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DEPARTAMENTO DE GEOCIENCIAS
RESEARCH GROUP IN GEOPHYSICS

PETROLOGY

Pressure-Temperature path of Arquía Group rocks (NW Colombia): a petrographic analysis from mineral assemblages

Yuly Tatiana Valencia-Morales, Luz Mary Toro Toro, Elvira Cristina Ruiz-Jiménez, Mario Moreno-Sánchez

Geological Sciences Department of Universidad de Caldas, Calle 65 # 26-10, Manizales, Colombia.

ABSTRACT

Based on the type locality mineral associations of the Arquía Group metamorphic rocks in Colombia, the pressure-temperature conditions of metamorphism were obtained and the associated P-T path was built. The analysis of the mineral assemblages indicates a prograde regional metamorphism, which varies from low to medium grade and is represented by greenschist, epidote-amphibolite and amphibolite facies. The results that are based on the prograde mineralogy [actinolite + chlorite + albite + quartz + muscovite + epidote minerals for greenschist facies and hornblende + epidote minerals + garnet + albite ± quartz for epidote-amphibolite and amphibolite facies] indicate a constant increase of metamorphic conditions from 433°C/11.8 kbar to 696°C/14.4 kbar in the metamorphic peak. Retrograde mineral assemblages [muscovite + chlorite + epidote minerals + albite + actinolite] indicate new metamorphic conditions between 417-357°C and 8.1-6.5 kbar. In addition, four deformation events and evidence of shear zone and intracrystalline deformation were found in these rocks.

Key words: Arquía Complex, Arquía Group, mineral assemblages, metamorphism, P-T path.

RESUMEN

Con base en las asociaciones minerales existentes en las rocas metamórficas del Grupo Arquía en su sección tipo en Colombia, se determinaron las condiciones de presión-temperatura del metamorfismo y se construyó la trayectoria P-T que siguieron estas rocas. El análisis de las asociaciones minerales es consistente con un metamorfismo regional progrado de bajo a medio grado, representado por facies de esquistos verdes, facies epidota-anfibolita y facies anfibolita. Las asociaciones minerales progradas [actinolita + clorita + albita + cuarzo + moscovita + epidota en facies de esquistos verdes y hornblenda + epidota + granate + albita ± cuarzo en facies epidota-anfibolita and anfibolita] indican un aumento constante en las condiciones del metamorfismo, desde 433°C/11.8 kbar hasta 696°C/14.4 kbar en el pico metamórfico. Las asociaciones minerales retrogradas [moscovita + clorita + epidota + albita + actinolita] señalan nuevas condiciones metamórficas entre 417-357°C y 8.1-6.5 kbar. Adicionalmente, estas rocas evidencian cuatro eventos de deformación, presencia de zonas de cizalla y deformación cristalina.

Palabras clave: Complejo Arquía, Grupo Arquía, asociaciones minerales, metamorfismo, trayectoria P-T.

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Introduction

The Arquía Complex is a suite of lithodemes formed from rocks with different origins and diverse ages, forming a narrow and elongated belt that extends from the Departamento de Antioquia in Colombia (north) to the Provincia de Oro in Ecuador (south) (Moreno-Sánchez & Pardo-Trujillo, 2002, 2003; Moreno-Sánchez et al., 2008). In Colombia, the Complex is located at the western flank of the Cordillera Central, being bounded by the Silvia-Pijao fault in the east and by the Cauca-Almaguer fault in the west (Maya & González, 1995; Pardo-Trujillo & Moreno-Sanchez, 2001; Moreno-Sánchez & Pardo-Trujillo, 2002, 2003; Nivia et al., 2006; Moreno-Sánchez et al., 2008). These authors proposed that the Arquía Complex is formed by medium to high pressure metamorphic rocks from igneous, sedimentary and metamorphic protoliths, although its origin, age and evolution is still unclear. Because of the mentioned above and the dense system of faults that juxtapose the lithodemes, this Complex has been the object of a wide discussion (Moreno-Sánchez & Pardo-Trujillo, 2003). With the aim of clarifying what the Arquía Complex is, in the latter study, it is proposed to be composed by Paleozoic, Mesozoic and Cenozoic blocks that were affected by subduction, magmatism and shear processes.

The lithodeme was first defined as an independent Group by Restrepo & Toussaint (1976) and Arias & Caballero (1978); it was later redefined as part of the Arquía Complex by Moreno-Sánchez & Pardo-Trujillo (2003). The Arquía Group is formed by garnet amphibolites, greenschists and mica schists, from basic, volcano-sedimentary and pelitic protoliths, respectively, metamorphosed under greenschist and amphibolite facies conditions (Restrepo & Toussaint, 1976; Arias & Caballero, 1978; Sánchez, 1988; Ríos-

Reyes, *et al.,* 2008; Marín, 2009; Ruiz-Jiménez, *et al.,* 2012). A K/Ar age analysis on a hornblende from an amphibolite by Restrepo & Toussaint (1976) indicating 110 ± 5 Ma is interpreted as the age of metamorphism. The metamorphism is related not only to overthrusting and the obduction of oceanic crust (Restrepo & Toussaint, 1976; Arias & Caballero, 1978) but also to a subduction zone setting (Sánchez, 1988). In a recent study by Ruiz-Jiménez, *et al.* (2012) based on geochemical analyses, it was concluded that these rocks originated from MORB basalt protoliths and were formed in the Early/Middle Cretaceous in a supra-subduction marginal ocean basin.

In this study, it was analyzed the type section of one of the lithodemes of the Arquía Complex, called the Arquía Group, which is located in the valley of the Arquía River between La Pintada village (Departamento de Antioquia) and La Felisa village (Departamento de Caldas, Colombia; Figure 1) (Restrepo & Toussaint, 1976; Arias & Caballero, 1978). Here, it is presented the results obtained from a detailed mineral assemblage analysis of the different rocks of Arquía Group, based on optical microscopy. This work also provides the deduced metamorphic conditions and its associated P-T path.

Geology of the area

The lithology of the area consists of greenschists, mica schists, quartzites, hornblende schists, amphibolites, garnet-amphibolites, serpentinites and porphyritic hypabyssal rocks with andesitic to dacitic composition (Figure 1). Metamorphic rocks show variable schistosity with westward dips and some local folds. These rocks also show shear zones, characterized by mylonitic foliation.

From east to west, rocks appear in the area as follows: The eastern rocks correspond to greenschists, which have a well-developed schistosity S_1 (Figure 2a), with strikes from N45°E to N60°W, and dips westward, with angles ranging from 29° to 85°. The greenschists in their middle section are intercalated with layers of mica schists, such intercalations vary in thickness from millimeters to meters. In addition, the local intrusions of andesitic and dacitic subvolcanic bodies can be observed in these lithologies (Figure 2b).

At the western section of the greenschists, these are in transitional contact with hornblende schists. This contact is represented by a small increase in grain size and a slight variation in color. Foliation in these rocks shows strikes ranging from N15 to 22°E and dips either 60°-80°NW or verticals (Figure 2c).

At their western part, the hornblende schists are in contact with serpentinites (Figure 1). Although it was not specifically observed, it is inferred to be a fault contact due to the presence of mylonitic foliation (N10°E/90°), which is defined by quartz and plagioclase porphyroclasts in the hornblende schists (Figure 2d). Marín (2009) also described a fault contact between these lithologies, with N15°E/54°NW fault plane, although the type of movement was not defined.

At their western section, serpentinites are in contact with amphibolites, separated by a normal fault with a N36°E/65°NW plane (Figure 2e). The amphibolites have a well-developed schistosity with a N31°E/52NW trend. In hand specimen, it is possible to observe red garnets up to 6 mm in size (Figure 2f). These rocks are in contact with mica schists through a N35°W/75°SW sinistral fault (Marín, 2009) (Figure 2g) at their western part. Mica schist are green or black (Figure 2h) in color, depending on the modal percentage of graphite. These rocks have a well-developed schistosity (N35°W-N28°E/50-69°W).

Quartzites and anthophyllite schists are also present in this zone, although they do not appear on the map (Figure 1) because of the scale. Quartzites outcrop as schistosity-concordant layers up to 15 cm in thickness and alternate with mica schists. Anthophyllite schists are restricted to hornblende schists, and they appear as anastomosed irregular lenses, with thicknesses between 4 and 11 cm, composed of translucent and fibrous minerals parallel to schistosity (Figure 2i).

Methodology

Petrographic observations and thermodynamic modeling have made it

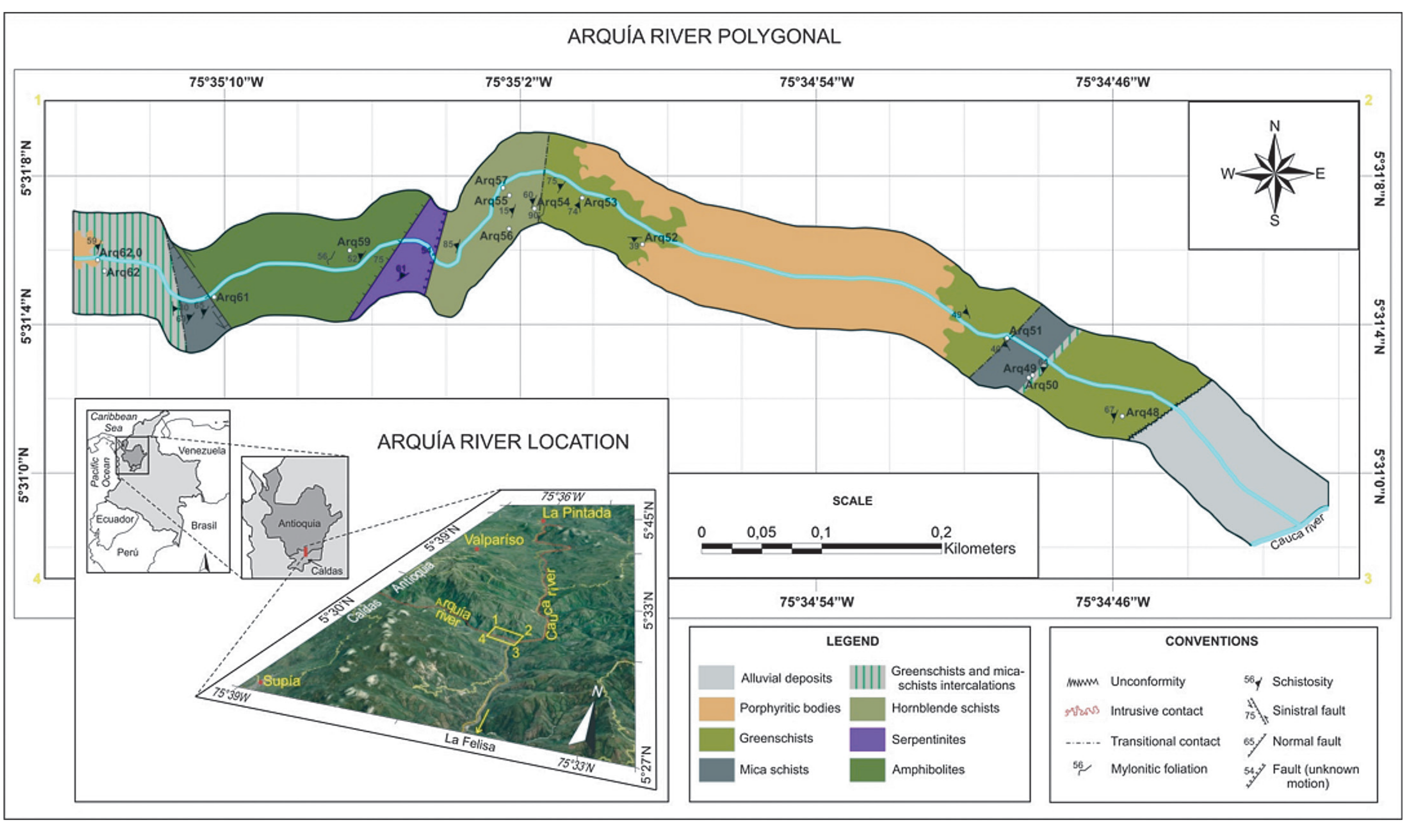


Figure 1. Lithological units of Arquía Group in its type section. Note the contacts among them. Anthophyllite schists and quartzites are much small to appear in this scale.

possible to determine the pressure and temperature conditions that occurred at the time *t* of the metamorphic processes and the construction of *P-T* paths from the mineral assemblages found in metamorphic rocks at equilibrium (e.g., Apted & Liou, 1983; Guiraud *et al.,* 1990; Pattison, 2002; Tibaldi *et al.,* 2007; Abbott & Bandy, 2008; Zhang *et al.,* 2009; Goswami *et al.,* 2009; Aoki *et al.,* 2009; Blanco-Quintero *et al.,* 2010). In this study, 18 thin sections from the Arquía Group were analyzed with the aim of determining the metamorphism conditions and the *P-T* paths of their rocks. The interpretations are based on the following: 1. the mineral assemblages at equilibrium found in greenschists, hornblende schists, garnet amphibolites, and amphibolites , and 2. The temperatures and pressures reached for similar mineral assemblages, as reported by Blanco-Quintero *et al.,* 2010 (Table 1).

The petrographic analysis was performed using a NIKON ECLIPSE E200 trinocular polarizing microscope with transmitted illumination. The mineral abbreviations correspond to those recommended by Siivola & Schmid (2007).

Petrography

This section describes the mineral assemblages and the textures observed in the metamorphic rocks of the Arquía Group as well as a likely protolith for each one. The modal percentages and mineral assemblages are shown in Tables 2 and 3, respectively.

Greenschists

The rocks correspond to actinolite schists and chlorite schists (Figure 3a and 3b) with mineral assemblages as follows: actinolite + chlorite + quartz + plagioclase (albite) + epidote minerals ± muscovite ± calcite. Titanite, zircon, opaque minerals and Fe and Ti oxides are also present as accessories. These rocks were formed in greenschist facies. Their protoliths correspond to volcano-sedimentary rocks and marls. The textures in the rocks are nematoblastic and granoblastic. The former is defined by an actinolite orientation and the latter by an inequigranular mosaic of epidote, plagioclase and quartz (Figure 3a and 3b).

Hornblende schists

The rocks have two different mineral assemblages. The first one corresponds to epidote-amphibolite facies, represented by hornblende

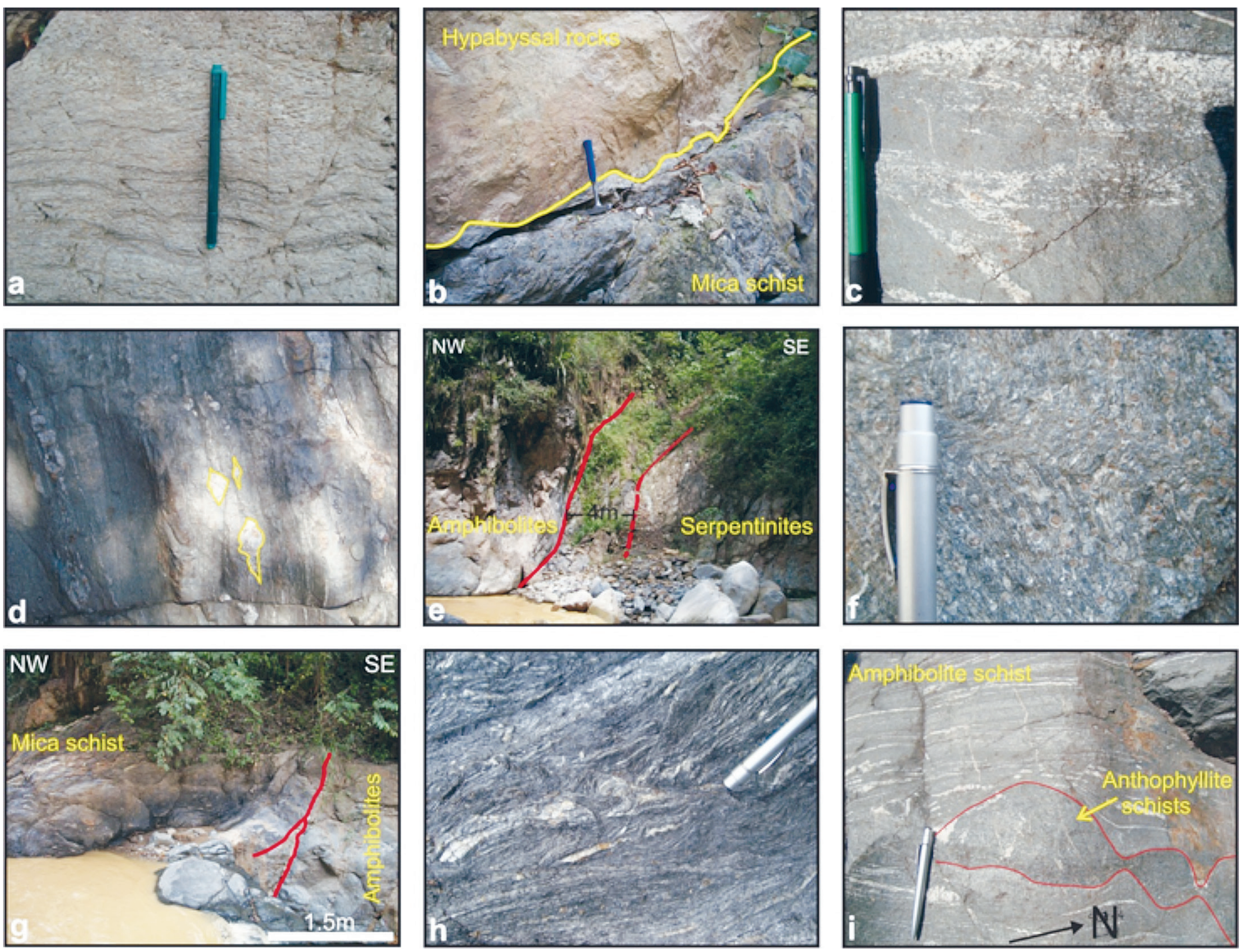
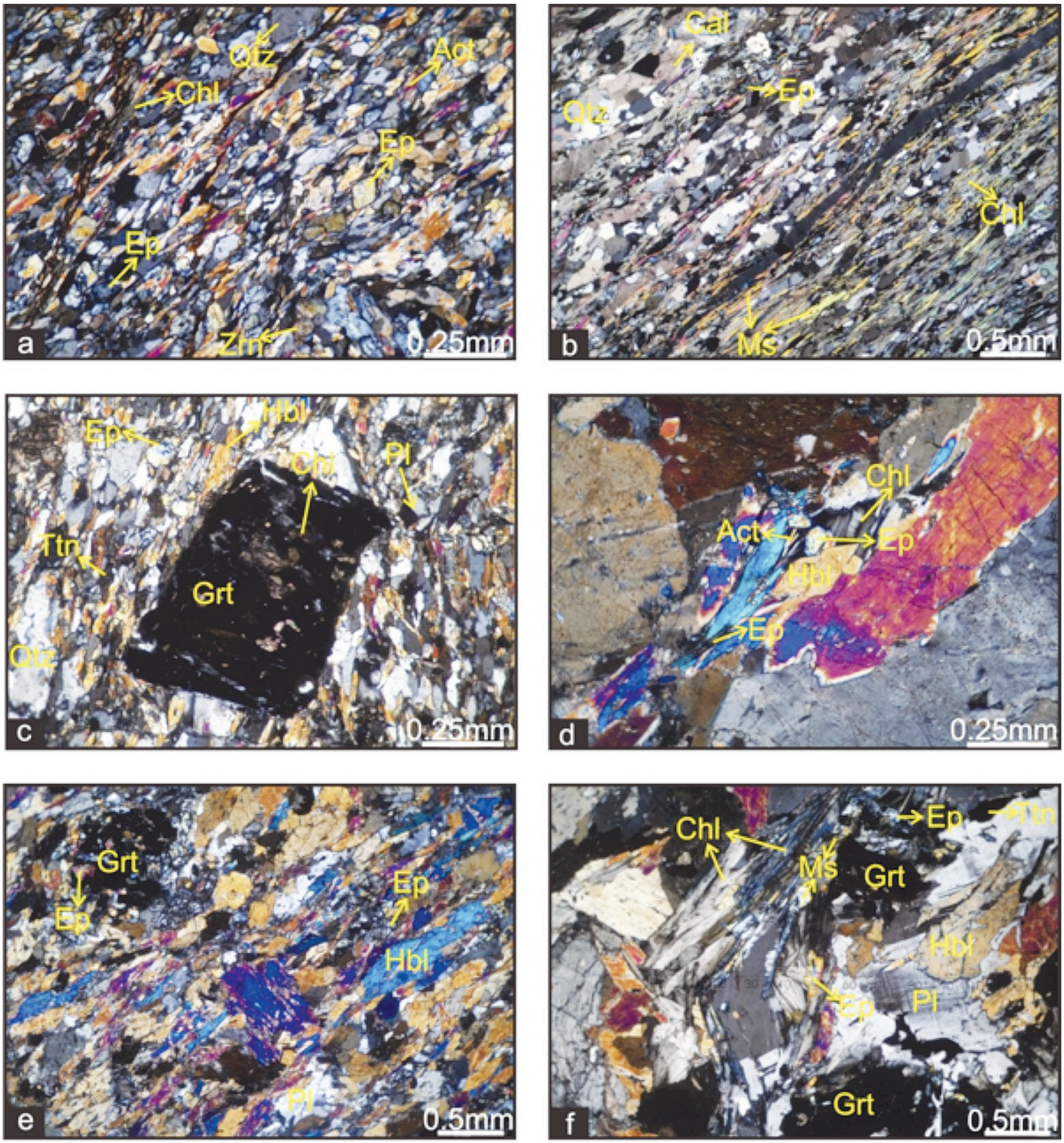


Figure 2. Rocks and contact among them in Arquía Group type section. **a.** Greenschist hand sample. **b.** Hypabyssal body intruding mica schists. **c.** Hornblende schist hand sample. **d.** Plagioclase and quartz porphyroblasts defining mylonitic foliation (N10°E/90°) in hornblende-schist. **e.** Faulted contact between the serpentinites to the east and the amphibolites to the west (fault plane N36°E/65°NW). f. Garnet amphibolite hand sample. **g.** Faulted contact between the amphibolites to the east and the mica schists to the west. **h.** Mica schist hand sample. **i.** Irregular lens of anthophyllite schists into hornblende schists.

+ epidote group minerals + quartz + albite ± garnet (Figure 3c). The second one shows the greenschist facies, represented by chlorite + actinolite + epidotes + quartz (Figure 3d). Zircon, opaque minerals, titanite and Fe oxides are present in the rock as accessory minerals. Protoliths of hornblende schists correspond to basic and volcano-sedimentary rocks. The textures found in the rocks are nematoblastic, granoblastic and porphyroblastic. The first texture is defined by hornblendes, the second one by plagioclase, quartz, and the epidote group, and the last one by garnet (Figure 3c).

Amphibolites and garnet amphibolites

Amphibolites and garnet amphibolites present two types of paragenesis. The first one corresponds to amphibolite facies (Figure 3e), defined by hornblende + plagioclase ± garnet ± quartz. The second one corresponds to greenschist facies (Figure 3f), represented by chlorite + muscovite + epidotes+ plagioclase (albite) + quartz + actinolite. Calcite, Fe oxides and opaque minerals are present in the rocks as accessory minerals. The protolith of these rocks corres-



ponds to basic rocks. The existent textures include nematoblastic, granoblastic, porphyroblastic and poikiloblastic. The nematoblastic texture is defined by its preferential orientation of hornblende (Figure 3e). The granoblastic texture is determined by plagioclase. The porphyroblastic texture is described by garnet and some plagioclase (Figure 3e). The poikiloblastic texture is defined by the inclusion of epidote minerals, titanite, muscovite, hornblende and garnet in the plagioclase (Figure 3g).

Mica schists

These rocks correspond to those whose principal components are mica minerals in the absence of actinolite and epidote. They are classified as quartz-muscovite-chlorite schists. Their mineral assemblage is quartz + graphite + muscovite + chlorite + plagioclase (Albite) ± biotite. Tourmaline, calcite, opaque minerals and Fe oxides are also present as accessory minerals. This mineral association is typical of greenschist facies (Figure 3h and 3i). These rocks have a pelitic protolith. Additionally, muscovite, chlorite, and graphite minerals define the lepidoblastic texture. Quartz, plagioclase and calcite define the granoblastic texture.

Anthophyllite schists

These rocks were classified as anthophyllite-quartz-hornblende schists. The mineral assemblage corresponds to anthophyllite + hornblende + quartz + plagioclase + chlorite + epidote minerals, with titanite and calcite as accessory minerals. These rocks likely have a basic protolith. Textures in these schists are nematoblastic, defined by anthophyllite and hornblende, and granoblastic, defined by quartz, plagioclase and epidotes (Figure 3j).

Quartzites

The mineral assemblage in these rocks corresponds to quartz + plagioclase ± muscovite ± chlorite, with biotite and zircon as accessory minerals. These rocks have a granoblastic texture with a domain of quartz and plagioclase of different shapes and sizes, showing evidence of recrystallization. The lepidoblastic texture is also observed due to the orientation of mica minerals. The possible protolith of these rocks is a quartz-feldspathic sedimentary rock, likely a sandstone.

Microstructures

The mineral assemblages and textures in the rocks allow for the inter-

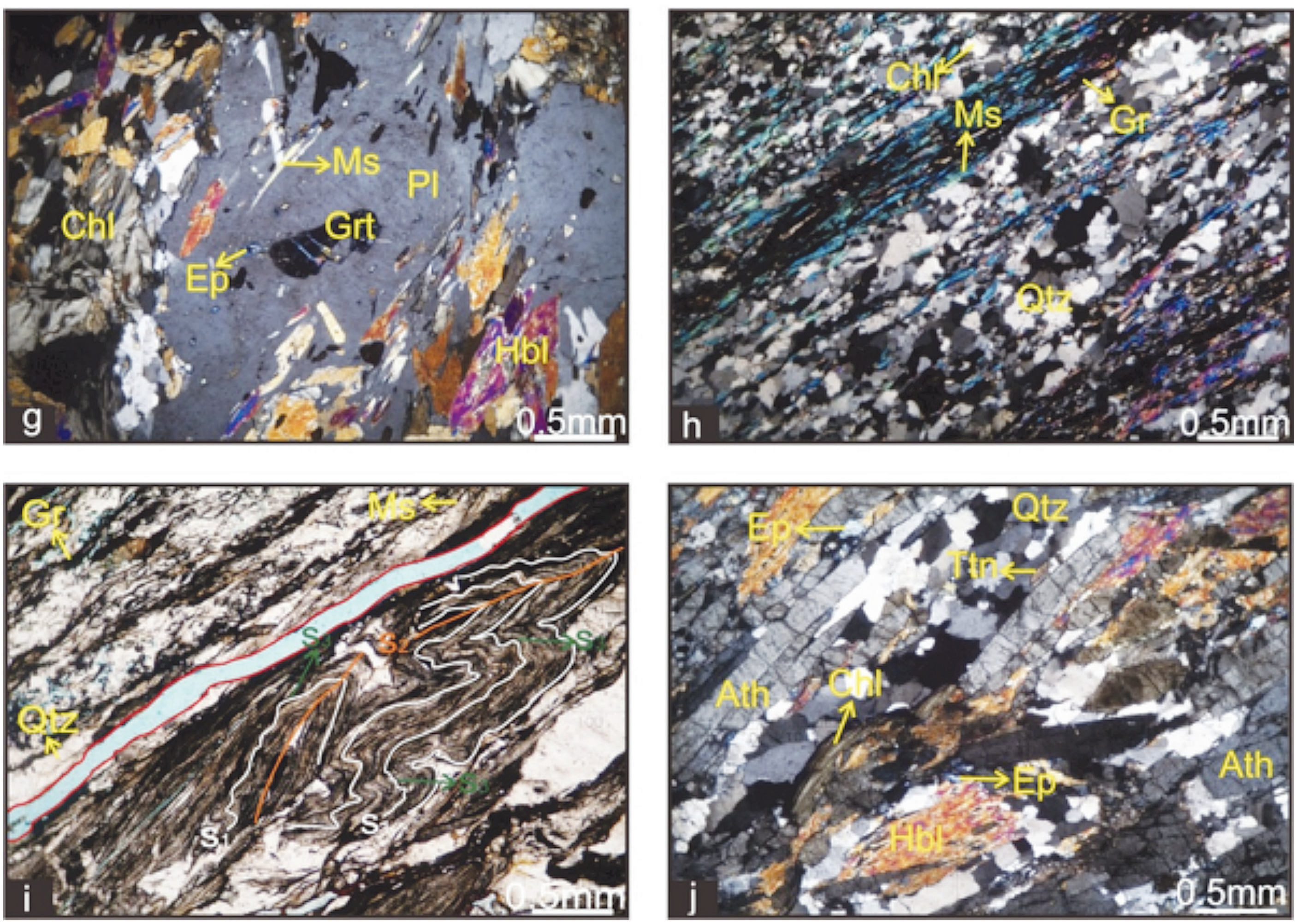


Figure 3. Photomicrographs of the rocks present in the area. **a.** Actinolite schist with nematoblastic and granoblastic textures. **b.** Chlorite schist with lepidoblastic and granoblastic textures. **c.** Prograde mineralogy (Hda+Ep+Qtz+Ab+Grt) in hornblende schist and nematoblastic, granoblastic and porphyroblastic textures. **d.** Hornblende schist with retrograde mineralogy (Chl+Act+Ep+Qtz). **e.** Prograde mineralogy (Hda+Grt+Pl±Qtz) of garnet amphibolites and nematoblastic and porphyroblastic textures. **f.** Retrograde mineralogy (Chl+Ms+Ep+Pl[albita]+Qtz+Act) in garnet amphibolites. **g.** Poikiloblastic texture in garnet amphibolites. **h.** Anthophyllite schist, nematoblastic and granoblastic textures. **i.** Mica schist and lepidoblastic and granoblastic textures. **j.** Three deformation phases that affected mica schists.

pretation of the relative sequence of metamorphic and deformation events. Consequently, four deformation phases were found using the relationship between the fabric elements and the minerals that define them.

Deformation phases:

Four deformation phases with the same number of deformation events were identified. Three phases are compressional, and one is extensional.

The first deformation phase (S_1) is indicated by schistosity (it is dipping to the west). This deformation phase is defined by actinolite, chlorite and muscovite in the greenschists (Figures 3a y 3b), by hornblende in the hornblende schists (Figure 3c) and the amphibolites (Figure 3e), by chlorite, muscovite and graphite in quartz-muscovite-chlorite schists or mica schists (Figures 3h and 3i), and by hornblende and anthophyllite in the anthophyllite schists (Figure 3j). In addition, some minerals of columnar habit (epidote group minerals) and elongated quartz crystals are parallel to schistosity, suggesting that their growth happened simultaneously with the deformation.

The second deformation phase (S_2) is manifested in all the rocks by the folding of schistosity, which is macroscopically observed (see Figures 2f and 2h). Microscopically, this phase is also well-recorded in quartz-muscovite-chlorite schists (mica schists). In these rocks, S_2 is observed as crenulation foliation and/or fracture cleavage that developed from S_1 (Figure 3i). Notably, the quartz is found in the hinges and not in the flanks of the folds developed by S_2, suggesting that this deformation phase was accompanied by the dissolution and recrystallization of this mineral. Moreover, muscovites are bent in the hinges of folds. Microsopically, this deformation phase also was recorded in the hornblende schists.

The development of a third deformation phase (S_3) is observed in quartz-muscovite-chlorite schists (mica schists). S_3 is represented by the folding of flanks of crenulation foliation (S_2) and defined by graphite and bent muscovites (Figure 3j).

A fourth deformation phase (S_4) is observed in hand specimen of greenschists by the presence of quartz-plagioclase *boudins*; this deformation event is extensional in character.

Textures of shear zone and other intracrystalline deformation

The Arquía Group rocks indicates that they were affected by shearing, as is evidenced by the presence of brittle shear zones manifested by microfaults, intensely sheared zones, broken crystals, and S-C fabrics. These rocks also show ductile shear zones, which are indicated by the formation of porphyroclasts with pressure shadows. The rocks present undulose extinction, deformation twinning, and evidence of dynamic recrystallization processes, including grain boundary migration, subgrain rotation recrystallization in quartz and plagioclase, and stylolitic surfaces in calcite.

Discussion

Prograde and retrograde metamorphism

The metamorphic rocks in the Arquía valley were affected by prograde metamorphism, which was followed by a retrograde event after reaching maximum temperature and pressure conditions. This statement is based on the following observations:

The relationships among the various types of rocks that form the Arquía Group are consistent with prograde metamorphism. This is shown by an increase in the metamorphic grade from east to west (Figure 1). Thereby, in the Arquía Group type section, the greenschists change in a transitional form to hornblende schists westward, and the amphibolites appear further to the west. It should be noted that a serpentinized peridotites body is located between the hornblende schists and the amphibolites; however, these three rock-bodies are separated by faults. (Figures 1 and 2e). Then, a progressive metamorphism in these rocks is marked by the passing of greenschist facies mineralogy [actinolite + chlorite + quartz + plagioclase (albite) + epidote minerals ± muscovite ± calcite] to epidote-amphibolite facies mineralogy [hornblende + epidote minerals + quartz + albite ± garnet], and finally to amphibolite facies mineralogy [hornblende + garnet + plagioclase ± quartz].

The prograde metamorphism was followed by a retrograde metamorphic event that affected the mineral associations formed at the metamorphic peak. This is supportd by the mineralogy of greenschist facies that is found among the mineral assemblages of the amphibolite and epidote-amphibolite facies, such as chlorite + actinolite + epidote minerals + quartz (mineralogy of greenschist facies), between hornblende + epidote minerals + quartz + albite ± garnet (mineralogy of epidote-amphibolite facies) in the hornblende schists (Figures 4d), and the chlorite + muscovite + epidote minerals + plagioclase (albite) + quartz (mineralogy of greenschist facies) between the hornblende + garnet + plagioclase ± quartz (amphibolite facies) in the garnet amphibolites (Figure 3f). In addition, there is textural evidence of retrograde metamorphism in amphibolites (sample Arq59A1 in Figure 1), such as the presence of muscovite, epidote minerals, hornblende and garnet as inclusions into the plagioclase (Figure 3g). These inclusions could represent mineral phases in formation [muscovite and minerals of epidote group] and previous mineral phases that were not fully consumed [garnets with very rounded (Figure 3g) and/or completely irregular boundaries].

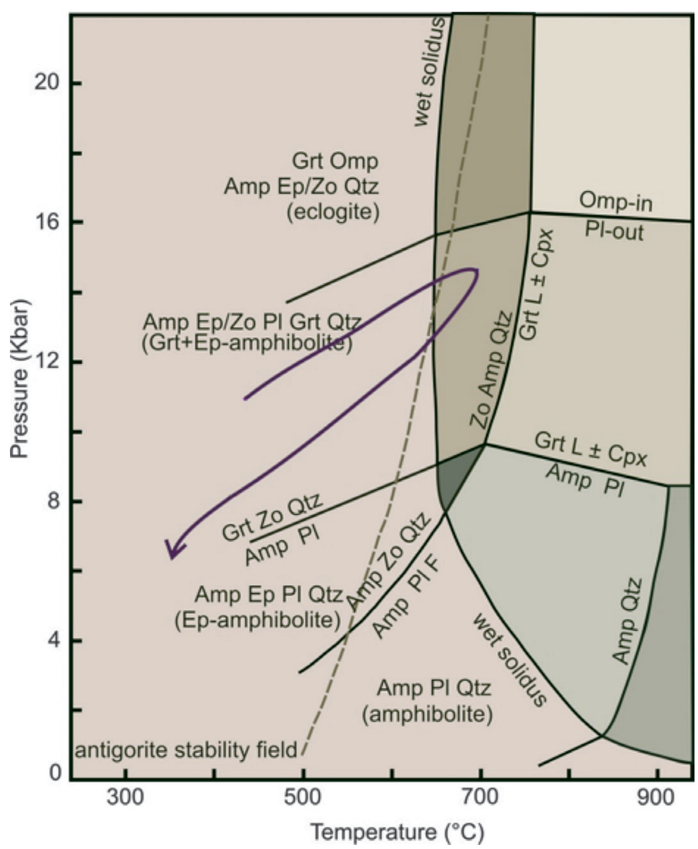


Figure 4. Pressure-Temperature path diagram of Arquía Group in its type section. Diagram adapted from Blanco-Quintero et al. (2010).

Metamorphic conditions

To define the intensive variable temperature and pressure values that affect the Arquía Group rocks, mineral assemblages of these rocks were compared with data obtained by Blanco-Quintero *et al.* (2010) (Table 1).

Table 1. Mineral assemblages and temperatures and pressures calculated for La Corea mélange rocks by Blanco-Quintero et al. (2010).

Metamorphic Phases		Metamorphic assemblages	T(°C)	P(Kbar)
Greenschist facies	Prograde metamorphism	Act+Chl+Ep+Ms+Ab+Qtz	433	11.8
Amphibolite facies		Grt+Amp+Ep+Pl+Qtz	696	14.3
Greenschist facies	Retrograde metamorphism	Act+Chl+Ep+Ms+Qtz	417	8.1
		Act+Chl+Ms+Ab+Qtz	357	6.5

Table 2. Location of samples taken in the type section of Arquía Group and mineral assemblages for each one.

Lithology	**Sample**	**Location**		**Mineral Assemblage**	
		N	**W**	**Prograde**	**Retrograde**
Greenschists	ARQ 48A	5° 31' 1,52"	75° 34' 45,73"	Act+Qtz+Chl+Ab +Ep.	
	ARQ 49	5° 31' 2,6"	75° 34' 48,18"	Act+Chl+Qtz+Ab +Ep.	
	ARQ 51	5° 31' 3,86"	75° 34' 48,76"	Act+Chl+Qtz+Ab+Ep.	
	ARQ 52	5° 31' 6,13"	75° 34' 58,48"	Chl+Ms+Qtz+Ab+ +Ep.	
	ARQ 53	5° 31' 7,43"	75° 35' 0,35"	Act+Qtz+Chl+Ab+Ep.	
Hornblende schists	Arq54	5° 31' 7,14"	75° 35' 1,68"	Hbl+Ep+Grt+Qtz+Ab	Chl+Ep+Qtz
	Arq55	5° 31' 7,68"	75° 35' 2,47"	Hbl+Ep+Ab	Act+Chl+Ep+Qtz.
	Arq55A	5° 31' 7,68"	75° 35' 2,47"	Hbl+Ep+Ab	Act+Chl+Czo+ Qtz.
	Arq56	5° 31' 6,53"	75° 35' 2,33"	Hbl+Ep+Ab	Act+Ep+Chl.
Amphibolites and garnet amphibolites	Arq59A	5° 31' 5,84"	75° 35' 6,65"	Hbl+Grt+Pl	Ms+Chl+ Ep+Ab+Act.
	Arq59A1	5° 31' 5,84"	75° 35' 6,65"	Hbl+Grt+Pl	Ms+Chl+Ep+Ab.
	Arq59B	5° 31' 5,84"	75° 35' 6,65"	Hbl+Grt+Pl	Ms+Chl+Ep+Ab.
	Arq60	5° 31' 4,63"	75° 35' 10,42"	Hbl+Grt+Pl	
	Arq61	5° 31' 4,70"	75° 35' 10,50"	Hbl+Pl	Ep
Anthophyllite schist	Arq57	5° 31' 7,32"	75° 35' 2,36"	Ath+Hbl+Chl+Qtz	
Quartzite	Arq60B	5° 31' 4,63"	75° 35' 1,42"	Qtz+Ab+Ms+Chl+Bt	
Mica schists or quartz-mus-covite-chlorite schists	Arq48	5° 31' 1,52"	75° 34' 45,73"	Qtz+Ms+Chl+Gr+Ab.	
	Arq50	5° 31' 2,53"	75° 34' 48,25"	Ms+Gr+Chl+Qtz+Ms+Ab	
	Arq60A	5° 31' 4,63"	75° 35' 10,42"	Qtz+Ms+Chl+Bt+Gr+Ab.	
	Arq62,0	5° 31' 5,41"	75° 35' 13,31"	Qtz+Ms+Chl+Cal+Ab.	
	Arq62	5° 31' 5,66"	75° 35' 13,49"	Qtz+Ms+Chl+Ms+Ab+Gr.	

Table 3. Modal percentages in the rocks of the Arquía Group in its type section.

Lithology	Modal percentages (%)
Greenschists	Act (22-26%) + Qtz (21-30%) + Chl (17-26%) + Ab (2-5%) + Czo (4-14%) + Ep (1-5%) + Zo (3-11) ± Ms (2-20%) ± Cal (4-15%).
Hornblende schists	Hbl (29-48%) + Czo (2-11%) + Zo (5-13%) + Ep (2-8%) ± Grt (0-16%) + Qtz (3-29%) + Ab (5-32%) + Chl (5-11%) + Act (1-8%).
Amphibolites and garnet amphibolites	Hbl (27-44%) + Grt (0-14%) + Pl (18-23%) ± Qtz (4-12%) ± Chl (4-19%) ± Ms (0-2%) ± Ep (0-2%) ± Zo (0-2%) ± Czo (1-6%) ± Act (0-2%) ± Ttn (2-5%).
Anthophyllite schist	Ath (33%) + Hbl (12%) + Czo (7%) +Zo (6%) + Chl (6%) + Qtz (29%)+ Pl (6%).
Quartzite	Qtz (82%) + Ab (5%) + Ms (8%) + Chl (3%) +Bt (2%)
Mica schists	Qtz (22-38%) + Ms (16-28%) + Chl (5-26%) + Gr (2-32%) + Ab (2-7%) ± Bt (0-7%).

P-T conditions of prograde metamorphism:

Blanco-Quintero *et al.* (2010) (Table 1) considered the equilibrium point of the Act+Chl+Ep+Ms+Ab+Qtz association at 433°C/11.8 kbar. This mineral assemblage was observed in the greenschists (sample Arq53; Figure 1; Table 2) with an Act+Qtz+Chl+Ab+Ep±Ms association. In addition, these authors considered the Grt+Amp+Ep+Pl+Qtz mineral assemblage equilibrium point to be at 696°C/14.4 kbar. This assemblage was observed in hornblende schists and garnet amphibolites with the Grt+Hbl+Ep+Pl+Qtz association (sample Arq54; Figure 1; Table 2), whereas the amphibole is represented in the Arquía Group rocks by hornblende.

P-T conditions of retrograde metamorphism:

Mineral assemblages Act+Chl+Ep+Ms+Qtz and Act+Chl+Ms+Ab+Qtz (Blanco-Quintero *et al.,* 2010) are in equilibrium at 417°C/8.1 kbar and 357°C/6.5 kbar, respectively. These correspond to retrograde mineral assemblages that are present in hornblende schists and garnet amphibolites (sample Arq59A; Figure 1), where the retrograde mineral association is Ms+Chl+Ep+Ab+Act.

Accordingly, during the prograde metamorphism that affected the Arquía Group, the rocks with mineral assemblages formed under greenschist facies conditions reached temperatures of 433°C and pressures of 11.8 kbar, whereas those with mineral assemblages formed under epidote-amphibolite and amphibolite facies reached values of 696°C and 14.5 kbar; the latter values correspond to metamorphic peak conditions. The garnet amphibolites and hornblende schists showed a retrograde metamorphic event at the greenschist facies. This event reached temperatures between 417 and 357°C and pressures between 8.1 and 6.5 kbar.

Plotting the values mentioned above in a *P-T* diagram (Figure 4), the Arquía Group rocks follow a clockwise trajectory. This graphic shows a constant increase in temperature and pressure until the metamorphic peak at 696°C and 14.5 kbar. The maximum conditions are followed by a decrease in temperature and pressure, which is shown by mineral assemblages that were retrograded from amphibolites and epidote-amphibolite facies towards greenschist facies.

Conclusions

The rocks of the Arquía Group at its type section show an increase of metamorphic grade from east to west. This is manifested by transitional changes from greenschists to hornblende schists and subsequently to amphibolites.

The mineral assemblages that record S_1 show a prograde metamorphism event with a continuous increase in temperature and pressure. This behavior is initially expressed in the mineral assemblages of greenschist facies passing for epidote-amphibolite facies, and continues until the maximum pressure and temperature conditions for amphibolite facies are reached.

The metamorphic peak was followed by one retrograde event, which manifested with the decrease in metamorphic conditions. This caused the development of greenschist facies assemblages from epidote-amphibolite and amphibolite facies mineralogy.

The metamorphic rocks of the Arquía Group record a clockwise *P-T* path, with initial conditions of 433°C and 11.8 kbar and a constant increase in temperature and pressure until values of 696°C and 14.4 kbar were reached. After this, there was a period of decompression and constant cooling until conditions of 417–357°C and 8.1-6.5 kbar were reached. The *P-T* path shows that the conditions that followed to the metamorphic peak caused a retrograde metamorphic event.

The Arquía Group in the Arquía River valley recorded four deformation events with the same number of deformation phases. Three of these events are compressional, and the last one is extensional. In addition, evidence of brittle and ductile shear zones and intracrystalline deformation is commonly found in these rocks.

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