Chapter 14

Two Cretaceous Subduction Events in the Central Cordillera: Insights from the High P–Low T Metamorphism

https://doi.org/10.32685/pub.esp.36.2019.14
Published online 6 December 2019

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Abstract The scarcity of high–pressure metamorphic rocks at the Earth's surface due to the specific conditions required for their formation and preservation makes it difficult to access the information about subduction zones that they can provide. The northern Andes are characterized by several occurrences of blueschists and, in minor proportions, eclogites, whose origins are yet to be unraveled. The metamorphic rocks found herein include the Pijao amphibolitized eclogites, Barragán blueschists and associated garnet–amphibolites, and Jambaló blueschists found in Colombia as well as the Raspas Metamorphic Complex in Ecuador. All these rocks have been correlated into a single Early Cretaceous high–pressure metamorphic belt based on regional geochemistry and geochronological data. A compilation of the most recent whole–rock geochemistry and Ar–Ar and Lu–Hf ages from the three high–pressure sequences in Colombia indicates that at least two different subduction events have been recorded in the Central Cordillera of Colombia. The first event, involving subduction and collision, occurred at ca. 130–120 Ma and is represented by the Pijao, Barragán, and Raspas high–pressure rocks, which have N–MORB–like protoliths and are contemporaneous with the end of the arc–related magmatism of the northern Andes, related to an oblique convergence between the Farallón Plate and the continental margin of South America. The second event of subduction is represented only by the Jambaló blueschists at ca. 70–60 Ma, whose protolith is akin to basalt formed in a plume–influenced intra–oceanic arc that was accreted to the continental margin. No reliable correlation is possible for these rocks as yet.

Keywords: *blueschist, eclogite, northern Andes, high–pressure metamorphism.*

Resumen Las rocas metamórficas de alta presión son escasas en la superficie de la Tierra debido a sus condiciones especiales de formación y conservación. Esta escasez dificulta el acceso a la información que este tipo de rocas puede proporcionar sobre las zonas de subducción. Los Andes del norte se caracterizan por varias ocurrencias de esquistos azules y, en menor proporción, eclogitas cuyo origen aún no es claro. Entre estas ocurrencias se incluyen las eclogitas anfibolitizadas de Pijao, los esquistos azules y anfibolitas granatíferas asociadas de Barragán, y los esquistos azules de Jambaló en Colombia, así como el Complejo Metamórfico Raspas en Ecuador. Todas se han correlacionado como un único cinturón metamórfico de alta presión del Cretácico Temprano sobre la base de datos regionales de geoquímica y geocronología. Una recopilación de los datos más recientes de geoquímica en roca total y las edades Ar–Ar y Lu–Hf de

Citation: Bustamante, C. & Bustamante, A. 2019. Two Cretaceous subduction events in the Central Cordillera: Insights from the high P–low T metamorphism. In: Gómez, J. & Pinilla–Pachon, A.O. (editors), The Geology of Colombia, Volume 2 Mesozoic. Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 36, p. 485–498. Bogotá. https://doi.org/10.32685/pub.esp.36.2019.14

las tres manifestaciones de alta presión en Colombia registra al menos dos eventos de subducción diferentes en la cordillera Central de Colombia. El primer evento de subducción y colisión ocurrió a ca. 130–120 Ma y está representado por las rocas de alta presión de Pijao, Barragán y Raspas, las cuales tienen protolitos tipo N–MORB y son contemporáneas con el final del magmatismo de arco de los Andes del norte, relacionado con una convergencia oblicua entre la Placa de Farallón y el margen continental de Suramérica. El segundo evento de subducción solo está representado por los esquistos azules de Jambaló con edades de ca. 70–60 Ma, cuyo protolito es afín a basaltos formados en un arco intraoceánico con influencia de una pluma mantélica y acrecionados a la margen continental. Hasta ahora no existe una correlación confiable entre estas rocas y otras similares.

Palabras clave: *esquisto azul, eclogita, Andes del norte, metamorfismo de alta presión.*

1. Introduction

Blueschists and eclogites represent some of the main lithological vestiges from which we can understand convergent margin processes since they are unequivocal evidence for paleo–subduction zones and collision between lithospheric plates (e.g., Ernst, 1988; Maruyama et al., 1996). Unfortunately, these rocks are rarely exposed at the Earth's surface owing to the difficulties involved in their exhumation and preservation, which are attributed to their high density and low buoyancy when compared with lower crustal materials (Agard et al., 2009).

The Mesozoic to Cenozoic orogenesis in the northern Andes including Ecuador and Colombia is characterized by a series of collisions of island arcs and oceanic plateau with the South American continental margin, accompanied by the formation of several subduction zones and the thrusting of oceanic crustal fragments, both on the continental margin and in the intra–oceanic domains (e.g., Cardona et al., 2012; Ramos, 2009; Restrepo & Toussaint, 1988; Spikings et al., 2015). These processes have resulted in the formation of ophiolitic complexes along with low–, medium, and high–pressure metamorphic rocks via the amalgamation of tectonostratigraphic terranes (Kerr et al., 1997; Pindell & Kennan, 2009; Ramos, 2009). Blueschist and eclogite defining suture zones have been identified in the Cordillera Real of Ecuador (Raspas Metamorphic Complex sensu Feininger, 1980) and in the Central Cordillera of Colombia (Figure 1; Arquía Complex sensu Maya & González, 1995).

The Arquía Complex is located in the Central Cordillera of Colombia, where high–pressure metamorphic rocks crop out in the Pijao, Barragán, and Jambaló areas (Figures 2, 3, 4 respectively; Bustamante et al., 2011, 2012; Feininger, 1982; Núñez & Murillo, 1978; Orrego et al., 1980a). The Jambaló rocks are limited in their distribution to the east by the Cajamarca Complex, comprising Jurassic metapelitic and amphibolic schists (Blanco–Quintero et al., 2014; Bustamante et al., 2017a), and to the west by Lower Cretaceous volcanic rocks of the Quebradagrande Complex (Figure 5; Botero, 1963; Kerr et al., 1997; Maya & González, 1995). The Pijao and Barragán rocks are within the Arquía Complex (Figure 5).

The tectonic significance of the abovementioned rocks is still under debate as relatively few geological data from selected occurrences have been used in existing interpretations. These rocks have been interpreted as being related to subduction events (Aspden & McCourt, 1986; Aspden et al., 1995; Bourgois et al., 1987) and exhumed during the Early Cretaceous, according to cooling ages varying between 132 and 110 Ma (Aspden & McCourt, 1986; Feininger, 1982). Furthermore, rocks from the Raspas Metamorphic Complex (Ecuador) and those in the Central Cordillera (Colombia) have been correlated due to their similar tectonic positions and regional geochemical data and thereby assigned Early Cretaceous metamorphic ages (Spikings et al., 2015; Villagómez & Spikings, 2013; Villagómez et al., 2011). Other studies (Bustamante et al., 2011, 2012) have suggested that blueschists from the Jambaló area have a volcanic arc protolith and a Late Cretaceous to Paleogene age of metamorphism.

Although high–pressure rocks of the Central Cordillera have long been recognized, no tectonic model combining their occurrences has been developed as yet. This study, therefore, aims to give an updated review of the high–pressure metamorphic rocks of Colombia, describing their distributions, ages of metamorphism, and differences in protoliths. We challenge current models that consider a single Lower Cretaceous high–pressure metamorphic belt in Colombia and Ecuador with an exclusively N–MORB protolith (García–Ramírez et al., 2017; Spikings et al., 2015; Villagómez & Spikings, 2013). Pressure and temperature constraints, together with metamorphic ages and whole–rock geochemistry, suggest that Barragán and Pijao eclogites have N–MORB protoliths with Early Cretaceous metamorphic ages (Bustamante et al., 2012; García–Ramírez et al., 2017), whereas the Jambaló area records Late Cretaceous metamorphism with a volcanic arc–like protolith (Bustamante, 2008). Thus, we propose a tectonic model for the Cretaceous to Paleogene evolution of the western margin of the northern Andes, with special emphasis in the high–pressure metamorphic record.

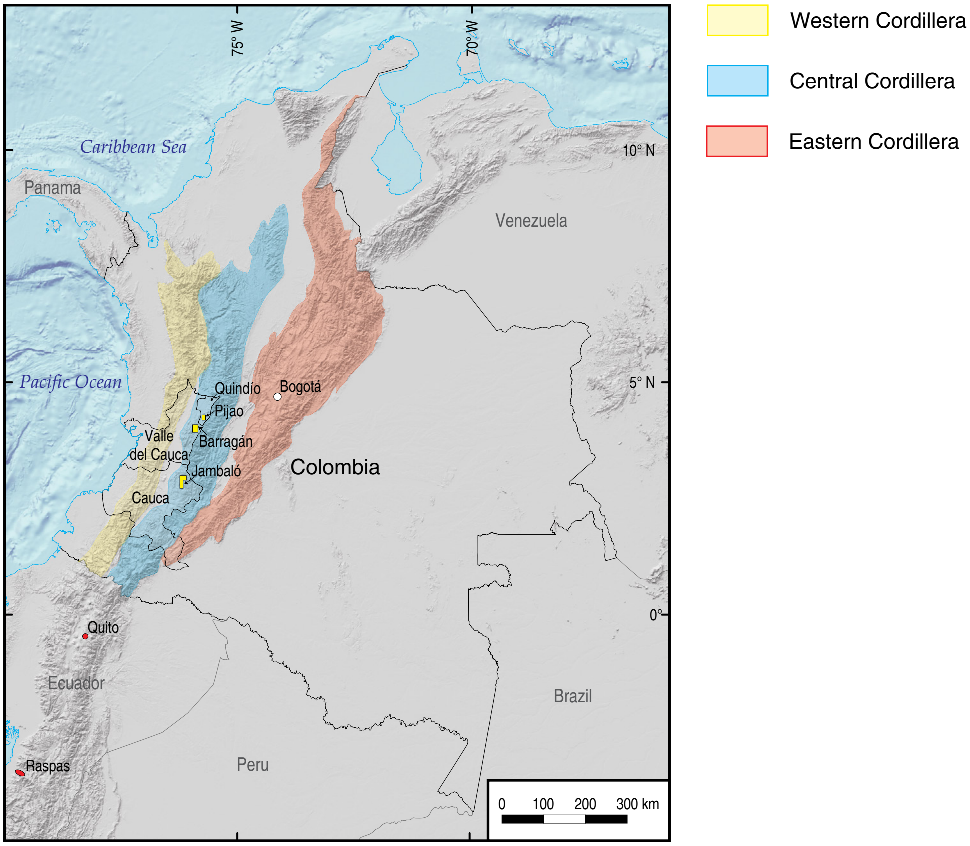

Figure 1. Map of Colombia showing the distribution of high–pressure rocks along the Central Cordillera. The Raspas Metamorphic Complex (Ecuador) is also shown as a reference.

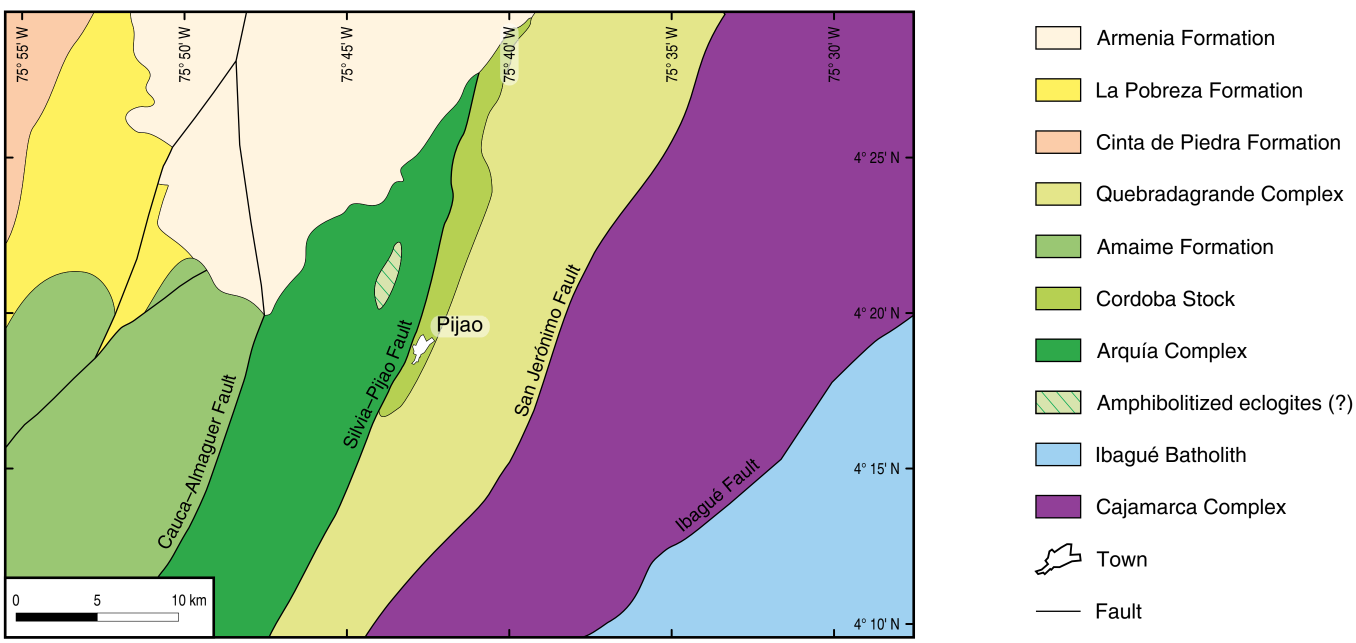

Figure 2. Simplified geological map of the Pijao area (Alcárcel & Gómez 2019).

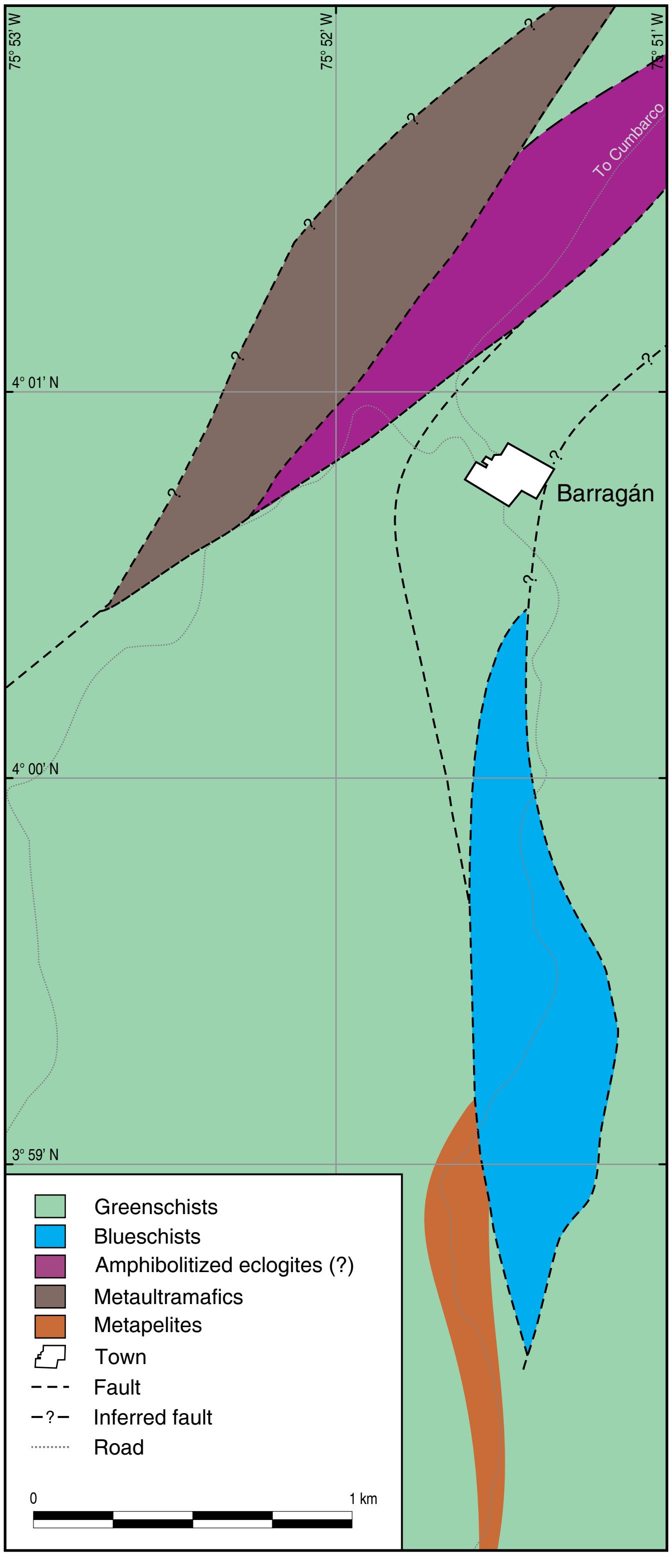

Figure 3. Simplified geological map of the Barragán area.

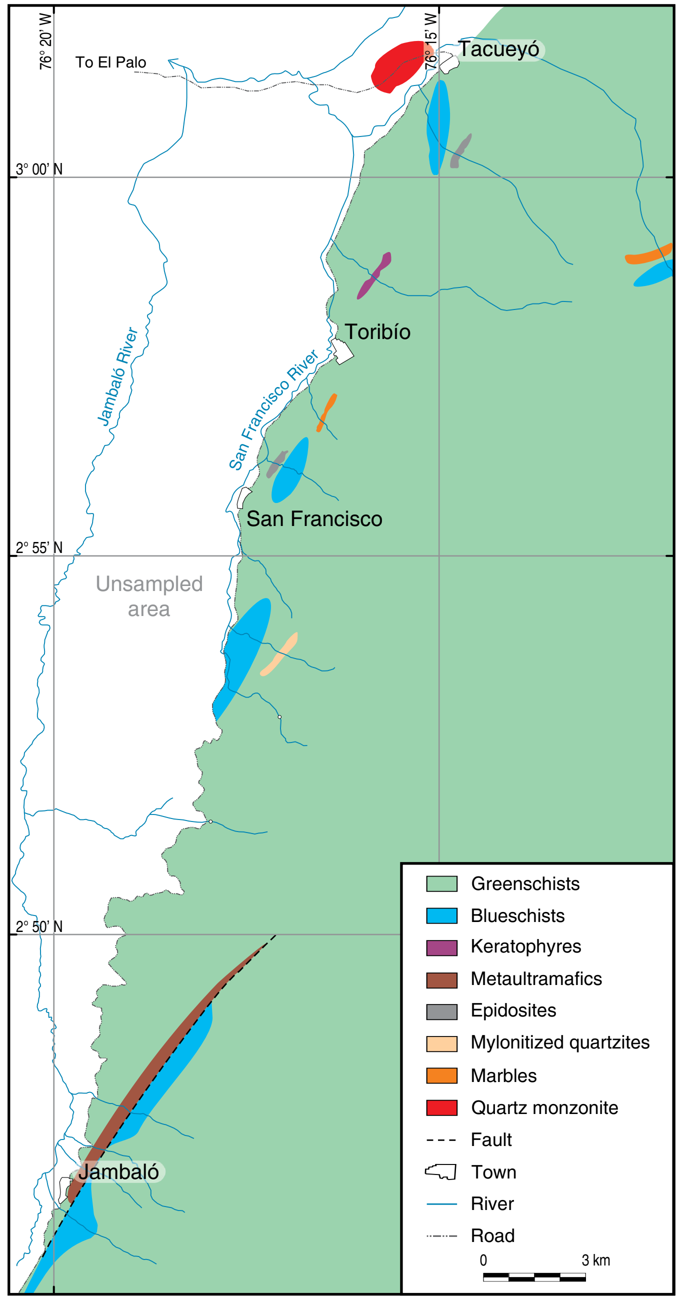

Figure 4. Simplified geological map of the Jambaló area.

2. Materials and Methods

Whole–rock geochemistry and geochronology have been previously published and peer reviewed: Details of the sampling and methodologies are provided in Bustamante (2008) for the Barragán and Jambaló blueschists, and in García–Ramírez et al. (2017) for the Pijao eclogites. Table 1 compiles the mineralogy, geochemistry, and ages of northern Andes high–pressure rocks available up to the present study. Table 2 compiles whole–rock geochemical data reported from Barragán blueschists (Bustamante et al., 2012), Pijao eclogites (García–Ramírez et al., 2017), and Jambaló blueschists (Bustamante, 2008).

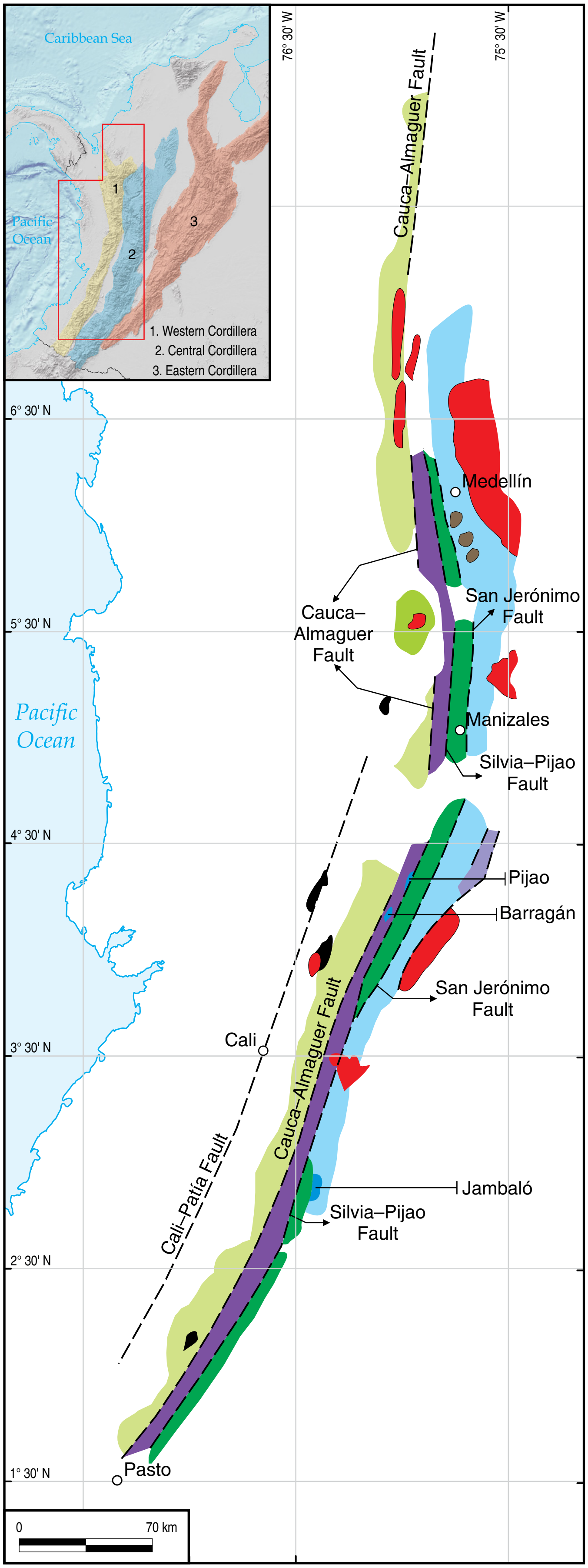

Figure 5. Geological map of the occurrences of high–pressure rocks in the Central Cordillera and their tectonic position related to the Quebradagrande and Cajamarca Complexes (Maya & González, 1995).

3. Results

Herein, we briefly summarize present knowledge of the high–pressure metamorphic rocks from the Central Cordillera and provide the current geochronological data along with the whole–rock geochemistry that has been used to define the protolith.

3.1. Pijao Eclogites

García–Ramírez et al. (2017) and Avellaneda et al. (2017) reported eclogites south of the Pijao region (Figures 2, 5) and described meter–scale lenses of eclogites, amphibolitized eclogites, and garnet–bearing amphibolites enveloped by chlorite–actinolite schists in faulted contact with amphibolites.

The geochemistry reported by García–Ramírez et al. (2017) indicates a basaltic protolith for the Pijao eclogites (Figure 6), similar to that of the Barragán blueschist and amphibolite–facies rocks. Chondrite–normalized rare earth elements (REE) define a flat pattern (Figure 7a), further supporting this finding. A subtle Nb anomaly is seen in the trace element variation plots normalized to N–MORB (Figure 8a; Table 1; Sun & McDonough, 1989).

A garnet–derived $^{176}Lu/^{177}Hf$ isochron age of 128.7 ± 3.5 Ma (MSWD = 4.0) has been reported for Pijao eclogite samples (Table 1; García–Ramírez et al., 2017). García–Ramírez et al. (2017) interpreted this age as that at which the Pijao rocks reached eclogite facies, which is related to a slab roll–back process characterizing the western margin of the northern Andes since the Jurassic (Spikings et al., 2015). García–Ramírez et al. (2017) also suggested that along with the Pijao eclogites, the entire Arquía Complex (Maya &

Table 1. Mineralogy, geochemical constraints, and ages of the high–pressure rocks of northern Andes, including the Raspas Metamorphic Complex (Ecuador).

Region	Pijao[1]	Barragán[2]		Jambaló[3]	Raspas[4, 5]	
Rock Type	Ecl (?) and Amp–ecl	BS	Amp–ecl (?)	BS	Ecl	BS
Mineralogy	Hbl, Pl*, Phg, Qtz, Ep, Czo, Zo, Ttn, Rt, Grt, Omp	Gln, Lws, Ilm, Pg, Phg, Ep, Czo, Chl, Pl*, Carb, Ttn, Pmp, Py	Hbl, Pl*, Phg, Qtz, Ep, Czo, Zo, Ttn, Rt, Scp	Gln, Brs, Act, Pg, Ep, Czo, Chl, Pl*, Carb, Ttn, Rt, Zrn, Ap, Grt, Ilm, Py	Omp, Grt, Brs, Qtz, Zo, Rt, Ap, Ilm	Gln, Phg, Pg, Qtz, Carb, Ttn, Rt, Grt, Ap, Pl*, Ilm
Geochemistry	MORB[1]	MORB[2]		MORB + OIB	MORB + seamounts[6]	
Age	ca. 130 Ma[1, A]	ca. 120 Ma[2, B]		71–63Ma[3, C]	ca. 130 Ma[6, D]	

(Ecl) eclogite; (BS) blueschist; (Amp–ecl) amphibolitized eclogites; (MORB) Mid Ocean Ridge Basalt; (OIB) Ocean Island Basalts; (Act) actinolite; (Ap) apatite; (Brs) barroisite; (Carb) carbonate; (Chl) chlorite; (Czo) clinozoisite; (Ep) epidote; (Gln) glaucophane; (Grt) garnet; (Hbl) hornblende; (Ilm) ilmenite; (Lws) lawsonite; (Omp) omphacite; Opaque minerals; (Pg) paragonite; (Phg) phengite; (Pl) plagioclase* (An contents varying from 2 to 28); (Pmp) pumpellyite; (Py) pyrite; (Qtz) quartz; (Rt) rutile; (Scp) scapolite; (Ttn) titanite; (Zo) zoisite; (Zrn) zircon.

[1]García–Ramírez et al. (2017); [2]Bustamante et al. (2012); [3]Bustamante et al. (2011); [4]Aspden et al. (1995); [5]Bosch et al. (2002); [6]John et al. (2010).

[A] Whole rock from metabasites using Lu–Hf method. Age of metamorphism; [B]Muscovite and separates from graphite–chlorite–muscovite–quartz schist associated with the blueschist–facies rocks using $^{40}Ar/^{39}Ar$ method. Age of exhumation event; [C]Paragonite and phengite from a blueschist using $^{40}Ar/^{39}Ar$ method. Age of metamorphism; [D]Whole rocks and mineral separates from an eclogite using Lu–Hf method. Age of metamorphism.

González, 1995) has the same basaltic protolith and was subjected to the same slab roll–back process.

3.2. Barragán Blueschists

Discontinuous outcrops of blue–gray fine–grained epidote–glaucophane and chlorite–lawsonite schists occur in the Barragán region. These outcrops are associated with hornblende and chlorite schists and metapelites made up of muscovite, graphite, and quartz, together with serpentinized ultramafic rocks (Figures 3, 5). Possible amphibolitized eclogites mainly comprising hornblende and garnet have also been described in the area (González, 1997; McCourt & Feininger 1984).

Whole–rock geochemistry of the blueschist– and amphibolite–facies rocks (Bustamante et al., 2012) indicates a basaltic protolith (Figure 6). Chondrite–normalized REE patterns (Figure 7b) show a slight depletion in the lightest rare earth elements (LREE) and an almost flat pattern in the middle rare earth elements (MREE) and heavy rare earth elements (HREE). Within the trace element variation plots normalized to N–MORB (Figure 8b; Sun & McDonough, 1989), Nb and Th show negative anomalies.

Bustamante et al. (2012) reported $^{40}Ar–^{39}Ar$ ages using muscovite and separates from a graphite–chlorite–muscovite–quartz schist associated with the blueschist facies rocks, obtaining plateau ages of 119.4 ± 3.8 Ma, 120.1 ± 1.0 Ma, and 120.8 ± 0.3 Ma (Table 1); the error–weighted average of these three plateau ages is 120.7 ± 0.3 Ma (MSWD = 0.29).

Both the geochemistry and geochronology were interpreted by Bustamante et al. (2012) to indicate a basaltic protolith metamorphosed under high–pressure conditions at ca. 120 Ma, representing the exhumation event associated with the development of a mylonitic foliation.

3.3. Jambaló Blueschists

The Jambaló blueschists constitute a series of blueschist–facies lenses embedded in greenschist–facies rocks. These rocks are associated with impure marbles, serpentinized peridotites, and quartzites (Figures 4, 5).

Geochemical results suggest that the Jambaló blueschists have a slightly more differentiated protolith compared with the high–pressure rocks from Pijao and Barragán (Figure 6). Additionally, chondrite–normalized REE patterns of the blueschists show a slight enrichment of LREE (Figure 7c). Eu anomalies are slightly negative in these blueschists (Eu/Eu* from 0.7 to 1.2). Trace element variation plots normalized to N–MORB (Sun & McDonough, 1989) are characterized by negative Nb, Zr, Hf, Ti, and Ta anomalies (Figure 8c).

Orrego et al. (1980b) reported a minimum whole–rock (from sericite schist) K–Ar age for the metamorphism of 125 ± 15 Ma, and De Souza et al. (1984) obtained ages of 104 ± 14

Table 2. Whole–rock geochemistry from the Pijao eclogites[1], Barragán blueschists[2], and Jambaló blueschists[2].

Region	Pijao	Pijao	Pijao	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló
Rock type	Ecl (?)	Ecl (?)	Ecl (?)	Amp–Ecl	Amp–Ecl	Amp–Ecl	Amp–Ecl	Amp–Ecl	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS	BS
Sample	ARQ–214	ARQ–378	ARQ–379	187A	187AA	187BA	188A	189A	195BS	196BS	196ABS	196DBS	197ABS	199BS	121B	123A	124G	124J	125I	125K	125M	129A
SiO_2	49.3	47.2	49.0	47.7	50.8	50.0	51.3	49.4	50.0	48.4	48.4	49.1	49.2	48.3	51.7	50.4	56.9	52.0	53.3	53.1	56.3	51.4
Al_2O_3	13.5	15.2	14.1	15.1	14.3	15.0	13.4	14.7	14.5	14.5	15.4	13.9	16.3	14.4	15.6	17.8	15.6	18.1	17.2	19.8	17.8	14.4
Fe_2O_3	4.5	2.4	2.7	14.5	10.8	10.6	12.2	12.2	11.2	10.3	11.7	10.8	10.4	12.7	9.7	9.8	9.5	8.8	9.1	10.9	8.1	9.5
MnO	0.230	0.160	0.200	0.519	0.222	0.176	0.230	0.190	0.187	0.157	0.200	0.161	0.168	0.158	0.441	0.139	0.123	0.145	0.240	0.080	0.103	0.129
MgO	7.680	7.480	8.390	7.990	7.910	8.240	6.010	8.720	6.180	9.280	6.740	6.600	8.590	7.600	3.490	3.270	4.020	4.480	5.410	2.590	4.680	5.330
CaO	8.0	13.4	9.0	8.8	10.3	11.2	9.4	8.8	8.4	8.1	8.7	10.8	4.2	7.6	5.8	11.6	2.9	3.5	3.7	1.7	1.6	4.0
Na_2O	2.6	2.4	3.6	2.6	2.4	2.3	3.9	2.6	2.0	2.7	3.4	2.4	0.2	3.3	4.8	2.6	4.5	5.6	5.1	3.4	5.7	5.2
K_2O	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.2	<0.01	0.6	0.1	0.5	0.0	0.1	0.3	0.4	0.8	0.7	0.5	2.9	0.7	0.2
TiO_2	2.390	1.230	1.860	1.300	1.230	1.270	2.040	1.370	1.980	1.400	1.730	1.480	1.240	1.920	1.430	1.460	1.710	1.480	1.530	2.080	1.170	1.840
P_2O_5	0.210	0.100	0.160	0.100	0.080	0.120	0.220	0.100	0.200	0.140	0.130	0.200	0.090	0.190	0.290	0.410	0.290	0.230	0.210	0.150	0.130	0.230
LOI	0.70	3.10	0.50	1.40	2.08	1.23	1.15	2.05	5.21	4.52	3.45	3.27	8.48	3.87	6.60	2.58	3.80	4.18	3.50	3.20	3.74	7.84
Total	99.8	99.9	99.9	100.1	100.2	100.3	100.0	100.3	99.9	100.1	99.8	99.3	98.9	100.1	100.1	100.4	100.2	99.2	99.7	99.8	100.0	100.0
Sc	41	39	44	44	43	45	42	44	46	43	47	42	35	42	29	20	27	25	30	31	28	37
V	428	263	377	285	275	305	395	331	418	315	386	334	290	380	214	184	238	185	252	170	194	278
Co	51.8	45.1	47.6	72	61	40	53	41	51	45	51	51	48	52	33	36	32	51	34.4	39.5	34	35
Ni	19.3	54	17	90	80	70	60	80	80	80	90	80	120	120	30	70	–	30	59.7	3.5	30	30
Cu	33.2	104.8	33.1	30	20	30	30	80	60	50	50	110	<10	70	–	50	–	–	3.3	1.1	50	30
Zn	24	16	17	110	80	90	140	130	150	100	130	110	130	140	70	80	130	130	125	41	110	130
Ga	18.1	14.3	18.5	14	16	18	18	19	21	17	21	18	18	19	17	25	20	22	18	24.7	19	20
Rb	0.8	2.8	0.3	4	2	4	<1	3	<1	11	3	12	<1	7	5	6	20	16	11.1	91.1	14	3
Sr	104.4	182.3	109.7	37	113	152	113	120	9	73	142	201	73	91	166	574	68	80	113.2	69.5	83	163
Y	49.3	27	41.2	37.5	29.2	30.3	48.8	33.2	51	30.9	41.9	38.3	21.9	40.8	33	23.5	35.8	48.6	39.7	32.7	23.8	38.4
Zr	164.2	82.4	117.4	59	62	69	134	68	123	80	107	88	53	120	126	224	186	264	139	230.2	147	175
Nb	3.0	2.5	1.8	2.0	1.1	1.0	2.5	0.9	4.2	3.4	4.1	3.6	2.2	5.0	5.3	15.4	7.2	9.5	6.2	9.1	4.9	7.7
Cs	0.9	0.3	<0.1	0.2	<0.1	0.1	<0.1	0.2	<0.1	0.8	0.2	0.7	<0.1	0.4	1.2	0.3	0.4	0.4	0.5	1.2	0.5	0.3
Ba	22	11	20	78	374	323	17	38	38	73	49	383	18	110	66	71	119	108	222	259	191	25
La	5.5	3.6	3.8	3.4	2.2	2.5	5.0	2.0	5.9	4.5	7.3	6.0	2.8	6.5	10.4	22.3	15.6	14.8	11.5	17.4	12.4	9.2
Ce	16.30	10.40	12.80	7.28	6.45	6.81	16.00	7.13	15.60	12.10	17.10	13.00	8.69	17.30	25.90	46.60	35.40	40.40	24.20	36.60	28.10	24.00
Pr	2.82	1.64	2.18	1.59	1.26	1.35	2.63	1.35	2.69	1.88	2.86	2.29	1.42	2.72	3.62	5.86	4.71	5.65	3.81	4.52	3.36	3.38
Nd	15.5	8.5	11.5	8.8	7.5	8.1	14.4	8.0	14.6	9.9	14.5	11.7	8.1	14.4	17.5	24.4	20.4	24.3	17.8	19.8	14.2	16.2
Sm	5.21	2.74	4.24	2.95	2.70	2.79	4.87	2.93	4.81	3.13	4.46	3.69	2.82	4.62	4.59	5.31	5.02	6.04	4.52	4.42	3.51	4.74
Eu	1.90	1.07	4.24	1.08	1.12	1.14	1.81	1.27	1.85	1.27	1.76	1.49	1.10	1.77	1.83	1.98	1.70	1.95	1.53	1.07	1.18	1.58
Gd	7.20	4.02	5.69	3.95	3.79	3.86	6.52	4.15	6.33	4.04	5.85	5.07	3.45	5.80	5.27	5.17	5.45	6.76	5.61	4.88	3.81	5.32
Tb	1.310	0.690	1.050	0.830	0.760	0.790	1.300	0.890	1.250	0.800	1.140	0.990	0.630	1.140	0.940	0.840	0.990	1.270	1.020	0.910	0.710	1.020
Dy	8.88	4.34	6.95	5.91	5.10	5.24	8.51	5.84	8.17	5.23	7.39	6.42	3.90	7.35	5.92	4.74	6.23	8.01	6.19	5.48	4.55	6.74
Ho	1.870	0.910	1.520	1.270	1.060	1.070	1.750	1.150	1.640	1.050	1.450	1.290	0.780	1.470	1.180	0.860	1.280	1.630	1.310	1.160	0.890	1.400

Table 2. Whole–rock geochemistry from the Pijao eclogites[1], Barragán blueschists[2], and Jambaló blueschists[2] *(continued).*

Region	Pijao	Pijao	Pijao	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán	Barragán
Rock type	Ecl (?)	Ecl (?)	Ecl (?)	Amp–Ecl	Amp–Ecl	Amp–Ecl	Amp–Ecl	Amp–Ecl	BS	BS	BS	BS	BS	BS
Sample	ARQ–214	ARQ–378	ARQ–379	187A	187AA	187BA	188A	189A	195BS	196BS	196ABS	196DBS	197ABS	199BS
Er	5.38	2.80	4.47	4.06	3.17	3.24	5.19	3.44	4.87	3.12	4.26	3.86	2.30	4.34
Tm	0.850	0.410	0.680	0.635	0.482	0.495	0.787	0.514	0.730	0.463	0.639	0.589	0.342	0.652
Yb	5.62	2.75	4.87	4.14	3.10	3.21	5.02	3.27	4.69	2.92	4.06	3.73	2.26	4.13
Lu	0.790	0.400	0.680	0.656	0.464	0.509	0.766	0.512	0.700	0.457	0.609	0.566	0.353	0.624
Hf	4.60	<0.01	3.50	2.10	1.90	1.90	3.90	2.20	3.60	2.40	3.00	2.50	2.00	3.40
Ta	0.300	0.100	<0.1	1.460	0.860	0.040	0.670	0.030	0.520	0.440	0.550	0.760	0.400	0.680
W	<0.1	<0.1	<0.1	208	230	3	137	2	94	66	90	163	93	97
Th	<0.2	<0.2	<0.2	0.11	0.06	0.06	0.19	0.06	0.29	0.23	0.28	0.24	0.20	0.37
U	<0.1	<0.1	<0.1	0.05	0.04	0.04	0.09	0.05	0.25	0.14	0.70	0.29	1.83	0.24

Region	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló	Jambaló
Rock type	BS	BS	BS	BS	BS	BS	BS	BS
Sample	121B	123A	124G	124J	125I	125K	125M	129A
Er	3.51	2.35	3.74	4.88	3.96	3.58	2.66	4.16
Tm	0.532	0.327	0.542	0.721	0.550	0.550	0.396	0.631
Yb	3.45	2.03	3.48	4.53	3.33	3.52	2.55	4.14
Lu	0.516	0.290	0.550	0.683	0.520	0.570	0.377	0.635
Hf	3.30	4.90	4.50	6.40	3.90	6.60	3.70	4.30
Ta	1.120	2.210	1.460	1.390	0.600	1.200	1.010	1.290
W	258	333	322	230	107	220	171	107
Th	1.00	1.48	3.64	3.74	1.70	5.10	3.09	1.20
U	0.39	0.34	0.93	1.38	0.60	1.10	0.75	0.52

[1] García–Ramírez et al. (2017)

[2] Bustamante (2008)

Ma and 217 ± 10 Ma using the same method in glaucophane. The K–Ar method has several limitations concerning the dating of metamorphic rocks since argon losses or excesses cannot be determined and the thermal history of minerals (i.e., white micas) cannot be discriminated (Clauer & Chaudhuri, 1999; Dallmeyer & Takasu, 1992). In addition, the use of glaucophane K–Ar geochronology may be unreliable since potassium contents could be attributed to very fine inclusions of K–bearing minerals (i.e., K–micas and barroisite). Recently, Bustamante et al. (2011) reported Ar–Ar ages in white micas from six samples of blueschist–facies rocks. The age range obtained was very different ca. 70 to 60 Ma (Table 1) and was interpreted as the record of the mylonitic event responsible for the exhumation of the blueschist–facies rocks.

Although high–pressure metamorphic rocks are presented as independent bodies, the available geochemistry data of the possibly amphibolitized eclogites (Avellaneda et al., 2017; García–Ramírez et al., 2017) and their estimated ages suggest a strong correlation with Barragán rock occurrences (Bustamante et al., 2012) that could represent subduction–collision complexes (e.g., Avellaneda et al., 2017; Bustamante et al., 2012) and need not be related to the roll–back processes proposed by Spikings et al. (2015) and García–Ramírez et al. (2017).

4. Discussion

4.1. Age of Metamorphism and Protoliths

The most recent and precise ages of the high–pressure metamorphic rocks of the Central Cordillera compiled in this review (Table 1) indicate that at least two different high–pressure metamorphic events occurred during the Cretaceous – Paleogene in the northern Andes, and are recorded at the western flank of the Central Cordillera. The first occurred between 128 and 120 Ma (Early Cretaceous) and is represented by the Barragán blueschists (Bustamante et al., 2012) and Pijao eclogites (García–Ramírez et al., 2017). The second occurred between 70 and 60 Ma (Late Cretaceous to Paleogene) when the Jambaló blueschists were formed (Bustamante et al., 2011). This hypothesis opposes models that consider the entirety of the high–pressure metamorphic rocks of the Central Cordillera to have been formed in a single Early Cretaceous event (De Souza et al., 1984; García–Ramírez et al., 2017; Orrego et al., 1980b; Spikings et al., 2015; Villagómez & Spikings, 2013).

Available whole–rock geochemistry from the Pijao, Barragán, and Jambaló high–pressure rocks shows that a basaltic protolith is common for the three, although in Jambaló a basaltic andesite may have been present (Figure 6). Despite similar mafic protoliths, we postulate that the Barragán and Pijao high–pressure rocks share the same N–MORB signature (Figures 7, 8) as suggested in the Zr–Nb–Y diagram (Figure 9). The Jambaló rocks may represent an intra–oceanic arc that

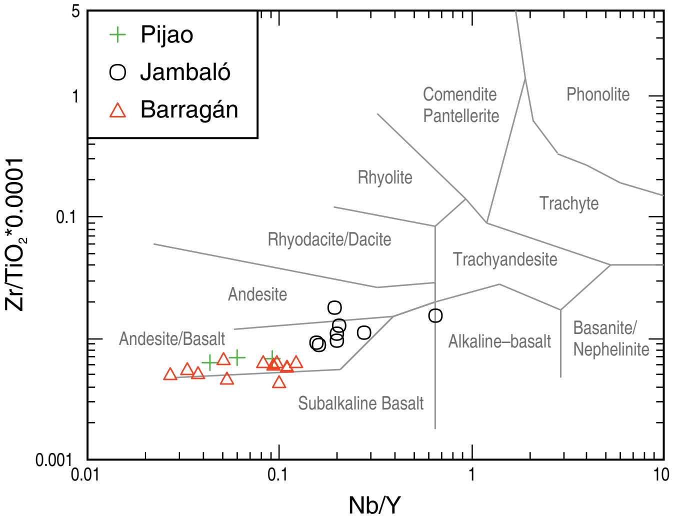

Figure 6. Classification of basic rocks based on the Nb/Y versus Zr/TiO_2 diagram, after Winchester & Floyd (1977).

grew over plume–modified oceanic crust (Bustamante, 2008). Thus, the Early Cretaceous metamorphic event may be linked to the subduction of the Farallón Plate, whereas the Late Cretaceous metamorphism is linked to the Caribbean Plate.

4.2. Tectonic Implications and Possible Correlations

The Early Cretaceous high–pressure metamorphic event recorded in the Central Cordillera (Figure 10; Barragán and Pijao rocks) may represent an event of subduction–accretion that occurred before the collision of the Caribbean Plate with the western margin of South America (Avellaneda et al., 2017; Bustamante et al., 2012). Until the high–pressure metamorphic event occurred, between 128 to 120 Ma according to the data presented above, the western margin of the northern Andes was characterized by an oblique convergence with the Farallón Plate which may have caused a transpressive margin and the ending of the arc–related magmatism that dominated between the Early Jurassic and Early Cretaceous (ca. 200 to 130 Ma sensu Bustamante et al., 2016). These tectonic scenarios differ from those proposed by García–Ramírez et al. (2017), who suggest the slab roll–back process during the same time interval as the western margin of the northern Andes, caused by the eclogitization of the subduction slab and, hence, an increase in its density. The slab roll–back model was previously proposed to explain the magmatic evolution of the northern Andes from the Jurassic until Early Cretaceous (Cochrane et al., 2014; Leal–Mejía, 2011; Spikings et al., 2015). However, this mechanism involves the progressive increase of back–arc extension, triggering the exhumation of high–pressure rocks and even ultra–high–pressure rocks (Brun & Faccenna, 2008).

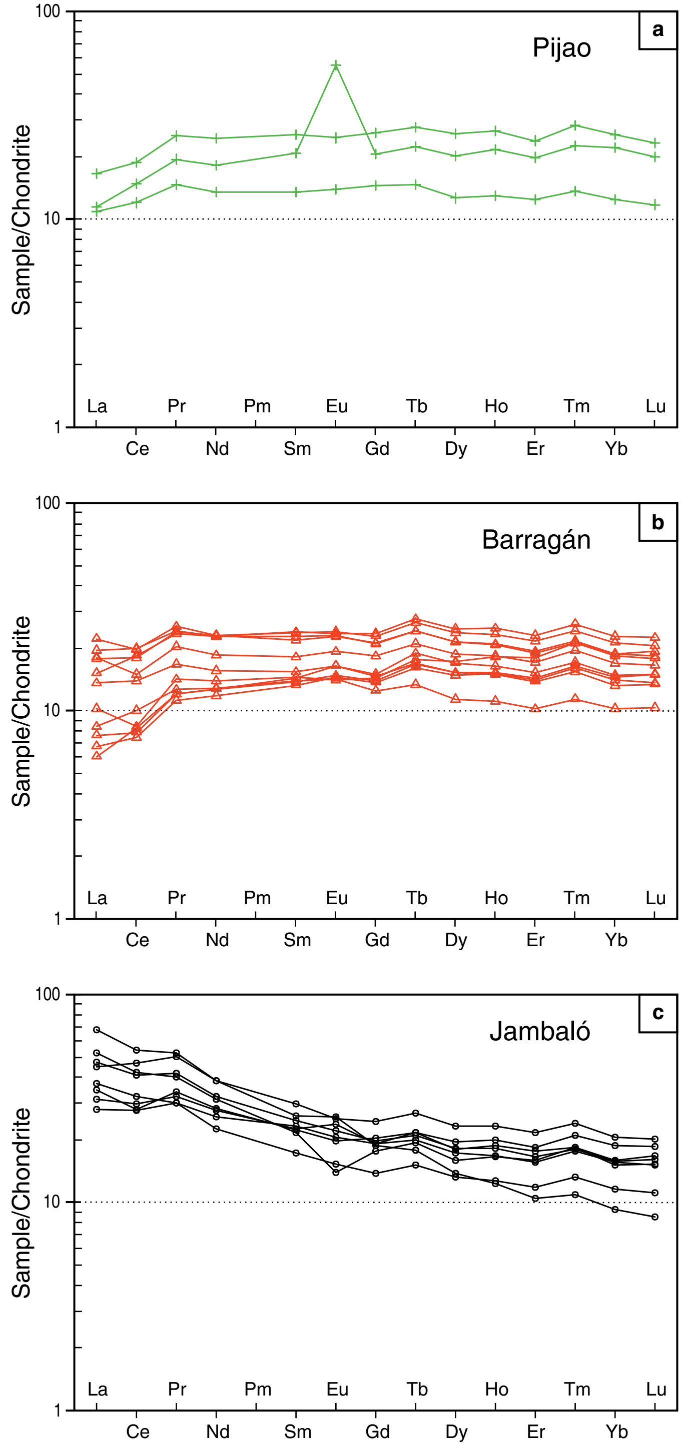

Figure 7. Chondrite–normalized REE patterns of the high–pressure metamorphic rocks. Diagram after Nakamura et al. (1974). **(a)** Pijao. **(b)** Barragán. **(c)** Jambaló.

Spikings et al. (2015) suggest that the Lower Cretaceous high–pressure metamorphic sequence (including the Jambaló blueschists) originated as a MORB and metamorphosed within the same subduction zone, followed by its exhumation between 120 and 112 Ma. Additionally, they report that the

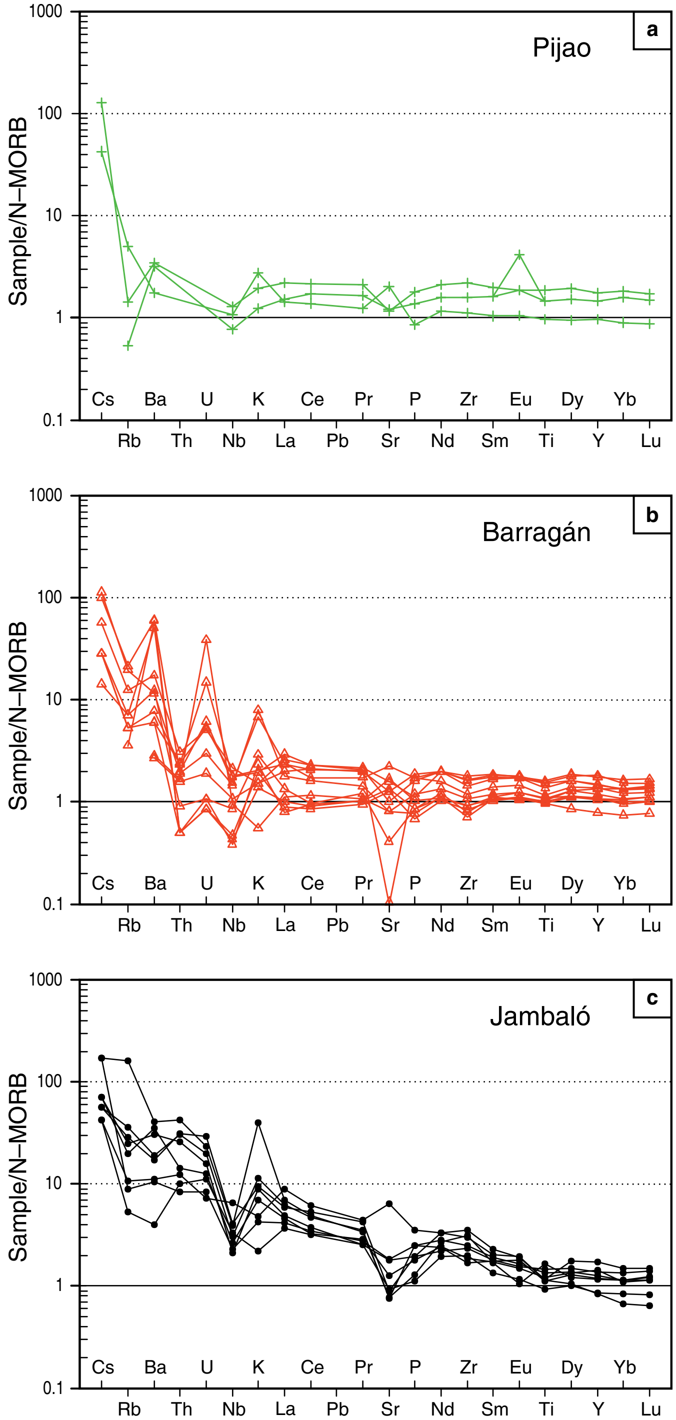

Figure 8. Multi–element plot normalized to primitive mantle after Sun & McDonough (1989). **(a)** Pijao. **(b)** Barragán. **(c)** Jambaló.

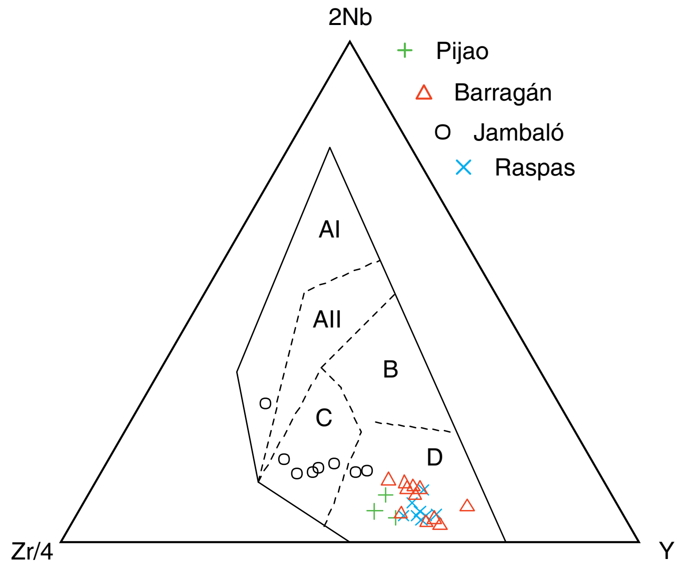

Figure 9. Zr/4–2Nb–Y diagram for classifying tholeiitic basalts from Meschede (1986).

high–pressure rocks of the Raspas Metamorphic Complex in Ecuador may be correlated with those of the Central Cordillera of Colombia, due to their similar tectonic position, lithological similarities, and degree of metamorphism. However, the Ar–Ar ages obtained in the Jambaló rocks (Bustamante et al., 2011) are discarded in that model as the geochemical constraints are, in fact, not based on the high–pressure rocks, but in associated garnet–amphibolites grouped in the Arquía Complex (Maya & González, 1995).

A second subduction zone, active during the Early Cretaceous, was the location of the high–pressure metamorphism of the Jambaló rocks (Figure 10). The basaltic rocks comprising their protolith may have formed in an intra–oceanic arc originated over a plume modified lithosphere, according to the results of Bustamante (2008). This intra–oceanic arc further collided with the continental margin of NW South America which contributed to an increase in its thickness as recorded in the Eocene high Sr/Y arc–related magmas distributed along the Central Cordillera (Bustamante et al., 2017b). This may be the only record of Caribbean–related high–pressure metamorphism in the northern Andes.

The blueschists and eclogites of the Raspas Metamorphic Complex in the Eastern Cordillera of Ecuador have MORB and seamount–like protoliths. These rocks reached their metamorphic peak conditions at ca. 130 Ma (John et al., 2010). Their geochemical trends and the age of metamorphism recorded within the Barragán high–pressure rocks, when compared with the Raspas Metamorphic Complex (Figure 9), allowed Spikings et al. (2015) to propose that these high–pressure belts shared the same geological history. Although such a comparison may be valid based on the abovementioned similarities, caution should be taken when evaluating this high–pressure metamorphic belt since the pressure–temperature–time (P–T–t) paths of its constituents have never been compared. It is clear that the Jambaló schists should not be considered as a continuation of the same high–pressure belt

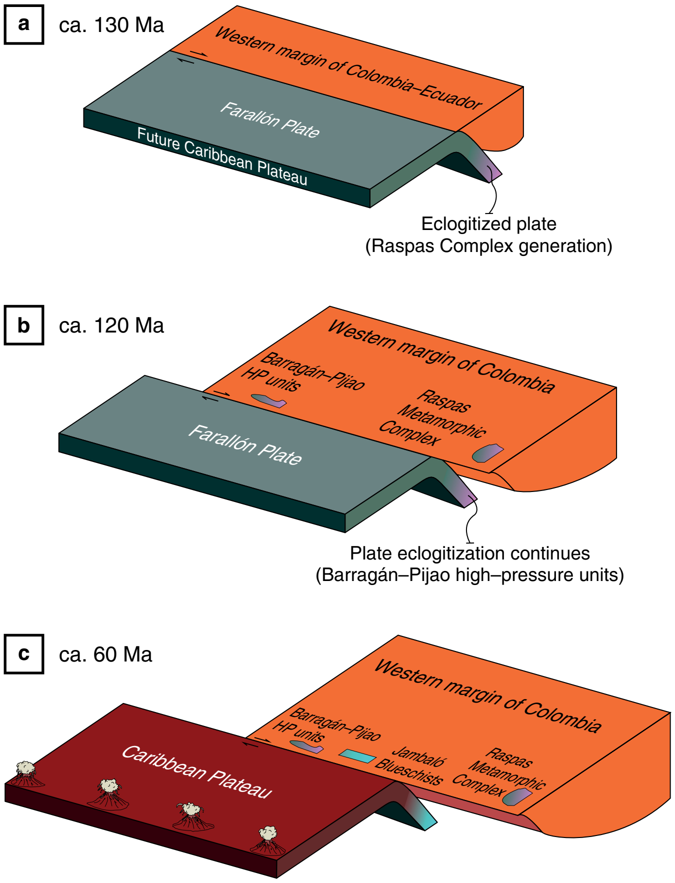

Figure 10. Cartoons (not to scale) of the proposed model for the generation of high–pressure metamorphic rocks at the northern Andes (including Raspas Metamorphic Complex) at three instances: ca. 130 Ma, ca. 120 Ma, and ca. 60 Ma. The figure suggests the relationships between oblique convergence and the exhumation of the high–pressure metamorphic units (HP units). **(a)** Farallón Plate subducts beneath South American Plate. Eclogitization of Farallón Plate results in Raspas Metamorphic Complex generation. **(b)** Farallón Plate eclogitization continues to form Barragán–Pijao high–pressure units. **(c)** Caribbean Plateau replaces Farallón Plate and begins its subduction process to form the Jambaló blueschists. In the portion shown, the eclogite facies is not reached. Oblique convergence continues.

as proposed by Spikings et al. (2015), according to the geochemical and age differences that these rocks present with the other high–pressure rock sequences (Bustamante, 2008). No other Lower Cretaceous – Paleogene blueschists are present in the northern Andes, and hence no similar rocks exist with which they can be compared.

5. Conclusions

High–pressure metamorphic rocks in Colombia, including blueschists and eclogites, are currently recognized at three localities: Pijao (eclogites), Barragán (blueschists and retrograded eclogites), and Jambaló (blueschists). The first two share the same N–MORB–like protolith, and an Early Cretaceous metamorphic age, whereas extensive geochemical data of the Jambaló blueschists is instead indicative of a protolith formed in a plume–influenced intra–oceanic arc, whose metamorphism occurred between the Late Cretaceous and Paleogene.

From these high–pressure lithologies in the Central Cordillera, it is postulated that two subduction events occurred during the Cretaceous. The first, characterized by episodes of subduction–accretion, would have provoked high–pressure metamorphism in an oblique subduction regime, forcing the slab roll–back process otherwise not plausible during this time. The second episode of subduction produced the Jambaló blueschists in an intra–oceanic arc, involving further collision with the continental margin and increasing its thickness, as recorded in the adakite–like magmatism of the Central Cordillera.

Possible correlations of the Pijao and Barragán rocks with similar rocks of the Raspas Metamorphic Complex in the Eastern Cordillera of Ecuador are possible as they are geochemically similar and contemporaneous. However, P–T–t paths are required to form these conclusions. Conversely, the Jambaló rocks have no similarities with Pijao and Barragán rocks, which impede their correlation.

Acknowledgments

We express our gratitude to the Servicio Geológico Colombiano for inviting us to contribute to this book. Interesting discussions with Agustín CARDONA (Escuela de Procesos y Energía, Universidad Nacional de Colombia) helped improve the style and conclusions of this work. The writers benefited from many discussions with Caetano JULIANI (Instituto de Geociências, Universidade de São Paulo, Brazil) and Antonio GARCÍA CASCO (Departamento de Mineralogía y Petrología, Universidad de Granada, Spain). Comments from Victor A. RAMOS and Franco URBANI helped improve the quality of this manuscript.

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Explanation of Acronyms, Abbreviations, and Symbols:

HREE	Heavy rare earth element
LREE	Light rare earth element
MREE	Middle rare earth element
N–MORB	Normal mid–ocean ridge basalt
REE	Rare earth element

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2020