-slab subduction and was possibly controlled by inherited Late Palaeozoic Gondwanide fabrics (Renda *et al.* 2019 and references therein).

Mesozoic and Cenozoic faulting

The observed W-E- to NW-SE-striking normal faults are comparable to Mesozoic extensional structures related to the opening of the Neuquén Basin (e.g., Bechis *et al.* 2010, 2014), which are also documented elsewhere in coeval basins in Patagonia (Renda *et al*. 2019; Giacosa 2020). On a regional scale, the early stages of opening of the Neuquén Basin partially overlap with the Late Triassic deformation and metamorphism of the Arroyo Coloco Metamorphic Complex, which may imply that the former was slightly younger (i.e., Early Jurassic) in the study area.

On the other hand, reverse-dextral deformation along the Rahue Fault can be attributed to Miocene-Pliocene Andean deformation, though some kinematic differences are observed when compared with faults in the Catán Lil depocenter, located immediately to the south (García Morabito *et al*. 2011). Kinematics thus indicate a partitioned dextral transpressional regime for the Miocene, as documented elsewhere in northwestern Patagonia (Diraison et al. 1998; Folguera et al. 2002), intimately related to reactivation of Palaeozoic basement fabrics (Fig. 5; Giacosa 2020). Andean deformation along the Rahue Fault controlled the final juxtaposition of the Cuesta de Rahue and Arroyo Coloco complexes.

Miocene deformation in the Southern Neuquén Precordillera has been commonly linked to inversion of pre-existing Mesozoic extensional structures (García Morabito *et al*.

2011). The latter commonly resulted from reactivation of Palaeozoic basement fabrics (Bechis *et al.* 2010, 2014; Giacosa 2020) and, though this is not clearly observed in the case of the Rahue Fault, it is thus evident that they played a significant role in Andean orogenic processes of the study area. In particular, the existence of NNW-SSE to WNW-ESE fabrics might have been determinant for the documented dextral transpressional deformational regime.

6. Conclusions

The Cuesta de Rahue Basement Inlier comprises a medium-grade metasedimentary sequence (i.e., Cuesta de Rahue Metamorphic Complex), late Carboniferous granitoids and a low-grade metavolcano-sedimentary unit (i.e., Arroyo Coloco Metamorphic Complex). The Cuesta de Rahue Metamorphic Complex was possibly deposited during the middle Palaeozoic and underwent Devonian low-pressure medium-grade metamorphism, which was related to the development of a retreating accretionary orogen. Subsequently, late Pennsylvanian granitoids linked with the Late Paleozoic Gondwanide Orogeny intruded at ca. 300 Ma, suggesting a connection with coeval intrusions exposed further southeast along the Palaeozoic Central Patagonian Igneous-Metamorphic Belt and the Coastal Batholith to the northwest, indicating the presence of a continuous Gondwanide magmatic arc in the region.

On the other hand, deformation and metamorphism of the Arroyo Coloco Metamorphic Complex, deposited prior to the Upper Triassic, occurred at epizonal conditions (> 300 °C) at ca. 232-199 Ma, as indicated by combined K-Ar and XRD illite data. Comparable Late Triassic deformation and metamorphism is also recorded further southeast along a NNW-SSE to NW-SE-striking belt, associated with WNW-ESE- to NW-SE metamorphic fabrics, thus suggesting a structural control of Gondwanide fabrics.

Finally, the Cuesta de Rahue Basement Inlier was affected by Mesozoic normal faulting and Miocene-Pliocene Andean deformation. The latter was intimately related to reactivation of inherited basement fabrics under a transpressional deformation regime.

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Fig. 1. (**a**) Main morphostructural units of Patagonia (modified after Ramos *et al*. 2011). The red rectangle shows the location of the map of Figure 1b. CP: Cordillera Principal, NNP: Northern Neuquén Precordillera, NPC: North Patagonian Cordillera, SH: Sañicó High, SNP: Southern Neuquén Precordillera, SRB: San Rafael Block. (**b**) Sketch map showing distribution of Palaeozoic igneous-metamorphic basement blocks of northern Patagonia (modified after Pankhurst *et al*. 2006; Ramos 2008; Hervé *et al*. 2018; Renda *et al*. 2019; Serra-Varela *et al*. 2021).

Fig. 2. Geological map of the Cuesta de Rahue Basement Inlier. The location of K-Ar samples is included.

Fig. 3. (**a**) Porphyroblastic (biotite) hornfels of the Cuesta de Rahue Metamorphic Complex. (**b**) Andalusite stretching lineation in paragneisses of the Cuesta de Rahue Metamorphic Complex. (**c**) Intrusive contact between foliated metasedimentary rocks of the Cuesta de Rahue Metamorphic Complex and the late Carboniferous granodiorite. (**d**) Intercalation of phyllites (P) and metasandstones (M) of the Arroyo Coloco Metamorphic Complex. (**e**) Felsic dykes cross-cutting foliated metasedimentary rocks of the Cuesta de Rahue Metamorphic Complex. Both units are affected by a normal fault.

Fig. 4. Photomicrographs of representative rocks of basement units. Biotite porphyroblast (**a**) and cordierite (**b**) in schists of the Cuesta de Rahue Metamorphic Complex. (**c**) Mylonitization in schist of the Cuesta de Rahue Metamorphic Complex, giving rise to microboudinage in biotite porphyroclast and a retrograde fine-grained mylonitic foliation (arrows) that lies parallel to the metamorphic foliation S_1. (**d**) Equigranular granodiorite. (**e**) Metasandstone of the Arroyo Coloco Metamorphic Complex. Arrows indicate white mica recrystallization in the matrix. (**f**) Volcanic metaconglomerate of the Arroyo Coloco Metamorphic Complex, with plagioclase-rich clasts in a fine-grained andesitic matrix and significantly replacement by chlorite, pumpellyite, and clay and opaque minerals.

Fig. 5. Schematic structural profile (see location in Fig. 2). Lower hemisphere equal area projection of poles of structural elements are also shown. Contour intervals at 2% per 1% area.

Fig. 6. Fault plane solution and P-T axes (blue and red, respectively) calculated for kinematic data of the Rahue Fault and associated minor faults (n=14). Arrows indicate hanging wall slip direction.

Fig. 7. Regional Devonian to Triassic igneous-metamorphic record of northern Patagonia. The study area is indicated with a yellow dot. (**a**) Devonian continental magmatic arc (yellow area, modified after Serra-Varela *et al*. 2021). Ages of associated regional metamorphism are indicated (1: K-Ar biotite, this work; 2: K-Ar whole-rock, Franzese 1995; 3: U-Pb titanite, Lucassen *et al*. 2004; 4: U-Pb titanite, Varela *et al*. 2005; 5: EPMA Th-U-Pb monazite, Renda *et al*. 2021; 6: EPMA Th-U-Pb monazite, Martínez *et al*. 2012; 7: EPMA Th-U-Pb monazite, Urraza *et al*. 2008). (**b**) Schematic position of the Late Carboniferous to Early Permian Gondwanide magmatic arc (red area). U-Pb SHRIMP and LA-ICP-MS zircon ages of granitoids are indicated (1: Hervé *et al*. 2018, 2: Deckart *et al*. 2014, 3: Pankhurst *et al*. 2006, 4: Renda *et al*. 2021, 5: Romero *et al*. 2019, 6: Oriolo *et al.* under review). The northern segment corresponds to the Coastal Batholith (CB; Deckart *et al.* 2014 and references therein), whereas the southern segment is recorded by the Palaeozoic Central Patagonian Igneous-Metamorphic Belt (PCPIMB; Renda *et al*. 2019 and references therein). (**c**) Late Triassic orogenic belt (violet area; modified after Navarrete *et al*. 2019). Ages correspond to the timing of deformation and metamorphism (see text for further explanation; 1: Urraza *et al*. 2019, 2: this work, 3: González *et al*. 2021; 4: Gregori *et al*. 2016; 5: Navarrete *et al*. 2019). The inset shows S_1 (black dots) and L_1 (red dots) structural data of the Arroyo Coloco Metamorphic Complex (see Fig. 5 for comparison), showing similarities in local WNW-ESE to NW-SE fabrics of the study area with the regional orientation of the belt. In turn, the latter partially coincides with the orientation of the PCPIMB, suggesting that reactivated Late Paleozoic fabrics might have played a major role in the Upper Triassic (Renda *et al.* 2019).

Table 1. *K-Ar biotite analytical results of the Cuesta de Rahue Metamorphic Complex.*

Table 2. *K-Ar and illite crystallinity (Kübler Index) analytical results of the Arroyo Coloco Metamorphic Complex.*

Figure 1

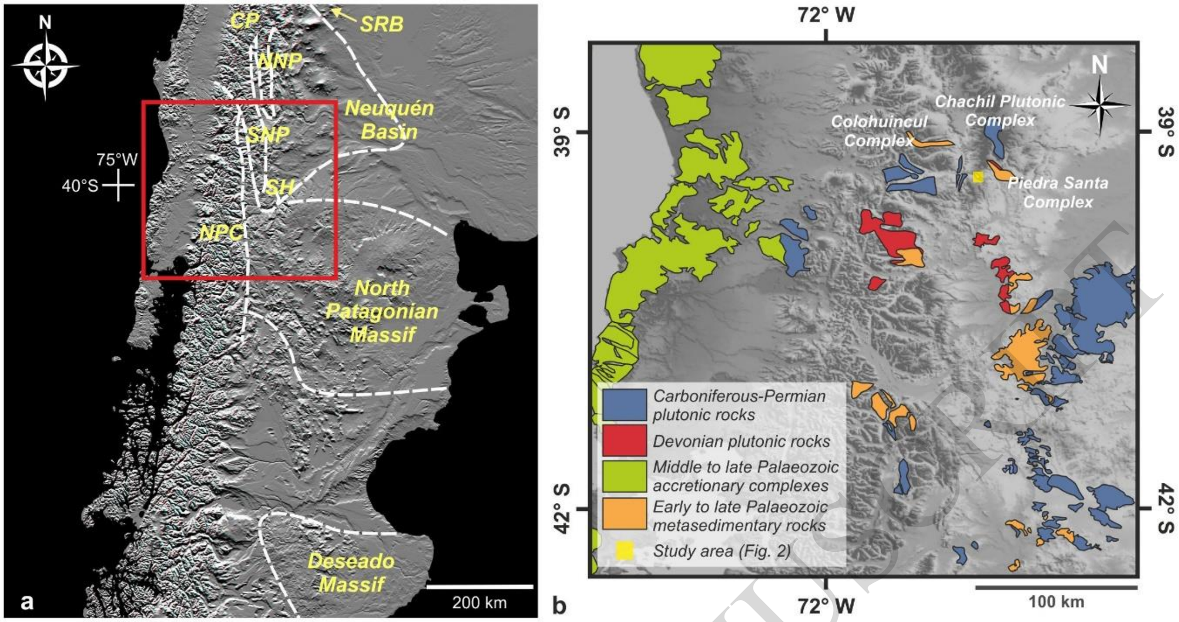
N
CP
SRB
NNP
Neuquén Basin
SNP
75°W
40°S
SH
NPC
North Patagonian Massif
Deseado Massif
200 km
a
72° W
N
Chachil Plutonic Complex
Colohuincul Complex
39° S
39° S
Piedra Santa Complex
Carboniferous-Permian plutonic rocks
Devonian plutonic rocks
Middle to late Palaeozoic accretionary complexes
Early to late Palaeozoic metasedimentary rocks
Study area (Fig. 2)
42° S
42° S
72° W
100 km
b

Figure 2

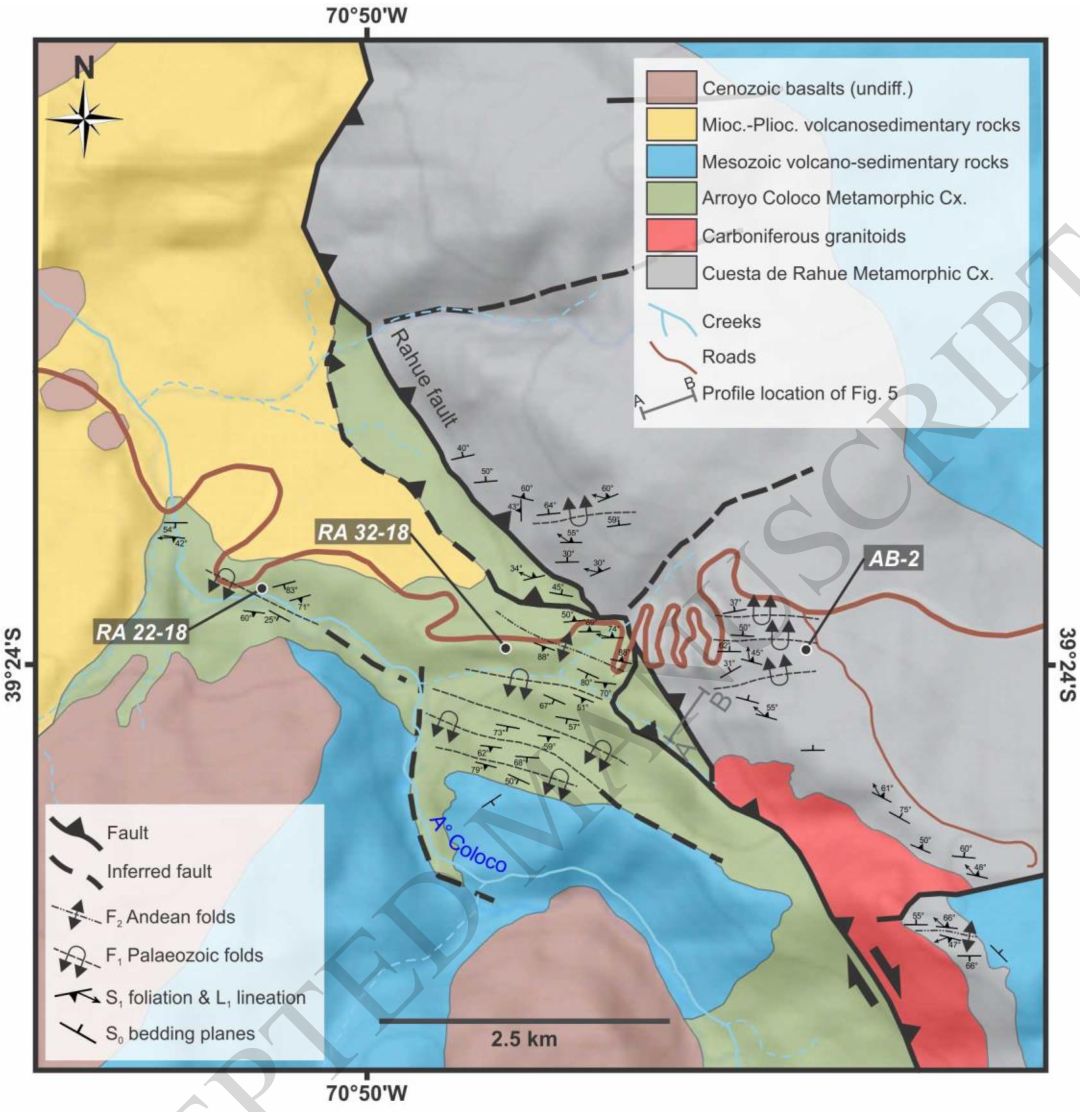
70°50'W
N
Cenozoic basalts (undiff.)
Mioc.-Plioc. volcanosedimentary rocks
Mesozoic volcano-sedimentary rocks
Arroyo Coloco Metamorphic Cx.
Carboniferous granitoids
Cuesta de Rahue Metamorphic Cx.
Creeks
Roads
A B Profile location of Fig. 5
Rahue fault
RA 32-18
RA 22-18
AB-2
39°24'S
39°24'S
A° Coloco
Fault
Inferred fault
F₂ Andean folds
F₁ Palaeozoic folds
S₁ foliation & L₁ lineation
S₀ bedding planes
2.5 km
70°50'W

Figure 3

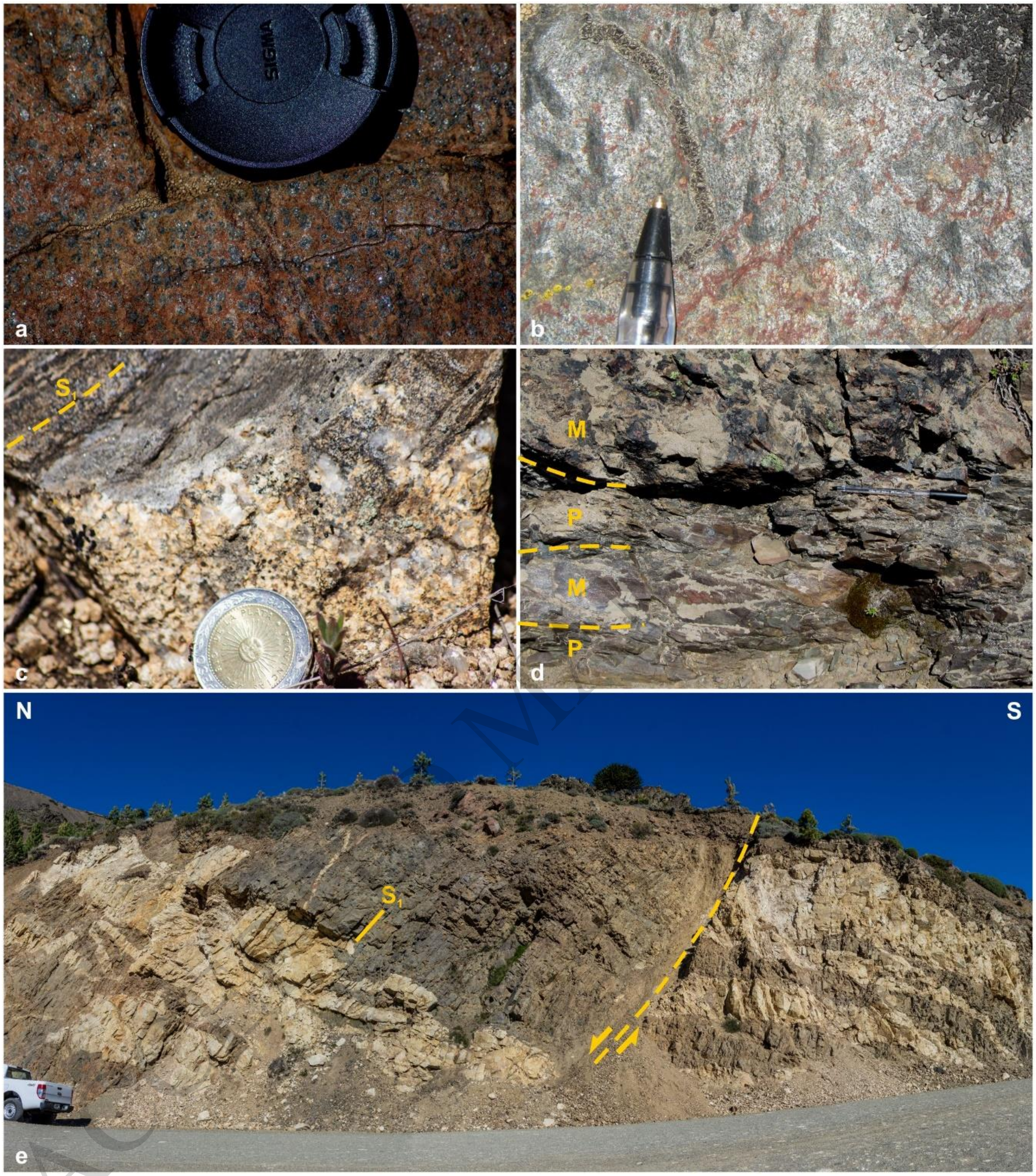

Figure 4

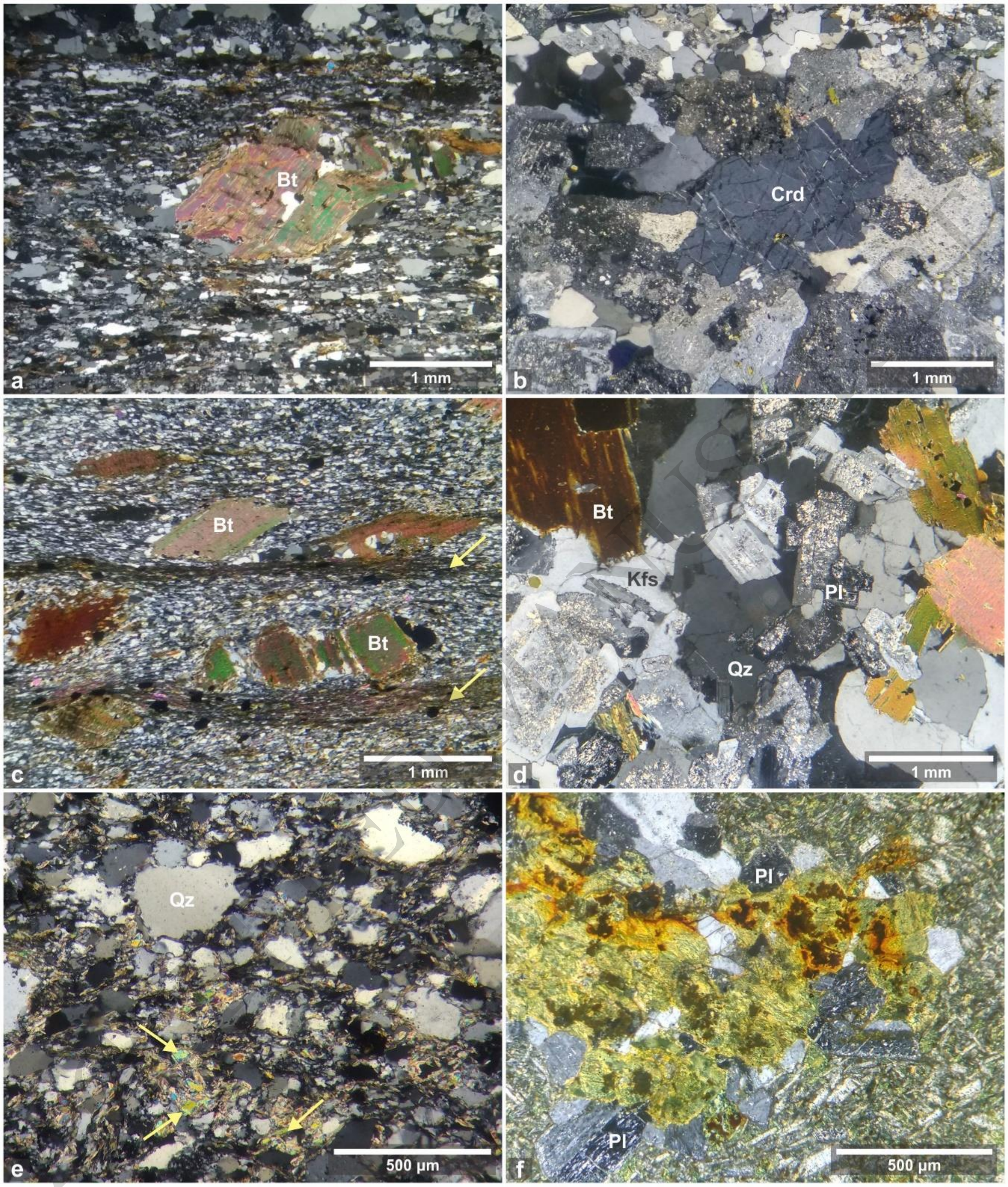
Bt
1 mm
a
Crd
1 mm
b
Bt
Bt
1 mm
c
Bt
Kfs
Pl
Qz
1 mm
d
Qz
500 µm
e
Pl
Pl
500 µm
f

Figure 5

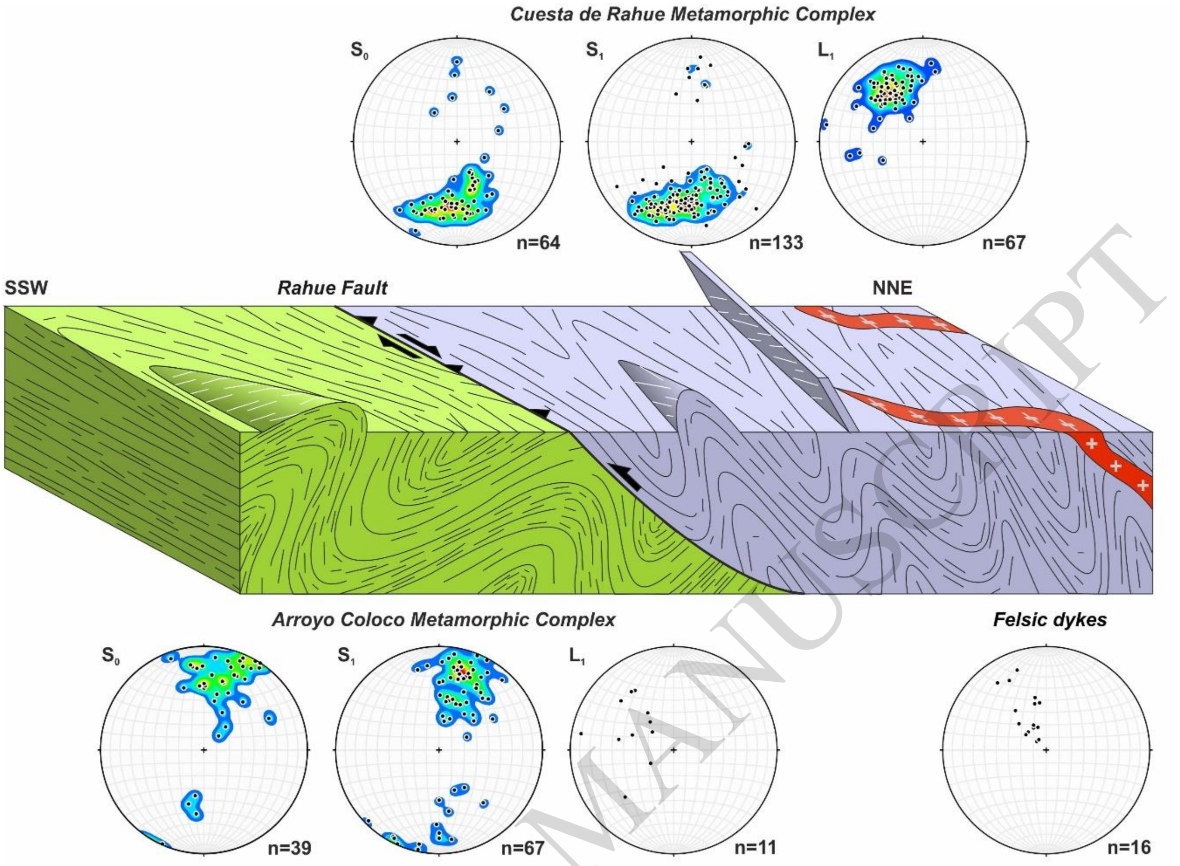
Cuesta de Rahue Metamorphic Complex
S0
n=64
S1
n=133
L1
n=67
SSW
Rahue Fault
NNE
Arroyo Coloco Metamorphic Complex
S0
n=39
S1
n=67
L1
n=11
Felsic dykes
n=16

Figure 6

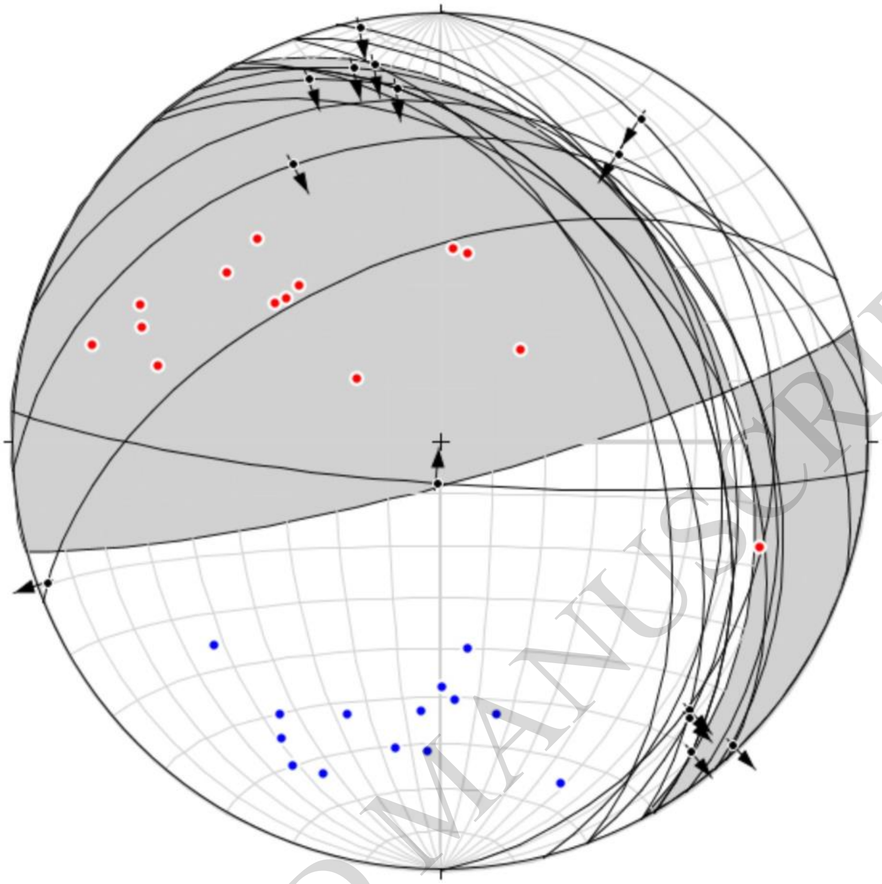

Figure 7

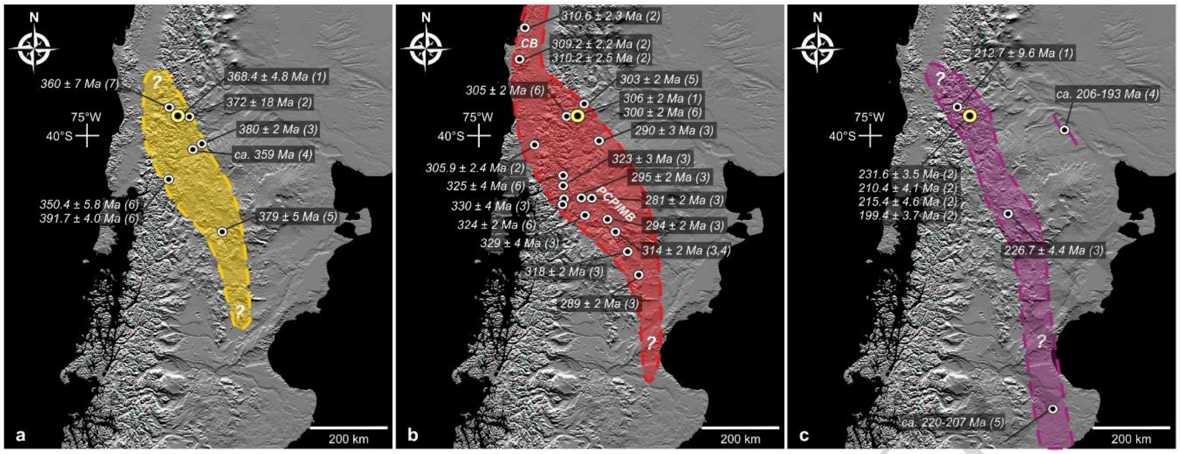
N
75°W
40°S
360 ± 7 Ma (7)
368.4 ± 4.8 Ma (1)
372 ± 18 Ma (2)
380 ± 2 Ma (3)
ca. 359 Ma (4)
350.4 ± 5.8 Ma (6)
391.7 ± 4.0 Ma (6)
379 ± 5 Ma (5)
?
?
a
200 km
N
CB
310.6 ± 2.3 Ma (2)
309.2 ± 2.2 Ma (2)
310.2 ± 2.5 Ma (2)
303 ± 2 Ma (5)
305 ± 2 Ma (6)
306 ± 2 Ma (1)
300 ± 2 Ma (6)
75°W
40°S
290 ± 3 Ma (3)
323 ± 3 Ma (3)
305.9 ± 2.4 Ma (2)
295 ± 2 Ma (3)
325 ± 4 Ma (6)
PCPIMB
330 ± 4 Ma (3)
281 ± 2 Ma (3)
324 ± 2 Ma (6)
294 ± 2 Ma (3)
329 ± 4 Ma (3)
314 ± 2 Ma (3,4)
318 ± 2 Ma (3)
289 ± 2 Ma (3)
?
b
200 km
N
212.7 ± 9.6 Ma (1)
?
ca. 206-193 Ma (4)
75°W
40°S
231.6 ± 3.5 Ma (2)
210.4 ± 4.1 Ma (2)
215.4 ± 4.6 Ma (2)
199.4 ± 3.7 Ma (2)
226.7 ± 4.4 Ma (3)
?
ca. 220-207 Ma (5)
c
200 km

Table 1

Sample	**Unit**	**K (wt. %)**	**2σ (%)**	**^{40}Ar* (ccSTP/g 10^{-6})**	**^{40}Ar Atm (%)**	**Age (Ma)**	**2σ (Ma)**
AB-2	Cuesta de Rahue Metamorphic Complex	5.2776	5.6540	69.56	23.93	368.4	4.8

Table 2

Sample	**Unit**	**Grain size (μm)**	**K_2O (wt. %)**	**$^{40}Ar^*$ (%)**	**Age (Ma)**	**2σ (Ma)**	**Illite cristallinity (Δ°2Θ)**		**Regional conditions**
							Air dry	**Glycolated**	
RA 22-18	Arroyo Coloco Metamorphic Complex	<2	3.70	85.21	231.6	3.5	0.172	0.174	Epizone
		<0.2	3.12	73.45	210.4	4.1	0.191	0.200	Epizone
RA 32-18		<2	3.76	66.15	215.4	4.6	0.168	0.164	Epizone
		<0.2	3.20	62.11	199.4	3.7	0.205	0.200	Epizone