U-Pb LA-ICP-MS GEOCHRONOLOGY AND REGIONAL CORRELATION OF MIDDLE JURASSIC INTRUSIVE ROCKS FROM THE GARZON MASSIF, UPPER MAGDALENA VALLEY AND CENTRAL CORDILLERA, SOUTHERN COLOMBIA

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ABSTRACT

New U-Pb zircon geochronology from four granitic units sampled along a southeast-northwest transect between the Garzón Massif and the Serranía de las Minas (Central Cordillera), records a Middle Jurassic magmatic activity with two different spatio-temporal domains at ca. 189 Ma and 180-173 Ma. Reconnaissance data suggest that the four granitoids are characterized by mineralogical and geochemical characteristics akin to a continental magmatic arc setting.
The new results suggest that the southern Colombian continental margin includes remnants of tectono-magmatic elements formed by the subduction of the Farallon plate under the South American continental margin. This Middle Jurassic arc magmatism is part of the broader Andean scale arc province, and is significant for understanding the tectonic and paleogeographic scenario that characterized the Mesozoic tectonic evolution of the Northern Andes.

Key words: U-Pb geochronology, Colombia, Jurassic, Intrusive rocks, Garzón Massif, Central Cordillera.

GEOCRONOLOGÍA U-Pb LA-ICP-MS Y CORRELACIÓN REGIONAL DE LAS ROCAS INTRUSIVAS DEL JURÁSICO MEDIO DEL MACIZO DE GARZÓN, VALLE SUPERIOR DEL MAGDALENA Y LA CORDILLERA CENTRAL, SUR DE COLOMBIA

RESUMEN

Se presentan nuevas edades U-Pb en circones de cuatro unidades graníticas muestreadas a lo largo de una transecta SE-NW entre el Macizo de Garzón y la Serranía de las Minas (Cordillera Central), las cuales registran una actividad magmática en el Jurásico Medio en dos dominios espaciales y temporales diferentes: 189 Ma y 180 a 173 Ma.
Estos cuatro granitoides tiene características mineralógicas y geoquímicas afines con un ambiente de arco magmático continental. Los nuevos resultados sugieren que la margen continental al sur de Colombia incluye remanentes de elementos tectono-magmáticos formados por la subducción de la placa Farallón bajo la margen continental suramericana. Este magmatismo de arco del Jurásico medio es parte de la provincia de arco que se presenta a lo largo de los Andes, y es importante para el entendimiento de la dinámica tectónica y la paleogeografía que caracterizó el Mesozoico de los Andes del Norte.

Palabras clave: Geocronología U-Pb, Colombia, Jurásico, Rocas intrusivas, Macizo de Garzón, Cordillera Central.

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INTRODUCTION

Early to Late Mesozoic tectonic evolution of the western margin of South America is related to successions of different tectonic regimes that recorded the initial effects of Pangea break-up, Pacific subduction, and in northern South America the formation of the proto-Caribbean ocean (Pindell, 1985; Jaillard *et al*., 1990; Toussaint, 1995; Ramos and Aleman, 2000; Ramos, 2009; 2010; Pindell and Keenan, 2010).

These events are responsible for overimposed tectonic scenarios of passive margin, rift and/or arc setting in the Colombian Andes, and potential along strike and lateral segmentation of the different geological environments (Aspden *et al*., 1987; Toussaint, 1995; Ramos and Aleman, 2000; Cediel *et al*., 2003; Sarmiento-Rojas *et al*., 2006; Vásquez *et al*., 2010).

Additional complexities include along strike translation and juxtaposition of a variety of Mesozoic continental magmatic related fragments (Bayona *et al*., 2006; 2010), that seems to be linked to the existence of an oblique subduction configuration with the Colombian margin as the final stop for the redistribution of continental para-authocthonous type terranes (Jaillard *et al*., 1990; Restrepo and Toussaint, 1988; Toussaint, 1993; Bayona *et al*., 2006; 2010; Keenan and Pindell, 2010).

In this contribution we present new U-Pb LA-ICP-MS zircon geochronology and reconnaissance geochemistry from four plutonic bodies sampled along an east-west transect between the Garzón Massif and the westernmost limit of the Upper Magdalena Valley in order to establish more precise time constrains on the Jurassic plutonism in Southern Colombia and contribute to the discussion of its tectonic scenario.

Geochronological data for these rocks has not been published so far, and their precise interpretation has been built on lithological correlations and geochronological data from plutonic rocks at the northern extension of this batholiths, which have shown mainly cooling ages that varies between ca. 177-136 Ma (Vesga and Barrero, 1978; Sillitoe *et al*., 1982; Brook, 1984; Aspden *et al*., 1987; Altenberger and Concha, 2005).

Therefore, the precise timing and tectonic implication of this Jurassic plutons provide insights on the Middle Jurassic tectonomagmatic regime of northwestern South American and serve as piercing point for understanding the variable Middle Mesozoic tectonic events (Ramos and Aleman; 2000; Sarmiento-Rojas *et al*., 2006; Bayona *et al*., 2006, 2010; Vásquez *et al*., 2010).

GEOLOGICAL SETTING

The Colombian Andes consist of three mountain ranges (Figure 1) built as a result of Paleozoic and Meso-Cenozoic phases of terrane relate accretion interspersed several periods of continuous subduction (Restrepo and Toussaint, 1988; Toussaint, 1995; Cediel *et al*., 2003; Pindell *et al*., 2005; Ordoñez *et al*., 2006).

The Western Cordillera includes volcanic rocks with intercalated marine sediments of Cretaceous age formed in an oceanic plateau environment (reviews in Kerr *et al*., 1997), whose accretion took place during the Late Cretaceous, linked to the advance of the allocthonous Caribbean Plate (Toussaint, 1996; Kerr and Tarney, 2005; Pindell *et al*., 2005). The Central Cordillera comprises a pre–Mesozoic polymetamorphic basement intruded by several Meso-Cenozoic plutonic rocks (Toussaint, 1993; Ordóñez-Carmona *et al*., 2006; Vinasco *et al*., 2006). Its major tectonic record reflect several collisional and subduction events between 290-230 Ma link to the agglutination of Pangea (Ordóñez-Carmona and Pimentel, 2002; Vinasco *et al*., 2006; Cardona *et al*., 2010). Albian to Aptian rocks are discontinuously and limited exposed (Toussaint, 1996).

Finally, the Eastern Cordillera includes Precambrian and Paleozoic metamorphic rocks, with overlain deformed Paleozoic sediments (Toussaint, 1993; Restrepo-Pace *et al*., 1997; Cediel *et al*., 2003; Cordani *et al*., 2005; Ordóñez-Carmona *et al*., 2006). Meso-Cenozoic sedimentary marine and continental successions are registered within this cordillera, and record the changing tectonic conditions from passive to active margin that end in the Andean orogeny (reviews in Cediel *et al*., 2003; Mora *et al*., 2006; Bayona *et al*., 2008).

JURASSIC MAGMATISM

Jurassic volcanic and plutonic rocks are widespread along the Colombian Andes (Figure 1), and can be related to a broader magmatic province that affect the entire western margin of South America (Aspden *et al*., 1987; Lucassen, *et al*., 1996; Noble, *et al*., 1997; Jaillard *et al*., 2000; Kramer *et al*., 2005; Oliveros *et al*., 2006; 2007; Mpodozis and Ramos, 2008).

Magmatic activity is recorded by an extensive series of elongated batholithic bodies distributed along the eastern margin of the Central Cordillera, the margins of the Upper Magdalena Valley and the Garzón and Santander Massifs. Similar elements are also found within several more isolated massifs in northern Colombian, including the San Lucas Serrania and the Caribbean massifs such as the Sierra Nevada de Santa Marta, Perijá and Guajira Serranias (Aspden *et al*., 1987; Alvarez, 1967; Tschanz *et al*., 1974; Toussaint, 1995 and references therein). Available geochronological data mostly obtained by the K-Ar method reveals the existence of at least three major magmatic peaks of magmatic activity between c.a. 195-180 Ma, 167-160 Ma and 151-142 Ma (review in Aspden *et al*., 1987). Most of these rocks are spatially associated with volcanic rocks of effusive and explosive character, which suggest a shallow level of emplacement and a protracted tectono-magmatic evolution.

Tectonic models related to the formation and evolution of this magmatism, include variable rift and arc to back-arc related settings (Tschanz *et al*., 1974; Pindell and Dewey, 1982; Maze, 1984; McCourt *et al*., 1984; Aspden *et al*., 1987; Ross and Scotese, 1988; Pindell and Erikson, 1993; Bayona *et al*., 1994; Toussaint 1995; Pindell and Tabutt, 1995; Meschede and Frisch, 1998; Cediel *et al*., 2003; Vásquez *et al*., 2006). However due to the changing nature of the Mesozoic tectonic regimes in northern South America (reviews in Toussiant, 1995; Pindell and Keenan, 2010; Ramos, 2010), the apparent existence of significantly displaced crustal segments (Bayona *et al*., 2006; 2010) and the paucity of geochronological and geochemical data, a distinction on the timing and evolving nature of the tectonic regimes or the along strike and lateral tectonic variation of the margin is not clear (Toussaint, 1995; Cediel *et al*., 2003; Bayona *et al*., 2006; Vásquez *et al*., 2006; Sarmiento-Rojas *et al*., 2006).

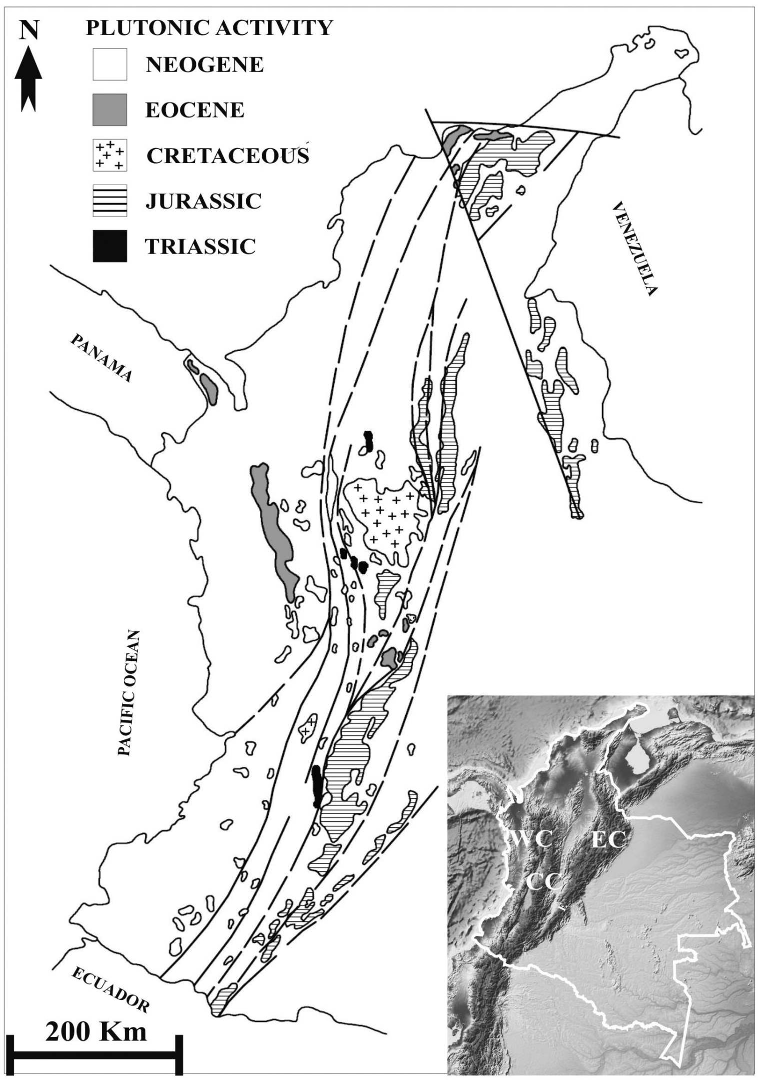

FIGURE 1. Major Mesozoic and Cenozoic plutons from the Colombian Andes (Modified from Aspden et al., 1987). WC: Western Cordillera; CC: Central Cordillera EC: Eastern Cordillera.

JURASSIC PLUTONISM BETWEEN THE GARZÓN MASSIF AND THE UPPER MAGDALENA VALLEY

In southern Colombia, along the Central Cordillera, Upper Magdalena Valley and Garzón Massif, several magmatic units are exposed (**FIGURE 2**). Based on regional correlations several Jurassic age plutonic and volcanic rocks have been recognized in these regions (Velandia *et al*., 2001a, 2001b). Within the Garzón Massif the plutonic bodies intrude Precambrian high grade metamorphic rocks whereas in the Upper Magdalena Valley, plutonic rocks intrude migmatites of unknown age (Álvarez, 1981; Kroonenberg, 1982; Álvarez and Linares, 1983; Velandia *et al*., 2001a, 2001b; Jiménez *et al*., 2006).

Four plutonic units were sampled in an east-west transect between the Garzón Massif and Serranía de las Minas in the western limit of the Upper Magdalena Valley (Figure 2). Most of the geological descriptions of these rocks are from the 1:100.000 regional mapping of the Colombian Geological Survey and presented below (Velandia *et al*., 2001a, b).

Garzón Granite: is an elongated intrusive body that intrudes Precambrian high grade metamorphic rocks from the Garzón Massif. The Garzón – Algeciras thrust fault juxtaposed this intrusive with Tertiary sedimentary rocks. The composition of this pluton ranges from granite to monzodiorite.

Altamira Monzogranite: this intrusive exposed in the eastern limit of the Upper Magdalena Valley has a faulted contact with Jurassic volcano-sedimentary rocks related to the Saldaña Formation. The Suaza Fault separates the Garzón massif from the Jurassic plutonic rocks. Its composition includes mainly monzogranites and is intruded in turn by different andesitic dikes.

Las Minas Monzodiorite: this intrusive outcrop in the central segment of the Upper Magdalena Valley and overthrusts Tertiary sedimentary rocks. At its western segment it presents intrusive contacts with metamorphic rocks included in the pre-Jurassic Las Minas migmatites. Its composition ranges from diorite to monzonite with gabbros at its border.

Ibagué Batholith: This is one of the largest Jurassic batholiths in Colombia and consists of several intrusions of different ages that span from ca. 151 to 142 Ma (Aspden *et al*., 1987; Altenberger and Concha, 2005). It extends both along the Upper Magdalena Valley and the Central Cordillera. In Southern Colombia is limited at the east by La Plata Fault and the Chusma Fault system which juxtaposes it with Jurassic and Tertiary sedimentary rocks. Along its western contact also intrudes metamorphic rocks of the Las Minas Migmatites. Compositionally it is made predominantly of tonalite and granodiorite.

ANALYTICAL TECHNIQUES

Whole rock Geochemistry

Bulk whole rock chemical analysis of 4 samples was determined by inductively coupled plasma-mass spectrometry (ICP-MS) at Acme Analytical Laboratories Ltd. in Vancouver, Canada. A 0.2 g aliquot is weighed into a graphite crucible and mixed with 1.5 g of $LiBO_2$ flux. The crucibles are placed in an oven and heated to 1050° C for 15 minutes. The molten sample is dissolved in 5% HNO_3.Calibration standards and reagent blanks are added to the sample sequence. Sample solutions are aspirated into an ICP emission spectrograph (Jarrel Ash Atom Comb 975) for determining major oxides and certain trace elements (Ba, Nb, Ni, Sr, Sc, Y & Zr), while the sample solutions are aspirated into an ICP-MS (Perkins-Elmer Elan 6000) for determination of the trace elements, including rare earth elements.

U/PB LA-MC-ICP-MS

U-Pb-Th geochronology was conducted in two sessions at the University of Arizona and Washington State University. Operating procedures and parameters are described in Valencia *et al*. (2005) and Chang *et al*. (2006), respectively.

Zircon crystals were analyzed in polished epoxy grain mounts with a Micromass Isoprobe multicollector ICP-MS equipped with nine Faraday collectors, an axial Daly collector, and four ion-counting channels.

U-Pb zircon crystallization ages were estimated and plot using Isoplot 3.0 (Ludwig, 2003) and Arizona LaserChron Excel macro age pick program.

Two uncertainties are reported on these plots. The smaller uncertainty (labeled mean) is based on the scatter and precision of the set of $^{206}Pb/^{238}U$ or $^{206}Pb/^{207}Pb$ ages, weighted according to their measurement errors (shown at 1-sigma). The larger uncertainty (labeled age), which is the reported uncertainty of the age, is determined as the quadratic sum of the weighted mean error plus the total systematic error for the set of analyses. The systematic error, which includes contributions from the standard calibration, age of the calibration standard, composition of common Pb, and U decay constants, is generally ~1-2% (2-sigma).

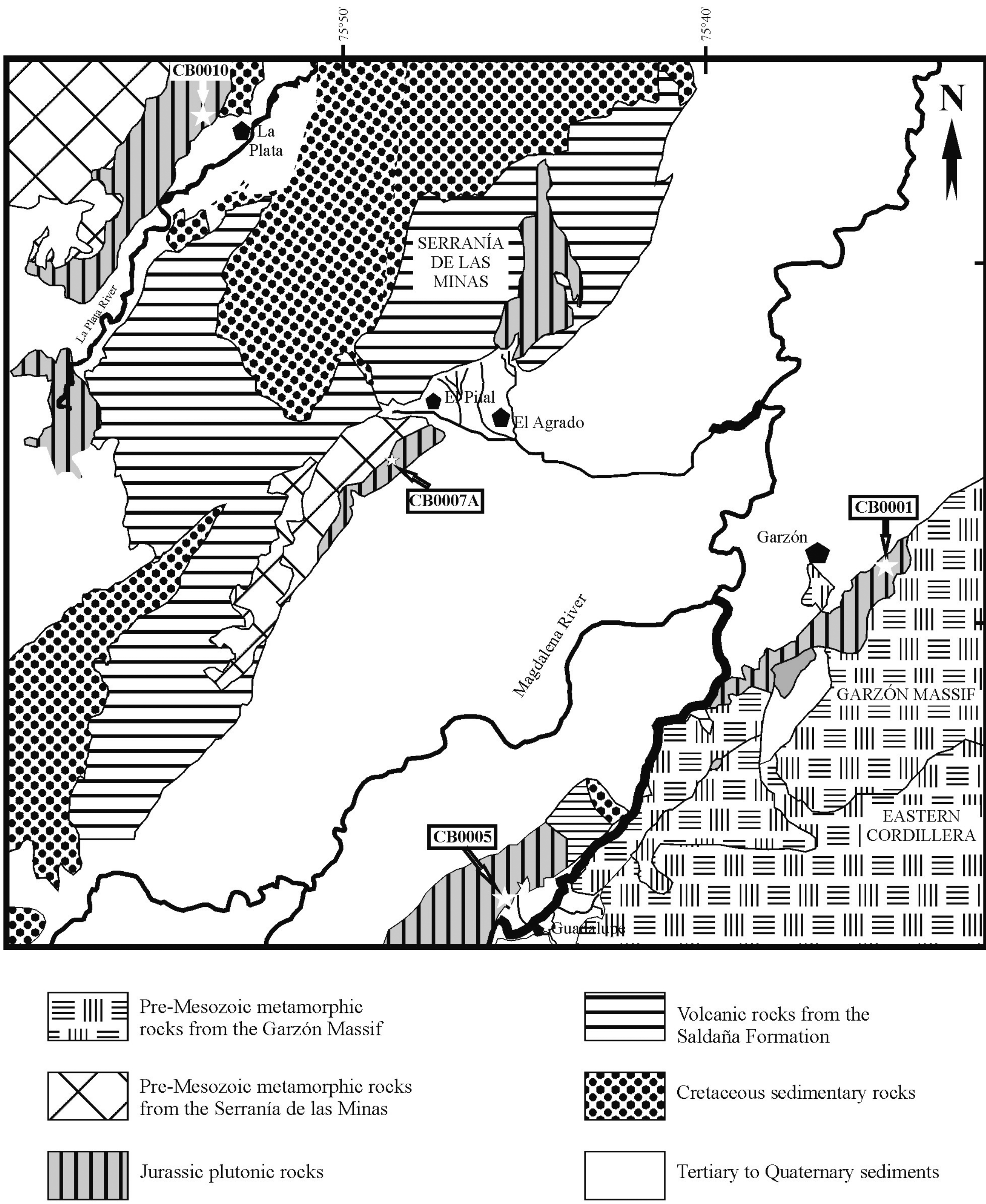

FIGURE 2. Geologic map of the studied area including samples location (Modified from Velandia et al., 2001a).

PETROGRAPHY

Four representative samples from the different intrusive rocks were analyzed. The rocks described include two samples from the Ibagué Batholith, one from Las Minas Monzodiorite and one from Garzón Granite. The main differences identified rely on the ferromagnesian minerals contents. The sample from the Altamira Monzogranite was extremely weathered and was not possible to review. Mineral abbreviations were taken from Kretz (1983) and Spear (1993).

Quartz crystals are xenomorphic and range from 20 to 30% in all samples. Plagioclase is the most abundant mineral and range from 40 – 50%. Crystals are commonly zoned and presents undulatory extinction and deformation twins. This mineral is often replaced by epidote, very fine muscovite and calcite. Microcline is forming a braided pattern due to albite lamellae in the Garzón Granite (**Figure 3a**). Hornblende is abundant in the Las Minas Monzodiorite (CB0007A) with values from 10 – 15% and contrast with the other rocks where it ranges from 5 to 10%. Las Minas Monzodiorite and the Ibague Batholith presents Augite (Figure 3b) as an accessory with less than 2% and commonly enclosed into biotite crystals (Figure 3c) forming poikilitic textures (Figure 3d). Biotite crystals range from 5% to 10% and is commonly replaced by chlorite.

Epidote is also widespread as a secondary mineral, and is found filling veinlets in the Ibagué Batholith (CB0011). Accessory minerals include zircon and opaque with limited contents of titanite.

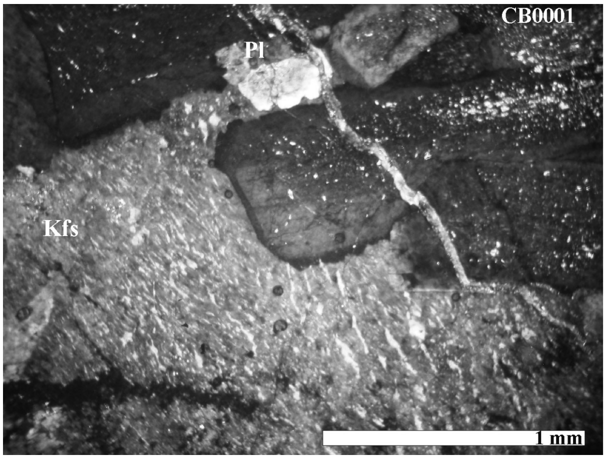

FIGURE 3a. Braided pattern due to albite lamellae in K-feldspar. Kfs: K-feldspar; Pl: Plagioclase.

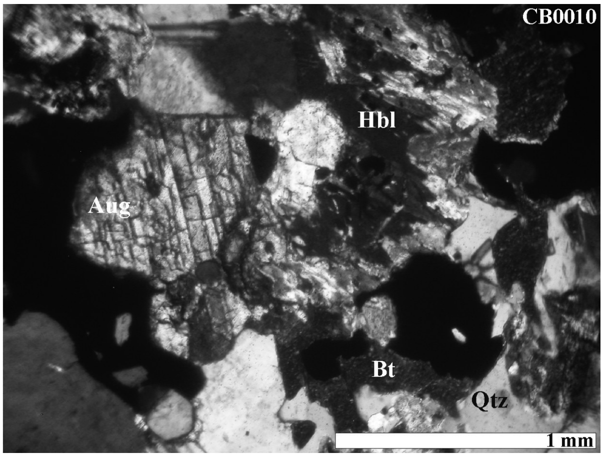

FIGURE 3b. Anhedral augite crystal surrounded by hornblende, biotite and quartz. Aug: Augite; Qtz; Quartz; Bt: Biotite; Hbl: Hornblende.

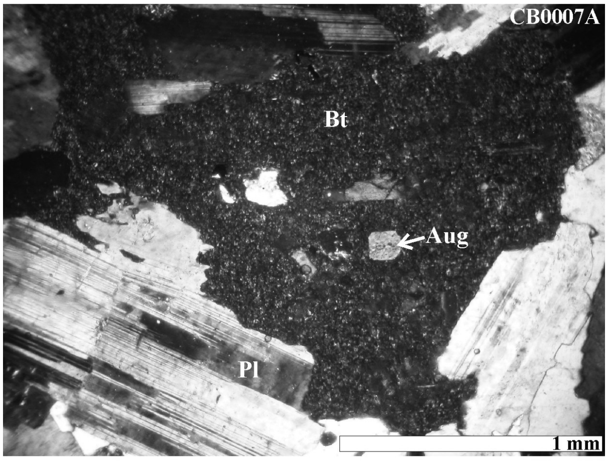

FIGURE 3c. Augite and plagioclase inclusions into a biotite crystal. Aug: Augite; Bt: Biotite; Pl: Plagioclase.

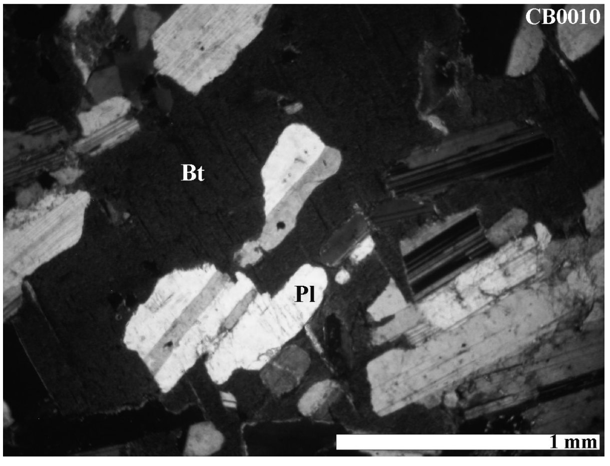

FIGURE 3d. Poikilitic textures were large plagioclase crystals are enclosed in biotite. Bt: Biotite; Pl: Plagioclase.

GEOCHRONOLOGY

Analytical results are included in Table 1. U-Pb LA-ICP-MS zircon ages were obtained in the Garzón Granite (CB0001), Altamira Monzogranite (CB0005), Las Minas Monzodiorite (CB0007A) and the southern segment of the Ibagué Batholith (CB0010).

The Garzón Granite and the Altamira Monzogranite represents the eastern segment yield ages from ca. 179 to 174 Ma (Figures 4a, 4b). Intrusive rocks located at the westernmost part of the profile are the Las Minas Monzodiorite and the Ibagué Batholith, and present ages at least 10 Ma older. These ages ranges from ca. 189 to 187 Ma (Figures 4c, 4d). All these ages are related to the zircon forming event which is a major record of the magmatic crystallization of the plutonic rocks.

TABLE 1. Analytical results of the U-Pb LA-ICP-MS zircon geochronology.

	Isotope ratios						Apparent ages (Ma)							
Analysis	**^{206}Pb/ ^{207}Pb**	**± (%)**	**^{207}Pb/ ^{235}U**	**± (%)**	**^{206}Pb/ ^{238}U**	**± (%)**	**^{206}Pb/ ^{238}U**	**± (Ma)**	**^{207}Pb/ ^{235}U**	**± (Ma)**	**^{206}Pb/ ^{207}Pb**	**± (Ma)**	**Best age (Ma)**	**± (Ma)**
							Altamira CB0005							
1	20,2	3,6	0,2	3,7	0,0	1,0	178,2	1,7	178,0	6,1	175,5	84,1	178,2	1,7
2	19,9	2,5	0,2	2,7	0,0	0,9	176,0	1,5	177,7	4,3	201,0	58,4	176,0	1,5
3	21,0	8,5	0,2	8,5	0,0	0,5	178,9	0,9	172,4	13,4	83,0	201,1	178,9	0,9
4	20,0	5,1	0,2	5,3	0,0	1,5	177,3	2,6	178,5	8,7	195,3	118,3	177,3	2,6
5	21,2	8,8	0,2	8,8	0,0	0,9	174,6	1,6	166,9	13,6	58,8	209,1	174,6	1,6
6	20,4	10,0	0,2	10,1	0,0	1,7	175,3	2,9	173,1	16,1	143,6	235,2	175,3	2,9
7	19,9	2,0	0,2	2,0	0,0	0,6	180,1	1,0	182,2	3,4	209,4	45,6	180,1	1,0
8	19,7	3,6	0,2	6,1	0,0	5,0	173,6	8,5	177,3	10,0	227,6	83,3	173,6	8,5
9	20,4	5,6	0,2	5,7	0,0	1,1	181,1	2,0	179,2	9,4	154,2	131,0	181,1	2,0
10	20,4	4,7	0,2	5,7	0,0	3,2	177,9	5,6	176,2	9,2	154,3	110,4	177,9	5,6
11	18,9	10,8	0,2	10,9	0,0	1,7	176,8	3,0	187,7	18,7	326,5	244,8	176,8	3,0
12	14,7	29,9	0,3	30,1	0,0	3,5	181,7	6,3	240,8	64,7	865,1	634,2	181,7	6,3
13	20,5	4,8	0,2	5,0	0,0	1,0	176,5	1,8	173,5	7,9	133,1	113,9	176,5	1,8
14	19,9	6,5	0,2	6,5	0,0	0,9	178,3	1,5	180,0	10,8	201,2	150,8	178,3	1,5
15	19,7	5,1	0,2	5,5	0,0	2,2	178,0	3,8	181,7	9,2	230,0	117,8	178,0	3,8
16	21,6	10,2	0,2	10,3	0,0	0,7	181,6	1,3	169,8	16,1	7,8	247,1	181,6	1,3
17	20,1	5,6	0,2	5,7	0,0	1,0	177,0	1,7	177,3	9,3	181,9	131,4	177,0	1,7
18	20,6	6,3	0,2	6,5	0,0	1,5	177,9	2,5	174,0	10,4	120,3	149,7	177,9	2,5
19	20,9	16,6	0,2	16,6	0,0	1,0	179,8	1,7	173,5	26,5	89,4	394,7	179,8	1,7
20	20,2	5,5	0,2	5,5	0,0	0,8	177,8	1,4	177,2	9,0	168,9	127,5	177,8	1,4
21	20,4	4,2	0,2	4,3	0,0	1,0	176,8	1,7	174,8	6,9	148,9	97,6	176,8	1,7
22	20,2	4,2	0,2	4,4	0,0	1,5	178,2	2,5	178,1	7,2	176,6	97,5	178,2	2,5
23	20,6	9,6	0,2	9,7	0,0	1,5	177,9	2,6	174,3	15,6	125,8	227,0	177,9	2,6
24	20,3	4,0	0,2	4,0	0,0	0,7	180,0	1,3	178,4	6,6	157,6	92,6	180,0	1,3
25	20,2	4,8	0,2	4,8	0,0	0,8	177,4	1,3	176,6	7,8	166,5	111,6	177,4	1,3
26	20,1	3,9	0,2	3,9	0,0	0,6	179,0	1,1	179,2	6,5	181,2	90,8	179,0	1,1
27	20,6	6,3	0,2	6,3	0,0	0,5	178,2	0,9	174,7	10,1	127,7	147,8	178,2	0,9
28	20,2	7,6	0,2	7,6	0,0	0,5	181,2	0,9	180,7	12,6	173,0	177,8	181,2	0,9
29	20,8	6,5	0,2	6,6	0,0	1,1	178,9	1,9	173,4	10,6	99,7	154,9	178,9	1,9
30	20,8	7,6	0,2	7,7	0,0	1,2	179,8	2,1	174,3	12,4	100,6	180,4	179,8	2,1
31	20,5	5,2	0,2	5,2	0,0	0,5	179,9	0,9	176,8	8,4	135,4	121,7	179,9	0,9
32	20,3	3,1	0,2	3,2	0,0	0,7	179,6	1,2	178,0	5,2	157,1	73,4	179,6	1,2
33	20,7	4,2	0,2	4,3	0,0	1,1	180,9	1,9	176,6	7,0	119,1	98,5	180,9	1,9
34	20,2	4,3	0,2	4,5	0,0	1,3	178,2	2,2	177,5	7,4	168,0	101,2	178,2	2,2
35	16,7	13,8	0,2	13,9	0,0	1,7	178,4	3,0	211,9	26,5	603,1	299,1	178,4	3,0
36	20,8	6,9	0,2	7,2	0,0	2,0	178,5	3,5	173,0	11,5	98,6	164,6	178,5	3,5

37	20,1	3,9	0,2	4,0	0,0	0,5	178,6	0,9	179,1	6,5	186,1	91,9	178,6	0,9
38	18,7	5,0	0,2	5,1	0,0	1,2	178,7	2,2	191,6	8,9	353,1	112,2	178,7	2,2
39	20,0	3,6	0,2	3,8	0,0	1,1	178,7	1,9	180,0	6,3	196,9	84,7	178,7	1,9
40	19,8	7,1	0,2	7,1	0,0	0,5	178,1	0,9	181,0	11,9	218,6	165,2	178,1	0,9
41	19,0	6,2	0,2	6,3	0,0	1,1	180,1	2,0	189,5	11,0	307,9	142,1	180,1	2,0
42	20,0	4,0	0,2	4,0	0,0	0,5	178,2	0,9	179,2	6,6	191,8	92,2	178,2	0,9
43	19,5	3,5	0,2	4,6	0,0	2,9	179,2	5,1	184,6	7,7	253,8	81,3	179,2	5,1
44	20,0	6,3	0,2	6,3	0,0	0,5	180,1	0,9	181,3	10,4	196,5	145,9	180,1	0,9
45	20,4	6,4	0,2	6,4	0,0	0,7	179,7	1,2	177,8	10,5	152,8	149,5	179,7	1,2
46	20,9	6,4	0,2	6,4	0,0	0,6	178,0	1,1	172,2	10,2	92,8	151,7	178,0	1,1
47	19,1	11,6	0,2	11,6	0,0	1,1	182,1	2,0	190,5	20,2	296,1	264,8	182,1	2,0
48	20,4	3,6	0,2	4,4	0,0	2,6	178,8	4,5	176,8	7,1	149,9	83,3	178,8	4,5
49	19,9	1,8	0,2	2,0	0,0	1,0	180,5	1,7	182,3	3,3	205,3	40,9	180,5	1,7
50	20,5	5,6	0,2	5,6	0,0	0,5	179,6	0,9	176,4	9,1	132,7	131,8	179,6	0,9
Las Minas CB0007A														
1	21,8	13,6	0,2	13,7	0,0	1,3	188,2	2,5	174,2	21,9	-12,9	330,8	188,2	2,5
2	14,1	4,6	0,3	4,8	0,0	1,7	189,5	3,1	260,4	11,1	959,2	93,2	189,5	3,1
3	20,1	5,0	0,2	5,1	0,0	0,6	188,1	1,0	187,4	8,7	177,8	117,5	188,1	1,0
4	19,9	3,7	0,2	3,8	0,0	0,9	186,3	1,6	187,9	6,6	208,0	86,9	186,3	1,6
5	21,5	15,9	0,2	15,9	0,0	0,7	185,8	1,3	174,9	25,5	29,8	382,4	185,8	1,3
6	21,6	13,2	0,2	13,3	0,0	1,9	188,7	3,6	176,5	21,6	16,4	318,2	188,7	3,6
7	20,3	10,4	0,2	10,4	0,0	0,5	187,0	0,9	184,9	17,6	157,9	243,4	187,0	0,9
8	20,5	6,5	0,2	6,5	0,0	0,8	188,0	1,4	184,0	11,0	132,3	152,9	188,0	1,4
9	22,0	14,9	0,2	14,9	0,0	0,5	186,7	0,9	171,5	23,6	-33,3	363,5	186,7	0,9
10	22,0	13,5	0,2	13,6	0,0	1,1	186,4	2,1	171,6	21,5	-28,9	329,6	186,4	2,1
11	20,8	9,0	0,2	9,1	0,0	0,6	186,9	1,1	181,0	15,0	105,0	213,9	186,9	1,1
12	20,7	8,6	0,2	8,6	0,0	0,5	187,7	0,9	182,5	14,3	116,2	202,1	187,7	0,9
13	20,6	11,9	0,2	12,0	0,0	1,9	189,4	3,5	185,1	20,3	130,6	280,2	189,4	3,5
14	21,1	16,8	0,2	16,8	0,0	0,5	187,1	0,9	178,5	27,5	66,1	402,1	187,1	0,9
15	21,1	18,8	0,2	18,8	0,0	1,3	186,1	2,3	177,8	30,7	69,1	450,5	186,1	2,3
16	20,7	8,9	0,2	9,0	0,0	1,4	186,6	2,6	181,3	14,9	113,2	209,5	186,6	2,6
17	15,8	6,0	0,3	6,2	0,0	1,7	187,2	3,1	232,3	12,9	717,1	127,0	187,2	3,1
18	21,0	11,2	0,2	11,3	0,0	1,3	188,5	2,4	181,0	18,7	83,1	267,1	188,5	2,4
19	20,8	10,7	0,2	10,7	0,0	1,2	184,8	2,1	178,6	17,6	97,9	252,7	184,8	2,1
20	14,3	12,4	0,3	12,4	0,0	0,6	188,0	1,0	254,7	28,0	924,4	255,8	188,0	1,0
21	21,5	13,0	0,2	13,1	0,0	1,9	186,2	3,5	175,2	21,1	28,0	312,9	186,2	3,5
22	19,2	9,3	0,2	9,4	0,0	1,5	185,2	2,6	192,9	16,6	288,4	213,3	185,2	2,6
23	20,0	4,2	0,2	4,5	0,0	1,6	185,0	3,0	185,8	7,7	196,0	98,4	185,0	3,0
24	23,3	22,5	0,2	22,5	0,0	0,7	183,5	1,3	160,4	33,3	-168,9	565,2	183,5	1,3
25	18,2	23,2	0,2	23,2	0,0	0,9	189,3	1,7	206,9	43,5	412,4	525,3	189,3	1,7
26	20,1	3,9	0,2	4,0	0,0	1,0	187,7	1,8	187,0	6,8	179,0	89,8	187,7	1,8
27	21,5	13,0	0,2	13,0	0,0	1,0	189,6	1,9	178,0	21,2	25,6	312,3	189,6	1,9
28	20,6	7,2	0,2	7,3	0,0	1,1	185,4	2,0	181,5	12,1	130,2	169,5	185,4	2,0
29	20,4	7,8	0,2	7,9	0,0	1,1	184,4	1,9	182,1	13,2	152,8	183,4	184,4	1,9
30	21,2	13,5	0,2	13,6	0,0	1,1	187,9	2,1	178,6	22,2	57,0	324,0	187,9	2,1
31	19,2	2,3	0,2	2,6	0,0	1,2	184,0	2,2	192,2	4,5	294,0	51,8	184,0	2,2
32	20,9	10,6	0,2	10,6	0,0	0,5	188,8	0,9	181,6	17,7	89,7	251,9	188,8	0,9
33	21,8	16,5	0,2	16,6	0,0	1,3	187,3	2,3	174,0	26,5	-4,3	400,4	187,3	2,3
34	17,5	6,4	0,2	6,5	0,0	1,1	186,7	2,1	211,1	12,3	492,8	140,8	186,7	2,1

35	20,1	6,3	0,2	6,3	0,0	0,7	186,3	1,3	186,5	10,7	188,4	145,7	186,3	1,3
36	20,5	7,6	0,2	7,6	0,0	0,5	193,4	1,0	189,0	13,2	135,0	179,4	193,4	1,0
37	20,8	10,5	0,2	10,6	0,0	1,8	188,2	3,3	181,9	17,7	101,7	247,9	188,2	3,3
38	19,1	3,8	0,2	4,0	0,0	1,3	187,9	2,4	196,2	7,2	297,0	87,3	187,9	2,4
39	21,6	11,7	0,2	11,8	0,0	1,2	187,7	2,1	175,6	19,0	15,9	282,2	187,7	2,1
40	15,7	21,2	0,3	21,4	0,0	2,6	187,4	4,8	234,3	44,7	735,7	453,9	187,4	4,8
41	21,2	11,6	0,2	11,7	0,0	1,0	187,2	1,8	177,7	19,0	53,6	278,5	187,2	1,8
42	21,0	10,4	0,2	10,5	0,0	1,7	190,1	3,2	182,0	17,6	77,3	247,8	190,1	3,2
43	23,4	22,8	0,2	22,8	0,0	1,3	185,4	2,4	160,9	34,0	-186,8	575,7	185,4	2,4
44	20,0	8,9	0,2	8,9	0,0	0,9	187,6	1,6	188,1	15,3	194,8	206,7	187,6	1,6
45	21,4	11,8	0,2	11,9	0,0	1,3	187,3	2,4	176,9	19,3	40,6	283,9	187,3	2,4
46	20,8	10,8	0,2	10,8	0,0	0,7	186,0	1,2	179,9	17,8	100,3	255,1	186,0	1,2
47	20,5	11,5	0,2	11,5	0,0	0,8	190,0	1,4	186,0	19,5	136,1	269,8	190,0	1,4
48	20,6	8,6	0,2	8,6	0,0	0,6	188,7	1,1	184,4	14,5	129,4	201,7	188,7	1,1
49	21,1	15,6	0,2	15,7	0,0	0,6	188,0	1,1	179,2	25,7	65,3	374,4	188,0	1,1
							Ibagué CB0010							
1	20,7	5,1	0,2	5,4	0,03	1,7	187,6	3,1	182,1	9,0	111,3	121,6	187,6	3,1
2	21,8	10,0	0,2	10,1	0,03	2,0	189,3	3,6	175,3	16,3	-8,9	240,8	189,3	3,6
3	20,1	13,8	0,2	13,8	0,03	1,3	189,3	2,4	188,8	23,8	182,8	322,0	189,3	2,4
4	20,4	4,4	0,2	4,5	0,03	0,8	189,7	1,6	186,9	7,7	151,8	103,3	189,7	1,6
5	19,8	12,4	0,2	12,4	0,03	0,7	191,0	1,2	192,8	21,8	215,2	288,3	191,0	1,2
6	20,3	7,9	0,2	8,0	0,03	1,1	188,2	1,9	186,5	13,6	165,6	185,5	188,2	1,9
7	20,4	4,7	0,2	5,1	0,03	2,0	188,1	3,7	185,4	8,7	150,2	111,1	188,1	3,7
8	22,0	10,8	0,2	10,9	0,03	1,1	188,5	2,0	173,3	17,4	-29,5	263,5	188,5	2,0
9	20,9	5,4	0,2	5,4	0,03	0,7	190,9	1,3	184,0	9,2	96,3	127,9	190,9	1,3
10	20,3	2,9	0,2	2,9	0,03	0,7	189,8	1,3	187,5	5,0	159,7	67,1	189,8	1,3
11	20,5	5,0	0,2	5,1	0,03	0,6	189,1	1,1	185,1	8,6	134,0	118,5	189,1	1,1
12	20,4	10,8	0,2	11,0	0,03	2,3	187,8	4,2	184,7	18,6	145,2	254,0	187,8	4,2
13	20,9	6,6	0,2	7,0	0,03	2,3	187,9	4,2	180,8	11,6	88,4	157,1	187,9	4,2
14	21,8	9,6	0,2	9,7	0,03	1,2	191,1	2,3	177,0	15,8	-8,7	233,3	191,1	2,3
15	20,9	6,4	0,2	6,5	0,03	0,7	189,1	1,4	182,1	10,8	91,5	152,1	189,1	1,4
16	20,1	4,9	0,2	5,0	0,03	0,8	188,0	1,5	187,5	8,6	181,3	115,3	188,0	1,5
17	20,1	3,9	0,2	4,3	0,03	1,7	192,3	3,1	192,1	7,5	188,5	91,6	192,3	3,1
18	22,7	13,5	0,2	13,6	0,03	1,3	189,6	2,4	169,0	21,2	-111,3	334,5	189,6	2,4
19	21,3	9,4	0,2	9,4	0,03	0,7	189,0	1,2	178,5	15,4	41,9	224,8	189,0	1,2
20	19,9	4,9	0,2	4,9	0,03	0,6	187,2	1,0	188,9	8,4	210,9	112,7	187,2	1,0
21	19,9	19,3	0,2	19,4	0,03	1,5	186,8	2,8	187,9	33,3	201,6	452,5	186,8	2,8
							Garzón CB0001*							
25	19,0	0,006	0,2	0,5	0,03	0,001	167,0	4,0	176,8	4,2	310,4	14,0	167,0	4,0
22	20,5	0,009	0,2	0,5	0,03	0,001	176,1	4,1	173,4	4,2	136,5	20,7	176,1	4,1
21	20,3	0,007	0,2	0,5	0,03	0,001	177,5	4,2	176,6	4,1	164,2	15,6	177,5	4,2
20	20,4	0,010	0,2	0,5	0,03	0,001	171,8	4,0	170,1	4,3	146,5	23,8	171,8	4,0
19	14,9	0,008	0,3	0,8	0,03	0,001	207,6	4,8	268,7	6,0	842,3	15,6	207,6	4,8
18	20,3	0,008	0,2	0,5	0,03	0,001	170,4	3,9	169,6	4,0	158,4	18,0	170,4	3,9
17	20,2	0,009	0,2	0,5	0,03	0,001	167,8	4,0	168,1	4,2	171,3	21,6	167,8	4,0
16	20,0	0,010	0,2	0,5	0,03	0,001	165,3	4,0	167,5	4,3	198,4	23,4	165,3	4,0
15	19,8	0,006	0,2	0,5	0,03	0,001	168,3	4,0	171,9	4,1	221,1	14,6	168,3	4,0
14	20,2	0,007	0,2	0,5	0,03	0,001	176,6	4,2	175,9	4,1	166,1	15,3	176,6	4,2
13	20,0	0,007	0,2	0,5	0,03	0,001	174,9	4,1	176,6	4,1	200,1	15,7	174,9	4,1

12	18,0	0,012	0,2	0,6	0,03	0,001	174,5	4,3	193,2	5,1	428,7	25,9	174,5	4,3
11	16,3	0,015	0,2	0,8	0,03	0,001	166,7	4,6	203,8	6,2	658,0	30,8	166,7	4,6
10	19,5	0,007	0,2	0,5	0,03	0,001	167,1	3,9	172,8	4,1	250,8	16,7	167,1	3,9
9	18,7	0,008	0,2	0,5	0,03	0,001	176,0	4,2	188,3	4,6	346,0	18,1	176,0	4,2
8	20,2	0,009	0,2	0,5	0,03	0,001	170,7	4,0	170,6	4,2	169,5	21,7	170,7	4,0
7	20,0	0,008	0,2	0,5	0,03	0,001	169,4	4,0	171,0	4,2	193,4	19,5	169,4	4,0
6	19,5	0,006	0,2	0,5	0,03	0,001	174,8	4,1	180,1	4,2	250,5	14,8	174,8	4,1
5	18,0	0,015	0,2	0,7	0,03	0,001	176,3	4,3	196,0	5,6	439,4	33,1	176,3	4,3
4	20,6	0,010	0,2	0,5	0,03	0,001	174,9	4,2	171,4	4,3	123,5	22,3	174,9	4,2
1	17,5	0,008	0,2	0,6	0,03	0,001	177,8	4,2	202,5	4,8	501,9	18,1	177,8	4,2

*** Isotope ratios errors with 1δ (absolute error)**

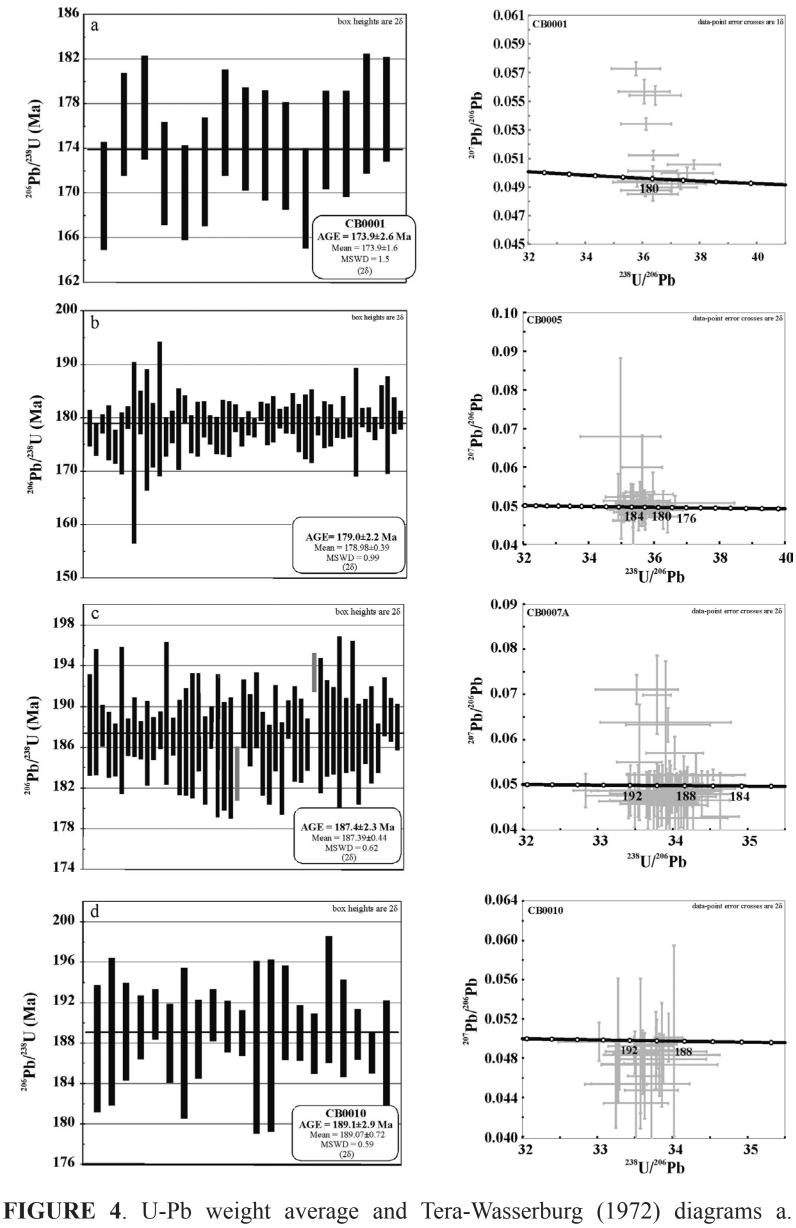

FIGURE 4. U-Pb weight average and Tera-Wasserburg (1972) diagrams a. Garzón Granite; b. Altamira Monzogranite; c. Las Minas Monzodiorite; d. Ibagué Batholith.

GEOCHEMISTRY

Four samples were selected for reconnaissance major and trace element geochemistry. Analytical procedures and results are presented in the Appendix and in Table 2. Samples have SiO_2 values between 56.58 to 63.54%, whereas Na_2O, K_2O and Al_2O_3values range between 3.71 and 4.73%, 1.71 and 3.91% and 15.63 to 18.7% respectively. MgO values are between 1.88% and 3.47% whereas Fe_2O_3 between 5.03 and 7.58%, and Mg# from 42.54 to 47.56.

Within the SiO_2 versus $Na_2O + K_2O$ (TAS) diagram after Cox *et al*. (1979), three samples are classified as diorites. In contrast sample CB0005 from the Altamira Monzogranite has a more acid trend and is classified as granodiorite (Figure 5a). Similar compositional characteristics are seen in the Winchester and Floyd (1977) diagram which classified volcanic rocks based on immobile elements rations such as Nb/Y versus Zr/Ti (Figure 5b).

The A/CNK vs. A/NK plot of (Shand, 1943) show a clear metaluminous character for all the samples and only a slightly peraluminous trend for the sample CB0011 from the Ibagué Batholith (Figure 5c) that can be related to the higher biotite content.

Within the alkaline series diagram after Peccerillo and Taylor (1976) the analyzed rocks have a west to east trend of K_2O enrichment. With the western Ibagué Batholith characterized by a middle K series signature and the Las Minas Monzodiorite and Altamira Granite showing affinity with the high K series trend (Figure 5d), near the Shoshonite series field.

REE patterns normalized to chondrite after Nakamura (1974) show enrichment in Light Rare Earth Elements (LREE) when compared with Heavy Rare Earth Elements (HREE) with $(La/Yb)_N$ ranging between 7.09 and 16.23 (Figure 5e). Eu anomaly present a negative to slightly positive pattern with Eu/Eu* relation between 0.83 and 1.03.

Multielements patterns normalized against primitive mantle according with Sun and McDonough (1989), show enrichment in K, Rb and Sr, and a well defined Nb, P and Ti negative anomaly (Figure 5f).

Within tectonic discrimination diagram after Pearce *et al*. (1984) all the samples has a volcanic arc affinity (Figure 5g). Similarly within the Hf - Rb/30 - Ta*3 discrimination diagram for granites after Harris *et al*. (1986), the analyzed samples plot in the volcanic arc setting (Figure 5h).

TABLE 2. Geochemical results. Major elements (wt%), minor and trace elements (ppm)

Sample	CB0005	CB0007A	CB0010	CB0011
SiO_2	63,5	58,1	56,6	57,1
Al_2O_3	15,6	17,2	17,8	18,7
Fe_2O_3	5,0	7,4	7,6	6,5
MnO	0,1	0,1	0,1	0,1
MgO	1,9	3,0	3,5	2,5
CaO	3,8	6,0	6,5	4,7
Na_2O	3,7	3,7	4,1	4,9
K_2O	3,9	2,2	1,7	1,9
P_2O_5	0,2	0,3	0,3	0,4
TiO_2	0,6	0,9	0,9	0,8
LOI	1,3	0,8	0,7	2,0
TOTAL	99,8	99,6	99,7	99,7
Ba	943,0	780,0	675,0	770,0
Ga	17,9	17,7	18,7	22,5
Nb	18,0	6,0	5,6	8,8
Rb	105,6	48,6	56,2	60,7
Sc	8,0	17,0	18,0	8,0
Sr	664,8	609,8	637,2	1043,0
V	90,0	150,0	147,0	106,0
Y	21,7	21,3	17,2	13,2
Zr	216,1	120,6	126,0	166,9
La	54,3	21,8	19,7	24,6
Ce	98,1	45,7	41,1	51,1
Pr	10,5	5,7	5,1	6,1
Nd	38,0	23,2	22,4	25,8
Sm	5,9	4,6	4,2	4,5
Eu	1,4	1,3	1,2	1,4
Gd	4,8	4,3	3,8	3,6
Tb	0,7	0,7	0,6	0,5
Dy	3,7	3,7	3,1	2,6
Ho	0,8	0,8	0,6	0,5
Er	2,2	2,1	1,8	1,2
Tm	0,4	0,3	0,3	0,2
Yb	2,2	2,1	1,8	1,2
Lu	0,4	0,3	0,3	0,2
Hf	5,9	3,5	3,4	4,3
Pb	3,9	2,5	1,3	2,8
Th	14,5	2,7	13,1	4,1
U	4,1	0,7	2,1	1,9
Cs	0,8	0,7	3,0	1,2
Ta	1,1	0,4	0,3	0,4

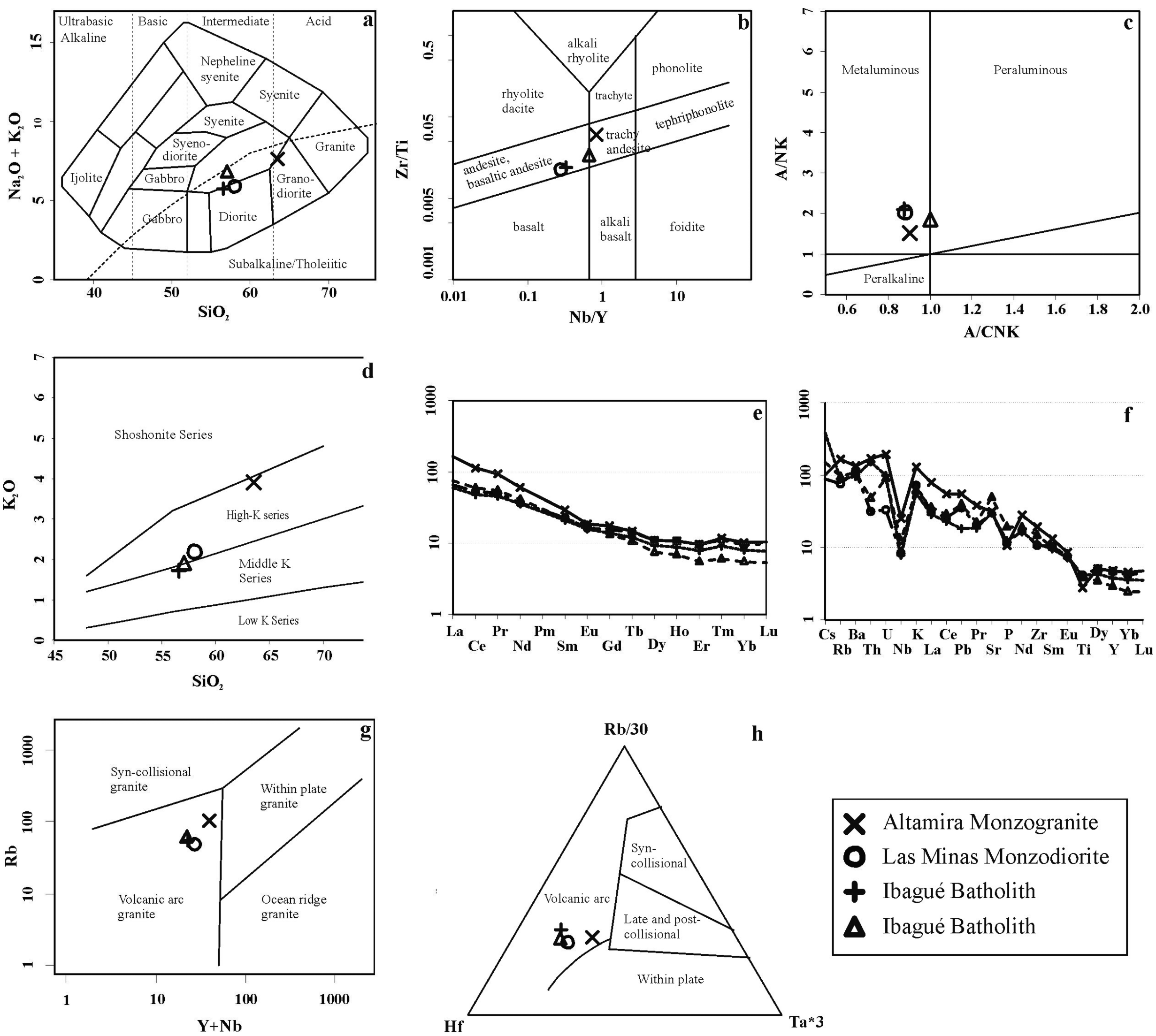

FIGURE 5. a. SiO2 vs. Na2O + K2O (TAS) diagram after Cox et al. (1979); b. Nb/Y vs. Zr/Ti diagram of Winchester and Floyd (1977); c. A/CNK vs. A/NK plot of Shand (1943); d. Alkaline series diagram of Peccerillo and Taylor (1976) e. REE patterns normalized to chondrite after Nakamura (1974); f. Multielements pattern normalized with primitive mantle according with Sun and McDonough (1989); g. Tectonic discrimination diagram after Pearce et al. (1984), h. Hf - Rb/30 - Ta*3 discrimination diagram for granites after Harris et al. (1986).

DISCUSSION

Geochronological results have shown the existence of a Middle Jurassic plutonic record, with the western plutons (Ibagué Batholith and Las Minas Monzodiorite) formed by ca. 189-187 Ma and those at the eastern at ca. 180-173 Ma crystallization ages recorded in the Garzón Granite and the Altamira Monzogranite. The similarity and overlapping in the U-Pb crystallization ages for the Las Minas and Ibagué plutons suggest that they are probably a genetically related plutonic event.

Reconnaissance geochemistry has also shown that the four granitic bodies of southern Colombia share a similar tectonic setting. The ubiquitous presence of hornblende and biotite in these granitoids is characteristic of wet melting within subduction related setting (Ernst, 1999). Both trace element patterns which well defined Nb and Ti anomalies and enrichment in large ion lithopile elements such as K, Rb, Ba, Th and C, together with tectonic discrimination diagrams show characteristic of a continental volcanic arc tectonic setting (Pearce *et al*., 1984, Harris *et al*., 1986; Rollinson, 1993). The west to east variations seen in the alkaline series diagram (Peccerilo and Taylor, 1974) is also a major characteristic of continental arcs, where the more inboard magmatic focus will record a higher alkalinity due either to more extensive crustal assimilation or lesser proportions of melting (Tatsumi and Eggins, 1995).

Two different tectonic models have been proposed for the Early to Middle Mesozoic tectonics of Northwestern South America including Colombia: (1) intracontinental rifting related to the break-up of Pangea (Pindell and Dewey, 1982; Ross and Scotese, 1988; Cediel *et al*., 2003) or (2) arc and back-arc subduction setting (Maze, 1984; McCourt *et al*., 1984; Aspden *et al*., 1987; Pindell and Erikson, 1993; Toussaint, 1995; Pindell and Tabutt, 1995; Meschede and Frisch, 1998; Vásquez *et al*., 2006). Whereas the former model have arise from considerations derived from a basin perspective (reviews Cediel *et al*., 2003; Sarmiento-Rojas *et al*., 2006), the later considered the spatial and particularly broader distribution of the Jurassic magmatic rocks (Maze, 1984; McCourt *et al*., 1984; Pindell and Erikson, 1993; Bayona *et al*., 1994; Toussaint, 1995; Vásquez *et al*., 2006). A more conciliated tectonic model have also suggested that a subduction related tectonic margin may applied from the displaced Jurassic terranes that were formed farther south, a rift related environment is probably characteristic of the authoctonous elements of the margin which are located to the east (Bayona *et al*., 2006; Sarmiento-Rojas *et al*., 2006).

Paucity of geochronological and geochemical data on the magmatic rocks have difficult appropriate test to this models (Vásquez *et al*., 2006). The reconnaissance geochemical and geochronological results presented here suggest that the Jurassic domains in southern Colombia are related with a Jurassic active continental margin and the built of a continental arc.

Although paleomagnetic data is missing; regional paleogeographic reconstructions have suggested that the Garzón Massif is an autochthonous crustal segment of the western margin of South America since at least the Late Mesoproterozoic (Kroonemberg, 1982; Toussaint, 1993; Restrepo-Pace *et al*., 1997; Cordani *et al*., 2005; Ordóñez-Carmona *et al*., 2006). Therefore within this framework the data presented here suggest that southern Colombian margin was part of a Middle Jurassic active continental margin.

Although paleomagnetic data from the upper Magdalena Valley have suggested that the crustal domain were the western granitoids are emplaced, was formed farther south (Bayona, *et al*., 2006), these granitoids together with other allocthonous magmatic remnants formed between 190-172 Ma and widespread along the Colombian margin (reviews in Aspden *et al*., 1987) are also part of the broader active margin formed along western South America during the Jurassic (Jaillard *et al*., 2000; Kramer *et al*., 2005; Oliveros *et al*., 2006; 2007; Hervé *et al*., 2007; Mpodozis and Ramos, 2008).

CONCLUSIONS

The new U-Pb and whole rock geochemical data from plutonic rock reveals the existence of remnants of Middle Jurassic arc related magmatism in Southern Colombia. When these domains are placed within tectonic models for the northern Andes, a picture of an active continental margin is envisioned at least for southern Colombia and for the westernmost Jurassic domains in the Central Cordillera. Within this margin several domains were translated to the north during the Cretaceous, probably as a consequence of the oblique configuration of the margin (Bayona *et al*., 2006, 2010), yielding the apparent juxtaposition of similar and unrelated magmatic arc domains.

More paleomagnetic data and additional geochronological and geochemical constrains from the Jurassic magmatic and sedimentary rocks in the main Andes and the adjacent cratonic region will allow to further understand the tectonic and evolving paleogeography of the Jurassic in the northern Andes and the probable north to south variation of tectonic styles in the margin.

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