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Early Paleogene magmatism in the northern Andes: Insights on the effects of Oceanic Plateau–continent convergence

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ABSTRACT

Recognition of magmatic events in polyphase arc–continent collision margin is critical for proper tectonic reconstructions that trace the short and changing nature of the configuration of the continental margin. Additionally, the recognition of the origin of detrital volcanic zircons within continental basins becomes a challenge if only distant oceanic and continental magmatic arcs are considered as the only possible source. In this study we report U/Pb zircon ages in isolated plutons that support an early Paleogene magmatic arc that extended ca 700 km along the northern Andean continental margin. Additional detrital zircon Paleogene ages (45–65 Ma), from Paleocene–lower Eocene continental sandstones and volcaniclastic rocks in 19 localities from Colombian and Venezuela Andean basins, indicate that volcanic detritus were supplied from a magmatic arc striking parallel to the subduction zone and also show the existence of intraplate magmatism extending more than 400 km inland.

The wide distribution of this Early Paleogene magmatism along the northern South America margin is related to subduction of the buoyant Caribbean plate; the relative short period of magmatism (<10 myr) and sudden stop in early middle Eocene time may be related to the difficulty of the thick plateau to subduct and the relative strike–slip movement of the South America and Caribbean plates since middle Eocene due to northward migration of those plates.

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1. Introduction

Identifying short periods of magmatic activity in long-term orogens is a difficult task because their signature is often dilute and barely detectable (Garzanti et al., 2007). This magmatism, however, is very important for a proper reconstruction of the short duration of arc-continent collisions (Dewey, 2005) and the evolution of accretionary orogens, which may experience multiple variations in the subduction parameters during short time intervals (Cawood et al., 2009). Volcanic zircons within a synorogenic succession is a powerful tool for tracking hidden magmatic events, improving stratigraphic correlation and tracing details on the tectonic evolution of convergent margins that may be hidden by erosion or over-imposed tectonic events (Garzanti et al., 2007; Malusà et al., 2011). This approach

* Corresponding author. E-mail address: gbayona@cgares.org (G. Bayona). links zircons accumulated in sedimentary sequences adjacent to the orogen with magmatic activity within the orogen itself (e.g., DeCelles et al., 2007; Dickinson and Gehrels, 2009; Fedo et al., 2003; Nelson, 2001).

The northern Andes is the result of complex processes of collision among continental plate margin, oceanic arcs, and the buoyant plateau-like Caribbean plate with its associated oceanic arcs (e.g., Cediel et al., 2003; Cooper et al., 1995; Kennan and Pindell, 2009; Kerr and Tarney, 2005; Kerr et al., 1997; Pindell and Kennan, 2009; Taboada et al., 2000). This long-term process of collision and subduction produced several phases of magmatism and deformation affecting both the margin (e.g., Cardona et al., 2011; Villagómez et al., 2011) and intraplate settings (e.g., Bayona et al., 2011; Cortés et al., 2005, 2006; Taboada et al., 2000). Discriminating the timing and spatial distribution of the different tectono-magmatic episodes of northern Andes evolution is critical to a proper understanding of the upper plate effects of oceanic—continent collisions and the faith on the subduction of oceanic plateaus (Cloos, 1993; Gutscher et al., 2000; Mann and Taira, 2004; Van Hunen et al., 2004).

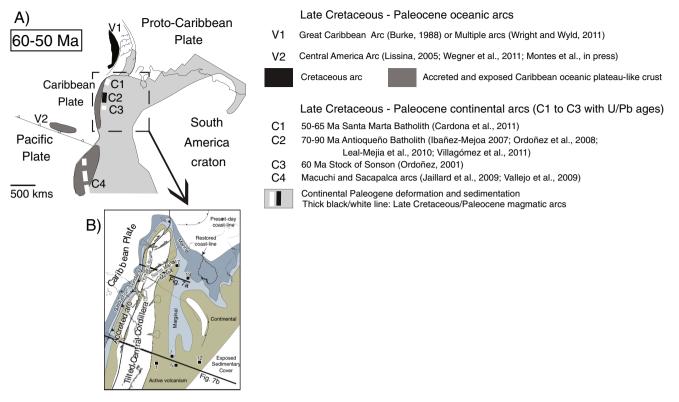


Fig. 1. A: Regional tectonic setting for Paleocene time (modified after Cardona et al., 2011) showing the location of late Cretaceous–Paleocene oceanic and continental magmatic arcs described in the literature. Antioqueño batholith, a Late Cretaceous magmatic arc, is shown for reference. B: Location of proposed emerge areas and depositional systems for Paleocene time (modified after Bayona et al., 2008; Pindell et al., 2005).

Recently reported detrital zircons ages in Paleocene successions of the northern Andes (Cardona et al., 2011; Saylor et al., 2011) and Paleocene volcanic rocks in intraplate settings (Bayona et al., 2010, 2011; Jaramillo et al., 2010) might have two possible sources (Fig. 1; see geological settings for details). One possible source is a continental magmatic arc that has been only detected punctually in the northernmost segment of the Andes and farther south in the Ecuador Andes (Macuchi and Sacapalca arcs; Jaillard et al., 2009; Vallejo et al., 2009) (Fig. 1). The other possible source of volcanic fragments is from oceanic arcs that developed in the trailing and leading edges of the Caribbean oceanic plate (Fig. 1). This study presents new constraints on the spatial and temporal extensions of Paleogene plutonic rocks along the continental margin of the northern Andes and the spatial and temporal records of detrital volcanic zircons in the Paleocene-middle Eocene synorogenic clastic wedge. The temporal and spatial distributions of magmatic events documented in this study allow tracing the effects of the collision and subduction of a buoyant oceanic plate with a continental margin.

2. Geologic setting

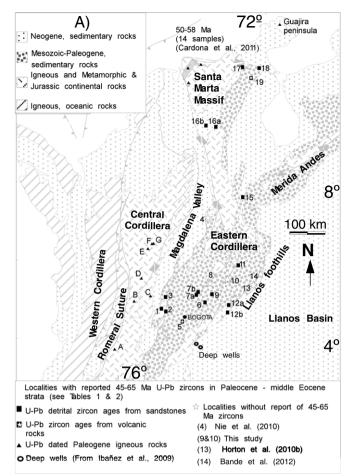
2.1. Late Cretaceous-Paleogene magmatic arcs

Previous studies in the northernmost Andes have reported evidence of Late Cretaceous–early Paleogene subduction and magmatic activity along the margin (Aspden et al., 1987; Jaillard et al., 2009; Pindell et al., 2005; Spikings et al., 2005; Vallejo et al., 2009; Villagómez et al., 2011). Widespread Late Cretaceous magmatic continental rocks have been documented by U–Pb zircon geochronology along the northern segment of the Central Cordillera (Antioqueño

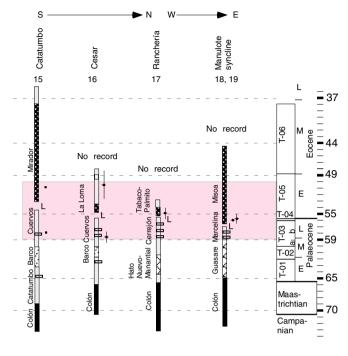
Batholith in Fig. 1); this magmatism has been associated either to the subduction of the Pacific-related Farallones plate or an older Proto Caribbean plate (Aspden et al., 1987; Ibañez-Mejia et al., 2007; Leal-Mejía et al., 2010; Ordoñez-Carmona et al., 2008; Pindell and Kennan, 2009; Restrepo-Moreno et al., 2009a; Restrepo-Pace et al., 2004; Villagómez et al., 2011). Its long-term Cenozoic exhumation has exposed the plutonic levels of this magmatism (Restrepo-Moreno et al., 2009a,b). In contrast, lower Paleogene intrusive rocks in the Central Cordillera are more scattered and tectonic implication remains scarcely known (Aspden et al., 1987; Leal-Mejía et al., 2010; Ordoñez, 2001; Ordoñez-Carmona and Pimentel, 2001; Ordoñez-Carmona et al., 2011). These bodies intrude older Mesozoic plutonic bodies and are followed by magmatic gap (Wadge and Burke, 1983), and then by a well-defined Miocene to recent magmatic belt due to present subduction of the Nazca Plate (Cediel et al., 2003; Taboada et al., 2000).

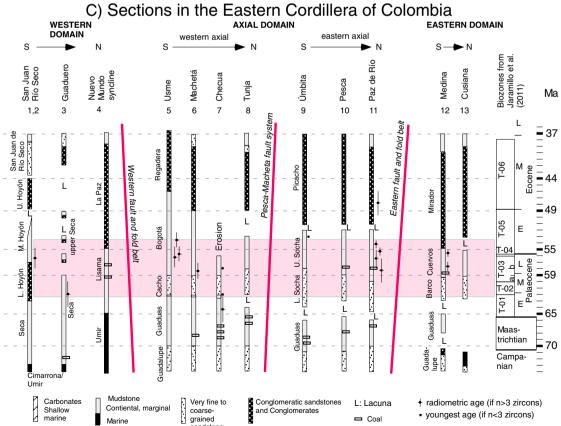
Paleocene–early Eocene magmatism events have been reported farther north within the Santa Marta Massif cutting both continental and oceanic basement rocks (Cardona et al., 2011) and in a small pluton in the Guajira peninsula that is intruding accreted oceanic basement rocks (MacDonald and Opdyke, 1972) (Fig. 2a). Cardona et al. (2011) recognize an older 63–65 Ma magmatism related to the Caribbean arc–continent collisional phase and the subsequent 60–50 Ma installation of a subduction setting. However, the southward extension of this magmatic event, its short-term expression and its continental scale meaning is still scarcely discussed.

Contemporaneous Paleocene–Eocene magmatic activity is also recorded in the leading and trailing edge of the Caribbean plate. The leading edge has began a major Late Cretaceous time-transgressive interaction with the northern margin of Colombia and Venezuela



B) Sections in northern Colombia-western Venezuela basins





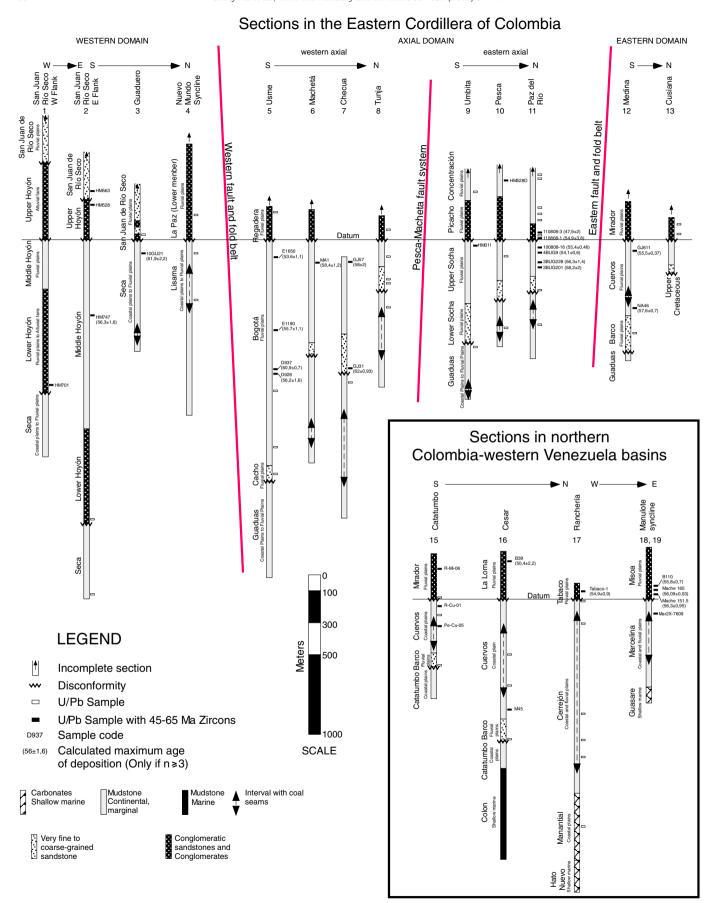


Table 1Intrusive rocks in the Central Cordillera with 45–65 Ma U–Pb zircon ages. U–Pb zircons ages reported in the Santa Marta batholith are indicated below for reference.

Sample coordinates			Sample information			Number of zircons					Reference
Latitude	Longitude	Locality	Sample ID	Unit	Rock name	Total analyzed zircons	45–65 Ma population	Mean age (Ma)	MSWD	Number of Zr	
6.5399	-74.9114	G	GR-II-01	Antioqueño Batholith	Tonalite			59.2 ± 1.2			Leal-Mejía et al. (2010)
6.4754	-75.0722	F	HLM-A-ER-001	Antioqueño Batholith	Granodiorite Porphyry			59.9 ± 0.9			Leal-Mejía et al. (2010)
6.5345	-74.9168	Е	HLM-A-G-029	Antioqueño Batholith	Tonalite			60.7 ± 1.0			Leal-Mejía et al. (2010)
5.7666	-75.3333	D	BSS-5	Stock of Sonson	Diorite	15	15	60.7 ± 1.4	1.3	15	Ordoñez (2001), U-Pb SHRIMP
5.1738	-74.9736	C	GCC-011	Stock El Hatillo	Quartzdiorite	49	49	54.6 ± 0.7	1.9	46	This study
5,0341	-75.4053	В	GCC-15	Stock of Manizales	Tonalite	40	37	59.8 ± 0.7	1.2	35	This study
3-3.5	−75.8	Α	Ordoñ1	Santa Barbara Batholith	Tonalite	9		58.9 ± 0.4			Ordoñez-Carmona et al. (2011)
3-3.5	−75.8	A	Ordoñ2	Santa Barbara Batholith	Tonalite	33		58.4 ± 0.8			Ordoñez-Carmona et al. (2011)

Santa Marta batholith ages (data from Cardona et al., 2011; 57.3, 56.6, 53, 53.5, 52.3, 51.9, 50.1, 50.2, 49.9, 55.3, 55.6, 57, 56, 50).

(Escalona and Mann, 2011; Lugo and Mann, 1995), as part of a single Great Caribbean oceanic arc (Burke, 1988) or as multiple oceanic arcs (Wright and Wyld, 2011). Paleogene arc related magmatism within the Great Caribbean arc has been reported in different granitoid units from the Greater and Leeward Antilles (Lidiak and Jolly, 1996). Within the trailing edge of the Caribbean plate, the Central American Arc has and arc related magmatic activity that began by ca. 70 Ma and was built over a Caribbean oceanic plateau-like substrate (Buchs et al., 2010; Lissinna, 2005; Montes et al., 2012; Wegner et al., 2011; Wörner et al., 2009). This arc has a well define intra-oceanic related Paleogene record (Lissinna, 2005; Montes et al., 2012; Wegner et al., 2011).

Late Cretaceous to early Paleogene paleogeographic reconstructions place the Caribbean Plate advancing between the Americas, but with its leading and trailing edges far from the northern Andes (Acton et al., 2000; Montes et al., 2012; Pindell and Kennan, 2009) (Fig. 1).

2.2. Paleocene-Eocene synorogenic clastic wedge

Paleogene synorogenic basins to the east of the Central Cordillera-Santa Marta Massif (Fig. 2) have been associated with the oblique collision of oceanic-cored terranes with the South American plate (Cardona et al., 2011; Cediel et al., 2003; Cooper et al., 1995; Gómez et al., 2005a; Pindell and Kennan, 2009; Pindell et al., 1998, 2005; Taboada et al., 2000; Villamil, 1999) (Fig. 2). This synorogenic clastic wedge records the encroachment of continental deposition and northward retreat of marine depositional environments (Bayona et al., 2008, 2011; Gómez et al., 2005a; Pindell et al., 1998; Saylor et al., 2011; Villamil, 1999) (Fig. 2). Maastrichtian-Paleocene strata in the Eastern Cordillera and adjacent basins (sections 1 to 11 in Figs. 2 and 3) consists mainly of fluvial quartzose sandstone to conglomeratic units that overlie disconformably fine-grained marginal to continental strata and underlie in a conformable contact finegrained continental strata. This siliciclastic signature of the lower Paleogene succession extends to the Cesar and Catatumbo basins (sections 15 and 16 in Figs. 2 and 3). Farther north, the lower-middle Paleocene succession changes to shallow-marine mixed lithologies and limestone beds of the Guasare platform (sections 17 to 19 in Figs. 2 and 3, and Maracaibo basin). Uppermost Paleocene-middle Eocene strata in all the sampled areas consist of fluvial sandstones and conglomerates that covered all the northern Andes.

Three sediment source areas have been proposed to explain the changes of Paleocene–middle Eocene sandstone composition from quartzarenite, to subarkoses, to sublithoarenite, to litharenite (Bayona et al., 2008). These source areas are: (1) the Central Cordillera and Santa Marta Massif, composed of metamorphic and intrusive rocks and <2-km-thick Cretaceous sedimentary cover (Bayona et al., 2010; Gómez et al., 2003, 2005b); (2) intrabasinal uplifts that exposes Cretaceous sedimentary cover of the Eastern Cordillera (Bayona et al., 2008; Parra et al., 2012); and sedimentary cover, metamorphic and igneous basement of the Guyana shield that mostly influenced the easternmost sections (e.g., Aalto, 1972; Gómez et al., 2005a).

U-Pb detrital zircon geochronology in clastic sequences in the northern Andes and southern Caribbean region has been also used to distinguish major source areas (Ayala Calvo, 2009; Ayala Calvo et al., 2009; Bande et al., 2012; Bayona et al., 2010, 2011; Cardona et al., 2009, 2011; Horton et al., 2010a,b; Nie et al., 2010, 2012; Saylor et al., 2011, 2012; Xie et al., 2010). Zircons supplied from basement rocks of the Central Cordillera–Santa Marta Massif have dominant Permo-Triassic and Mesozoic ages (65–300 Ma). Zircons supplied from basement rocks in the Eastern Cordillera and Santander Massifs have ages dominantly ranging from 300 to 1300 Ma. Zircons supplied from basement rocks in the Guyana craton have Neoproterozoic ages (500–600 Ma) and populations older than 1300 Ma.

Age control of this succession has been mainly obtained by palynology (Jaramillo et al., 2011; and references therein). In this contribution we also document absolute depositional ages for Paleocene units that supports the palynological age determination.

3. Methods

Two granitoid units from the Central Cordillera were selected for U/Pb zircon geochronology in order to assess their magmatic crystallization ages (localities B and C in Fig. 1). Biotite and hornblende from these granitoids have been previously dated with the K/Ar method (Aspden et al., 1987). Results have yield 57–53 Ma ages that probably reflect their cooling below 450 °C–250 °C (McDougall and Harrison, 1999). Other four magmatic bodies from the Central Cordillera (localities, A, D, E and F) have been also previously dated by the same methods. Their U/Pb ages and geological distribution are presented in Table 1 and Fig. 2.

In the clastic wedge, the 19 localities indicated in Figs. 2 and 3 include U/Pb detrital zircon geochronology data that are either already

Fig. 3. Stratigraphic correlation of upper Maastrichtian to middle Eocene lithological units showing thickness, dominant lithologies and the stratigraphic position of U/Pb geochronological samples for each section. Samples with volcanic zircons of 45–65 Ma ages, selected for this study, are indicated for each section. Calculated maximum age of deposition for each sample is indicated only if n > 3. See Appendix 2 for references used for thickness, depositional environment, age and geochronological analysis of each locality.

published or are in process of publication or are presented in this study. Fig. 3 shows the stratigraphic position of all the geochronological samples for each section, but only samples with detrital zircons population of 45–65 Ma were selected for this study (Figs. 2 and 3).

Sample preparation for separation of zircons was done using standard procedures, which include mechanical crushing, fragmentation, pulverization and manual sieving with disposal 400 µm sieves. This fraction was concentrated in the water table followed by magnetic separation with the Frantz isodynamic and finally the non-magnetic fraction was separated using heavy liquids (methylene iodide, 3.30–3.33 g/cm³) in order to get highly pure zircon concentrates.

U-Pb geochronology of zircon single grains was conducted by laser-ablation-multicollector inductively coupled plasma-mass spectrometry at the University of Arizona Laserchron Center following the method of Gehrels et al. (2006, 2008) at Washington State University following the method of Chang et al. (2006). Unknowns and standard zircons were mounted in the central half of the mount area, to reduce possible fractionation effects. Detrital zircon grains to be analyzed were selected randomly from all of the zircons mounted from each sample. For magmatic zircon tips and cores were selected for analysis, in order to check for the younger magmatic crystallization age and inherited domains. In detrital sample cores of grains were preferred to avoid possible thin metamorphic overgrowth. At the Arizona Laserchron 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. The isoprobe is equipped with an ArF excimer laser ablation system, which has an emission wavelength of 193 nm. The collector configuration allows measurement of ²⁰⁴Pb in the ion-counting channel while ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³²Th and ²³⁸U were simultaneously measured with Faraday detectors. All analyses were conducted in static mode with a laser beam diameter of 35-50 diameter, operated with an output energy of ~32 mJ (at 23 kV) and a pulse rate of 9 Hz. Each analysis consisted of one 20second integration on peaks with no laser firing and twenty 1-second integrations on peaks with the laser firing. Hg contribution to the ²⁰⁴Pb mass position was removed by subtracting onpeak background values. Inter-element fractionation was monitored by analyzing an inhouse zircon standard, which has a concordant TIMS age of 564 ± 4 Ma (2 σ) (Gehrels, unpublished data).

This standard was analyzed once for every five unknowns in detrital grains. Uranium and Th concentrations were monitored by analyzing a standard (NIST 610 Glass) with ~500 ppm Th and U. The lead isotopic ratios were corrected for common Pb, using the measured

²⁰⁴Pb, assuming an initial Pb composition according to Stacey and Kramers (1975) and respective uncertainties of 1.0, 0.3 and 2.0 for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$. The age of standard, calibration correction from standard, composition of the common Pb, and the decay constant uncertainty are grouped and are known as the systematic error. For these samples the systematic errors range between $\sim 1.0-1.4\%$ for $^{206}\text{Pb}/^{238}\text{U}$ and $\sim 0.8-1.1\%$ for $^{206}\text{Pb}/^{207}\text{Pb}$. Other details of the methods used for samples in localities 18 and 19 are found in Jaramillo et al. (2010). LA-ICP-MS U-Pb analyses at Washington State University were conducted using a New Wave Nd:YAG UV 213-nm laser coupled to a ThermoFinnigan Element 2 single collector, double-focusing, magnetic sector ICP-MS. Laser spot size and repetition rate were 30 µm and 10 Hz, respectively. He and Ar carrier gases delivered the sample aerosol to the plasma. Each analysis consisted of a short blank analysis followed by 300 sweeps through masses 204, 206, 207, 208, 232, 235, and 238, taking approximately 35 s.

Weight average and concordia age calculations as well as detrital zircon histograms were plotted using Isoplot 3 (Ludwig, 2007) and Arizona Laserchron Excel macro age pick program. For the Paleogene ages we used ²³⁸U/²⁰⁶Pb age, as these ages are more appropriate for zircons with ages younger then ca. 900 Ma. Tera-Wasserburg diagrams were tested to review the potential existence of Pb loss or common Pb. All errors of the U-Pb ages are given at 1-sigma level. Maximum depositional ages using early Paleogene detrital zircons were calculated for each sample with at least three detrital zircons. Raw data are presented in Appendix 1.

4. Results

4.1. U/Pb geochronolohy in granitoids

We have select samples from two granitoid bodies in the Central Cordillera of Colombia (Manizales and Hatillo Stocks). Samples are mainly hornblende-biotite granodiorites that intrude Triassic s-type granitoids and greenschist rocks. Zircon tips from the Manizales Stock yield a weight average age of 59.8 ± 0.7 Ma (MSWD = 1.2), whereas the Hatillo Stock yields an age of 54.6 ± 0.7 Ma (MSWD = 1.9) (Table 1); these ages are related to magmatic crystallization. All their U/Th ratios are below 12, which are characteristic of magmatic zircons (Rubatto, 2002) (Fig. 4).

We considered that published K/Ar ages from these stocks are relatively close to their magmatic crystallization as seen by the

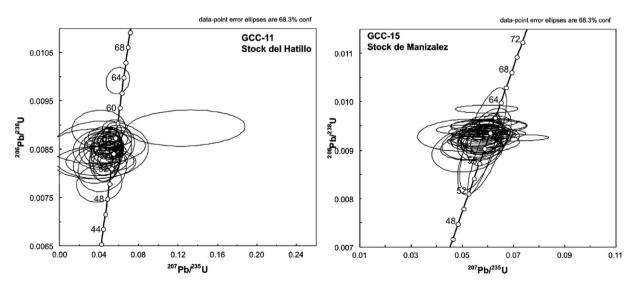


Fig. 4. Concordia diagrams from the Hatillo and Manizales plutonic rocks. See Appendix 1 for raw data.

Table 245–65 Ma detrital zircons ages reported in localities of the Eastern Cordillera of Colombia and northern Colombia–western Venezuela basins. See Fig. 2 for location, 3 for stratigraphic position and 6 for age-population diagrams.

Sample coordinates		Sample information				Number of zircons		Maximum depositional ages			Reference	
Latitude	Longitude	Locality	Sample ID	Unit	Palynological age	Rock name	Total analyzed zircons	45-65 Ma population	Mean age (Ma)	MSWD	N of Zr	
Southern	Colombia sedi	mentary ro	cks (localities 1 to 12)									
4.737	-73.023	12b	GJ611	Cuervos Fm.	Paleocene-Eocene boundary	Litharenite	89	13	55.5 ± 0.6	0.15	9	This study
4.906	-72.993	12a	Na 46	Cuervos Fm.	Middle Paleocene	Litharenite	97	21	57.6 ± 0.7	0.114	6	This study
5.8623	-72.812	11	100808-3	Lower Picacho Fm	Early Eocene	Sublitharenite	164	4	47.9 ± 2.0	1.8	4	Saylor et al. (2011, 2012)
.8623	-72.812	11	110808-1	Lower Picacho Fm	Early Eocene	Sublitharenite	98	4	54.9 ± 3.6	2.7	3	Saylor et al. (2011)
.8623	-72.812	11	110808-16	Upper Socha Fm.	Late Paleocene-Early Eocene	Sublitharenite	97	16	55.4 ± 0.5	0.47	6	Saylor et al. (2011)
.8623	-72.812	11	4BUG9	Upper Socha Fm.	Late Paleocene-Early Eocene	Sublitharenite	107	6	54.1 ± 0.6	0.83	6	Saylor et al. (2011)
.969	-72.746	11	3BUG228	Upper Socha Fm.	Late Paleocene-Early Eocene	Sublitharenite	97	6	56.3 ± 1.4	0.18	3	Saylor et al. (2011)
.969	-72.746	11	3BUG201	Upper Socha Fm.	Late Paleocene-Early Eocene	Sublitharenite	100	8	58.2 ± 2.0	0.14	8	Saylor et al. (2012)
.587	-73.023	10	PES-Tco-HM528D	Concentracion Fm.	Middle Eocene	Sublitharenite	93	4	45.2 ± 1.6	0.15	3	This study
.214	-73.424	9	UMB-Tss-HM-011	Upper Socha Fm.	No reported age	Litharenite	88	2	Min. age of 53 Ma			This study
.276	-73.778	7b	CHE-Tb-GJ57	Bogota Fm.	Middle-late Paleocene	Litharenite	75	2	Min. age of 58 Ma			This study
.214	-73.809	7a	CHE-Tc-GJ31	Cacho Fm.	No reported age	Sublitharenite	98	4	64.3 ± 2.1	0.25	3	This study
.045	-73.593	6	MA-1	Bogota Fm.	Early Eocene	No reported	54	4	58.4 ± 1.2	1.09	3	Horton et al. (2010b)
.537	-74.163	5	E1650	Bogota Fm.	No reported age	Litharenite	108	36	53.6 ± 1.1	0.17	9	This study
.537	-74.163	5	E1190	Bogota Fm.	No reported age	Litharenite	79	33	55.72 ± 1.1	0.35	6	This study
.537	-74.163	5	D937	Bogota Fm.	Late Paleocene Felds.	Litharenite	89	24	60.96 ± 0.7	0.21	10	This study
.537	-74.163	5	D928	Bogota Fm.	Late Paleocene	Tuff	98	45	56.2 ± 1.6	0.17	6	This study
.068	−74.566	3	10GU-21	Seca Fm.	No reported age	No report	105	13	61.9 ± 2.2	0.3	5	Caballero et al. (submitte for publication)
1.869	-74.579	2	HM563	San Juan de Río	No reported age	Sublitharenite	124	1	Min. age of 64 Ma			This study
.852	-74.585	2	HM528	Upper Hoyón Fm.	Middle Eocene	Sublitharenite	90	1	Min. age of 55 Ma			This study
.792	-74.569	2	HM747	Middle HoyónFm.	No reported age	Sublitharenite	76	11	56.3 ± 1.6	0.35	4	This study
.893	-74.713	1	HM701	Lower Hoyón Fm.	No reported age	Litharenite	105	2	Min. age of 62 Ma			This study
Vorthern	Colombia and	western V	enezuela sedimentarv 1	rocks: (localities 15 to 19)							
0.802		19	B110	Misoa Fm.	Early Eocene	Felsic tuff	49	28	55.8 ± 0.7	_	18	Jaramillo et al. (2010)
0.802	72.346	19	Mache 165 m	Misoa Fm.	Paleocene–Eocene boundary	Felsic tuff	10	9	56.09 ± 0.03	1.5	6	Jaramillo et al. (2010), U-Pb CAN-TIMS
0.802	72.346	19	Mache 151,5-7056	Misoa Fm.	Late Paleocene	Lithic arkose	93	4	56.3 ± 0.95	0.29	3	This study
1.126		18	Mar2X-7609	Marcelina Fm.	Late Paleocene Felds.	Litharenite	98	3	Min. age of 53 Ma			This study
1.141		17	Tabaco-1	Tabaco Fm.	Late Paleocene	Subarkose	90	33	54.9 ± 0.9	0.13	6	Cardona et al. (2011)
,602		16	B39	Eoceno La Loma unit	No reported age	Litharenite	97	5	50.4 ± 2.2	0.035	3	Ayala Calvo et al. (2009)
.540	-73.285	16	Sororia M45	Cuervos Fm.	Late Paleocene	Sublitharenite	96	3	58.7 ± 0.9	0.14	3	This study
.739		15	RM-6	Mirador Fm.	Middle Eocene	Quartzarenite	80	2	Min. age of 51 Ma			This study
7.739	-72.608	15	RC-1	Cuervos Fm	No reported age	Litharenite	71	3	Min. age of 58 Ma			This study
7.739		15	Pe-5	Cuervos Fm.	No reported age	Sublitharenite	92	3	Range: 50 to 57 Ma			This study

comparison of the new U–Pb zircon ages that we present here and the previous K–Ar geochronology.

4.2. U/Pb detrital zircon geochronolohy

For the Eastern Cordillera and adjacent basins (localities 1 to 11), zircon age population between 45 and 65 Ma was reported in 9 of the 14 localities. Sandstone composition from the 9 localities with 45–65 Ma ages ranges from sublitharenite, litharenite and feldspathic litharenite (Table 2), with locality 5 (Usme) including an interval of volcaniclastic rocks. Maximum age of deposition was calculated for 14 samples (Table 2); 2 samples collected in middle Eocene strata yield ages between 45 and 49 Ma at nearby localities 10 and 11 (Pesca and Paz de Río areas) (Table 2), 2 samples from undated lower Paleocene units have mean ages between 62 and 64 Ma in localities 3 and 7 (Guaduero and Checua areas), whereas the other 10 samples are in the range of 54 to 60 Ma. The latter 10 samples were collected from Paleocene–lower Eocene units, with exception of sample HM563 that correspond to a middle Eocene unit.

In locality 5 (Usme), volcanic zircons recovered from volcaniclastic deposits in the Bogotá Formation (sample D928) yield a depositional age of 56.2 ± 1.6 Ma (Figs. 2, 3 and 5a). Other 3 samples

collected above that level have a high concentration of 45–65 Ma volcanic zircons (Figs. 3 and 6a), but other 3 samples analyzed below that level do not report 45–65 Ma detrital zircons.

For the basins in the northern segment of Colombia (localities 15 to 19 in Figs. 2 and 3), 45–65 Ma ages were reported in 5 localities in samples collected in units of Paleocene–lower Eocene age. Locality 19 (Manuelote Syncline) includes an interval of a felsic tuff, and sandstone composition from the 5 localities is very variable. Maximum age of deposition was calculated for 6 samples (Table 2); 4 samples yielded ages between 54 and 56 Ma, and the other two of 50 Ma and 58 Ma. In locality 19, volcanic zircons recovered from the felsic tuff yield a depositional age of 56.09 ± 0.03 Ma (Jaramillo et al., 2010; Fig. 5b).

Detrital zircon age populations older than 65 Ma show lateral variation in these samples (Fig. 6a and b). Those adjacent to the Central Cordillera (localities 1 to 3; San Juan de Río Seco and Guaduero, Fig. 6a) and Santa Marta Massif (localities 16 and 17; Cesar and Ranchería basins, Fig. 6b), Cretaceous (70–90 Ma), Jurassic (150–190 Ma) and Permo-Triassic (230–300 Ma) ages are the dominant age populations. In contrast, age populations older than 1300 Ma are the dominant in locality 12 on the eastern flank of the Eastern Cordillera (Medina section, Fig. 6b), whereas ages in the range of 65 to 300 Ma

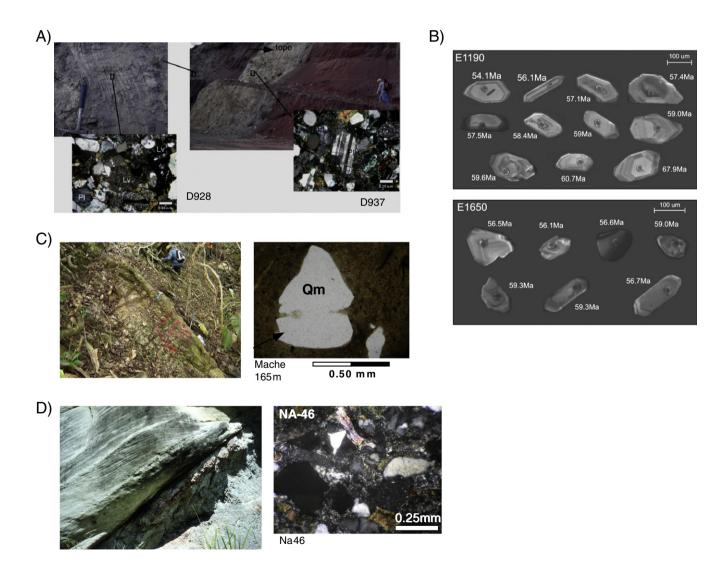


Fig. 5. Results from (A) volcaniclastic rocks in locality 5 (Usme) with fragments of volcanic rocks (Lv) and fresh plagioclase (Pl), and (B) cathodoluminescense images of detrital volcanic zircons in the same locality from upper volcaniclastic beds. (C) Delsic tuff in locality 19 (Manuelote Syncline, taken from Bayona et al., 2011). (D) siliciclastic rocks with sedimentary and metamorphic rock fragments in section 12a (Medina).

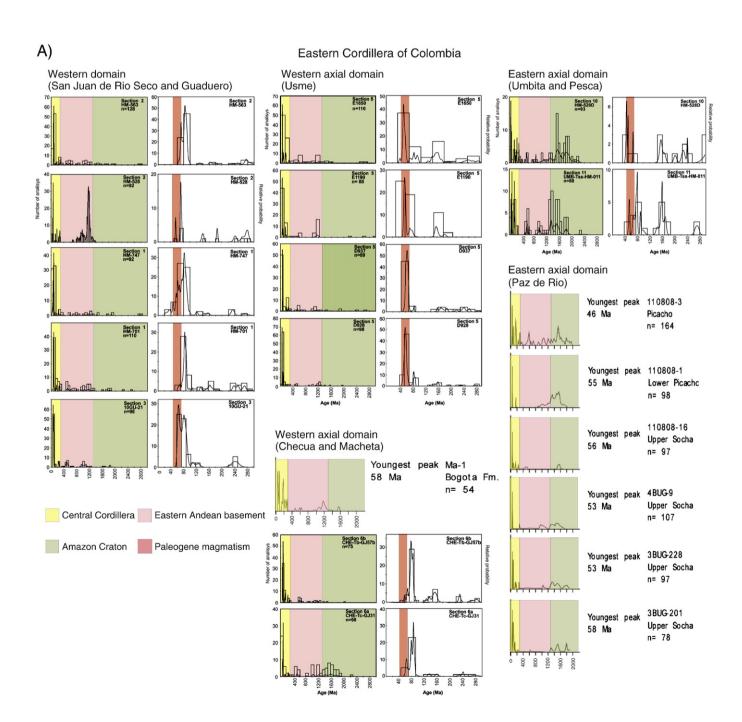
are in very low amount. Samples from the other localities in the axial zone of the Eastern Cordillera (Fig. 6a) and Catatumbo basin (Fig. 6b) have age populations that vary from the Mesozoic to the Precambrian.

5. Discussion

45–65 Ma U/Pb ages reported above in plutonic rocks of the Central Cordillera and in the synorogenic clastic wedge document clearly a major regional event of magmatism, and the absence of younger zircons ages marks a shutdown of magmatism ca 45 Ma. Magmatic activity extended along the continental margin for ca 700 km, and detrital volcanic zircons are reported in localities as far as 400 km from the collided margin (Figs. 7 and 8). Plutonic remnants of the extinct early Paleogene volcanic arc that was documented in the Santa Marta Massif to the north (Cardona et al., 2011) can be also extended southward to the Central Cordillera, as indicated by the newly

obtained U–Pb zircon crystallization ages from lower Paleogene intrusive rocks (Fig. 1), and likely continued farther north in the restored position of the Guajira peninsula.

The nearly coeval magmatic and sedimentary ages reflect the input from volcanic complexes and the associated erosion of the shallower level plutonic complexes (Malusà et al., 2011). Detrital zircon populations recorded in Paleocene–middle Eocene strata indicate that volcanic detritus were transported by fluvial systems and volcaniclastic processes that developed on both the collided continental margin and intraplate settings rather from distant oceanic magmatic arcs. Even though ash-fall deposits may extend thousands of kilometers from the magmatic arc (Ingersoll et al., 2003), sedimentological evidences are more akin to continental subaerial volcanic sources (Bayona et al., 2010). Geochemical analysis in zircon fragments and volcaniclastic rocks should be carried out to test the hypothesis of marginal and intraplate magmatism.



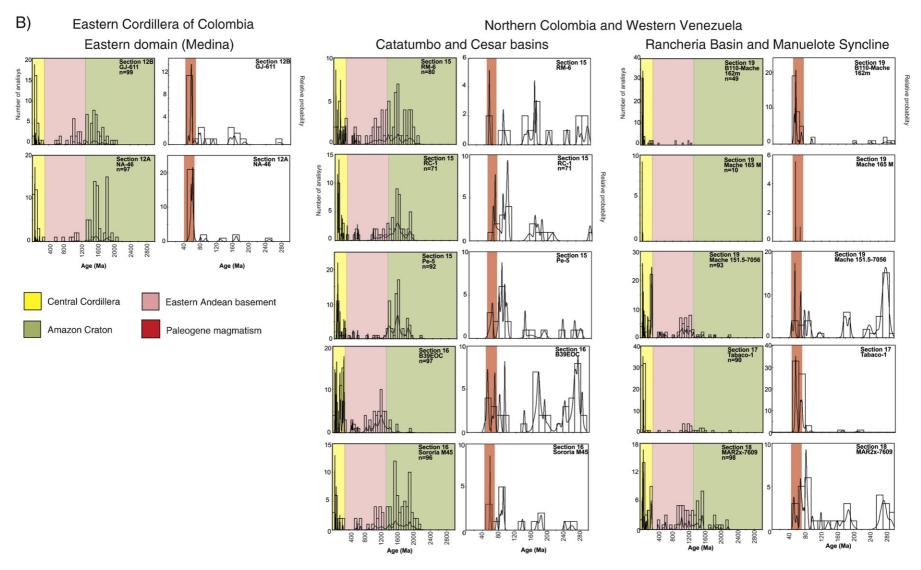


Fig. 6. a and b: U/Pb ages for detrital zircons from the Eastern Cordillera localities and northern Colombia—western Venezuela basins, shown as total number of analysis and PROBABILITY density distribution histograms following ISOPLOT (Ludwig, 2007). Left diagrams show the whole zircon populations, whereas right diagrams show populations younger than 300 Ma. Curves of probability density distribution from other studies are shown for comparison. In the western domain of the Eastern Cordillera (Fig. 6a, San Juan de Río Seco and Guaduero) note the very low amount of Amazon craton zircon population and high content of 70–100 Ma detrital zircon ages, whereas in the eastern domain (Fig. 6b, Medina) the dominant population is from the Amazon craton and zircon age population from 70 to 100 Ma are almost absent. Also, note the relative abundance of Paleogene zircons in Usme, Paz de Río (Fig. 6a), Medina and Manuelote syncline areas (Fig. 6b) that are not adjacent to magmatic arc of the Central Cordillera and Santa Marta Massif (Fig. 2).

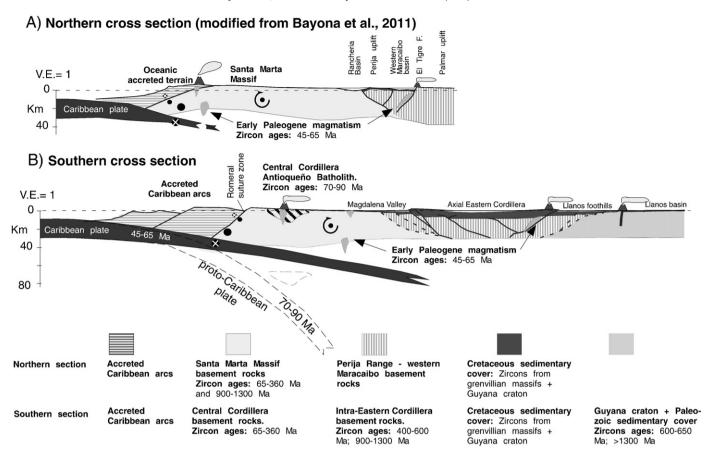


Fig. 7. Regional cross sections (see Fig. 2A for location) showing the relationship of subduction, magmatic activity and basin filling at two different latitudes. (A) Northern Colombia and (B) central Colombia.

The dominance of Cretaceous to Permian (70–300 Ma) detrital zircon populations in the westernmost localities indicates that their magmatic arc source growth along the Central Cordillera–Santa Massif belt. The fluvial system mixed volcanic zircons with synorogenic detritus produced by the uplift of basement rocks exposed along the collided margin of the Central Cordillera (Bayona et al., 2011; Gómez et al., 2003; Nie et al., 2012). Mesoproterozoic and older detrital zircon populations reported in the easternmost localities differ significantly from the westernmost localities, indicating that the fluvial systems transporting volcanic detritus in the easternmost locality were derived from a clearly different source.

In the sedimentary record of tropical basins, the Paleocene basins of the northern Andes (Wing et al., 2009), intense chemical weathering precludes the persistence of unstable fragments in fluvial systems for more than 100 km, contrasting with zircon grains that are usually more prompt to survive fluvial transport of hundreds to a thousand of kilometers (e.g., Amorocho et al., 2011; Ingersoll et al., 2003; Johnsson et al., 1991; Mapes, 2009). Unstable metamorphic and volcanic rock fragments observed in litharenitas and sublitharenites with 45–65 Ma volcanic zircons (see references in Appendix 2) point to nearby source areas. The existence of intraplate volcanic centers, as suggested here, also could explain the irregular thin interbeds of pyroclastic flows reported in localities 5 and 19 (Fig. 5).

Intraplate magmas could be related to reactivated faults that involve basement rocks and become a main pathway for the construction of intraplate magmatic centers. Bayona et al. (2011) interpreted intraplate magmatic activity in the western Perija Range (locality

19), coeval with Paleocene magmatism in the collided margin (Santa Marta Massif; Cardona et al., 2011) to the reactivation of Jurassic extensional faults of the Perija Range (Fig. 7).

A similar tectonic scenario may be proposed farther south, linking Paleocene magmatism in the Central Cordillera and reactivation of faults in the Eastern Cordillera and proximal Llanos basin. Eastern basement highs, like those presently buried by Cenozoic foreland strata in the southern proximal Llanos Basin (Bayona et al., 2007) have yielded zircon ages > 1300 Ma in Neoproterozoic low-grade metasedimentary rocks (Ibañez-Mejia et al., 2009). These basement highs could explain both the craton-derived zircon population (>1300 Ma) as well the presence of metamorphic rock fragments in Paleocene sandstone beds of easternmost localities (Bayona et al., 2008). Although Paleogene magmatic rocks have not been reported yet in the Eastern Cordillera or southern Llanos basin, these magmatic bodies could be totally eroded, or buried either by tectonic loads of the Eastern Cordillera or by foreland sediments in the Llanos basin. Intraplate magmatism is a common feature on the Meso-Cenozoic magmatic evolution of the Andes, and it has been well recognized in the Eastern Cordillera and adjacent basins for Cretaceous (Vasquez et al., 2010) and Mio-Pliocene time (Taboada et al., 2000; Vasquez et al., 2009).

Magmatic activity had a maximum peak in 54–60 Ma, as recorded both in the Central Cordillera–Santa Marta plutons and detrital volcanic zircons from the synorogenic clastic wedge. Volcanic zircons provide a new chronostratigraphic constraint for correlation of Paleocene–Lower Eocene strata (Figs. 2 and 3), mainly in localities where biostratigraphic studies in alluvial to fluvial continental deposits gave negative results. Even though a more systematic sampling

A) 50-60 Ma. Continental magmatic arc and intraplate magmatism related to subduction of the Caribbean plate; Central America magmatism (Montes et al., 2012); fault reactivation in intraplate settings (Bayona et al., 2008, 2011), relative westward motion of South America plate (Somoza, 2007)

B) 37-45 Ma. Shutdown of continental magmatism; strike-slip movement of the Caribbean plate; decrease of Central America magmatism (Montes et al., 2012); deformation concentrates only in the Magdalena Valley (Bayona et al., 2008), change to relative northward motion of South America plate (Somoza, 2007)

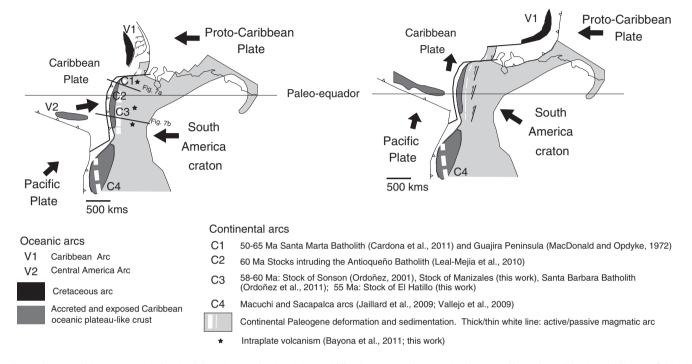


Fig. 8. Paleogeographic reconstruction showing (A) maximum volcanic activity in middle Paleocene–early Eocene time due to Caribbean plate subduction, and (B) stop of volcanism in middle Eocene time due to northward migration of Caribbean plate relative to South America plate in middle Eocene time.

is needed to constrain the end of syn-depositional magmatic record, the data compiled here indicate that magmatism in both the collided margin and intraplate settings ceased at 50 Ma, although in few intraplate localities the youngest record is ca 45 Ma. This suggests that magmatism ended in early middle Eocene time.

Late Cretaceous arc–continent collision was followed by Early Paleogene magmatism along the collided continental margin (Central Cordillera and Santa Marta Massif) and intraplate volcanism. Early Paleogene magmatism was associated with the subduction of the Caribbean plate beneath the South America margin (Fig. 8A), as it has been suggested for areas farther north (Bayona et al., 2011; Cardona et al., 2011). This plate, which seems to be formed in a Pacific position (Acton et al., 2000; Montes et al., 2012), migrated to its current inter-America position by consuming a former proto-Caribbean plate building a series of oceanic arcs that obliquely collided with the South American margin (Burke, 1988; Kerr et al., 2003; Pindell, 1993; Pindell et al., 2005; Wright and Wyld, 2011).

Geophysical and ODP and IODP sampling within the Caribbean ocean and its margin suggest that this plate includes a relatively thick oceanic plateau-like crust (Kerr et al., 2003; Mauffret and Leroy, 1997). Therefore, once the Caribbean plateau-like began to occupy its inter-American position, it was also forced to subduct – or underthrust – under the South American margin, and maybe clog the margin, and providing a snapshot of magmatic and deformational effects of the subduction of oceanic plateaus (Cloos, 1993; Gutscher et al., 2000; Mann and Taira, 2004; Van Hunen et al., 2004).

The installation of a shallow-angle subduction regime in the Paleocene-early Eocene may be explained by the subduction of a

plateau-like crust (Van Hunen et al., 2004). Shallow subduction explains the wider areal distribution of this magmatism along the margin and the intraplate magmatism proposed in this paper. Widening of continental arc link to shallow subduction and intraplate deformation has been document in other proposed Andean flat slab segments (Folguera and Ramos, 2009). The rapid end of magmatic activity both along the margin and intraplate settings may be related to: (1) the difficulty of the thick plateau to subduct, (2) obliqueness of the margin and the northeastern migration of the Caribbean plate (Kennan and Pindell, 2009), and (3) the northward migration of the South America craton (Somoza, 2007) and trailing segment of the Caribbean plate (Panama arc, Montes et al., 2012) that transformed the Caribbean–South American margin from a convergent magmatic margin to a transpressive non magmatic margin (Fig. 8).

The faith on the existence of this former Caribbean slab in the Colombian margin is also seen by the tomographic and seismic record of a relict slab over the Nazca plate within the Colombian Andes (Cortés et al., 2005; Taboada et al., 2000) (Fig. 9).

6. Conclusions

U/Pb plutonic and detrital zircon ages found in intrusive rocks and synorogenic lower Paleogene strata, respectively, document an early Paleogene continental volcanic activity in the northern Andes that longitudinally extended ca 700 km. Magmatic activity occurred predominantly between 54 and 59 Ma, providing a new

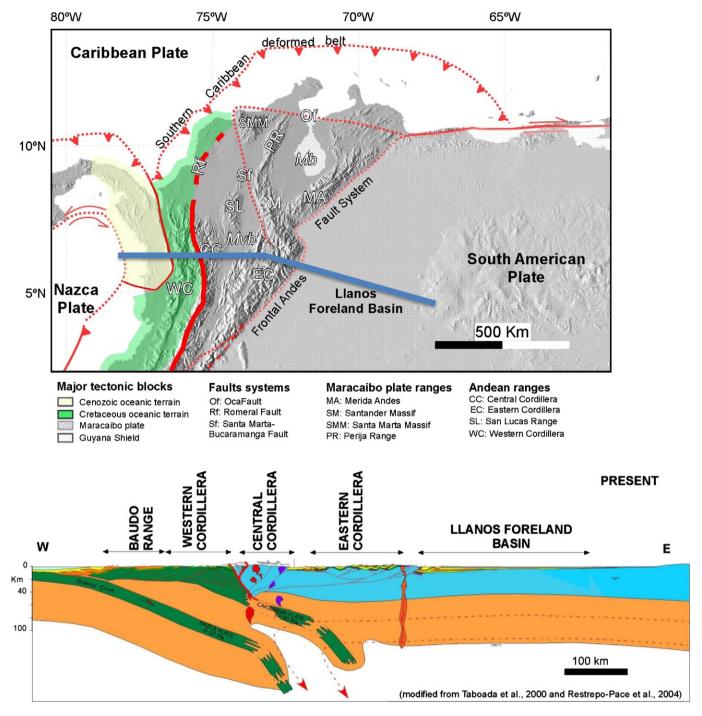


Fig. 9. Present location of the subducted Caribbean slab beneath of the Eastern Cordillera, as proposed by Taboada et al. (2000), and the actual subduction slab as proposed by Restrepo-Pace et al. (2004).

chronostratigraphic constraint for correlation of continental Paleocene–Lower Eocene strata.

The differences in whole detrital zircon population between west-ernmost and easternmost localities, the presence of unstable rocks fragments in sandstone beds that contain volcanic zircons, and irregular thin volcaniclastic deposits allow to infer that volcanic activity reached intraplate settings as far as 400 km from the collisional margin.

This short period of magmatism is related to the oblique and shallow subduction of an oceanic plateau-like crust beneath the northwestern corner of South America plate. This magmatic activity reinforce the hypothesis on the subduction of oceanic plateaus and their effects in the modification of the continental crust. The rapid

termination of magmatic activity in middle Eocene time is related to the difficulty of the plateau to subduct and the northward migration of the Caribbean and South America plates.

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