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Late Cretaceous to Cenozoic Uplift of the Northern Andes: Paleogeographic Implications

Andrés MORA[1], Diego VILLAGÓMEZ[2], Mauricio PARRA[3], Víctor M. CABALLERO[4], Richard SPIKINGS[5], Brian K. HORTON[6], Josué Alejandro MORA–BOHÓRQUEZ[7], Richard A. KETCHAM[8], and Juan Pablo ARIAS–MARTÍNEZ[9]

Abstract In this chapter, we summarize recent work on the geologic evolution of the northern Andes. Our intention is to present current information so that scientists from other disciplines can differentiate data from interpretations. In this effort, we focus on thermochronological data that provide precise places, dates, and rates. Thermochronological data provide cooling histories for rocks of the upper crust, whereas provenance data offer insights on rocks that have been eroded away. In reviewing published data, we provide a critical overview of recent paleogeographic interpretations. Specifically, we discuss hypotheses such as (i) Eocene proto–Magdalena River draining toward the Maracaibo Basin, (ii) the presence of a closed proto–Magdalena basin from the late Eocene to middle Miocene, (iii) the Miocene closure of the Isthmus of Panamá, (iv) the late Cenozoic surface uplift of the Eastern Cordillera, and (v) the Cenozoic eastward advance of the Orinoco River. We conclude that in most cases, favored ideas remain as intriguing hypotheses, but there remains room for alternative interpretations. The present summary is intended to provide a cautionary note on the use of limited datasets to make paleogeographic interpretations of the northern Andes.

Keywords: *paleogeography, thermochronology, U–Pb geochronology, sedimentary provenance, rock uplift, surface uplift, paleoelevation, paleodrainages.*

Resumen En este capítulo se resumen trabajos recientes relacionados con la evolución geológica de los Andes del norte. La principal intención es presentar información actual para que los científicos de otras disciplinas puedan diferenciar entre datos e interpretaciones. Este trabajo se enfoca en datos termocronológicos que brindan localizaciones, edades y tasas precisas. Los datos termocronológicos proporcionan historias de enfriamiento para las rocas de la corteza superior, mientras que los de procedencia sedimentaria contribuyen con información sobre las rocas que se han erosionado. A partir de la revisión de datos públicos se da una visión crítica de las interpretaciones paleogeográficas publicadas recientemente. Específicamente,

1 andresro.mora@ecopetrol.com.br
Ecopetrol, Brasil
Bogotá, Colombia

2 diego.villagomez@gmail.com
University of Geneva
Department of Earth Science
Rue des Maraîchers13. CH–1205
Geneva, Switzerland

3 mparra@iee.usp.br
Universidade de São Paulo
Instituto de Energia e Ambiente
Av. Professor Luciano Gualberto 1289, Cidade Universitária, 05508–010
São Paulo, Brasil

4 victor.caballero@ecopetrol.com.co
Ecopetrol S.A.
Instituto Colombiano del Petróleo
Centro de Innovación y Tecnología
Km7 via Bucaramanga–Piedecuesta
Piedecuesta–Santander, Colombia

5 richard.spikings@unige.ch
University of Geneva
Department of Earth Sciences and the Environment
Rue des Maraichers 13, Geneva 1205
Switzerland

6 horton@jsg.utexas.edu
University of Texas at Austin
Department of Geological Sciences and Institute for Geophysics, Jackson School of Geosciences
Austin, Texas 78712, USA

7 alejandro.mora@hocol.com.co
Hocol S.A.
Vicepresidencia de Exploración
Carrera 7 n.° 113–46, piso 16
Bogotá, Colombia

8 ketcham@jsg.utexas.edu
The University of Texas at Austin
Jackson School of Geosciences
Austin, Texas 78759

9 juanpabloarma@gmail.com
Ecopetrol S.A.
Vicepresidencia de Exploración
Bogotá, Colombia

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se discuten las siguientes hipótesis: (i) el proto río Magdalena del Eoceno drenando hacia la Cuenca de Maracaibo, (ii) la presencia de una proto cuenca cerrada del Magdalena entre el Eoceno tardío y el Mioceno medio, (iii) el cierre del Istmo de Panamá durante el Mioceno, (iv) el crecimiento topográfico de la cordillera Oriental en el Cenozoico tardío y (v) el avance hacia el este del trazo del río Orinoco durante el Cenozoico. Se concluye que, en la mayoría de los casos, las ideas más sustentadas permanecen como hipótesis interesantes, pero queda espacio para otras interpretaciones. Este trabajo intenta advertir sobre el uso de una cantidad limitada de datos para hacer interpretaciones paleogeográficas de los Andes del norte.

Palabras clave: *paleogeografía, termocronología, geocronología U–Pb, procedencia sedimentaria, levantamiento de roca, levantamiento de superficie, paleoelevación, paleodrenajes.*

1. Introduction

The northern Andes, which are positioned north of the Huancabamba Deflection at 6° S (Gansser, 1973), differ from other segments of the Andes because of the presence of accreted oceanic material and a transpressional deformation regime during Cenozoic mountain building (Figure 1; Aleman & Ramos, 2000; Mégard, 1989; Taboada et al., 2000; Trenkamp et al., 2002). The evolution of the northern Andes is of interest not only for geologists and tectonicists, but also for other disciplines. For example, biologists rely on the evolution of topography interpreted by geologists to infer linkages between landscape evolution and the distribution of species deduced from phylogenetics (e.g., Bacon et al., 2012). However, hypotheses proposed by geologists are often imprecise because of the poor preservation of stratigraphic and structural records and a lack of high resolution 3D constraints. With the dawn of the XXI century, techniques such as geochronology and low–temperature thermochronology have become more precise and modeling approaches have become more sophisticated, providing higher resolution timing constraints on tectonic events and episodes of exhumational cooling in the upper crust. In recent years, pioneering studies (Figures 2, 3) have highlighted the role of low temperature thermochronology (Mora, 2015; Mora et al 2010a, 2013a, 2013b, 2015a, 2015b; Parra et al., 2009a, 2009b, 2010, 2012; Saylor et al., 2012a; Spikings et al., 2000, 2001; Villagómez et al., 2011a, 2011b) and detrital geochronology (Caballero et al., 2013a, 2013b; Horton et al., 2010a, 2010b, 2015; Nie et al., 2010, 2012; Saylor et al., 2011, 2012b, 2013; Silva et al., 2013) in the Cretaceous to Cenozoic evolution of the northern Andes. Paleoelevation techniques have also become more sophisticated, but their use has been limited in the tropical northern Andes (Anderson et al., 2015) relative to their use in the arid central Andes (Garzione et al., 2017; Saylor & Horton, 2014).

These developments have prompted a revolution in our understanding of interrelated processes pertaining to *rock uplift*, *surface uplift*, and *exhumation* as defined by England & Molnar (1990; Figure 3). Unfortunately, in the northern Andes and elsewhere, these terms have been commonly and incorrectly grouped under a broad and vague definition of "uplift". For example, some classic interpretations of the Eastern Cordillera of Colombia suggest that molasse deposition, deformational cross–cutting relationships, and topographic growth (e.g., Hooghiemstra et al., 2006; van der Hammen et al., 1973) were all manifestations of a single Miocene event that could be grouped under the broad term of "uplift" (Cooper et al., 1995; Dengo & Covey, 1993).

An appreciation of the role of surface processes only arrived well after many studies of orogenesis in the northern Andes were conducted. Whereas studies in the central Andes recognized the interplay of tectonics, erosion, and climate (Horton, 1999; Masek et al, 1994; Montgomery et al., 2001; Sobel et al., 2003; Strecker et al., 2007, 2009), their role in the northern Andes was only recognized when palynological and thermochronological techniques were combined with structural and geomorphic analysis (e.g., Mora et al., 2008).

Understanding and differentiating *rock uplift* from *surface uplift* and *exhumation*, with their attendant implications for landscape evolution and mountain building, was so new to the northern Andes that, in the words of Henry HOOGHIEMSTRA, it gave a "new eye" to numerous scientists from diverse disciplines. These expanded perspectives have positively impacted new generations of geologists, so it is not uncommon for current studies of the northern Andes to integrate paleoelevation studies with exhumation and structural analyses (Cuervo–Gomez et al., 2015).

Although many pioneering studies have applied state–of–the–art techniques, their results have not been compiled or integrated in a critical way. In this review, we provide an updated summary of recent studies with the intention to filter, present, and discuss the evidence of crustal deformation, surface uplift, and exhumation in the northern Andes and their diverse impacts on Cenozoic surface processes. This manuscript is organized in chronological order with each time interval considered from west to east across the northern Andes.

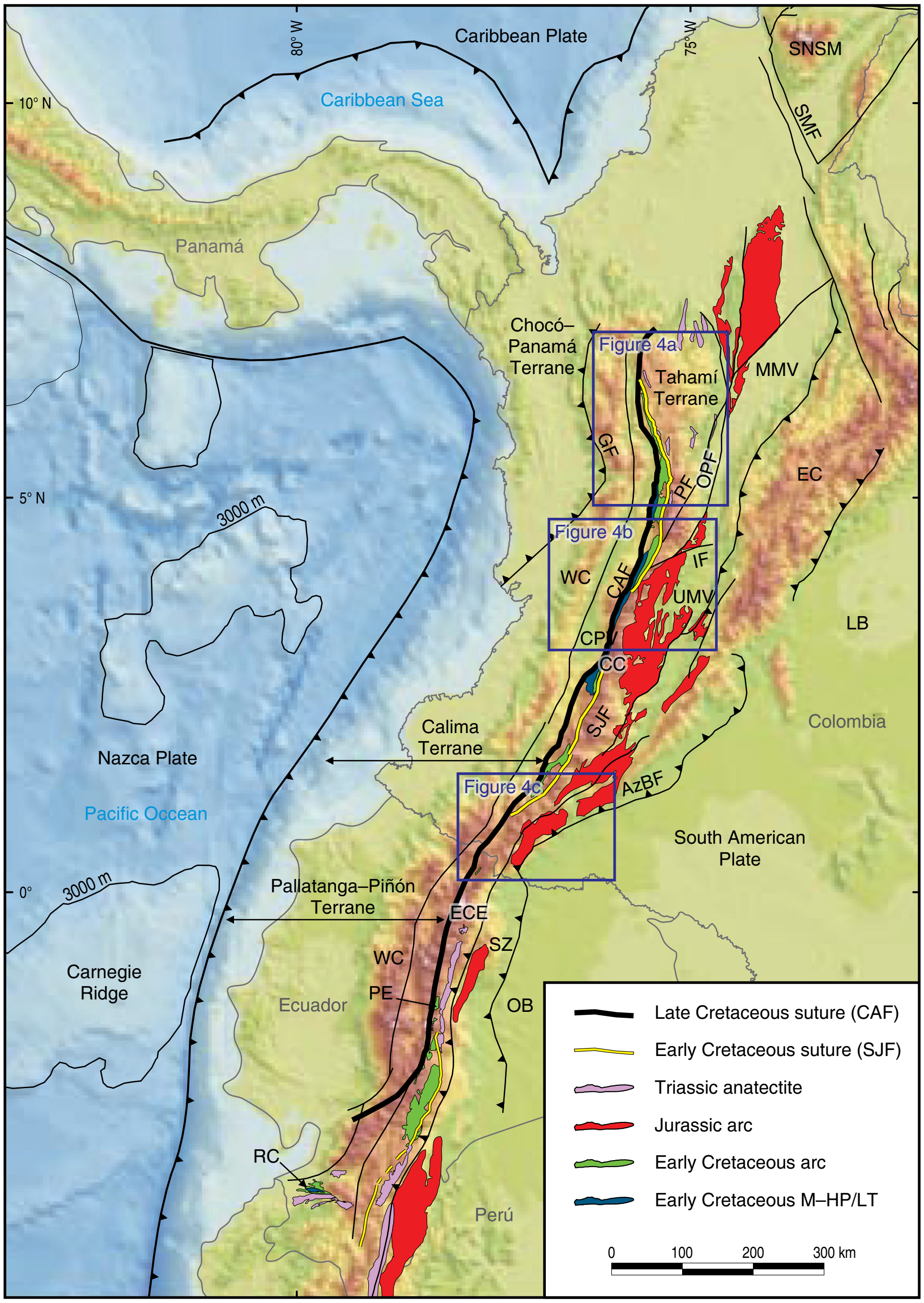


Figure 1. Shaded relief image of northwestern South America and surrounding tectonic plates showing the main cordilleras, faults, and the subducting Carnegie Ridge (background model from Gómez et al., 2007). Cretaceous sutures are shown as thick black and yellow lines, and the three sample regions (a, b, c) by Villagómez & Spikings (2013) in Figure 4 are highlighted. Major rock sequences of the Central Cordillera (Colombia) and Eastern Cordillera (Ecuador) are shown. (SNSM) Sierra Nevada de Santa Marta; (SMF) Santa Marta–Bucaramanga Fault; (GF) Garrapatas Fault; (MMV) Middle Magdalena Valley Basin; (PF) Palestina Fault; (OPF) Otú–Pericos Fault; (WC) Western Cordillera; (CPV) Cauca–Patía valley; (CAF) Cauca–Almaguer Fault; (IF) Ibagué Fault; (UMV) Upper Magdalena Valley Basin; (EC) Eastern Cordillera; (CC) Central Cordillera; (LB) Llanos Basin; (SJF) San–Jeronimo Fault; (AzBF) Amazon Border Fault; (ECE) Eastern Cordillera Ecuador; (WC) Western Cordillera; (SZ) Sub–Andean Zone (Ecuador); (PE) Peltetec Unit; (OB) Oriente Basin; (RC) Raspas Complex. After Villagómez & Spikings (2013).

2. Geological Setting

The northern Andes are the result of complex interactions between the Nazca, Caribbean, and South American Plates. The northern Andes of Ecuador and Colombia comprise an orogenic system with three N– to NNE–trending mountain chains—the Western, Central, and Eastern Cordilleras, which are separated by prominent topographic depressions (Figures 1, 2). The Cen-

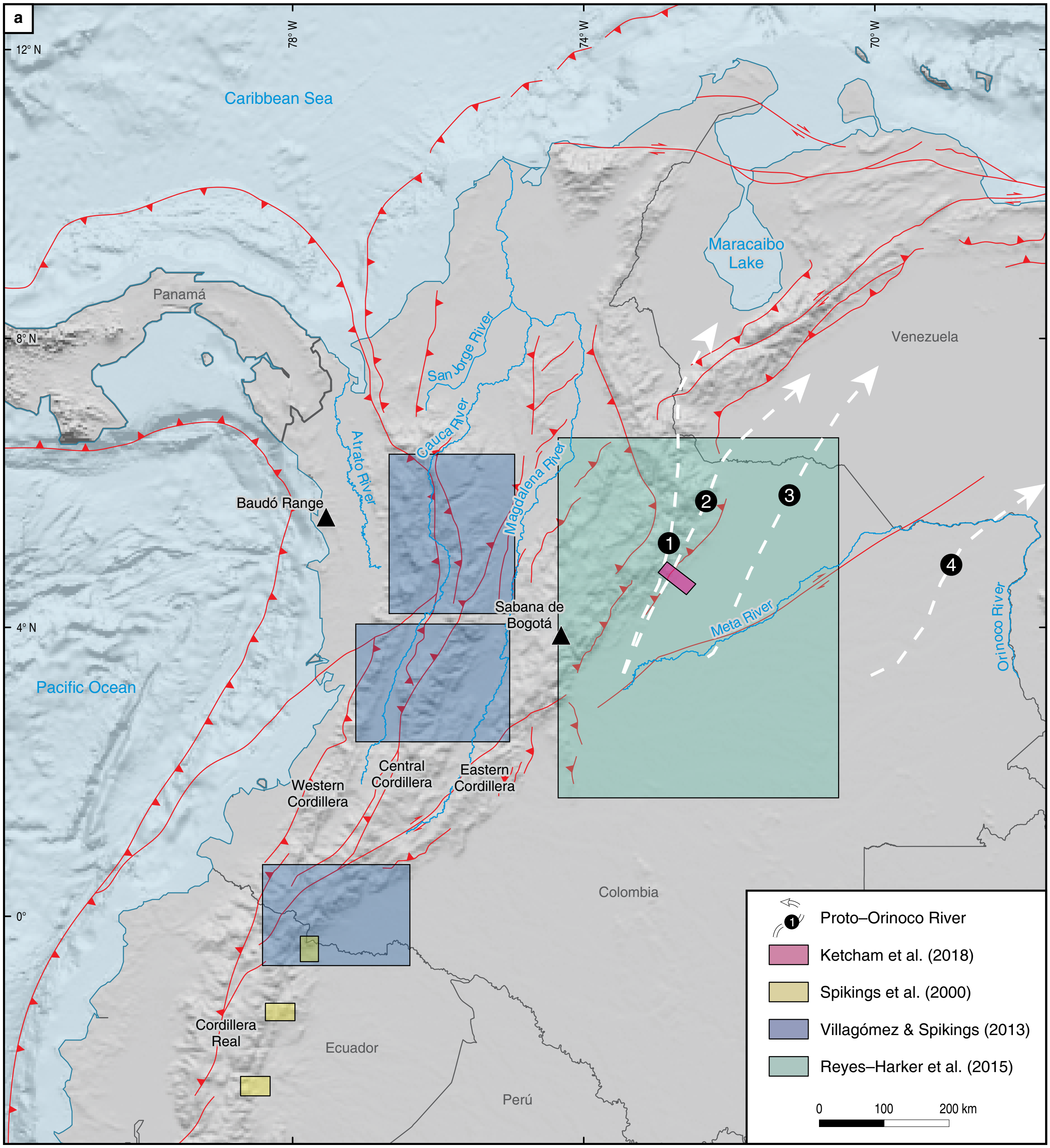
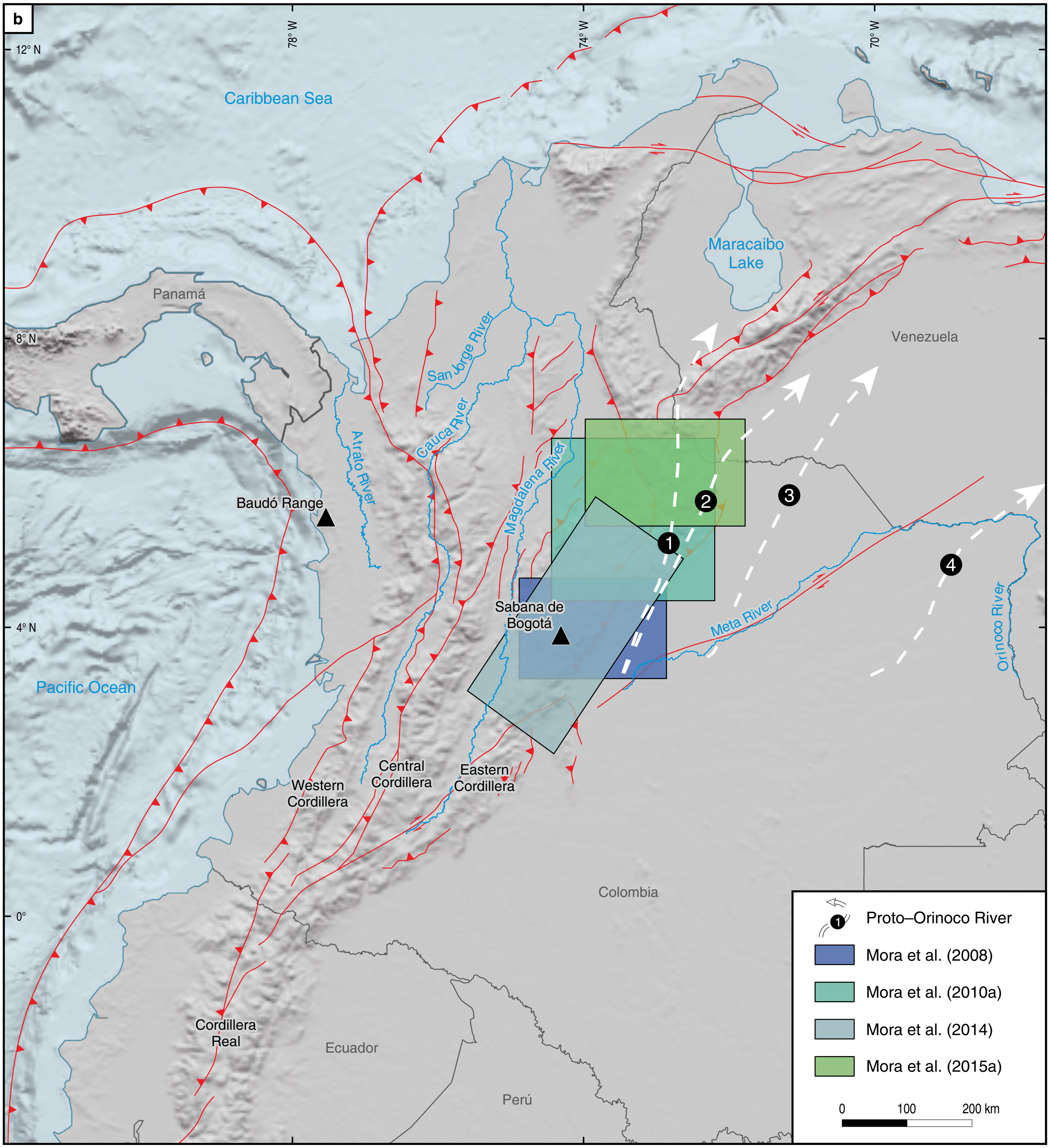


Figure 2. Shaded relief image with the main geographic features (mostly rivers and mountain ranges) discussed in the text as well as the main studies cited. Panels a, b, and c are based on different studies and study areas. White dashed lines with arrows show the inferred locations of the proto–Orinoco River (after Reyes–Harker et al., 2015) at the following times: 1—Paleocene (ca. 60 Ma); 2—middle Eocene (ca. 44 Ma); 3—middle Miocene (ca. 14 Ma); 4—close to recent times.

tral Cordillera of Colombia is referred to as Cordillera Real (or Eastern Cordillera) in Ecuador, whereas the Eastern Cordillera of Colombia has no topographic expression in Ecuador (Figure 2).

The main orogenic phases of the northern Andes have been attributed to Cenozoic changes in plate convergence, the accretion of oceanic terranes (plateaus and island arcs), and the



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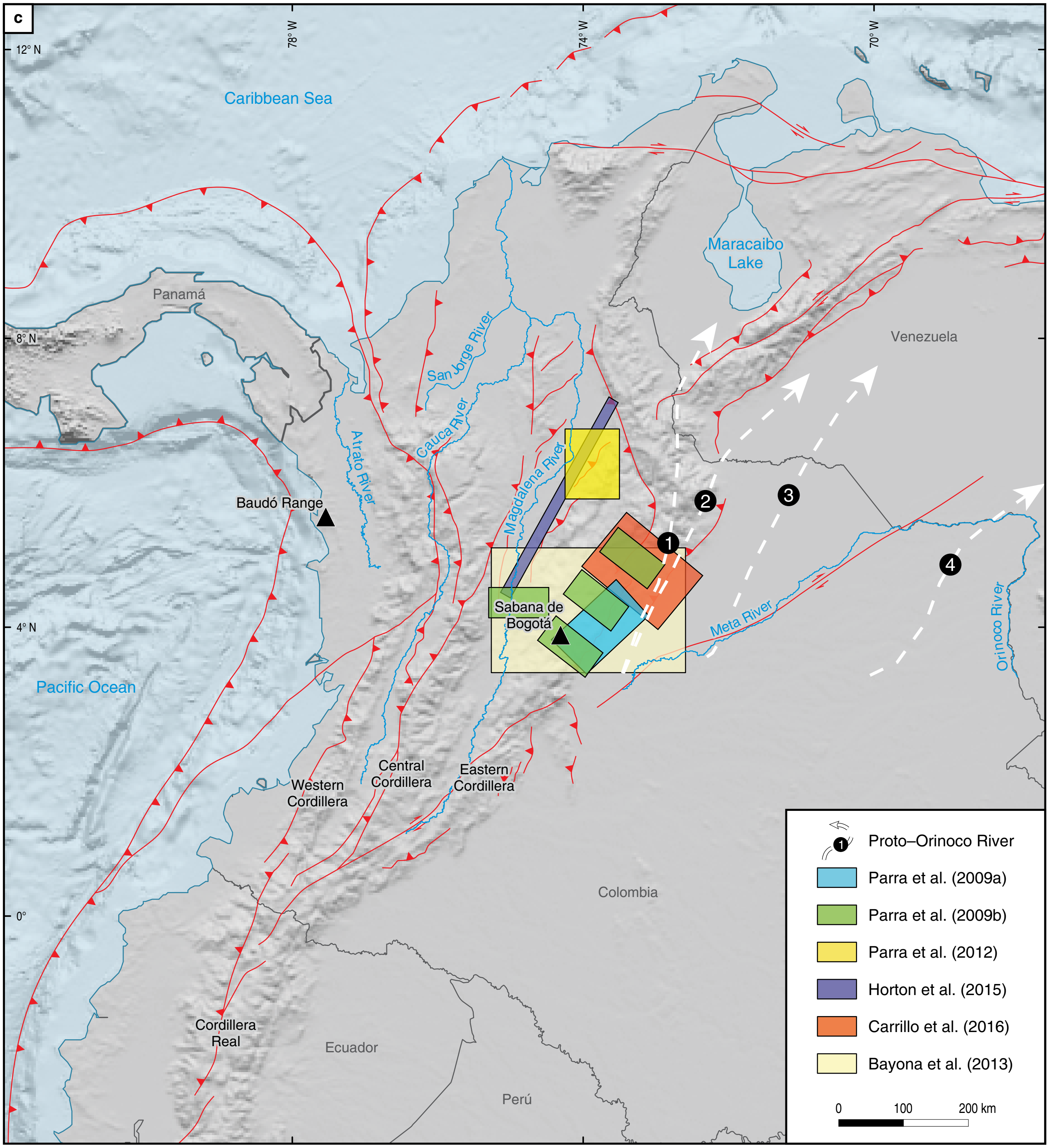
subduction and collision of aseismic ridges. In Colombia, allochthonous oceanic terranes are exposed in the Western Cordillera and forearc region (serranía de Baudó) and have been juxtaposed against South America along the diffuse, regional–scale Romeral Fault System and its southern continuation toward Ecuador (the Cauca–Almaguer Fault; Figure 1). These allochthonous oceanic



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rocks, which are termed the Panamá–Chocó and Calima Terranes, include areas west of the Garrapatas Fault (Figures 1, 2). The terranes correspond to relict slivers of the Caribbean Large Igneous Province (100–88 Ma; Kerr et al., 1997; Sinton et al., 1998; Villagómez et al., 2011a) accreted to northwestern South America between the latest Cretaceous and middle Miocene.

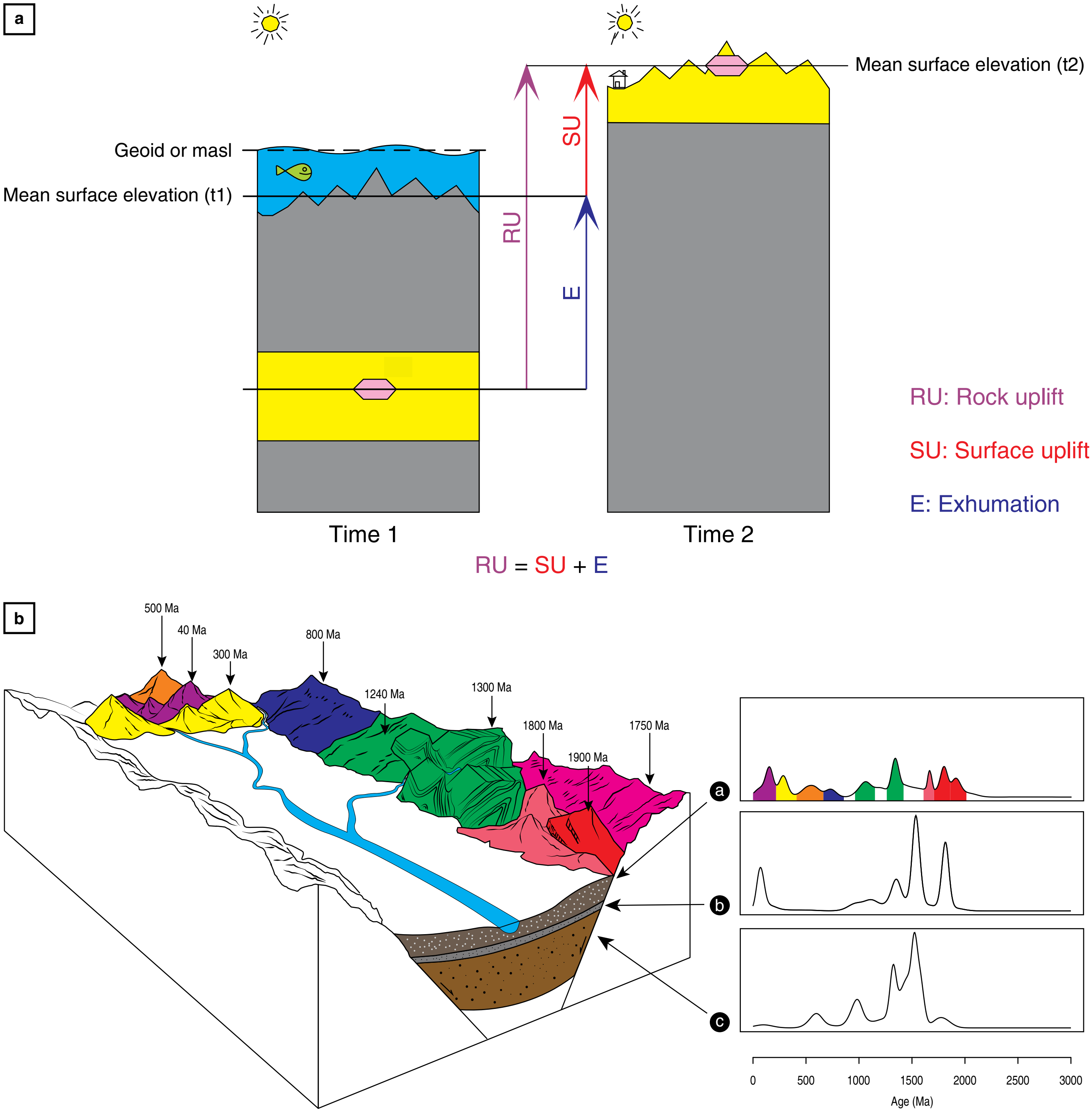


Figure 3. (a) Diagram summarizing definitions of rock uplift, surface uplift, and exhumation. Surface uplift is the displacement of the earth's surface relative to the geoid. Rock uplift is the displacement of rock relative to the geoid and exhumation is the displacement of rock relative to the surface. Rock uplift equals the sum of exhumation plus surface uplift. The diagram shows as an example a two–phase model of progressive cooling in the upper crust that considers the exhumation of an apatite crystal from several kilometers depth to the surface. The process also involved some rock uplift and surface uplift. **(b)** Simplified diagram showing a typical context in which detrital geochronology is applied. In this case, there is a river from which tributaries drain from basement terrains (mountain areas) of different but typical geochronological ages. All age signals are then collected by the main river trunk. When detrital geochronology analyses (e.g., U–Pb) are carried out on active sediments drained by the river, data are typically presented as age versus probability histograms that document different age populations. Different horizons (a, b, and c) can also be sampled in the sedimentary record and show to what extent different basement terrains contributed sediments to the river in geological history. If those basement terrains occupied thousands to even hundreds of thousands of square kilometers in the past and only crop out in specific areas today, one of the challenges is to infer the configuration or headwaters of past drainages. In most cases, geologists do not have enough information to accurately perform such reconstructions.

The Romeral Fault System and Cauca–Almaguer Fault border the Central Cordillera in Colombia (Figure 1) and mark the western limit of the continental lithosphere. The continental basement is traditionally considered to include the Tahamí and Chibcha Terranes (Toussaint &Restrepo, 1989). The Tahamí Terrane forms the core of the Central Cordillera, whereas the Chibcha Terrane forms the basement of the easternmost Central Cordillera, Eastern Cordillera, Santander Massif, and Sierra Nevada de Santa Marta (Figure 1; Martens et al., 2014). This broad continental domain is a complex assemblage of poorly mapped lower Paleozoic ortho– and para–gneisses, which were reheated during Triassic magmatism (e.g., Cochrane et al., 2014; Litherland et al., 1994; Restrepo–Pace et al., 1997). Pre–Jurassic rocks were subsequently intruded by elongated Jurassic granitoids and localized Upper Cretaceous batholiths.

3. Methods Discussed in This Review

In this review we summarize previous research on the northern Andes focused on bedrock low temperature thermochronology and subordinate detrital geochronology. Low temperature thermochronology (Figure 3a) seeks to determine the time at which rocks at depth reached a particular temperature in the upper crust. Apatite fission track (AFT) and zircon fission track (ZFT) techniques (e.g., Ketcham et al., 1999; Wagner & van den Haute, 1992; Reiners et al., 2004) use different mineral species to date the timing when rocks at depth were at temperatures of ca. 140 °C to ca. 50 °C (AFT) and ca. 250 °C (ZFT). Other thermochronological techniques include the use of apatite (U–Th)/He (AHe) and zircon (U–Th)/He (ZHe) for temperatures of ca. 40 °C to ca. 90 °C (AHe) and ca. 100 °C to 190 °C (ZHe) and the use of $^{40}Ar/^{39}Ar$ techniques for temperatures of >300 °C.

As an example (Figure 3), a two–phase model of progressive cooling in the upper crust considers the exhumation of an apatite crystal from several kilometers depth to the surface. Because the age when the apatite reached those temperatures can be determined via low temperature thermochronology, the amount of cooling over geological time can be evaluated. Moreover, when assuming a uniform, time–invariant temperature gradient with depth, the original rock overburden and amount of erosional exhumation can be assessed.

While thermochronological data can be simply represented in ages, it is desirable to generate thermal models from those ages that provide cooling histories in the form of time–temperature (T–t) paths that define rock locations through time relative to isotherms (lines of the same temperature in the upper crust). Models and ages obtained through thermochronology can be confidently linked to the exhumation of the precise areas and locations from which samples are taken.

Detrital geochronology is another technique used to evaluate exhumation and the evolution of landscapes and river drainages. It relies on the fact that resilient minerals such as zircons crystallize at very high temperatures (>700 °C) and persist as hard, dense, chemically stable, and often diagnostic signatures of different geological terranes and crustal provinces (e.g., Ibañez–Mejia et al., 2015 and references therein) forming at different temperatures (e.g., Figure 3b). Various basement and sedimentary rocks have diagnostic populations of zircons that can be discriminated on the basis of their contrasting crystallization ages (Figure 3b). For example, the predominantly igneous rock units of the Central and Western Cordilleras (Figure 2) are younger than ca. 250 Ma while most basement rocks of the Eastern Cordillera and South American Craton are older than ca. 250 Ma (Aspden et al., 1987; Cordani et al., 2005; Horton et al., 2010a, 2010b; McCourt et al., 1984; Restrepo–Pace et al., 1997; Silva et al., 2013).

Detrital zircon U–Pb ages (e.g., Ibañez–Mejia et al. 2015 and references therein) have the technical advantage of efficiently dating hundreds of zircon crystals from sedimentary rocks (Figure 3b). In identifying major zircon age populations in the northern Andes, multiple studies have been able to more precisely suggest when particular sediment sources in the northern Andes shed sediments to adjacent basins (e.g., Bande et al., 2012; Caballero et al., 2013a, 2013b; Horton, 2018a; Horton et al., 2010a, 2010b, 2015, 2020; Nie et al., 2010, 2012; Silva et al., 2013;). In addressing the timing of terrane accretion, other works have applied this technique to reveal that basement rocks of the Panamá–Chocó Terrane have a dominant Eocene age signature (ca. 59 to ca. 42 Ma) that contrasts with that of older basement rocks to the east (e.g., Montes et al., 2015).

One issue of detrital geochronology pertains to the fact that contributions of different source areas are often mixed in large drainage systems and may be recycled from older sedimentary rocks. Therefore, the method relies on the presence or absence of diagnostic age populations diagnostic of particular source areas. In practice, interpretations of the northern Andes focus on whether sediment was derived from particular regions (for example, the Eastern Cordillera, Central Cordillera, or Panamá–Chocó Terrane). As a result, geologists have developed hypothesis regarding regions of elevated topography that may have once acted as sources of sediments. Because these source materials have been largely eroded away, there remains considerable ambiguity regarding the precise locations of former regions of positive relief. This problem can be addressed in regions that have not been eroded away, by using low temperature thermochronology results in areas where cooling has occurred in situ in the upper ca. 3–6 km of crustal blocks. In those provinces ages can still be measured today. In this paper, we review several key data sets and discuss interpretations that impact our understanding of the paleogeographic evolution and uplift of the northern Andes.

4. Latest Cretaceous to Early Eocene Accretionary and Deformational Events

4.1. Western and Central Colombia and Ecuador

To decipher the timing and consequences of the accretion of Cretaceous oceanic terranes, several authors have obtained thermochronological data from accreted oceanic rocks and adjacent continental rocks (Figures 1, 2a, 4, 5; e.g., Restrepo–Moreno et al., 2009; Spikings et al., 2000, 2001; Villagómez & Spikings, 2013).

Villagómez & Spikings (2013) concluded that the collision of the Caribbean Large Igneous Province in Colombia started in the Campanian and triggered shortening in the continental interior. The collision is interpreted to have driven uplift and erosional exhumation (at rates of 1 km/my) that persisted until ca. 65 Ma based on modeled AFT and ZFT time–temperature histories for the oceanic and continental blocks (Figures 4–7). Villagómez & Spikings (2013) provide AFT and ZFT data for the Bolívar Batholith in the Western Cordillera that show rapid Late Cretaceous to Paleocene exhumation (Figure 6) similar to that observed in the Central Cordillera (Figure 7 after Villagómez & Spikings, 2013). In northern Colombia, more moderate exhumation rates probably lasted until ca. 55 Ma in the east consistent with progressively more recent cooling east of the Romeral Fault System. Syn– and post–accretionary sedimentary rocks within the accreted terranes and adjacent continental margin confirm the onset of this accretionary event (Villagómez & Spikings, 2013). Similarly, Spikings et al. (2001, 2010) constrained rapid exhumation (>1 km/my) in Ecuador between 73 and 55 Ma and attributed this exhumation to the collision and accretion of the Caribbean Large Igneous Province (Figure 8). A similar Late Cretaceous – Paleocene onset of Andean orogenesis is recorded along the length of the Andes, including the central and southern Andes where oceanic materials were not accreted (Horton, 2018a, 2018b; Ramos, 2009; Ramos & Aleman, 2000).

4.2. Exhumation and Deformation in the Middle Magdalena Basin

By Late Cretaceous time, the Middle Magdalena Valley formed part of an active foreland basin of the proto–Andean orogen. In this area, a widespread unconformity marks a pre–Eocene contractional event in which inverted Jurassic grabens and shortened Cretaceous rocks are documented in surface and subsurface datasets (Figure 2c for location; e.g., Gómez et al., 2003, 2005; Parra et al., 2012). The age of this contractional event was originally attributed to the middle Eocene (Villamil, 1999) or late Paleocene – late Eocene (Restrepo–Pace et al., 2004). However, using thermochronology combined with vitrinite reflectance data, Parra et al. (2012) demonstrated that deformation predating the widespread unconformity mostly occurred in latest Cretaceous – Paleocene time (Figure 9). Rodríguez–Forero et al. (2012) dated the oldest deposits above the unconformity, the La Paz Formation, and found that they were actually deposited by the earliest Eocene. In addition, Caballero et al. (2010, 2013a, 2013b) documented a folded Paleocene Lisama Formation beneath the unconformity in northern areas of the Middle Magdalena Valley.

Along the western margin of the Eastern Cordillera close to the Arcabuco Anticline, late Paleocene shortening and exhumation are consistent with structural relationships (Restrepo–Pace et al., 2004) and ZHe ages from rocks in which vitrinite reflectance data suggest temperatures sufficient to fully reset the ZHe thermochronometer (Caballero et al., 2013a; Reyes–Harker et al., 2015). Bayona et al. (2013; Figure 2c) further documented thickness changes in Paleocene strata within the axial zone of the Eastern Cordillera, and Mora et al. (2013a) documented minor cooling in the Llanos Basin.

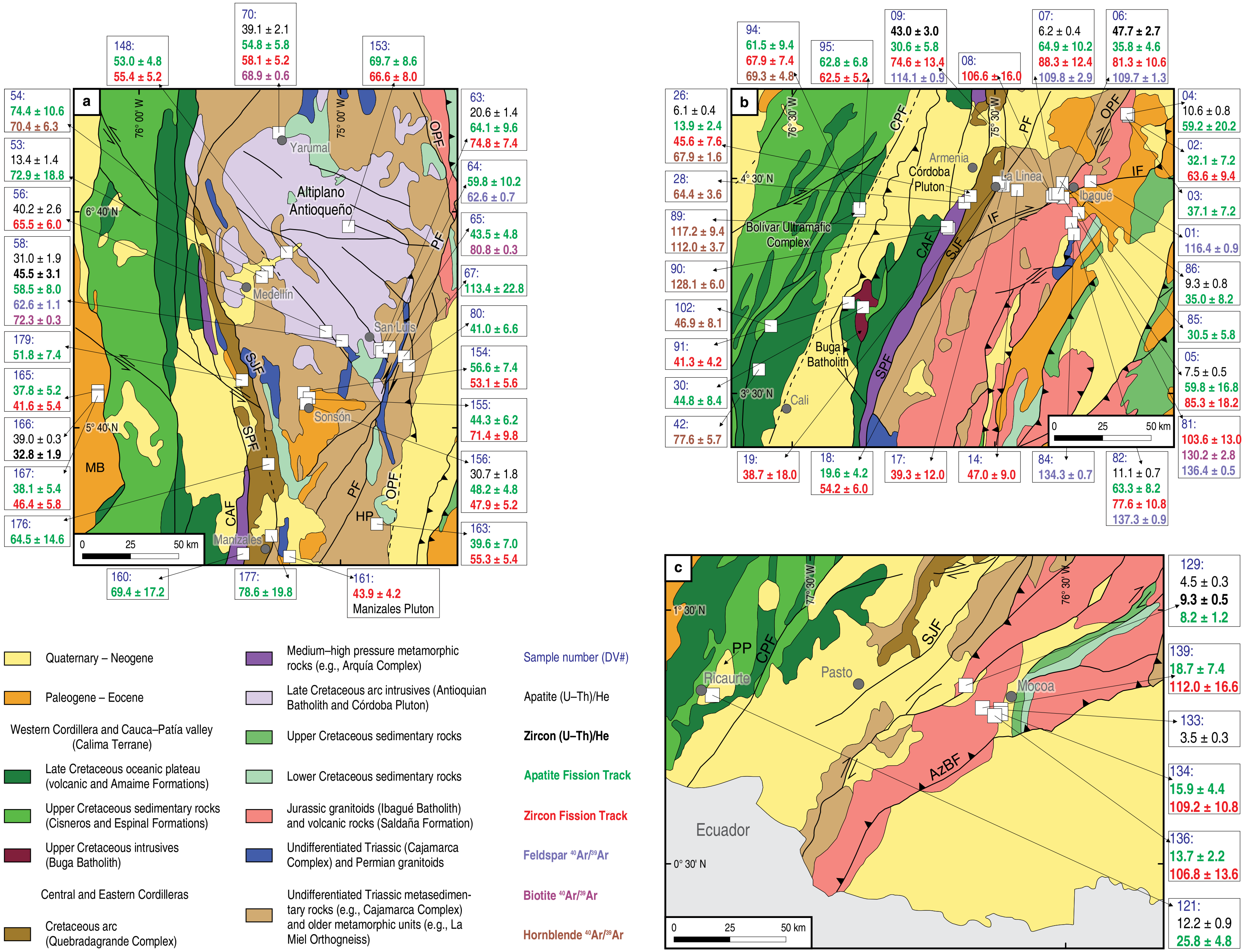
To the south, the Amazon Foreland Basin shows evidence of the initial uplift of the Eastern Cordillera in Ecuador (southern continuation of the Central Cordillera) as recorded by initial input of Andean material within nonmarine sandstones and shales of the Tena Formation (Horton, 2018a; Martin–Gombojav &Winkler, 2008; Spikings et al., 2010).

From the above–mentioned evidence, we suggest that deformation during the collision of the Caribbean Large Igneous Province persisted from the latest Cretaceous through Paleocene time and influenced the growth of the early Andean Foreland Basin. This early shortening prompted strong exhumation in the Central Cordillera and localized basement uplifts in the Middle Magdalena Valley with deformation possibly persisting into the early Eocene (Mora et al., 2013a).

5. Middle Eocene to Early Oligocene Evolution of the Northern Andes (48–28 Ma)

5.1. Middle Eocene to Early Oligocene in Western and Central Colombia and Ecuador: Increased Exhumation and Convergence

Spikings et al. (2001) suggested that in Ecuador <1 km/my exhumation occurred along the Western and Eastern Cordilleras from ca. 43 to 30 Ma (Figure 8). Spikings et al. (2001, 2010) proposed that this exhumation was the product of an abrupt increase in Farallon–South America convergence rather than accretion of an Eocene island arc. This increased exhumation was accompanied by foreland deposition of the coarse–grained Upper Tiyuyacu Formation (Baby et al., 2013). Similarly, the Central Cordillera of Colombia experienced moderate exhu-


a
b
c
54:
74.4 ± 10.6
70.4 ± 6.3
53:
13.4 ± 1.4
72.9 ± 18.8
56:
40.2 ± 2.6
65.5 ± 6.0
58:
31.0 ± 1.9
45.5 ± 3.1
58.5 ± 8.0
62.6 ± 1.1
72.3 ± 0.3
179:
51.8 ± 7.4
165:
37.8 ± 5.2
41.6 ± 5.4
166:
39.0 ± 0.3
32.8 ± 1.9
167:
38.1 ± 5.4
46.4 ± 5.8
176:
64.5 ± 14.6
148:
53.0 ± 4.8
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39.1 ± 2.1
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69.7 ± 8.6
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20.6 ± 1.4
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74.8 ± 7.4
64:
59.8 ± 10.2
62.6 ± 0.7
65:
43.5 ± 4.8
80.8 ± 0.3
67:
113.4 ± 22.8
80:
41.0 ± 6.6
154:
56.6 ± 7.4
53.1 ± 5.6
155:
44.3 ± 6.2
71.4 ± 9.8
156:
30.7 ± 1.8
48.2 ± 4.8
47.9 ± 5.2
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39.6 ± 7.0
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160:
69.4 ± 17.2
177:
78.6 ± 19.8
161:
43.9 ± 4.2
Manizales Pluton
76° 00' W
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Yarumal
Altiplano
Antioqueño
Medellín
San Luis
Sonsón
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0 25 50 km
94:
61.5 ± 9.4
67.9 ± 7.4
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95:
62.8 ± 6.8
62.5 ± 5.2
09:
43.0 ± 3.0
30.6 ± 5.8
74.6 ± 13.4
114.1 ± 0.9
08:
106.6 ± 16.0
07:
6.2 ± 0.4
64.9 ± 10.2
88.3 ± 12.4
109.8 ± 2.9
06:
47.7 ± 2.7
35.8 ± 4.6
81.3 ± 10.6
109.7 ± 1.3
26:
6.1 ± 0.4
13.9 ± 2.4
45.6 ± 7.6
67.9 ± 1.6
28:
64.4 ± 3.6
89:
117.2 ± 9.4
112.0 ± 3.7
90:
128.1 ± 6.0
102:
46.9 ± 8.1
91:
41.3 ± 4.2
30:
44.8 ± 8.4
42:
77.6 ± 5.7
04:
10.6 ± 0.8
59.2 ± 20.2
02:
32.1 ± 7.2
63.6 ± 9.4
03:
37.1 ± 7.2
01:
116.4 ± 0.9
86:
9.3 ± 0.8
35.0 ± 8.2
85:
30.5 ± 5.8
05:
7.5 ± 0.5
59.8 ± 16.8
85.3 ± 18.2
81:
103.6 ± 13.0
130.2 ± 2.8
136.4 ± 0.5
19:
38.7 ± 18.0
18:
19.6 ± 4.2
54.2 ± 6.0
17:
39.3 ± 12.0
14:
47.0 ± 9.0
84:
134.3 ± 0.7
82:
11.1 ± 0.7
63.3 ± 8.2
77.6 ± 10.8
137.3 ± 0.9
76° 30' W
75° 30' W
4° 30' N
3° 30' N
Armenia
Córdoba
Pluton
La Línea
Ibagué
Bolívar Ultramafic
Complex
Buga
Batholith
Cali
CPF
IF
0 25 50 km
129:
4.5 ± 0.3
9.3 ± 0.5
8.2 ± 1.2
139:
18.7 ± 7.4
112.0 ± 16.6
133:
3.5 ± 0.3
134:
15.9 ± 4.4
109.2 ± 10.8
136:
13.7 ± 2.2
106.8 ± 13.6
121:
12.2 ± 0.9
25.8 ± 4.8
77° 30' W
76° 30' W
1° 30' N
0° 30' N
PP
Ricaurte
Pasto
Mocoa
AzBF
Ecuador
0 25 50 km
Quaternary – Neogene
Paleogene – Eocene
Western Cordillera and Cauca–Patía valley
(Calima Terrane)
Late Cretaceous oceanic plateau
(volcanic and Amaime Formations)
Upper Cretaceous sedimentary rocks
(Cisneros and Espinal Formations)
Upper Cretaceous intrusives
(Buga Batholith)
Central and Eastern Cordilleras
Cretaceous arc
(Quebradagrande Complex)
Medium–high pressure metamorphic
rocks (e.g., Arquía Complex)
Late Cretaceous arc intrusives (Antioquian
Batholith and Córdoba Pluton)
Upper Cretaceous sedimentary rocks
Lower Cretaceous sedimentary rocks
Jurassic granitoids (Ibagué Batholith)
and volcanic rocks (Saldaña Formation)
Undifferentiated Triassic (Cajamarca
Complex) and Permian granitoids
Undifferentiated Triassic metasedimen-
tary rocks (e.g., Cajamarca Complex)
and older metamorphic units (e.g., La
Miel Orthogneiss)
Sample number (DV#)
Apatite (U–Th)/He
Zircon (U–Th)/He
Apatite Fission Track
Zircon Fission Track
Feldspar 40Ar/39Ar
Biotite 40Ar/39Ar
Hornblende 40Ar/39Ar

←

Figure 4. Geological maps of the study regions of Villagómez & Spikings (2013) (see Figures 1, 2a) within the Central and Western Cordilleras and the Cauca–Patía valley of Colombia (after Gómez et al., 2007) showing sample locations and the thermochronological ages acquired in this study. **(a)** Northern Colombia; **(b)** Central Colombia; **(c)** Southern Colombia. All ages are given in Ma with an uncertainty of ±2σ, and sample codes are shown in blue (DV#). (OPF) Otú–Pericos Fault; (PF) Palestina Fault; (SJF) San–Jeronimo Fault; (MB) Mande Batholith; (CAF) Cauca–Almaguer Fault; (SPF) Silvia–Pijao Fault; (HP) Hatillo Pluton; (CPF) Cali–Patía Fault; (IF) Ibagué Fault; (PP) Piedrancha Pluton; (AzBF) Amazonian Border Fault.

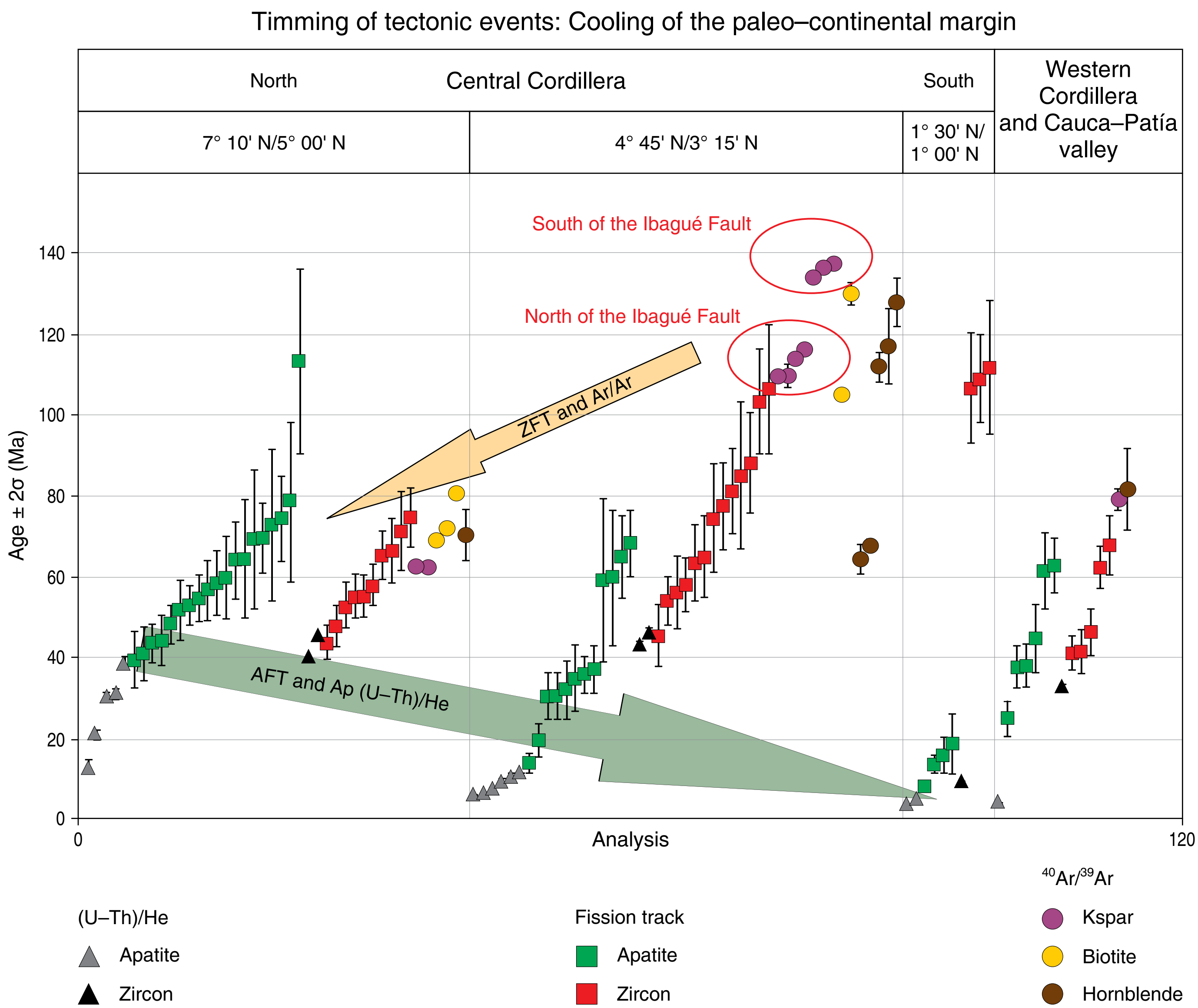

Figure 5. Compilation of thermochronological ages (±2σ) of the Central and Western Cordilleras and of the Cauca–Patía valley in Colombia (after Villagómez & Spikings, 2013). Apatite FT and (U–Th)/He ages decrease toward the south of the Central Cordillera.

mation (<0.3 km/my) at 40–30 Ma near major faults such as the Palestina, Ibagué, and Otú–Pericos Faults (Figure 10; e.g., Villagómez & Spikings, 2013). A modest ca. 45 to 40 Ma episode of exhumation (<0.2 km/my) has also been identified in the northern Central Cordillera and ascribed to a shift in Farallon–South America convergence (Restrepo–Moreno et al., 2009).

5.2. Middle Eocene in Eastern Colombia: Tectonic Quiescence (48–38 Ma)

Mora et al. (2013a) suggest that the middle Eocene was a time of tectonic quiescence in the Magdalena Basin and Eastern Cordillera on the basis of: (a) Low accumulation rates in the middle Eocene Upper Mirador and Lower Esmeraldas Formations of

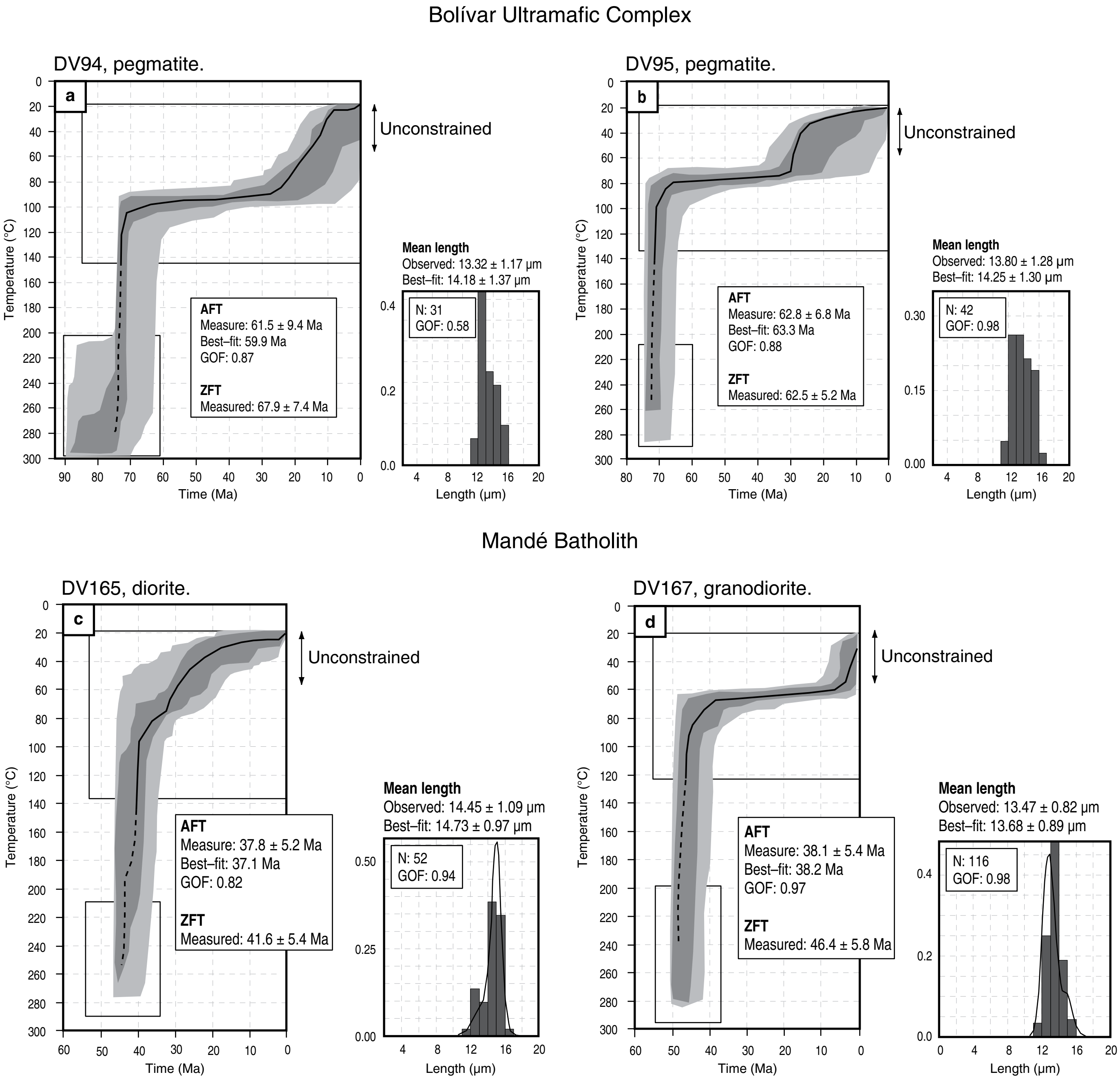

Figure 6. Time–temperature solutions for allochthonous rocks of Colombia's Western Cordillera obtained by (i) the inverse modeling of apatite FT age and length data, (ii) weighted mean (U–Th)/He dates and grain size data (calculated from the weighted mean of diffusion lengths). The modeling referred to Reiners et al. (2004) kinetic relationship for the diffusion of He in zircon, Flowers et al. (2009) for the diffusion of He in apatite and Ketcham et al. (2007) for FT annealing in apatite. A controlled random search procedure was used to search for best–fit data. Dark gray regions are envelopes of "good fit" and light gray areas denote "acceptable fit." The thick black line shows the statistically best fitting solution. Measured and predicted data for the best fit model are shown. Solutions are considered to show good fit when track length histograms and model ages pass Kuiper's statistic test with values of >0.5 and are considered acceptable for values of >0.05. The models are extrapolated to temperatures for the partial retention of argon when (i) the $^{40}Ar/^{39}Ar$ ages of ferromagnesian phases overlap with the timing of cooling obtained by inverting the FT and (U–Th)/He data or when (ii) there are interpretable alkali feldspar $^{40}Ar/^{39}Ar$ ages. Dashed lines show paths manually interpolated from the $^{40}Ar/^{39}Ar$ data. (GOF) Goodness–of–fit. After Villagómez & Spikings, 2013.

the Eastern Foothills and Middle Magdalena Valley, respectively (Mora et al., 2013a) and (b) U–Pb data suggestive of drainage divide advance toward the deformation front (Silva et al., 2013).

Elevated exhumation rates in Ecuador during the middle Eocene are difficult to reconcile with regional quiescence in Colombia. We speculate that this could be related to along–

strike variations in Pacific margin architecture and Farallon–South America convergence.

5.3. Late Eocene to Early Oligocene in Central and Eastern Colombia: Renewed Deformation

Saylor et al. (2012b) used lag time analyses of detrital zircon low–temperature thermochronological data (Figure 11) to propose late Eocene to early Miocene deformation in the Eastern Cordillera. These findings were interpreted by Mora et al. (2013a) and Reyes–Harker et al. (2015) to represent renewed tectonic activity along the western half of the Eastern Cordillera. In this context, the Soápaga and Machetá Faults would represent the active deformation front of the northern Andes during late Eocene to early Oligocene time with the rapid subsidence of the developing Llanos Foreland Basin to the east. This facilitated a deposition of fine–grained marine units corresponding to the shaly C8 Member of the Carbonera Formation.

6. Middle to Late Oligocene Evolution (28 to 23 Ma)

6.1. Western and Central Colombia and Ecuador

Spikings et al. (2010) linked the fragmentation of the Farallon Plate and associated changes in convergence at 23 Ma (Lonsdale, 2005) to cooling and moderate exhumation (<0.5 km/my) in the Eastern Cordillera of Ecuador. Spikings et al. (2010) suggested that this Oligocene deformation was limited in the Western Cordillera and only affected fault blocks with a favorable orientation.

No evidence of significant Oligocene exhumation has been detected in the Western and Central Cordilleras of Colombia from available, albeit limited, thermochronological data (Villagómez & Spikings, 2013). This could be a consequence of strain partitioning through which the preferential reactivation of the Amazonian Border Fault System and Santa Marta–Bucaramanga Fault deformed and exhumed the Eastern Cordillera of Colombia (Mora et al., 2010a; Parra et al., 2012; Saylor et al., 2012a) and uplifted the Sierra Nevada de Santa Marta (Villagómez et al., 2011b; Piraquive et al., 2018), thus isolating the Central and Western Cordilleras.

6.2. Eastern Cordillera of Colombia

Different studies suggest that the eastern flank of the Eastern Cordillera (Figure 2c) was actively exhuming (Figure 12; Parra et al., 2009b) and shedding sediments (Figure 13; Horton et al., 2010a, 2010b; Parra et al., 2010) to the Llanos Foreland Basin by the Oligocene. Mora et al. (2010a, 2013a; Figure 2b) further employed thermochronological analyses to demonstrate

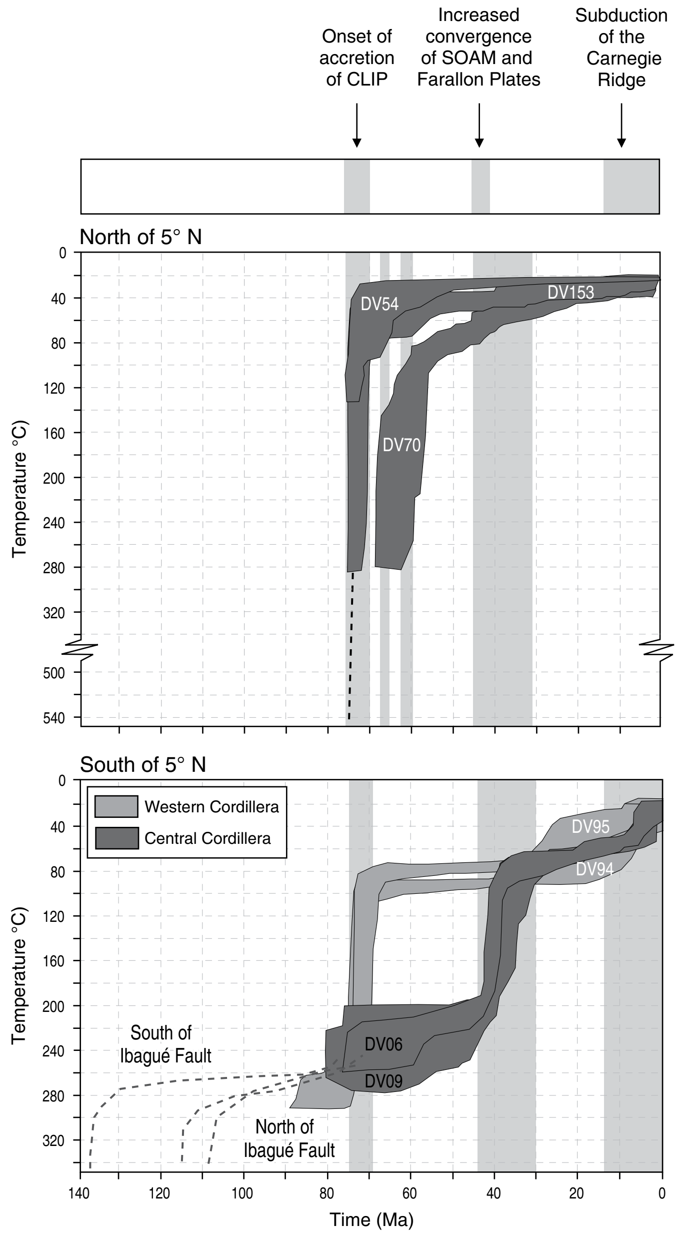

Figure 7. Summary of good–fit thermal history solutions for a representative selection of samples of the Central Cordillera (Late Cretaceous continental margin; dark gray) and Western Cordillera (Late Cretaceous indentor; light gray) after Villagómez & Spikings, (2013). Figure 6 explains their calculation and constraining data. The solutions highlight the main periods of exhumation of the Central and Western Cordilleras. Vertical bands highlight the timing of rapid cooling and exhumation in Colombia, and labels denote sample numbers. (CLIP) Caribbean Large Igneous Province. (SOAM) South America.

that this behavior can be related to the inversion of the entire Neocomian graben of the Eastern Cordillera. In addition, Mora et al. (2013b) use fracture patterns, fluid inclusions, and thermochronology to document several locations with Oligocene low–amplitude folding in the Eastern Cordillera and in coeval growth strata (Figure 14; Mora et al., 2013a). The study covers

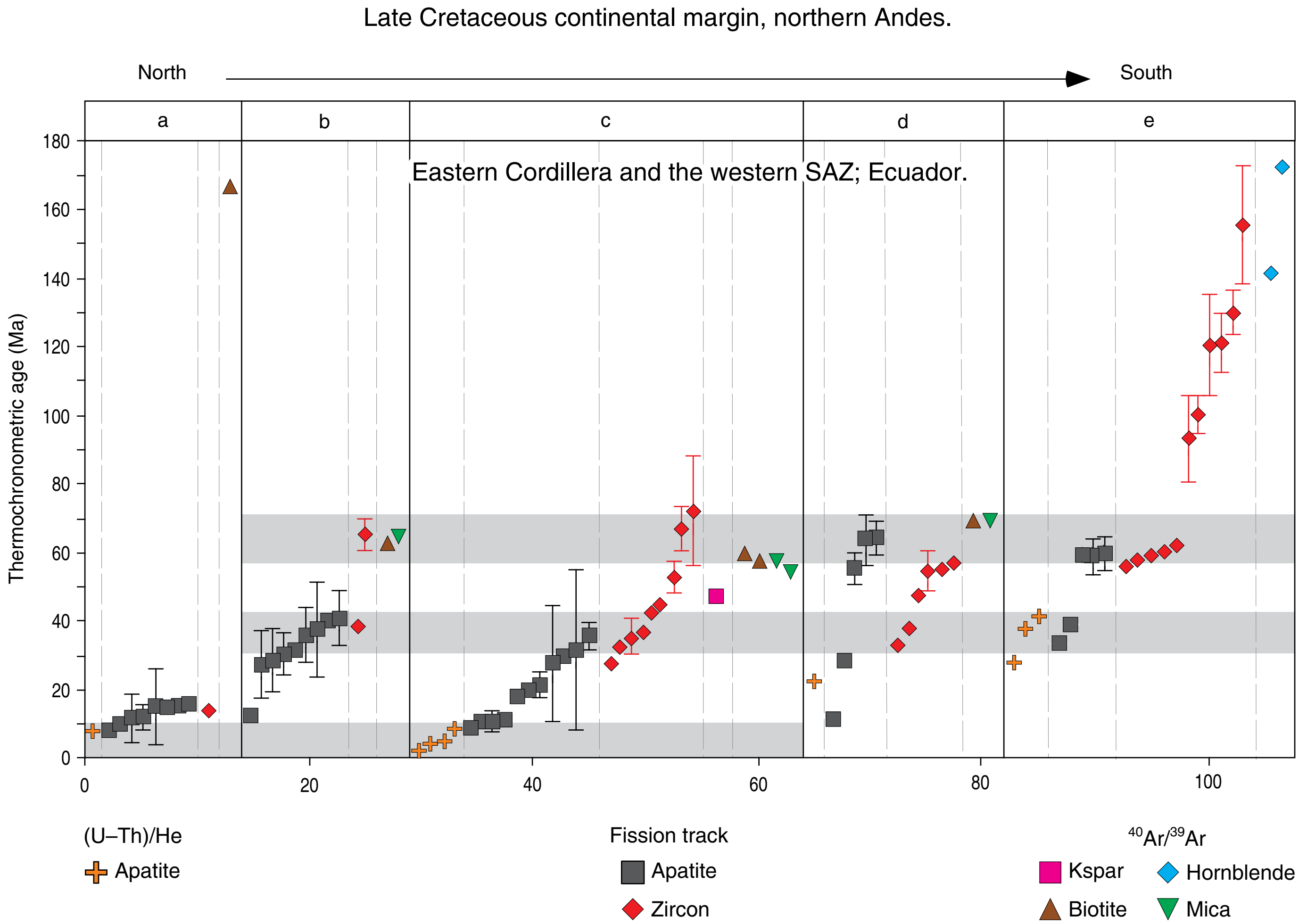

Figure 8. A compilation of white mica and biotite $^{40}Ar/^{39}Ar$ and ZFT and AFT ages obtained from traverses across the Cordillera Real of Ecuador. Shaded horizontal bars denote time periods in which regional scale exhumation was occurring at its highest rate (modified after Spikings et al., 2000, see Figure 2a for the location). (SAZ) Sub–Andean Zone (Ecuador).

western and eastern sectors of the Eastern Cordillera, in the Magdalena and Llanos Foothills, respectively.

7. Latest Oligocene to Early Miocene in Northern Colombia (25–16 Ma)

In studying the northernmost Central Cordillera (Figure 1), Restrepo–Moreno et al. (2009) used apatite (U–Th)/He data to constrain modest exhumation in discrete fault blocks during the latest Oligocene – early Miocene (ca. 25–20 Ma). Exhumation rates reached roughly ca. 0.2 km/my and are attributed to increased Nazca–South America convergence (Restrepo–Moreno et al., 2009). Farris et al. (2011) suggest that the early Miocene involved the most interactions of the Panamá–Chocó Terrane with northern Colombia. This exhumation might have been a response to initial Panamá accretion, which ultimately led to the closure of the Central American Seaway (Duque–Caro, 1990; Montes et al., 2015).

For the Eastern Cordillera, Parra et al. (2009a, 2009b; Figure 2c) document continued tectonic activity and exhumation. However, there is no direct evidence of elevations of above 1 km; in fact, pollen records (Figure 15; Hooghiemstra et al., 2006) show that areas of above 2 km elevation today are inferred to be at temperatures equivalent to those of low elevation tropical areas. New paleoelevation records based on geochemistry (lipid biomarkers) support this interpretation (Anderson et al., 2015).

8. Middle Miocene to the Present (16 to 0 Ma)

8.1. Western and Central Colombia and Ecuador

In Ecuador, Spikings et al. (2001) identified a northward–younging, along–strike progression of exhumation during the middle to late Miocene. Spikings et al. (2001, 2010) suggested

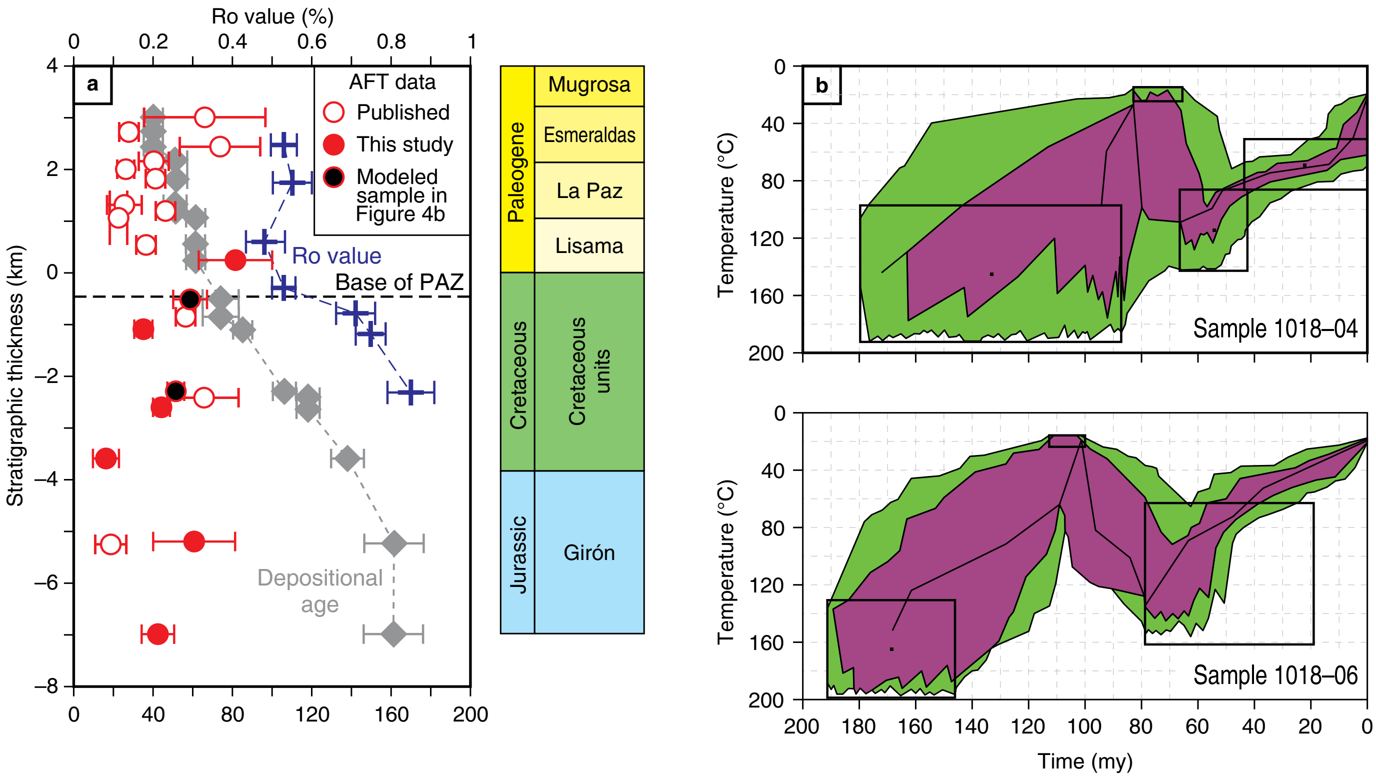

Figure 9. (a) Plot showing apatite fission–track (AFT) ages (red), vitrinite reflectance (Ro) values (blue), and stratigraphic ages (gray). Zero represents the base of the Cenozoic section. (PAZ) Partial annealing zone. **(b)** Thermal modeling results depicting time–temperature histories of two reset Cretaceous sandstones. Black boxes define time–temperature constraints for provenance, deposition, and burial–exhumation. Purple and green fields represent good and acceptable model fits, respectively. Figure after Parra et al. (2012). See Figure 2c for the location.

that the Eastern Cordillera of northern Ecuador (Central Cordillera of Colombia) was positioned at depths of roughly 3.5 km at ca. 15 Ma while southern latitudes were positioned at depths ≤1.3 km. This variation is attributed to rock uplift and exhumation driven by the collision of the Carnegie Ridge with South America. Villagómez & Spikings (2013) similarly constrained amplified exhumation rates at which rocks were exhumed from depths of ≥3 km since ca. 15 Ma in the southern Central Cordillera of Colombia (Figure 5).

On the other hand, the northernmost continuation of the northwestern Andes and of southern Central America experienced increased tectonic deformation and uplift in the Miocene potentially related to the main collision of the Panamá–Chocó Terrane (Duque–Caro, 1990; Farris et al., 2011; Montes et al., 2015). After the middle Miocene accretion of the Panamá–Chocó Terrane, renewed coupling and the increased convergence of the Nazca Plate beneath South America led to intense magmatism in Colombia and Ecuador south of ca. 5.5° N. Farther north, arc volcanism started to vanish from 9 to 4 Ma due to slab flattening. In around 4 Ma, slab rollback and renewed magmatism occurred as a result of slab failure along the Caldas Tear (Wagner et al., 2017), possibly renewing sedimentation in the Cauca and Magdalena intermontane basins.

8.2. Eastern Cordillera of Colombia

In the Eastern Cordillera of Colombia (Figure 2b), a recent acceleration of exhumation is recorded in the Quetame Massif and Cocuy Range (Figure 16; Mora et al., 2008, 2015a). In these areas, young AFT ages (<3 Ma) indicate accelerated cooling, and cross–cutting relationships show that most shortening occurred from the late Miocene onward (e.g., Mora et al., 2013a). Finally, paleoelevation data from palynology (Wijninga, 1996) and lipid biomarkers (Anderson et al., 2015) support an interpretation of topographic growth starting by the middle Miocene and finalized by 3 Ma.

Other geomorphic features in Colombia such as deep canyons in the northern Cauca River valley between the Western and Central Cordilleras may suggest youthful rock uplift and river incision. Another outstanding feature is the Sierra Nevada de Santa Marta (Figure 1), whose prominent relief adjacent to the Caribbean Sea suggests renewed tectonic activity consistent with thermochronometric data (Villagómez et al., 2011b). These geomorphic features appear to suggest that recent topographic growth is a ubiquitous phenomenon in the northern Andes. Such rock uplift has been instrumental in renewing coarse–grained sedimentation and basin compartmentalization

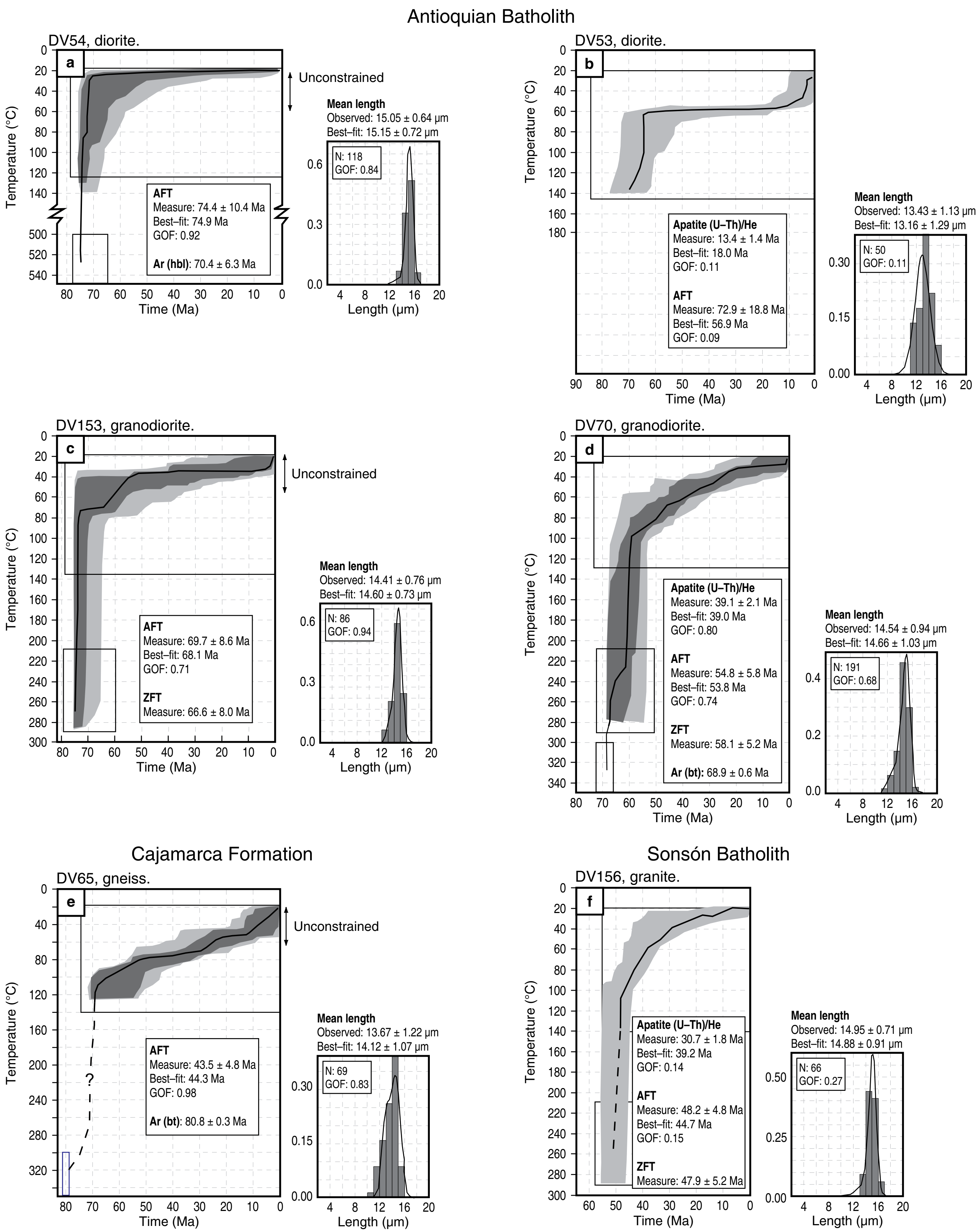
Antioquian Batholith
DV54, diorite.
a
Unconstrained
Temperature (°C)
Time (Ma)
AFT
Measure: 74.4 ± 10.4 Ma
Best–fit: 74.9 Ma
GOF: 0.92
Ar (hbl): 70.4 ± 6.3 Ma
Mean length
Observed: 15.05 ± 0.64 μm
Best–fit: 15.15 ± 0.72 μm
N: 118
GOF: 0.84
Length (μm)
DV53, diorite.
b
Apatite (U–Th)/He
Measure: 13.4 ± 1.4 Ma
Best–fit: 18.0 Ma
GOF: 0.11
AFT
Measure: 72.9 ± 18.8 Ma
Best–fit: 56.9 Ma
GOF: 0.09
Mean length
Observed: 13.43 ± 1.13 μm
Best–fit: 13.16 ± 1.29 μm
N: 50
GOF: 0.11
DV153, granodiorite.
c
Unconstrained
AFT
Measure: 69.7 ± 8.6 Ma
Best–fit: 68.1 Ma
GOF: 0.71
ZFT
Measure: 66.6 ± 8.0 Ma
Mean length
Observed: 14.41 ± 0.76 μm
Best–fit: 14.60 ± 0.73 μm
N: 86
GOF: 0.94
DV70, granodiorite.
d
Apatite (U–Th)/He
Measure: 39.1 ± 2.1 Ma
Best–fit: 39.0 Ma
GOF: 0.80
AFT
Measure: 54.8 ± 5.8 Ma
Best–fit: 53.8 Ma
GOF: 0.74
ZFT
Measure: 58.1 ± 5.2 Ma
Ar (bt): 68.9 ± 0.6 Ma
Mean length
Observed: 14.54 ± 0.94 μm
Best–fit: 14.66 ± 1.03 μm
N: 191
GOF: 0.68
Cajamarca Formation
DV65, gneiss.
e
Unconstrained
?
AFT
Measure: 43.5 ± 4.8 Ma
Best–fit: 44.3 Ma
GOF: 0.98
Ar (bt): 80.8 ± 0.3 Ma
Mean length
Observed: 13.67 ± 1.22 μm
Best–fit: 14.12 ± 1.07 μm
N: 69
GOF: 0.83
Sonsón Batholith
DV156, granite.
f
Apatite (U–Th)/He
Measure: 30.7 ± 1.8 Ma
Best–fit: 39.2 Ma
GOF: 0.14
AFT
Measure: 48.2 ± 4.8 Ma
Best–fit: 44.7 Ma
GOF: 0.15
ZFT
Measure: 47.9 ± 5.2 Ma
Mean length
Observed: 14.95 ± 0.71 μm
Best–fit: 14.88 ± 0.91 μm
N: 66
GOF: 0.27

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Figure 10. Time–temperature solutions for autochthonous rocks of Colombia's northern (ca. 6° N) Central Cordillera obtained by the inverse modeling of AFT age and length data, and weighted mean (U–Th)/He dates and grain size data (calculated using the weighted mean of the diffusion lengths) obtained from Reiners et al. (2004) kinetic relationship for the diffusion of He in zircon, Flowers et al. (2009) for the diffusion of He in apatite and Ketcham et al. (2007) for FT annealing in apatite. A controlled random search procedure was used to search for best–fit data. Dark gray regions denote envelopes of "good fit" and light gray denote "acceptable fit." The thick black line denotes the statistically best fitting solution. Measured and predicted data for the best fit model are shown. Solutions were considered to show good fit when track length histograms and model ages passed Kuiper's statistic test with values of >0.5 and were considered to be acceptable with values of >0.05. The models are extrapolated to temperatures for the partial retention of argon when (i) the $^{40}Ar/^{39}Ar$ ages of ferromagnesian phases overlap with the timing of cooling obtained by inverting the FT and (U–Th)/He data or when (ii) there are interpretable alkali feldspar $^{40}Ar/^{39}Ar$ ages. Dashed lines denote paths manually interpolated from the $^{40}Ar/^{39}Ar$ data. (GOF) Goodness–of–fit. (After Villagómez & Spikings, 2013).

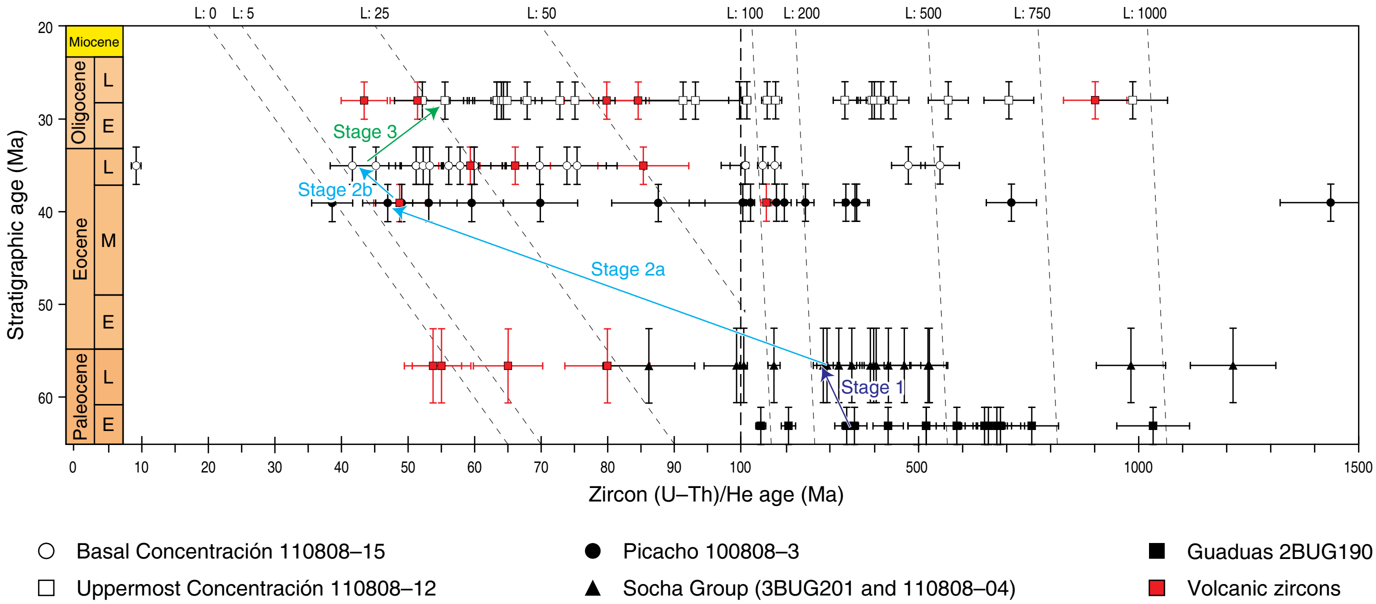


Figure 11. Double–dated ZHe ages plotted by stratigraphic age and lag time (dashed diagonal lines). Zircons are identified as of volcanic origin when their ZHe and Zircon U–Pb ages overlap within their 2σ uncertainty. Volcanic zircons (red) are excluded from the lag time analysis. The three stages are interpreted as episodes of rapid exhumation (Stages 1 and 2) and of the introduction of new supra–partial retention zone sedimentary sources (Stage 3). Lag time values (L) are given in my. Note that the Socha Group includes data from both the Upper Socha and Lower Socha Formations. After Saylor et al. (2012b).

within the Amazonas Foreland and Upper Magdalena Basin. For example, continued fault activity in southern Colombia accommodated the uplift and exhumation of the Garzón Massif (Anderson et al., 2016) between the Late Miocene and Pliocene. This uplift is of paramount importance to large river systems draining northern South America, topographically isolating the Magdalena, Orinoco, and Amazon watersheds (Anderson et al., 2016; Mora et al., 2010b).

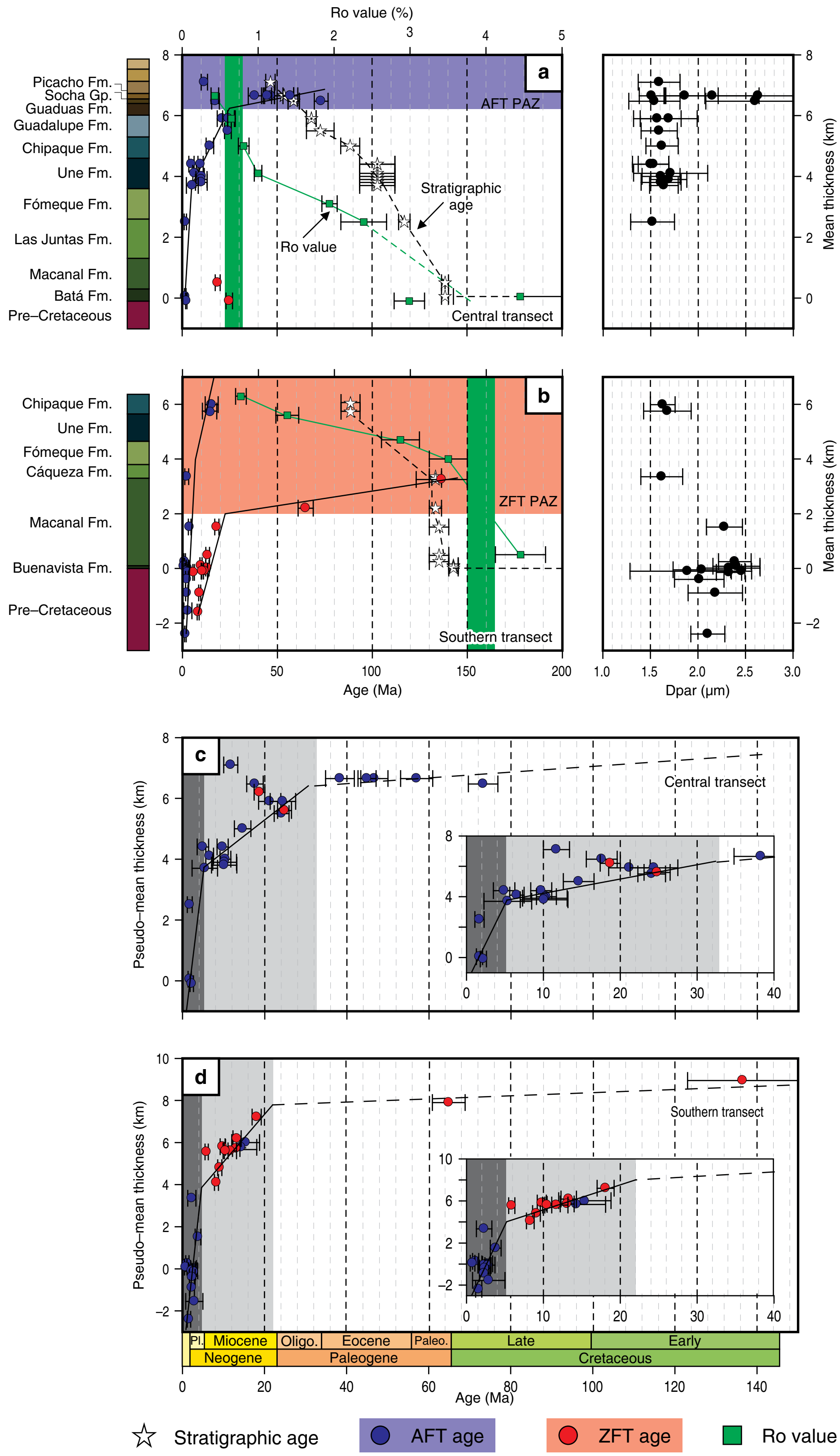
In contrast, neotectonic studies have dated Late Pleistocene to Holocene deformation in the Eastern Foothills (Ketcham et al., 2018; Mora et al., 2010c; Veloza et al., 2015). Relative to late Miocene to Pliocene topographic growth, where vertical uplift appears to dominate, the neotectonic deformation of the Eastern Foothills suggests the occurrence of mostly horizontal shortening perpendicular to frontal ranges (Mora et al., 2006, 2009, 2010c, 2014; Veloza et al., 2012)

Recent thermochronometric and kinematic analyses (Carrillo et al., 2016; Mora et al., 2015b) summarize different deformational styles in a single geometric reconstruction. Carrillo et al. (2016) suggested that the Eastern Cordillera reconstructions require late Miocene to Plio–Pleistocene topographic growth unrelated to fault–related folding with subsequent Pleistocene to Holocene horizontal shortening in the Eastern Foothills. It is intriguing that vertical topographic growth and horizontal shortening in the foothills appear to be non–synchronous phenomena.

9. Discussion

9.1. Discussion of Paleogeographic Implications

Regional geological reconstructions are important for several disciplines and help address recent appreciation of the interac-



tions between genetics and geology (e.g., Baker et al., 2014). This diversification of scientific interest has been particularly impressive in studies of the northern Andes. In the preceding synthesis, we summarize evidence for the timing of different geological processes from thermochronological records. In this section, we emphasize key interpretations while recognizing that geological reconstructions of past configurations are limited and must be used with caution to review major processes

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Figure 12. Fission track data and vitrinite reflectance (Ro) values for samples from the **(a)** central and **(b)** southern transects of the Colombian Eastern Cordillera at roughly 4.5° N. The data are plotted against the stratigraphic position of the base of Cretaceous rift–related units (see Figure 1 for the location). Stratigraphic thicknesses and ages are compiled from Ulloa & Rodríguez (1979) and Mora et al. (2008). Vertical green bars represent the range of Ro values corresponding to the temperature delimiting the base of the AFT (central transect) and ZFT (southern transect) partial annealing zones (blue and pink shaded areas, respectively). Stacked pseudovertical profiles are obtained for the **(c)** central and **(d)** southern transects. AFT data are plotted at their original stratigraphic positions as in Figure 9a and 9b, but ZFT data are offset upward by an amount proportional to the depth difference between the ZFT and AFT isotherms estimated at 5.7 km. The first break in slope denoted by the vertical light gray band at ca. 40 – 25 Ma (central profile) and 20 Ma (southern profile) marks the onset of thrust–induced cooling through the AFT and ZFT total annealing isotherms, respectively.

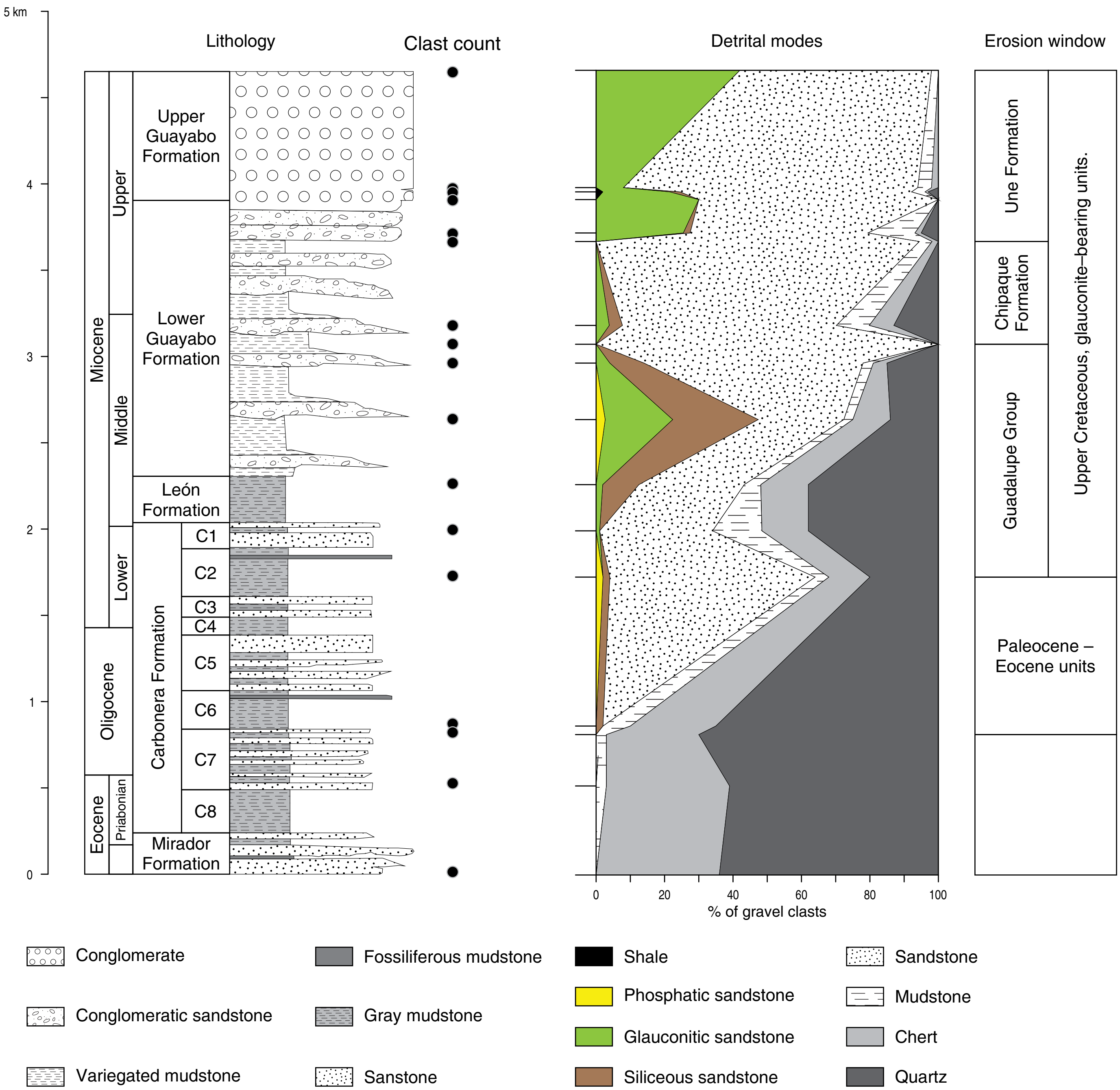

Figure 13. Compositional trends in Eocene to upper Miocene conglomerates of the Medina Basin. Black circles denote the stratigraphic positions of conglomeratic samples. Clasts of Upper Cretaceous glauconitic sandstone, phosphatic sandstone, and siliceous siltstone occur in Miocene strata of the Carbonera Formation and Guayabo Formation, documenting the progressive unroofing of the Eastern Cordillera (right panel). Figure after Parra et al. (2010).

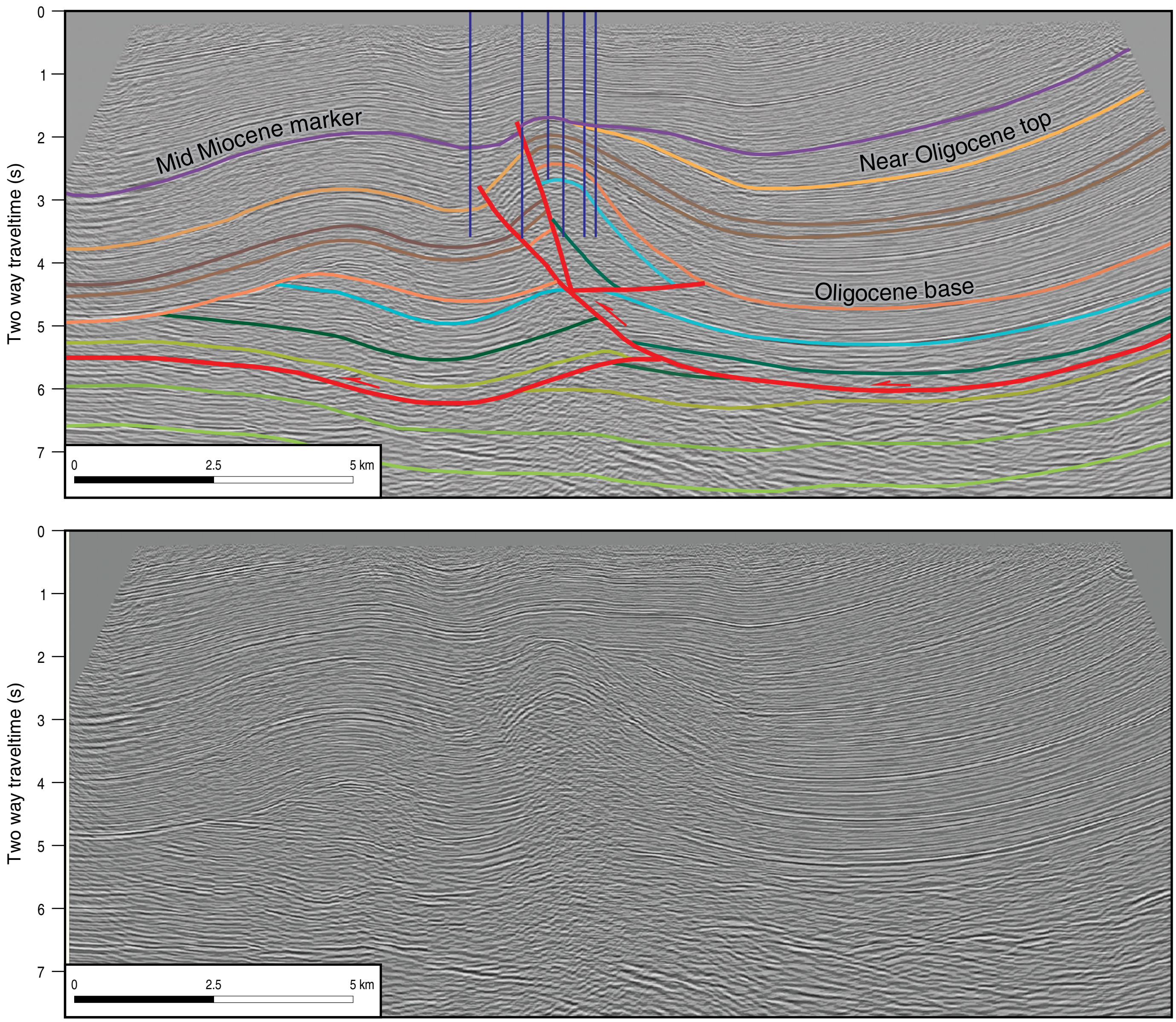

Figure 14. Oligocene growth strata in the Provincia Oil Field of the Middle Magdalena Basin.

and paleogeographic conditions of the Cenozoic evolution of the northern Andes.

Thin– and thick–skinned fold–thrust deformation has prevailed in Colombia throughout the Cenozoic. By the early Cenozoic, the basement of the present–day Western Cordillera was already juxtaposed to the continental margin. The accretion of a buoyant oceanic plateau coincided with the growth of a proto Western and Central Cordillera and the delivery of west–derived sediment to the proto–Magdalena Basin. However, the early Cenozoic accretion of the Western Cordillera did not require complete land emergence or ubiquitous mountain building.

The northern Central Cordillera and Cordillera Real of Ecuador record renewed exhumation during the Eocene based on very limited thermochronological data. A paucity of data on western Colombia has hampered paleogeographic reconstructions and hindered the identification of Eocene tectonic events. Systematic sampling for thermochronology, paleoelevation, and provenance investigation is required. Fortunately, sedimentary records of the Eastern Cordillera and Magdalena Basin provide valuable information for Eocene and younger reconstructions.

9.1.1. Eocene Proto–Magdalena River Draining to the Maracaibo Basin

Evidence for Eocene mountain building in the Central Cordillera and western Eastern Cordillera allowed Caballero et al. (2013a, 2013b) and Silva et al. (2013) to interpret a proto–Magdalena River draining toward the Maracaibo Basin rather than its present outlet in the Caribbean (Figure 2). Using detrital

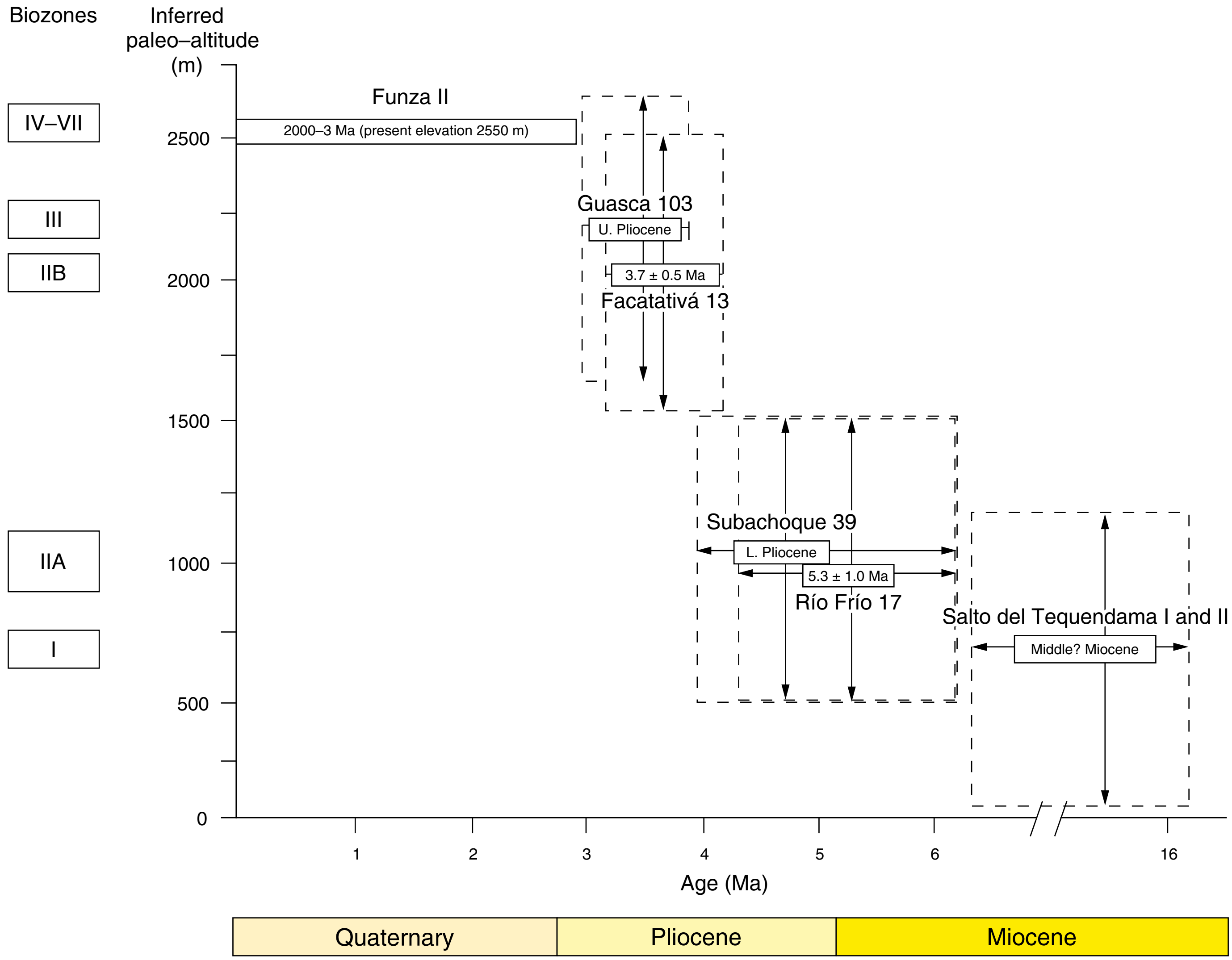

Figure 15. Inferred paleoelevation from reconstructed altitudinal vegetation belts based on characteristic pollen and paleobotanical associations found in sections Salto del Tequendama I and II, Río Frío 17, Subachoque 39, Facatativá 13, and Guasca 103 and in sedimentite core Funza–2. Sections are located in the outer parts of the Bogotá Basin. Uncertainties in age control and inferred paleoaltitude are shown as arrows. Biozones I to VII refer to stages of the uplift history and paleobiogeography of main (arboreal) taxa of the Eastern Cordillera (after van der Hammen et al., 1973; Wijninga, 1996).

zircon U–Pb age signatures, Horton et al. (2015) suggest that local small drainages were not fully integrated into a continuous proto–Magdalena River. Therefore, the main question is not whether Eocene rivers drained toward the Maracaibo region (e.g., Reyes–Harker et al., 2015) but whether a proto–Magdalena River existed. Although there was likely positive relief adjacent to the modern Magdalena valley, current ideas regarding the associated paleodrainage remain speculative.

9.1.2. Late Eocene to Middle Miocene Closed Middle Magdalena Valley

A significant element of Paleogene paleogeography concerns the hypothesis of Caballero et al. (2013a, 2013b) that the Middle Magdalena Valley (Figure 2) was an internally drained basin with no outlet toward the modern delta or Maracaibo Basin, an idea supported by others (e.g., Horton et al., 2015; Mora et al., 2018; Reyes–Harker et al., 2015). It seems clear that the Central and Eastern Cordilleras were topographically positive areas in the Paleogene. Because thermochronological data cannot address past drainage geometries, we await clear provenance data to provide support for this closed–drainage hypothesis or for possible alternative hypotheses.

9.1.3. Oligocene Proto–Sabana de Bogotá

Mora et al. (2013a) suggested that the axial Eastern Cordillera (Figure 2; i.e., the proto–Sabana de Bogotá) may have been an internally drained basin analogous to closed basins in the Bolivian Altiplano (Strecker et al., 2007, 2009). This idea is based

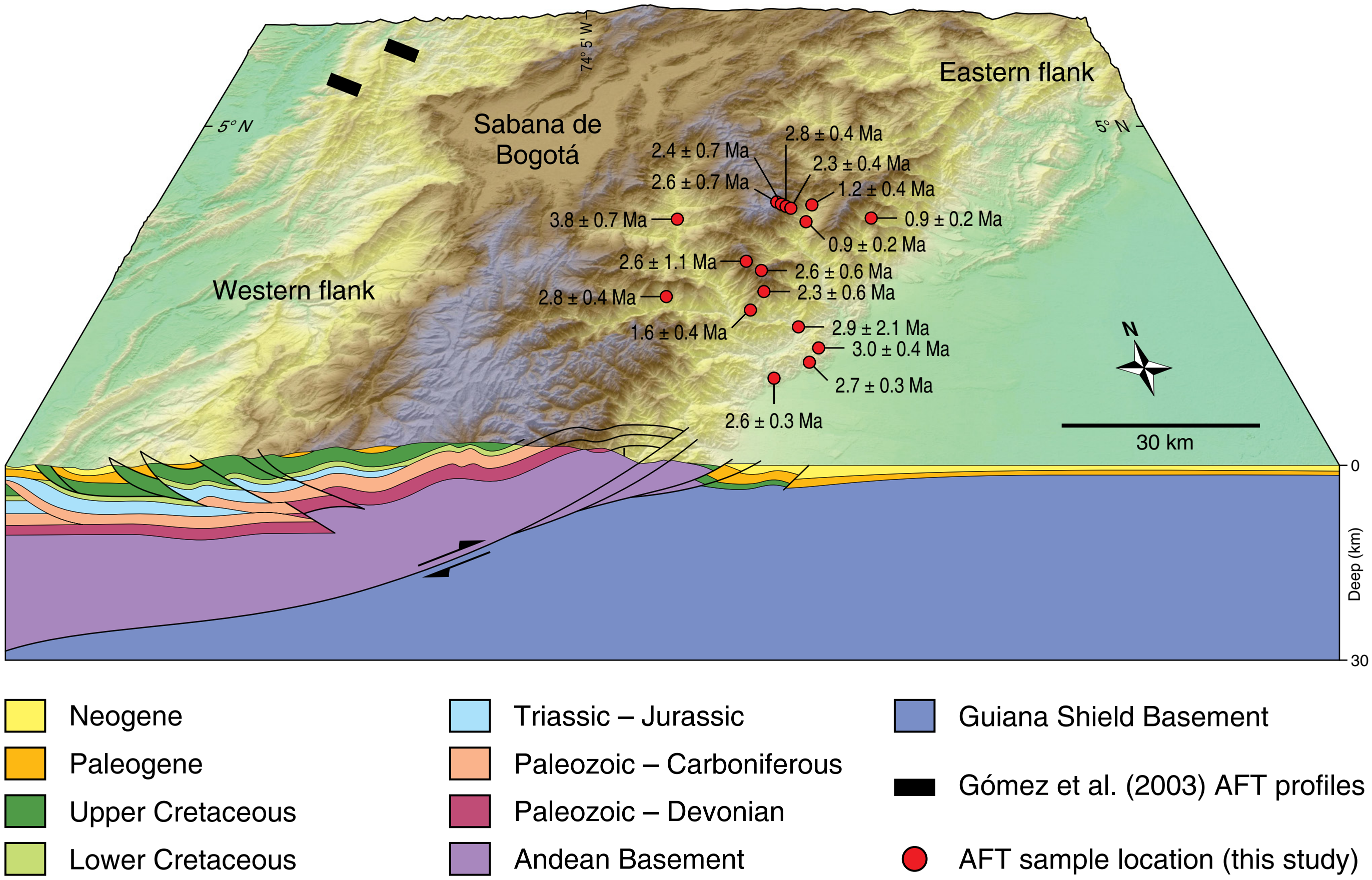

Figure 16. Digital elevation model of the Eastern Cordillera including the deeply dissected Eastern flank, the central flat–lying Sabana de Bogotá Basin, and the topographically lower western flank.

on evidence showing active exhumation on both flanks of the Eastern Cordillera (Figures 1, 2) while Oligocene deposition occurred in the axial zone. An alternative interpretation is that a proto–Sabana de Bogotá was externally drained to the Maracaibo region. More data are required, and therefore, it remains prudent to consider multiple hypotheses.

9.1.4. Middle Miocene Onset of the Magdalena River

Neogene provenance data suggest ongoing contributions from two different sources: The Central Cordillera to the west and the Santander Massif to the east (Caballero et al., 2013a; Horton et al., 2015; Reyes–Harker et al., 2015). The data suggest that the Magdalena Valley Basin (Figure 2) was no longer an internally drained basin based on seismic evidence for middle Miocene sedimentation above former barriers, although the seismic coverage is not robust enough to fully understand the 3D scenario.

Horton et al. (2015) suggest that the appearance of 100–0 Ma zircon grains and a regional switch to broad, multimodal age distributions reflect the late Miocene integration of the longitudinal proto–Magdalena River, linking the Middle Magdalena Valley Basin to southern headwaters of the Upper Magdalena Valley. The presence of fully integrated Magdalena River draining toward its delta should be detected in contemporaneous deposits. Mora et al. (2018) suggest that delta plain sandstones, mudstones, and coals indicate the presence of a proto–Magdalena delta in the Lower Magdalena Valley by middle Miocene time. However, no data yet link these deposits to potential source areas of the Magdalena valley. Near the modern delta, sedimentary units of the proto–Magdalena River delta and Magdalena submarine fan yield a late Miocene to Pliocene age (Cadena & Slatt, 2013). It could be that a middle Miocene delta feeding the Lower Magdalena Valley was replaced with a larger late Miocene delta in its present location, which was fed by an expanded drainage network comparable to the modern Magdalena watershed.

In summary, present data cannot determine whether the onset of the Magdalena River delta occurred by middle or late Miocene times. Fortunately, Miocene sedimentary records for the Magdalena headwaters to the modern delta have been preserved, providing opportunities for further investigations to distinguish among the competing hypotheses.

9.2. Panamá Accretion and the Central America Seaway

The accretion of the Panamá–Chocó Terrane (Figure 1) to continental Colombia probably commenced in the early Miocene (Farris et al., 2011) with the complete accretion and closure of the Central American Seaway occurring by the middle to late Miocene (Duque–Caro, 1990; Montes et al., 2015) and later (e.g., O'Dea et al., 2016).

Recent studies show that the emergence of Panamá involved a long and complex process starting in the Oligocene (Farris et al., 2011; Sepulchre et al., 2014). Montes et al. (2015) proposed that the Miocene appearance of significant populations of Eocene age zircons (ca. 59 to ca. 42 Ma) near the San Jorge River (e.g., Figure 2a) suggests derivation from Panamá. These studies make a key argument for a middle Miocene closure of the seaway. However, Montes et al. (2015) proposal involves an irregular drainage geometry with sediment coming from a slightly emergent Panamá in the northwest and making a U–turn toward the Lower Magdalena Valley in contrast to the roughly rectilinear fluvial drainage network in the south (Chocó) with the same Panamanian signature. On the basis of such difficulties and of additional geological challenges (e.g., Babault et al., 2013; Silva et al., 2013), paleogeographic reconstructions of emerged land masses do not yet provide an unambiguous answer regarding the timing of the closure of the Central American Seaway. Therefore, it is important to consider alternative hypotheses and to acquire new data regarding the emergence of land masses and the closure of the Central American Seaway.

9.2.1. Cauca and San Jorge Rivers

Geologic data for the region near the Cauca and San Jorge Rivers (Figure 2) provide evidence of Miocene deformation and suggest that positive topography in the westernmost Andes served as source areas for these rivers (Montes et al., 2015; Villagómez & Spikings, 2013). However, it is virtually impossible to know the elevation and continuity of these emergent areas and whether precursors to the modern Cauca and San Jorge Rivers were already in place at the time. Regarding this point, Mora et al (2018) propose a connection of the Lower Magdalena Valley to the Cauca valley as supported by middle Miocene provenance signatures and delta–plan facies for the Upper Member of the Amagá Formation (Montes et al., 2015; Piedrahita et al., 2017). The interpretation of ancestral rivers reaching the proto–Caribbean is speculative, but Mora et al. (2018) also suggest the presence of a Lower Amagá–Ciénaga de Oro delta by the late Oligocene – early Miocene based on provenance data (Montes et al., 2015), detrital zircon fission track thermochronology, and borehole facies analyses.

Mora et al. (2018) suggest that the first clear appearance of fluvial sedimentites in the Lower Magdalena Valley, Urabá, and southern Sinú Basins was delayed until the Pliocene deposition of the Corpa Formation. The presence of uplifted regions to the south near the modern Cauca and San Jorge River valleys (Villagómez & Spikings, 2013; Piedrahita et al., 2017) may suggest an advancing pair of prograding river deltas by late Oligocene to middle Miocene time in the Lower Magdalena Valley with the appearance of proximal fluvial sedimentites by the Pliocene. This hypothesis provides an alternative explanation according to which Late Paleogene to Neogene rivers originated in the south rather than from an emergent Isthmus of Panamá. More evidence is needed to discriminate between a proto–Cauca and proto–San Jorge Rivers provenance from the south and U–shaped river drainage from Panamá.

9.3. Key Neogene Tectonic Events

The Neogene subduction of the Carnegie Ridge (Figure 1) in northern Ecuador and southern Colombia had important consequences for the geometry of the subducting slab and the post–middle Miocene uplift and exhumation of the northern Andes. Miocene tectonic events are largely responsible for the present–day topography of Colombia (described in section 7).

9.3.1. Late Cenozoic Surface Uplift in the Eastern Cordillera

The Eastern Cordillera of Colombia (Figure 2) is one of the few areas of the northern Andes with paleoelevation constraints. In one of the oldest studies on this topic, van der Hammen et al. (1973) argued, as later reinforced by others (e.g., Andriessen et al., 1993; Helmens & van der Hammen, 1994; Hooghiemstra, 1984; Hooghiemstra & van der Hammen, 1998; Hooghiemstra et al., 2006; Kroonenberg et al., 1990; Wijninga, 1996; Wijninga & Kuhry, 1990), that late Miocene vegetation records collected at high elevations in the Eastern Cordillera resemble modern tropical lowland regions adjacent to the Eastern Cordillera.

Based on ZFT age control for sedimentary host units (Andriessen et al., 1993), it has been suggested that topographic growth from elevations <1000 m to present >2500 m elevations took place between 6 and 3 Ma (Mora et al., 2008). A refined magnetostratigraphic chronology suggests roughly 1 km of elevation increase between 7.6 and 3 Ma (Anderson et al., 2016). Mora–Páez et al. (2016) further suggested that confining topographic growth to 6–3 Ma is too rapid when compared to extrapolated Global Position System (GPS) rates of shortening. Ultimately, the original proposal made by van der Hammen et al. (1973) of late Miocene topographic growth has been generally confirmed by subsequent studies (Anderson et al. (2016; Mora et al., 2008).

Despite these paleoelevation estimates, many studies suggest that deformation has been active and that thrust–induced denudation was in place in all areas of the current Eastern

Cordillera since roughly 25 Ma (Horton et al., 2010a, 2010b; Mora et al., 2010d, 2013a, 2013b; Nie et al., 2010, 2012; Parra et al., 2009b; Saylor et al., 2011, 2012a, 2012b). This means that there was positive topography in the Eastern Cordillera, but the height of the mountains remains unclear. In other words, paleoelevation studies indicate that late Miocene topographic growth was finalized by 3 Ma (e.g., Wijninga, 1996; Anderson et al., 2016), but given the Paleogene onset of shortening, we do not yet know when topographic growth commenced.

For the cases mentioned above, it is important to realize that the geological record is incomplete. For example, a lack of early to middle Miocene sedimentary records for the Eastern Cordillera (e.g., Ochoa et al., 2012) precludes an assessment of paleoelevations for that time. Once again, such incomplete records suggest the need to consider multiple hypotheses.

9.4. Eastward Advance of the Orinoco River

Based on a detrital (U–Pb) zircon analysis, Escalona & Mann (2011) suggest an eastward advance of a proto–Orinoco River during the Cenozoic evolution of the northern Andes (Figure 2). This assessment was further refined by Reyes–Harker et al. (2015) and Mora et al. (2019) by correlating abundant new provenance data with exhumation in the Eastern Cordillera of Colombia. The main basis for this hypothesis is the presence of U–Pb ages inferred to originate from the orogen on the western side of the Llanos–Barinas Foreland Basin rather than from cratonic provenance. Although a provenance divide has been proposed by Reyes–Harker et al. (2015) and Mora et al. (2019) as the trace of a proto–Orinoco channel belt, further data are needed to reach a definitive conclusion.

9.5. Tectonic and Climatic Interactions

Mora et al. (2008) reported one of the youngest apatite fission track data sets of the Andes so far (Figures 2, 16). This set of Plio–Pleistocene ages postdates most topographic growth in the Eastern Cordillera of Colombia (e.g., Hooghiemstra et al., 2006 Anderson et al., 2016), yet coincides with faster deformation rates.

Mora et al. (2008) suggested that faster denudation rates may have promoted faster shortening rates during the latest Cenozoic. However, other studies have later demonstrated that rapid shortening occurred in zones of focused transpressional deformation, possibly independent of enhanced denudation (e.g., Bermúdez et al., 2013; Graham et al., 2018; Mora et al., 2015a; Ramirez–Arias et al., 2012). Although focused denudation helps, it is unlikely to be the single main factor in enhancing shortening rates. From this discussion, it appears that climate, precipitation, and associated denudation are important but not the principal factors that induce rapid motion along major faults, at least in the northern Andes.

10. Conclusions

In conclusion, although biologists and other scientists understandably desire high resolution data and finalized debates regarding various aspects of the paleogeography, none of the cases we have discussed in the northern Andes and Panamá be considered "solved," and the current data are consistent with multiple hypotheses. In our view, the geological record has two main problems: (i) In many areas, erosion and general preservation factors render the record incomplete and spatially fragmented, and (ii) in those areas where it is complete, we do not have enough information.

Ideal new information would be 3D seismic data in marine areas, where the quality of the seismic images is high. In contrast, seismic exploration in the northern Andes has its own problems: (i) its quality is poor due to the problems caused by the presence of mountains and deformation interfering with acquisition of proper images; and (ii) seismic coverage is far from being dense. One of the few areas where geological data provide a very good picture of complete geological evolution with the resolution sought by biologists and other scientists is the North Sea in northern Europe (e.g., IHS, 2018).

While some data sets like thermochronology can provide precise information on the places being exhumed and eroded, provenance tools (U/Pb or to an even greater extent petrography) always allow for multiple interpretations regarding drainage directions and timing for fluvial networks. The Orinoco, Magdalena, and Cauca Rivers histories and the Panamá Isthmus history serve as clear examples of this ambiguity. Other studies linked to the Amazon are even more difficult.

Definitive statements regarding the growth of topography are made even more complex by the fact that topography is always destroyed, and thus far we have not considered or been able to detect paleo–elevations of the northern Andes for times preceding the Oligocene (ca. 33 Ma). While undocumented pre–Oligocene high mountains of the northern Andes are possible, it is also possible that Neogene relief features have been destroyed and rebuilt such that river trajectories and connections that we have never imagined may have existed. For example, we assume that the Garzón Massif was already a positive topographic area by the middle Miocene, separating the Orinoco and Amazonas Basins from the Magdalena River Basin. However, Perez–Consuegra et al. (2018) have found paleontological signals of Orinoco and Amazonas Rivers connections by the late Miocene in the San Jacinto belt.

In general, we can conclude that thermochronological techniques are the most precise of the three tools discussed here in achieving location–specific rates while provenance techniques are very ambiguous when geologists try to suggest the location of ancestral drainages. In the meantime, paleo–elevation studies of the northern Andes are still very experimental. With the data available, we can identify general patterns of the Eastern

Cordillera, but data on rates and ages can still be improved. To create robust reconstructions, it is necessary to combine bed rock exhumation data with provenance and paleo–elevation studies. Few studies have combined both or all three since the pioneering studies by Mora et al. (2008) and Parra et al (2009a).

In sum, while a number of aspects of Colombia's Cenozoic tectonic evolution remain unclear, our lack of paleogeographic knowledge is more severe. Furthermore, our understanding of Central and Western Cordilleras responses to different regional events is even more limited. Therefore, more detailed and systematic thermochronological data and provenance and paleo–elevation studies will be instrumental to geologists providing more precise answers and support for other disciplines. In the meantime, working with multiple hypotheses and never with rigid assumptions is the most convenient and robust approach.

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Explanation of Acronyms, Abbreviations, and Symbols:

AFT	Apatite fission track
AHe	Apatite (U–Th)/He
GPS	Global Position System
T–t	Time–temperature
ZFT	Zircon fission track
ZHe	Zircon (U–Th)/He

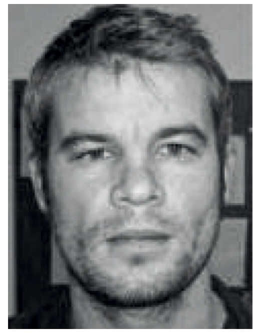
Authors' Biographical Notes

Andrés MORA is the chief geologist of Onshore Exploration at Ecopetrol. He received his BS in geology from the Universidad Nacional de Colombia and PhD from the Institut für Geowissenschaften, Universität Potsdam. His research interests include structural geology, petroleum exploration, and petroleum geology.

Diego VILLAGÓMEZ is a binational Swiss–Ecuadorian geologist. He has hands–on experience in the E&P of natural resources in Africa, Mexico, the Caribbean, and northern South America. Diego is particularly interested in the thermal fingerprint of processes that occur in the middle and upper parts of the crust, which is fundamental to understanding the "source to sink" relationship between erosional areas and basinal deposition.

Mauricio PARRA is an assistant professor at the Instituto de Energia e Ambiente of the Universidade de São Paulo, where he leads the Low–Thermochronology Laboratory. He received his BS in geology from the Universidad Nacional de Colombia and his PhD from the Institut für Geowissenschaften, Universität Potsdam. His research focuses on the tectonic evolution of mountain belts using thermochronometry and sedimentary basin analysis.

Víctor M. CABALLERO is a senior geologist and researcher of sedimentology and depositional systems at Ecopetrol–ICP. He received his BS and MS degrees in geology from the Universidad Industrial de Santander at Bucaramanga Colombia. His research interests include sedimentology, sequence stratigraphy, thermochronology, geochronology, and basin analysis.



Richard SPIKINGS graduated in geochemistry at the University of St. Andrews in 1993. His research in thermochronology earned a PhD in geology in 1998 from La Trobe University, Melbourne. Since 1998, he has worked as a postdoctoral fellow at the ETH–Zurich, and as tenured research staff at the University of Geneva where he currently manages the $^{40}Ar/^{39}Ar$ laboratory. His research has focussed on thermochronology and geochronology of the Andean cordilleras in Ecuador, Colombia, Venezuela, Perú, and Chile. More recently, Richard has focussed his research efforts on bulk and in–situ U–Pb thermochronology of accessory phases.

Brian K. HORTON is the Alexander Deussen professor of Energy Resources at The University of Texas at Austin and has a joint appointment with the Department of Geological Sciences and Institute for Geophysics in the Jackson School of Geosciences. He received his BS from the University of New Mexico, MS from Montana State University, and PhD from the University of Arizona. His research addresses the tectonics of sedimentary basins and the evolution of orogenic systems.

Josué Alejandro MORA–BOHÓRQUEZ graduated as a geologist from the Universidad Nacional de Colombia, Bogotá, in 1998, then obtained a MS degree in basin evolution and dynamics at Royal Holloway, University of London, United Kingdom, in 2001 and he is currently pursuing a PhD degree at the Free University of Berlin/GFZ Potsdam, Germany. He works as senior exploration geologist for Hocol S.A. since 2006. Prior to working for Hocol S.A., he was an exploration geologist at Petrobras Colombia doing regional studies of the Upper and Middle Magdalena Valley Basins from 2002 to 2004, and then he worked in coalbed methane and conventional hydrocarbon exploration for Drummond Ltd. Colombia, from 2004 to 2006. His research interests are tectonics and sedimentation, basin analysis, petroleum exploration, and hydrocarbon systems.

Richard A. KETCHAM is an associate professor with the Jackson School of Geosciences at the University of Texas at Austin. He received his BS in geology and computer science from Williams College in 1987 and his PhD in geological sciences from the University of Texas at Austin in 1995. His active research interests include thermochronology and geological applications of high–resolution X–ray computed tomography.

Juan Pablo ARIAS–MARTÍNEZ holds a BS degree in geology from the Universidad de Caldas, Colombia. He is currently an exploration geologist at Ecopetrol. His research interests include structural geology, sedimentology, and petroleum geology.