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Sedimentary signatures in Jambaló Blueschist:

Tectonic implications

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Degree project

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Abstract

The aim of this contribution is to analyze the sedimentary influence on the protoliths that gave rise to the blue schists of Jambaló, Cauca, Colombia, through the detailed identification of their mineralogical and structural characteristics. The hypothesis posits that the protolith of the Jambaló blue schists exhibits significant signs of a sedimentary component, which may reflect the proximity of an oceanic arc to the western margin of South America during the Cretaceous period. Fieldwork and petrographic analyses were conducted to characterize the blue and green schists in the area. Previous geochemical data were also reanalyzed. The results indicate that both types of schists share a common origin but followed distinct metamorphic paths. Geochemistry suggests a mixture of pelagic and terrigenous sediments in the protoliths, with a higher proportion of pelagic sediments. This supports the hypothesis of the proximity of an oceanic arc that accumulated these sediments. In conclusion, the Jambaló blue schists represent a metamorphic belt distinct from those previously proposed for the region. Their protoliths reflect the approach of an intra-oceanic arc to the continental margin during the Cretaceous.

Kay words: Jambaló blueschist, Sediment input, North Andes, Geochemistry, Petrography

1. Introduction

Subduction zones are found at convergent plate boundaries, where Earth's lithospheric plates descend back into the deeper mantle (Zheng & Zhao, 2017). Subduction zone metamorphism is recognized through the presence of glaucophane-bearing schist and related metamorphic rocks in elongated, narrow, often associated with rocks of oceanic origin such ophiolites and pelagic sediments (Ernest, 1971). These zones are typically deployed around the margins of the Pacific Ocean like (i) California, USA (Ernest, 1984); (ii) Diego de Almagro Island, Chile (Hyppolito et al., 2016); El Guayabo, Ecuador (Riel et al., 2014) and Kanto, Japan (Aoki et al., 2008).

The Mesozoic to Cenozoic orogenesis in the northern Andes, is marked by a sequence of collisions involving island arcs and oceanic plateaus with the western South American continental margin (Spikings et al., 2015). These collisions led to the formation of multiple subduction zones and the thrusting of oceanic crustal fragments. These processes occurred both on the continental margin and within intra-oceanic domains (Cardona et al., 2012; Bustamante & Bustamante, 2019). Consequently, ophiolitic complexes were formed, along with low-, medium-, and high-pressure metamorphic rocks, as a result of tectonostratigraphic terrane amalgamation (Ramos, 2009). Suture zones, characterized by blueschist and eclogite rocks, have been identified in the Cordillera Real of Ecuador in the Raspas Metamorphic Complex (Feininger, 1980; Riel, et al., 2014) and in the Central Cordillera of Colombia where high-pressure rocks outcrops are identified in the areas of Jambaló, Pijao and Barragán (Bustamante, 2008).

In the Central Cordillera of Colombia, high-pressure metamorphic units are part of the Arquía complex (Feininger, 1980; McCourt and Feininger, 1984; Aspden & McCourt, 1986; Bourgois et al., 1987; Aspden et al., 1995; Maya & Gonzales, 1995; Bustamante, 2008). However, they are distinguished as two different units from the early and late Cretaceous periods. The first occurrence includes retrograded eclogites and blue schists with normal mid-ocean ridge basalt (N-MORB) characteristics in the Barragán region. These were formed by the subduction of the Farallon Plate beneath the northwestern margin of the South American Plate approximately 120 million years ago (Ar - Ar dating in muscovite) (Bustamante et al., 2011). The second occurrence comprises the blueschists of Jambaló, which originated from basic and intermediate protoliths in a supra-subduction zone (SSZ) setting (Bustamante et al., 2021). These schists date back to approximately 62 million years ago (Ar-Ar dating in paragonite) and reflect the interaction between the Caribbean Oceanic Plate and the northern Andes (Bustamante & Bustamante 2019). Particularly in the blueschists of Jambaló, a sedimentary component has been detected through whole-rock geochemistry (Bustamante et al., 2021), which is associated with the influx of continental sediments into the trench as the interoceanic arc approached the South American margin (Bouilhol et al., 2013; Bustamante et al., 2021). However, a detailed study addressing the tectonic implications of the sedimentary signal in the blue schists of Jambaló has not been presented to date.

This study presents the petrography of rocks in the blueschist and greenschist facies of Jambaló, Cauca, along with structural data and field relationships, and new interpretations of the geochemistry presented by Bustamante and Bustamante (2019) to understand the implications of the sedimentary signal in the blueschists of Jambaló.

2. Generalities

2.2. Research question

¿What are the implications of a sedimentary component in the Jambaló blueschist in the geological evolution of the western margin of South America during the Cretaceous period?

2.3. Hypothesis

The protolith of the blueschists of Jambaló shows signs of a significant sedimentary component that may reflect the proximity of an oceanic arc to the western margin of South America during the Cretaceous period.

2.4. Objectives

2.4.1. General objective

Analyze the sedimentary influence in the protoliths that originated the Jambaló blueschists, Cauca, through the detailed identification of the mineralogical, geochemical, and structural characteristics present in these rocks.

2.4.2. Specific objectives

- Identify the compositional nature of the blueschist protolith from its mineralogical composition.

- Identify the relationships that exist between greenschist and blueschist from field relationships.
- Determine the origin of the sedimentary component of the protoliths from geochemistry.

3. Methods

3.1. Fieldwork

The fieldwork was carried out during a two-day campaign in the eastern area of the municipality of Jambaló, Cauca, along the Calambás and Muñoz creeks, which is covered by sheet 343 of the Colombian Geological Survey. During the field campaign, the methodology proposed by Maya et al. (2019) was used. Seventeen samples were collected (10 of blueschists and 7 of greenschists) to describe their mineralogical composition, texture, grain size, and mineralogical paragenesis. Structural information was obtained from the foliation planes of the outcrops where the samples were collected.

3.2. Petrographic analyses

Thin sections were made with the purpose of describing the mineralogy, textures, structures, and paragenesis to identify the minerals and classify the samples. The descriptions were carried out using a petrographic microscope counting 500 points per sample, and the microphotographs were taken using a digital microscopic camera (Zeiss). All processes were conducted in the petrography laboratory at EAFIT University.

The petrographic classification was made using the recommendations provided by the *Subcommision on the Systematics of Metamorphic Rocks* (SCMR, 2007). The texture identification was made using the methodology provided by Winter (2014).

3.3. *Whole-rock geochemistry reanalysis*

For the reprocessing of trace element concentrations and major oxides in the blue schists of Jambaló, data obtained by Bustamante (2008) were utilized. To achieve this, Ba/La vs. Th/Yb, and Rb/Nb vs. Th/Yb diagrams of (Zhao et al., 2019) where applied to determinate the possible enriched component in the mantle source of the Jambaló blueschists and greenschist. The Lu/Hf vs. Th/La, and Lu/Hf vs. Th/Yb diagrams (Zhao et al., 2019) where used to determinate the possible subducted sediments that participate in the generation of Jamabló blueschist.

All geochemical analyses were conducted using GCDKit software, version 5.0 (Janoušek et al., 2006).

4. Geological setting

The Colombian Andes are divided into three major mountain ranges: The Eastern Cordillera, the Central Cordillera, and the Western Cordillera, which are separated by the Cauca and Magdalena valleys (Restrepo, 2019). The Eastern Cordillera is composed of an ancient Precambrian to Paleozoic basement, where metamorphic rocks in amphibolite facies and plutonic igneous rocks predominate (Bustamante et al., 2021); this basement is below Upper Cretaceous marine siliciclastic sedimentary sequences, which in turn are intruded by gabbroic dikes and sills (Cortés et al., 2006; Mora et al., 2009; Vásquez et al., 2010). The Central Cordillera is mainly composed of a Paleozoic to Early Mesozoic polymetamorphic basement, which is intruded by a Cenozoic magmatic arc (Vinasco et al., 2006; Bustamante et al., 2011; Cochrane et al., 2014). Finally, the Western Cordillera is composed of sequences of basic volcanic rocks of allochthonous origin and Cretaceous sedimentary rocks (Kerr et al., 1997; Villagómez et al., 2011).

4.1. Jambaló area

The field observations and samples collected by Bustamante (2008) in the study area indicate the presence of marbles, meta-marbles, quartzites, Keratophyres, serpentinites and blueschist where this lithologies occur as lenses of varying lengths surrounded by a matrix of green schists (Bustamante et al., 2021).

Marbles are located to the north part of Jambaló and are composed of calcite and aragonite, along with accessory minerals such as epidote/clinozoisite, quartz, talc, apatite, chlorite, opaque minerals, rutile, and titanite (Bustamante et al., 2021). **Metamarbles** are found near the municipality of Jambaló and consist of epidote/clinozoisite, carbonates, opaque minerals, amphibole, plagioclase, chlorite, quartz, pumpellyite, micas, and zircon (Bustamante et al., 2021). **Quartzites** are limited in occurrence to the north of Jambaló and are composed of micas, opaque minerals, plagioclase, clinozoisite, chlorite, glaucophane, zoisite, stilpnomelane, and garnet

(Bustamante, 2021). **Keratophyres** are found in Toribío and are composed of plagioclase An5 (>90%) and trace amounts of quartz (Bustamante et al., 2021). **Serpentinites** are associated with the occurrence of blueschists and consist of opaque minerals, chlorite, actinolite, and remnants of olivine and pyroxene (Bustamante et al., 2021).

In the study area outcrops of metamorphic rocks as Jambaló blueschist, and Jambaló greenschist are found (Fig. 1).

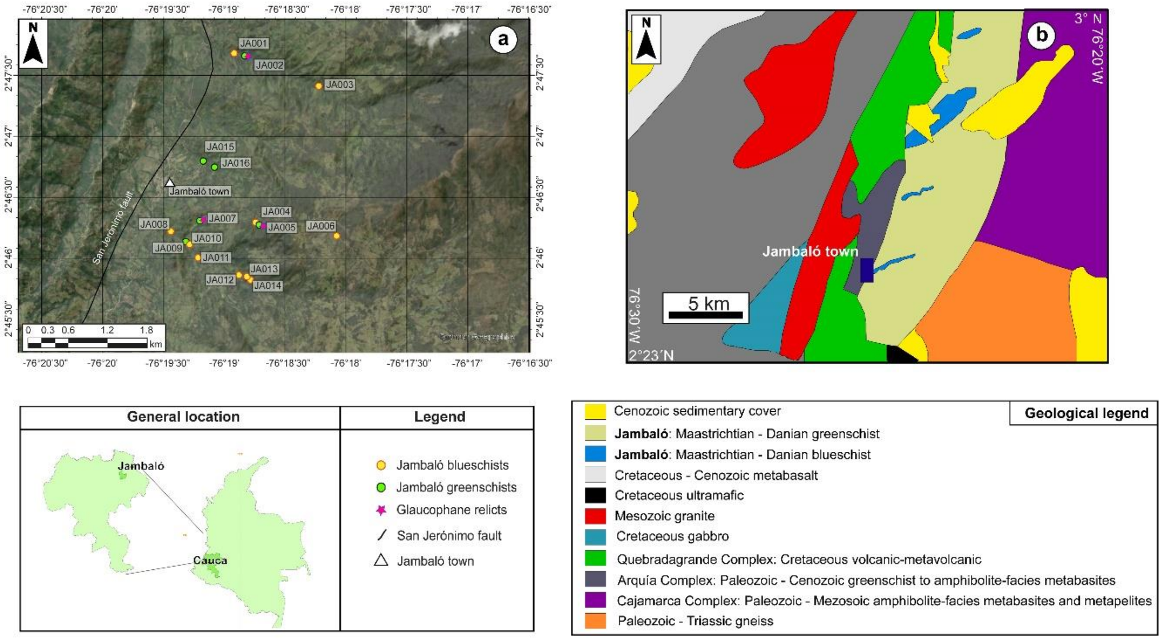


Fig. 1. (**A**)Map of Jambaló town in Colombia. The satellite image (©Garmin) shows the location of the samples collected in the town, and (**B**) Schematic map of Jambaló showing geological and structural relationships, after Bustamante et al. (2021)

5. Results

5.1. *Field work relationships and petrography*

5.1.1. *Glaucophane mica-schist*

Ten samples of this type of rock were collected along the Calambás and Muñoz creeks in the municipality of Jambaló, Cauca (JA001, JA003, JA004, JA006, JA008, JA009, JA011, JA012, JA013 and JA014). Generally, blueschists are found in the form of lenses preserved due to retro-metamorphism to the greenschist facies (Fig.2b). However, in the eastern part of the Calambás creek, only rocks in the blueschist facies are found (Fig. 2a). All the samples present mylonitic foliation in the N43°E direction.

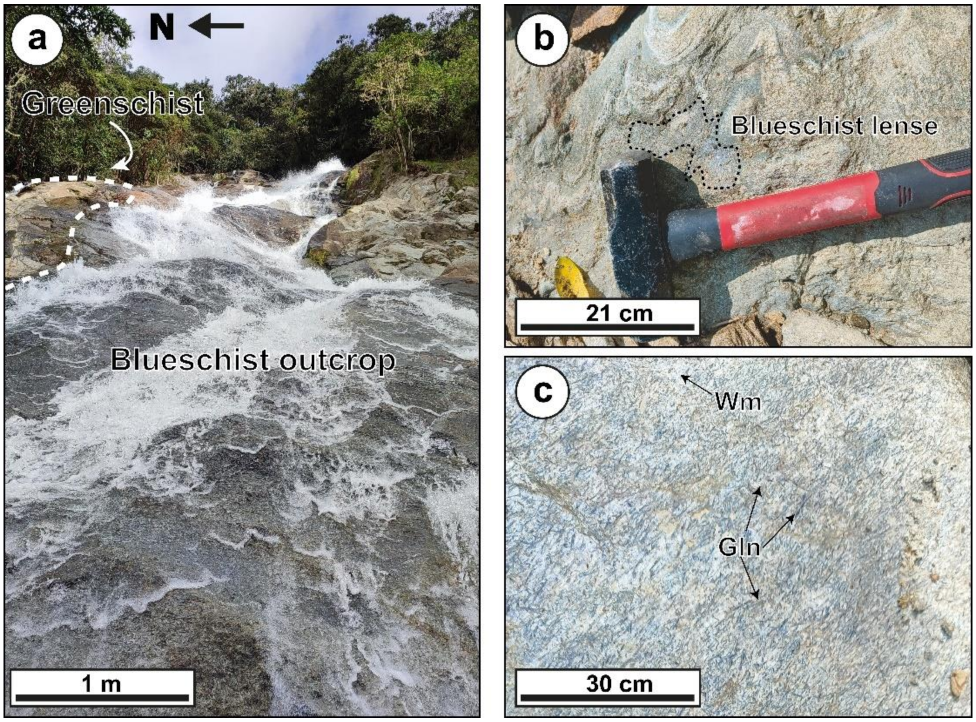
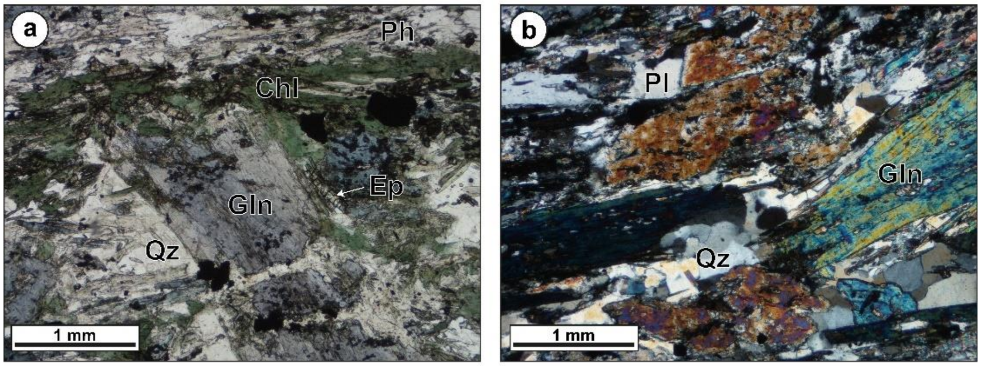


Fig. 2. Blueschist outcrops at Calambás and Muñoz creek in Jambaló town: (**A**) blueschist outcrop with retrometamorphism to greenschist rocks in the eastern part of the Calambás creek, (**B**) lens of blueschist preserved in greenschist facies rocks in Muñoz creek (hammer as scale), and (**C**) Outcrop of only blueschist facies rocks. The abbreviatures of the minerals are: glaucophane (Gln), and white mica (Wm).

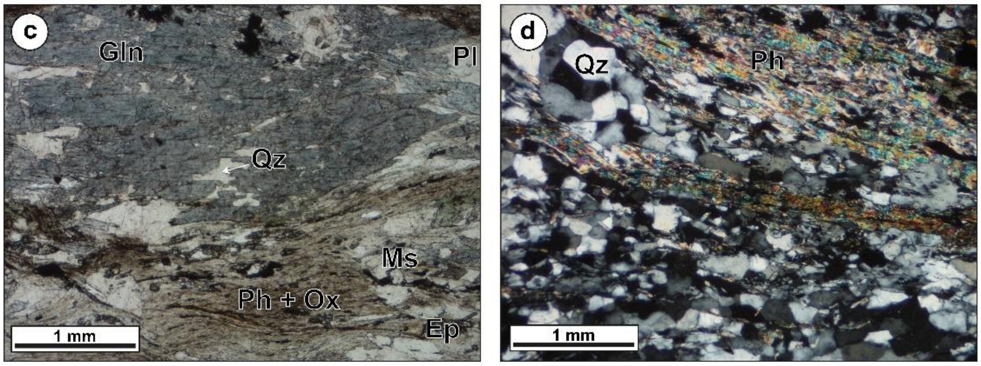
The hand samples of these specimens display a characteristic mylonitic texture, in which the radial texture in glaucophanes is also observed. These rocks are primarily composed of glaucophane, white mica, and quartz.

Blueschist Samples

JA006: Glaucophane - mica schist



JA003: Glaucophane - mica schist



JA014: Glaucophane - mica schist

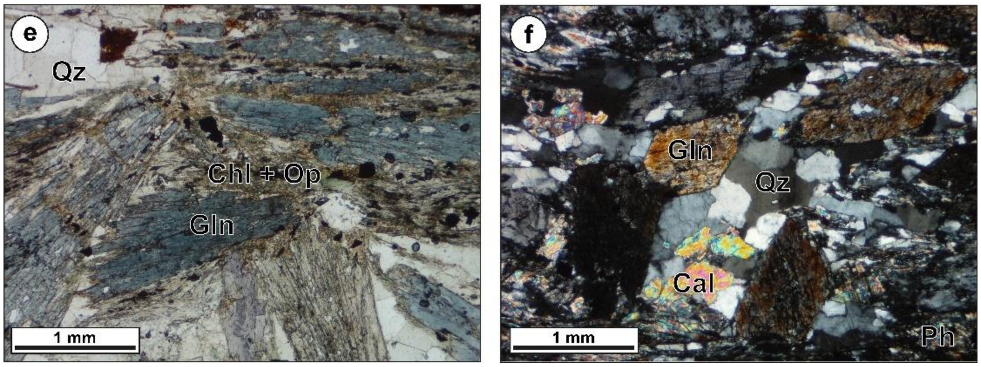
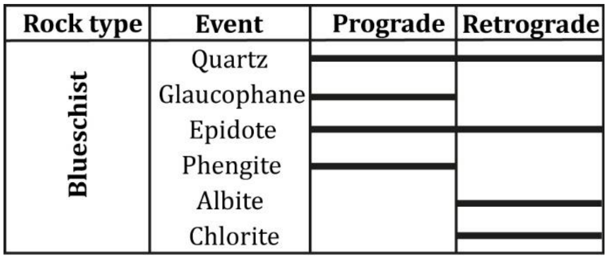


Fig. 3. Petrographic samples of the Jambaló blueschist: (**A**) zoned glaucophane, partially altered by chlorite, also the main S$_2$ foliation is showed, (**B**) nemato-lepidoblastic texture characterized by glaucophane, plagioclase, and quartz, (**C**) subidoblastic glaocpchane as a oikocrystal with quartz as chadacrystal, (**D**) granolepidoblastic texture characterized by quartz and phengite, (**E**) radial glaucophane partially altedes by chlorite, and (**F**) subidoblastic to idoblastic glaucophane crystals partially altered by chlorite and with inclusions of quartz. The abbreviatures of the minerals are: glaucophane (Gln), phengite (Pg), chlorite (Chl), epidote (Ep), quartz (Qz), calcite (Cal), plagioclase (Pl), and opaque minerals (Op).

Thin sections reveal medium- to fine-grained schists displaying a lepido-nematoblastic to nemato-lepidoblastic texture, which varies based on the proportions of amphibole and mica present in the sample. Additionally, radial and porphyroblastic textures are discernible, both influenced by the presence of amphibole. These schists are primarily composed of glaucophane (35-50%), phengite (20-40%), quartz (10-20%), plagioclase (10-12%), along with accessory minerals such as epidote/clinozoisite, chlorite, calcite, zircon, titanite, apatite, and opaque minerals. The main foliation S_2 is mainly defined by sodic amphiboles and white mica (Fig. 3a). Vestiges of foliation S_1 can be observed as small glaucophane crystals arranged perpendicular to the main foliation. When blueschist facies rocks retrogressed to the greenschist-facies, the most common features are: (i) chloritization of glaucophane forming pseudomorphs; (ii) presence of tremolite in glaucophane rims, and (iii) chloritization along S_2 foliation association with the presence of epidote.

Glaucophane forms in fine- to medium-sized crystals in S_1 and S_2 foliations, idoblastic to subidoblastic, with sizes ranging from 0.20 – 0.9 mm, exhibiting zoning with cores that are more pleochroic than their exteriors, **Phengite** appears in fine-grained crystals in S2, with sizes from 0.02 - 0.5 mm, and texturally, its crystals are xenoblastic to subidoblastic. **Quartz** is commonly found as subidoblastic crystals with a polygonal texture, and in some cases as pressure shadows in glaucophanes; they have a fine to medium grain size of 0.02 – 0.8 mm. **Plagioclase** classified as albite in the form of subidoblastic crystals (0.2 - 0.4 mm), associated with quartz and partially altered to sericite. **Epidote/clinozoisite** occurs as very-fined-sized crystals (<0.04 mm), subidoblastic to xenoblastic, flowing the main foliation S_2. **Chlorite** occurs in the form of subidoblastic to xenoblastic crystals (0.02 - 0.6 mm), resulting from the substitution of glaucophane. **Calcite** is found as small crystals (<0.03 mm) revealing xenoblastic forms. **Zircon** occurs as small idoblastic crystals (<0.05 mm), which are generally found in the form of inclusions in phengite and glaucophane. **Titanite** presents subidoblastic crystals with sizes in the range between 0.02 to 0.1 mm, which follow the preferred foliation S_2. **Apatite** occurs disseminated in the section, presenting elongated idoblastic crystals with sizes ranging from 0.1 - 0.3 mm**. Opaque minerals** have very fine-sized subidoblastic grains, smaller than 0.1 mm, which follow the preferred foliation S_2, and on some occasions are found within S_1.

Table. 1. Paragenetic sequence of blueschist facies rocks in Jambaló samples.



Rock type	Event	Prograde	Retrograde
Blueschist	Quartz	▬	▬
	Glaucophane	▬	
	Epidote	▬	▬
	Phengite	▬	
	Albite		▬
	Chlorite		▬

5.1.2. *Chlorite-plagioclase schist*

Six samples of this type of rock were collected along the Calambaz and Muñoz creeks in the municipality of Jambaló, Cauca (JA002, JA005, JA007, JA009, JA015 and JA016). where on some occasions (JA002, JA005 and JA007) relics of glaucophane are partially replaced by chlorite. All the samples present mylonitic foliation in the N43°E direction (Fig. 4a-b).

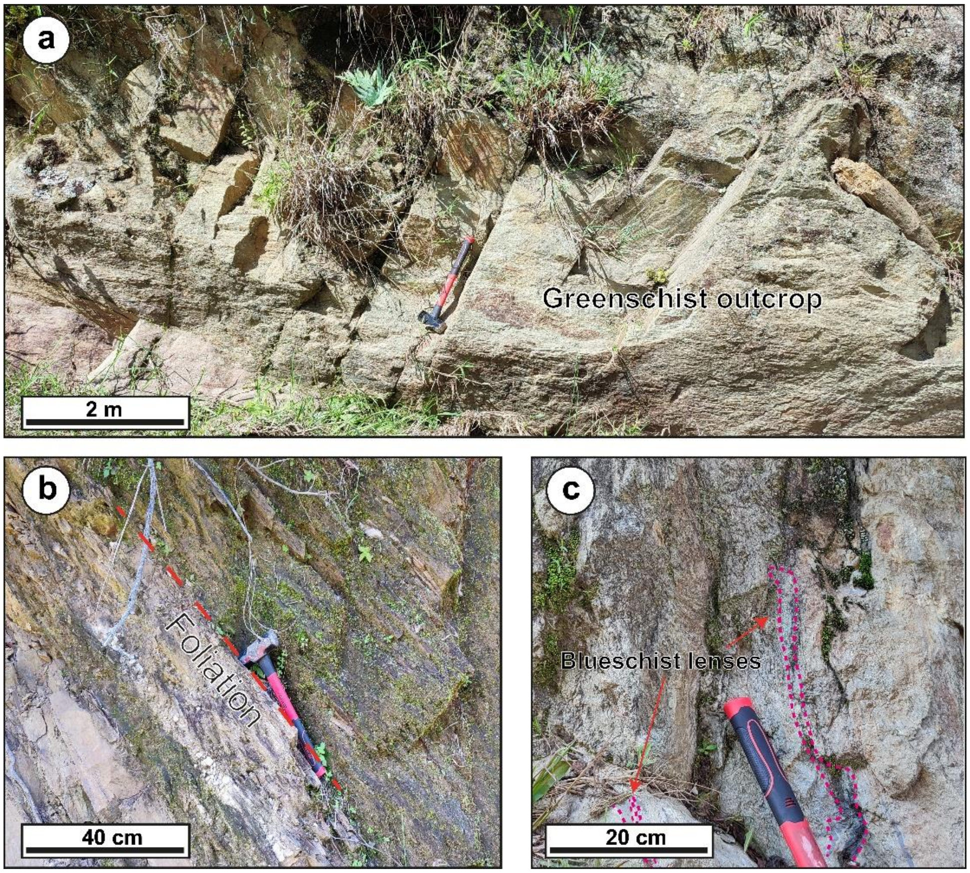
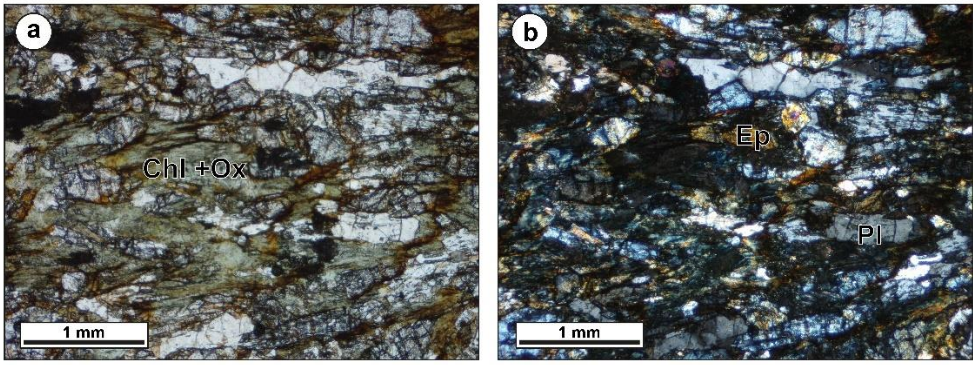


Fig. 4. Greenschist outcrops at Calambás and Muñoz creeks in Jambaló town: (**A**) greenschist facies rocks outcrop at Calambás creek, (**B**) foliation in the N43°E direction in greenschist facies rocks at Muñoz creek, and (C) greenschist outcrop with lenses of blueschist facies rocks at Muñoz creek. Hammer as scale in all photos.

The hand samples of these specimens display a characteristic mylonitic texture. These rocks are primarily composed of chlorite and plagioclase.

Greenschist Samples

JA002: Chlorite - epidote schist



JA007: Chlorite - plagioclase schist

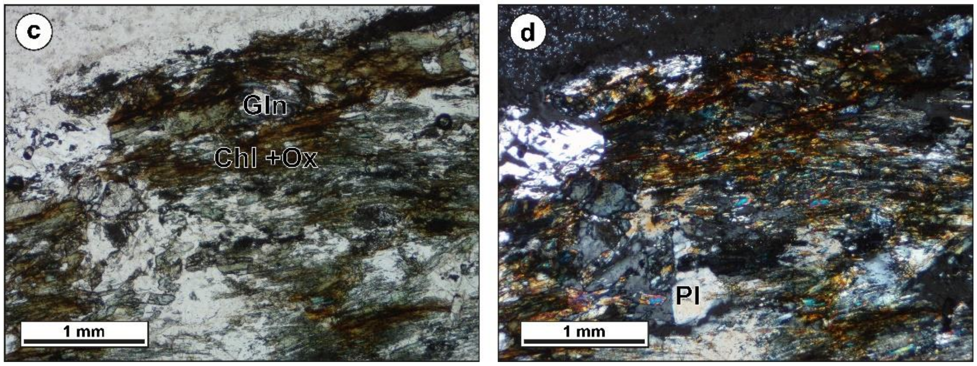
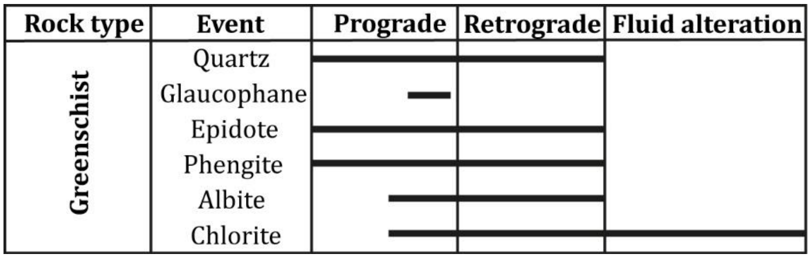


Fig. 5. Petrographic samples of the Jambaló greenschist: (**A & B**) nematoblastic texture characterized by chlorite, epidote, quartz, and plagioclase, (**C & D**) glaucophane relict surrounded by chlorite, tremolite and oxides. The abbreviatures of the minerals are: glaucophane (Gln), chlorite (Chl), epidote (Ep), quartz (Qz), plagioclase (Pl), and oxides (Ox).

Thin sections reveal medium to fine-grained schists with a nematoblastic texture, where additionally in samples JA005 and JA009, there are pseudomorphic chlorites with a radial texture. These rocks are primarily composed of plagioclase (44-68%), chlorite (8-35%), epidote/clinozoisite (10-30%), quartz (1-8%), tremolite (3%), along with accessory minerals such as biotite, titanite, apatite, and zircon. The main S2 foliation is defined by chlorite and zoisite (Figure 5a-c). In the cases of JA002, JA005, and JA007, there are remnants of glaucophane, almost entirely replaced by chlorite.

Plagioclase classified as albite forms xenoblastic crystals with sizes ranging from 0.20 – 2.80 mm, exhibiting partially alteration to sericite. **Chlorite** occurs in the form of subidoblastic to xenoblastic crystals (0.03 - 0.4 mm), resulting from the substitution of glaucophane, where, in some cases, relicts of glaucophane are found, and follow the main foliation S_2. **Epidote/clinozoisite** is commonly found as subidoblastic to idoblastic crystals; they have a fine to medium grain size of 0.03 – 0.7 mm and follow the main foliation S_2. **Quartz** occurs as very fine-sized xenoblastic to subidoblastic grains size of 0.2 to 0.82 mm with undulose extinction in some samples (JA007). **Tremolite** are fine-sized grains xenoblastic (0.09 to 0.3 mm). **Biotite** appears in fine-grained crystals in S2, with sizes from 0.02 - 0.09 mm, and texturally, its crystals are xenoblastic. **Titanite** occurs in very-fined-grained crystals (<0.15 mm), texturally subidoblastic. **Apatite** occurs disseminated in the section, presenting elongated idoblastic to xenoblastic (0.08 mm - 0.4 mm). **Zircon** occurs as small idoblastic crystals (<0.05 mm).

Table. 2. Paragenetic sequence of greenschist facies rocks. Dotted line indicates that the mineral is not present in all samples.



Rock type	Event	Prograde	Retrograde	Fluid alteration
Greenschist	Quartz	━━━━	━━━━	
	Glaucophane	━		
	Epidote	━━━━	━━━━	
	Phengite	━━━━	━━━━	
	Albite	━━	━━━━	
	Chlorite	━━	━━━━	━━━━

5.2. Geochemistry

Major oxide and trace elements data were acquired from eighteen samples by Bustamante (2008) (Table. 3), in which then samples are from greenschist in the Jambaló area, and eight samples are from blueschist in the Jambaló area.

Table 3. Lu/Hf, Th/La, Th/Yb, Ba/La, and Rb/Nb values of the Jambaló blueschist (BS) and greenschist (GS). Analyses form the data obtained by Bustamante & Bustamante (2019).

Rock type	Lu/Hf	Th/La	Th/Yb	Ba/La	Rb/Nb
Unit Symbol	ppm	ppm	ppm	ppm	ppm
GS107	0.16404762	0.16607143	0.65339578	58.8095238	4.64285714
GS107A	0.154375	0.14785374	0.56024096	72.8139905	4.50000000
GS107B	0.18045455	0.17428571	0.76890756	87.7142857	7.50000000
GS110	0.21666667	0.07142857	0.1875	247.619048	31.0000000
GS114	0.16631579	0.1620155	0.97209302	34.1085271	7.50000000
GS121C	0.17909091	0.07799443	0.21052632	42.8969359	1.25000000
GS124C	0.14864865	0.07142857	0.11560694	3.57142857	0.08695652
GS127A	0.15714286	0.18461538	0.55299539	56.7692308	6.14814815
GS127B	0.17368421	0.12162162	0.41474654	51.6216216	1.89285714
GS128A	0.09605263	0.08928571	0.42283298	7.76785714	0.21851852
BS121B	0.15636364	0.09615385	0.28985507	6.34615385	0.94339623
BS123A	0.05918367	0.06636771	0.72906404	3.1838565	0.38961039
GS124G	0.12222222	0.23333333	1.04597701	7.62820513	2.77777778
BS124J	0.10671875	0.2527027	0.82560706	7.2972973	1.68421053
BS125I	0.13333333	0.14782609	0.51051051	19.3043478	1.79032258
BS125K	0.08636364	0.29310345	1.44886364	14.8850575	10.010989
BS125M	0.10189189	0.24919355	1.21176471	15.4032258	2.85714286
BS129A	0.15119048	0.13015184	0.28985507	2.71149675	0.38961039

The Lu/Hf vs. Th/Yb, and Rb/Nb vs. Th/Yb diagrams of Plank (2005) use to track the contribution of sediments to enrichment processes of subarc mantle. Both diagrams show a strong influence of sediments for the greenschist and blueschists form Jambaló, despite for the sample GS110 that shows an enrichment in slab fluid (fig. 6a-b).

The Lu/Hf vs. Th/La, and Lu/Hf vs. Th/Yb diagrams of greenschist and blueschist (Fig. 6c-d) shows a mixture enrichment between pelagic and terrigenous sediments, however, it´s evident that pelagic sediments are the major contributors. when compared to Lu/Hf values 0.10-0.22 (0.16 on average) for greenschist and 0.07-0.18 (0.11 on average) for blueschist. These Lu/Hf values shows that greenschists are slightly richer in pelagic sediments than blueschists, in addition to that, in the blueschist samples BS124G, BS124J, BS125K, and BS125M with Th/La values 0.23, 0.25, 0.29, and 0.24 respectively, and Th/Yb values 1.04, 0.82, 1.44, and 1.21, respectively shows a enrichment in terrigenous sediments (Fig. 6c-d).

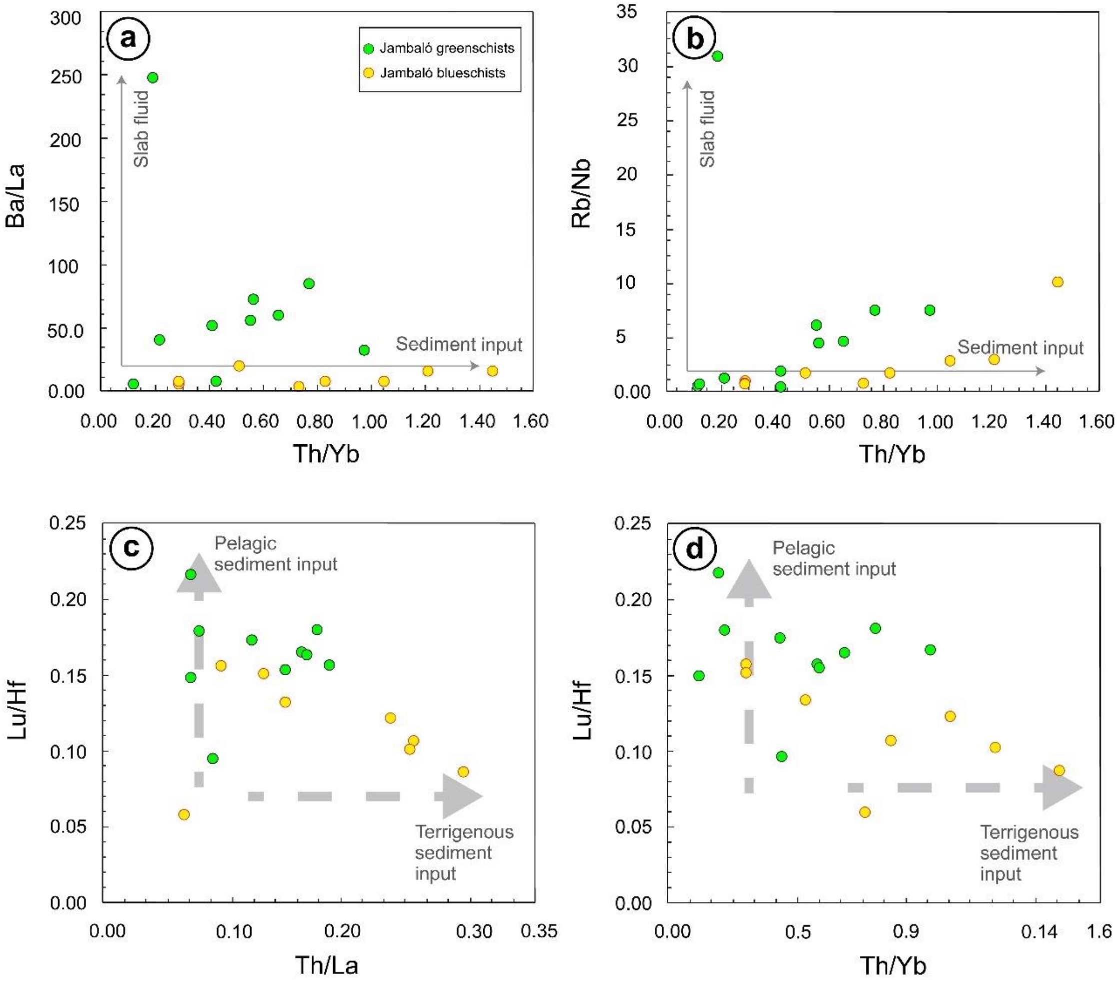


Fig. 6. Lu/Hf, Th/La, Th/Yb, Ba/La, and Rb/Nb ratios for the Jambaló blueschist and greenschist. (a) Ba/La vs. Th/Yb, (b) Rb/Nb vs. Th/Yb (Zhao et al., 2019) diagrams showing the possible enriched components in mantle source of the Jambaló blueschist and greenschist. (c) Lu/Hf vs./La and (d) Lu/Hf vs./Yb (Zhao et al., 2019) diagrams showing the possible subducted sediments that gave rise to the formation of Jambaló blueschist and greenschist.

6. Discussion

6.1. *Protoliths of Jambaló blueschist and greenschist*

The blueschists found in the Jambaló region are the result of mafic to intermediate protoliths originating from an island arc setting, as noted in Figure 7c. According to the geochemical analysis provided by Bustamante and Bustamante (2019), the protoliths of both blue- and green schists share a common origin within the same geological block. However, they underwent distinct metamorphic paths characterized by variations in pressure and temperature conditions (Bustamante et al., 2021). In the field, blueschists manifest in two distinct forms: (i) as preserved lenses within greenschist facies rocks where the lenses are of different sizes and do not have a preferential distribution along the outcrops and (ii) as continuous rock bodies exclusively representing the blueschist facies. The most noticeable distinction occurs in the lower reaches of the Calambás stream (Fig. 4ab), where greenschist rocks dominate, and blueschist lenses are relatively sparse. Nevertheless, as one progresses upstream along the Calambás stream towards the east, the amount of blueschist lenses progressively rises. This ultimately culminates in the prevalence of rocks exclusively within the blueschist facies in the upper sections of the Calambás stream (Fig. 2c). In contrast, the transition pattern from greenschist rocks with embedded blueschist lenses to rocks solely belonging to the blueschist facies in the Muñoz stream is less distinct, primarily due to a scarcity of rock outcrops and high rates of weathering in that area.

Based on the petrographic characterization of Jambaló blue and green schists from the current investigation and the earlier work by Bustamante (2008), it is evident that these rock types share a similar mineralogical composition. The greenschists are closely linked to the retrometamorphism of the blueschists, as indicated by remnants of glaucophane that have undergone transformation into chlorite and epidote (Fig. 5c), this is further validated by their mineral paragenesis, comprising albite + quartz + chlorite + white mica + epidote + calcite, and occasionally titanite, aligning with the paragenesis described by Graham et al. (1983) for a type III metabasite that is devoid of dolomite. This type III metabasite is the product of the metamorphic transformation of type I metabasite, as highlighted in Carmona (2017). Conversely, blueschists in the Jambaló region exhibit a distinct paragenesis, featuring glaucophane, quartz, phengite, epidote, chlorite, and albite, this paragenesis is consistent with a pelitic protolith. Furthermore, the rock samples, including JA003 (Fig. 3c), JA006, JA009, and JA014, display lepido-nematoblastic textures characterized by notable concentrations of phengite, quartz, and zircon. These textures indicate a significant sedimentary influence on the protoliths of these rocks, reflecting their origin and history within the geological context. An additional feature that can be found in these rocks is the abundance of zircons, which are rare in metabasic rocks, but in these rocks, they are plentiful, indicating an additional sedimentary source that is being mixed with the basic protoliths.

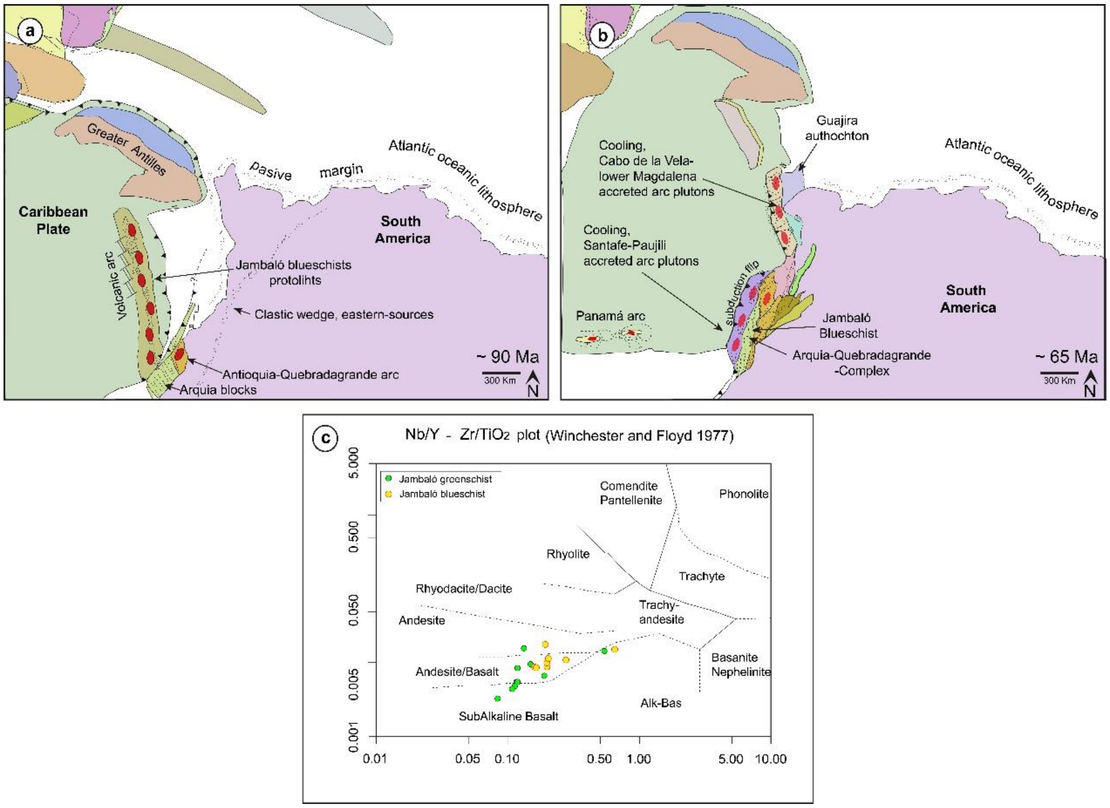


Fig. 7. Jambaló blueschist generation model and classification diagram of Winchester and Floyd (1977). (A)Late Campanian-erly Maastrichtian pre-collisional Norwest corner of South America (modified form Montes et al., 2019), (B) Paleocene snapshot shows the collisional event that results in the Jamabló blueschist generation (modified form Montes et al., 2019), and (C)Nb/Y – Zt/TiO2 classification diagram of Winchester and Floyd (1977).

6.2. *Tectonic implications*

There are two main hypotheses to explain the events that led to the generation of high-pressure rocks in Colombia: (i) Spikings et al. (2015); Carmona (2017); and Camargo (2020) suggest that the Jambaló blueschists are part of a high-pressure metamorphic sequence in western Colombia, dated between 112 to 120 Ma during the Early Cretaceous. (ii) Bustamante and Bustamante (2019), and Bustamante et al. (2021) propose that during the Cretaceous two distinct subduction events were recorded, where both are reconstructed thanks to the high pressure rocks present in Colombia, the first event originated 120 Ma ago giving rise to the Pijao and Barragán blueschists through oblique subduction between the Farallon and South American plates (Bustamante & Bustamante, 2019); while the second event occurred approximately 62 Ma, resulting in the Jambaló blueschists, where their protoliths were originated and form in an intra-oceanic arc originated on a modified lithospheric mantle plume (Bustamante, 2008; Bustamante & Bustamante 2019; Bustamante et al., 2021), this arc subsequently collided with the NW margin of South America and during this process, accumulated sediments and ultramafic rocks were separated in the accretionary prism and along with the blueschists were incorporated into the continental crust through faults generated by the subduction process (Camargo, 2020). This latter event is also characterized by the presence of mineral phases: glaucophane, garnet, phengite and paragonite (Orrego et al., 1977; Carmona, 2017).

The Si concentrations (4.0 apfu) reported by Carmona (2017) in the phengites of the Jambaló blueschists show that the pressures to which these rocks were subjected in their generation stage are between 6 - 17 kbar, in addition, the chemical variations in the garnet reported by Carmona (2017) would represent that it formed under prograde conditions, in contrast to the textural and mineralogical characteristics reported by this work and that carried out by Bustamante (2008), in addition to the geochemical interpretations and mineralogical associations, it is feasible to consider that the Jambaló blueschists describe a clockwise metamorphic path, which is determined by two main stages described by Camargo (2020) (i) the basic protoliths were subjected to a progressive increase in pressure which allowed them to reach the blueschist facies and (ii) it is defined by the retrogradation of the blueschists, where glaucophane is partially or completely transformed by chlorite or actinolite (Fig. 6).

When comparing the Jambaló blueschists with other rocks from the Caribbean Cretaceous arcs, the Nd isotopes show a radiogenic character. However, Bustamante et al. (2021) proposes two hypotheses to explain these data: (i) The isotopes reflect the incorporation of continental sediments into the trench as the intra-oceanic arc approached South America (Bustamante et al., 2021); (ii) the protoliths and metamorphism took place at the continental margin, where the basement and sediments contributed to the genesis of the magmas. Based on the geochemical results in this contribution, it is clear that the blue and greenschists facies rocks in Jambaló reflect the incorporation of continental sediments during subduction and accretion of the Caribbean plateau to northwestern South America evidenced in the Ba/La vs. Th/Yb, Rb/Nb vs. Th/Yb, Lu/Hf vs. Th/La, and Lu/Hf vs. Th/Yb diagrams (Fig. 6a-d). The

Jambaló blue and green schists exhibit small variability in Ba/La and Rb/Nb, accompanied by high variability in Th/Yb (Fig. 6a-b), indicating an increase in sediment contribution to the source of the protolith melts. The greenschists have a higher Lu/Hf ratio compared to the blueschists, suggesting they are more enriched in pelagic sediments (Fig. 6c-d). Considering that petrographic features and field relationships indicate the greenschists result from the retrometamorphism of the blueschists (Bustamante, 2008; Carmona, 2017; Bustamante et al., 2019; Gómez & Ramírez, 2022), the high Lu/Hf values in the greenschists can be explained by ion mobility generated during the blueschists retrometamorphism. Specifically, the small variability in Ba/La and Rb/Nb in both schist types suggests the sedimentary source had a relatively homogeneous composition in terms of Ba, Rb, La and Nb contents. On the other hand, the high variability in Th/Yb indicates differences in sediment involving and mixing with igneous material. Higher Th/Yb values relate to a higher proportion of pelagic sediments rich in Th over terrigenous sediments rich in Yb. Thus, the protoliths of the blue and green schists received variable inputs from these two sediment types. Regarding the Lu/Hf ratio, the higher values in the greenschists compared to the blueschists suggest a higher enrichment in pelagic sediments for the former. This can be attributed to ion mobility associated with the retrometamorphism, where Lu would have preferentially migrated and concentrated in the greenschists relative to the blueschists. Thus, although both schist types derive from protoliths with similar amounts of pelagic and terrigenous sediments according to Ba/La and Rb/Nb, the retrometamorphism generated chemical fractionation with Lu enrichment in the greenschists. Based on the above interpreted and the results obtained by this contribution, it is possible to associate that the sediments involved in the generation of the Jambaló blueschists come from the same source. This source is of terrigenous origin (Fig. 6a-b) where the sediments come from the western margin of South America. These results support the first interpretation proposed by Bustamante et al. (2021) (Fig. 7a-b) and contradict the models proposed by Spikings et al. (2015); Carmona (2017); Spikings et al. (2019). The latter suggest the Jambaló blueschists are related to the other high-pressure rocks in Colombia, and they also suggest the protoliths of this high-pressure rock belt have MORB-like characteristics and represent a subduction channel that records Early Cretaceous convergence at the northeastern margin of South America (Carmona, 2017)

Considering the premises exposed in this contribution, the Jambaló blueschists belong to a metamorphic belt different from that proposed by Spinkings et al. (2015); Carmona (2017); Spikings et al. (2019). The understand of their protoliths explains the approach of an intra-oceanic arc with basaltic to andesitic compositions. It also documents the entry of terrigenous sediments from the South American margin into the oceanic trench. As well as the retrometamorphism caused by the exhumation of the blueschists. Finally, it is proposed to perform new dating for the Jambaló blueschists, such as U-Pb in zircon, in order to understand the nature of their protoliths, their provenance and correlation with other units. In addition to new structural, geochronological, and geochemical data from volcanic units near the blueschists, which could reflect the Late Cretaceous arc-continent collision. Additionally, it is necessary to perform geochemical, mineral chemistry, geothermobarometric and geochronological studies on the San José de Albán and Tacueyó blueschists to make correlations or discrepancies between these high-pressure rocks in Colombia.

7. Conclusions

- Along the transects carried out in the Calambás and Muñoz creeks, it is possible to determine a correlation determined by the greater occurrence of blueschists in the upper parts of both creeks and in contrast, a greater occurrence of greenschist facies rocks with lenses of blueschist facies rocks in the lower parts of the creeks.
- Compositional, textural and geochemical data of the Jambaló schist suggest that their protoliths are not only constituted by basalts and andesites, but also possess a sedimentary component, mainly of terrigenous sediments evidenced in the Ba/La vs. Th/Yb, Rb/Nb vs. Th/Yb, Lu/Hf vs. Th/La, and Lu/Hf vs. Th/Yb relationships, which supports the hypothesis proposed by Bustamante et al. (2021) where the proximity of the oceanic arc to the western margin of South America during the Late Cretaceous is reflected.
- The differences between the affinity of pelagic sediments in the greenschist facies rocks is caused by ion mobility generated during the retrometamorphism of the blueschist

facies rocks during their exhumation. During the retrometamorphism of the blueschists they re-equilibrated under greenschist facies conditions, characterized by the mineral association albite, quartz, chlorite, white mica, epidote, calcite, and occasionally titanite.

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