Resolving uplift of the northern Andes using detrital zircon age signatures

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ABSTRACT

Uplift of the Eastern Cordillera in the northern Andes has been linked to orographic climate change and genesis of South America's largest river systems. The timing of initial uplift remains poorly constrained, with most estimates ranging from ca. 60 to ca. 5 Ma. New detrital zircon U-Pb ages from proximal fill of the Llanos foreland basin in Colombia reveal a pronounced mid-Cenozoic shift in provenance from an Amazonian craton source to an Andean fold-thrust belt source. This shift corresponds with changes in detrital zircon (U-Th)/He ages, a conglomeratic unroofing sequence, and a sharp increase in foredeep accumulation rates. These nearly simultaneous changes in zircon age spectra, clast compositions, and sediment accumulation are attributable to latest Oligocene uplift of the eastern flank of the Eastern Cordillera. The timing relationships suggest an early activation of the frontal thrust system, implying a long-term (up to 25 m.y.) cessation of orogenic wedge advance, potentially driven by structural inheritance and/or climate change.

INTRODUCTION

Surface uplift of the Eastern Cordillera in the northern Andes has had a profound effect on orographic climate change (Mora et al., 2008), growth of large continental drainage systems (Fig. 1) (Amazon, Orinoco, and Magdalena rivers; Hoorn et al., 1995; Díaz de Gamero, 1996), and biologic evolution of neotropical rainforests (Hooghiemstra and Van der Hammen, 1998; Jaramillo et al., 2006). Most estimates for the onset of uplift along the eastern flank of the Colombian Andes (Fig. 2) range from Paleocene to Pliocene time (Van der Hammen et al., 1973; Dengo and Covey, 1993; Cooper et al., 1995; Bayona et al., 2008; Parra et al., 2009a).

Initial uplift has proven difficult to constrain by conventional methods. First, recent zircon fission track data provide a minimum age but do not uniquely pinpoint the precise onset of earliest uplift-induced exhumation (Parra et al., 2009b). Second, insights from synorogenic growth strata are commonly limited by inadequate exposure, poor seismic resolution, and minimal variation in stratal dip (e.g., Toro et al., 2004). Third, clastic compositional records of erosional unroofing are hindered by the uniformly high-maturity (quartz-dominated) sand compositions imposed by intense tropical weathering (e.g., Johnsson et al., 1988).

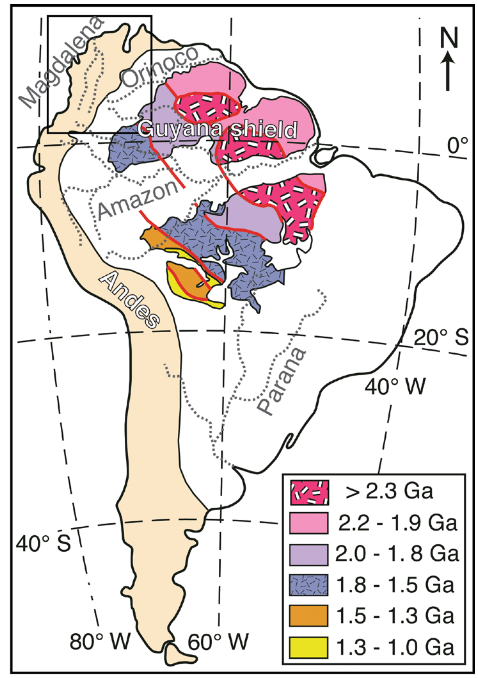

Figure 1. Map of South America showing main river systems (Magdalena, Orinoco, Amazon, and Parana) and Precambrian crustal provinces of the Amazonian craton (after Cordani et al., 2000; Chew et al., 2007).

In this study, we utilize U-Pb and (U-Th)/He ages of detrital zircon grains from the Colombian Andes to demonstrate that initial uplift-induced exhumation along the eastern flank of the fold-thrust belt had commenced by ca. 26–23 Ma. Timing relationships revealed by geochronological data coincide with shifts in conglomerate clast compositions and sediment accumulation rates and provide new insights into the pace of orogenic wedge advance.

GEOLOGIC SETTING

The Eastern Cordillera of Colombia forms a 1–4-km-high orographic barrier separating the intermontane Magdalena Valley from the Llanos foreland basin (Fig. 2). The 100–200-km-wide range is bounded by a frontal thrust system consisting of inverted normal faults and newly formed fold-thrust structures (Cooper et al., 1995; Mora et al., 2006). Following Jurassic–Early Cretaceous rifting, Andean orogenesis began with latest Cretaceous–Paleocene shortening in the Central Cordillera and early foreland basin evolution in the present-day Magdalena

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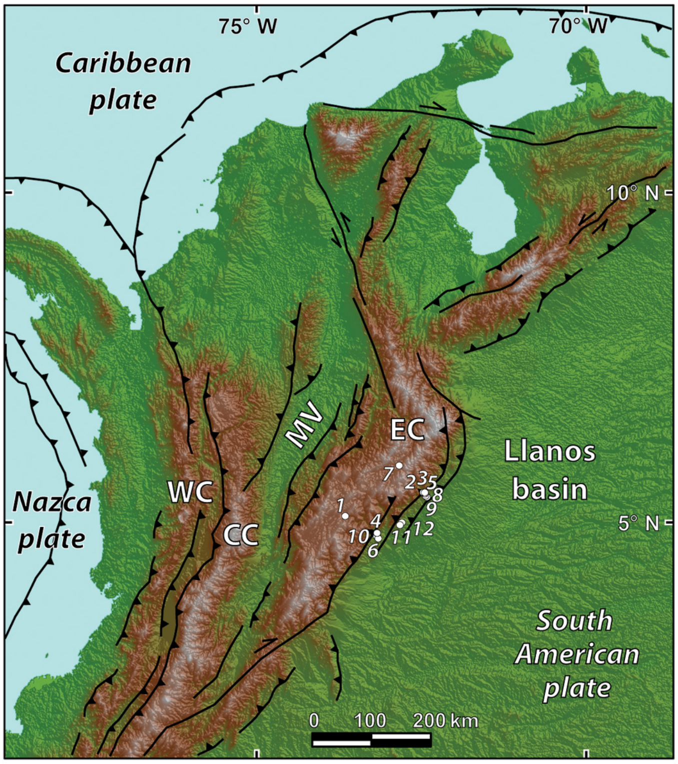

Figure 2. Shaded relief map showing tectonomorphic provinces of the northern Andes (after Mora et al., 2006) and 12 sample locations (white dots). CC—Central Cordillera; EC—Eastern Cordillera; MV—Magdalena Valley; WC—Western Cordillera.

Valley and Eastern Cordillera (Cooper et al., 1995; Gómez et al., 2003). The locus of deformation advanced eastward, reaching the western edge of the Eastern Cordillera by middle Eocene–Oligocene time (Restrepo-Pace et al., 2004; Gómez et al., 2005a; Montes et al., 2005; Parra et al., 2009b; Nie et al., 2010).

The Eastern Cordillera consists of Cretaceous quartzose sandstone and mudrock with subordinate Cenozoic, Jurassic, and Paleozoic clastic units capping localized occurrences of crystalline basement. Phanerozoic clastic units are quartz rich (Villamil, 1999), rendering sandstone petrography less effective in addressing provenance history (Johnsson et al., 1988). Prior to Andean uplift, terrigenous clastic sediment was derived from basement exposures to the east, in the Guyana shield of the northern Amazonian craton (Fig. 1) (Cooper et al., 1995). A reversal in sediment transport was triggered by uplift of principally magmatic-arc rocks in the Central Cordillera (Villamil, 1999; Gómez et al., 2005b) followed by uplift and erosional recycling of sedimentary rocks in the Eastern Cordillera (Cooper et al., 1995; Bayona et al., 2008).

The Cretaceous-Cenozoic stratigraphic successions of the Eastern Cordillera and Llanos basin (Fig. 3) consist of clastic units assigned to synrift, postrift, and foreland basin deposition (Cooper et al., 1995). Principally marine facies characterize the 3–8-km-thick Cretaceous succession, including diagnostic glauconitic sandstones in the Une, Chipaque, and Guadalupe units. The overlying 2–3-km-thick Paleogene section contains a range of nonmarine sandstone units that can be correlated from the interior of the Eastern Cordillera into the Llanos basin (e.g., Cacho, Barco, Regadera, and Mirador Formations). The youngest basin fill includes an upward coarsening, 3–5-km-thick Neogene section composed of mudstone, sandstone, and conglomerate of the Carbonera, León, and Guayabo Formations (Fig. 3).

U-Pb GEOCHRONOLOGY

Methods

Zircon grains from 12 samples of Cenozoic sandstones were separated by standard heavy liquid techniques, selected randomly, and analyzed by laser-ablation–inductively coupled plasma–mass spectrometry. Analyses and associated age calculations followed methods outlined by Chang et al. (2006), utilizing results for zircon standards Peixe (564 ± 4 Ma) and Temora (416.8 ± 1.1 Ma).

We report a total of 1107 U-Pb ages (see supplemental data Table DR1[1]) obtained by analyses that generally yielded <10% discordance, <5% reverse discordance, and <10% uncertainty. Interpreted ages represent $^{206}Pb/^{238}U$ ages for grains younger than 900 Ma and $^{207}Pb/^{206}Pb$ ages for grains older than 900 Ma. Results are plotted on relative age probability diagrams (Fig. 4) and normalized such that age-distribution curves for all

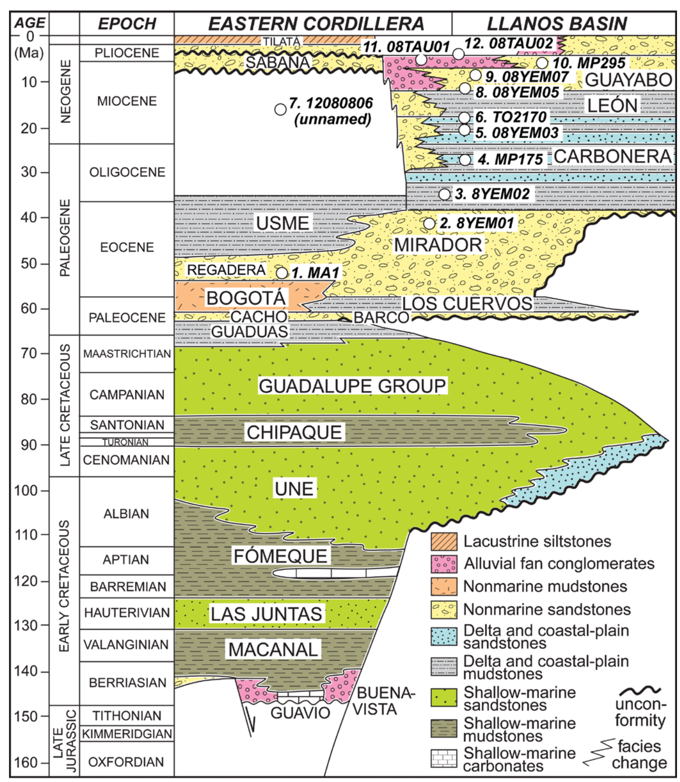

Figure 3. Generalized Mesozoic-Cenozoic stratigraphy of the Eastern Cordillera and Llanos basin, Colombia (after Parra et al., 2009a), showing approximate stratigraphic levels of 12 samples (circles).

[1]GSA Data Repository item 2010140, Table DR1, U-Pb geochronologic analyses, and Table DR2, (U-Th)/He results, is available at www.geosociety.org/pubs/ft2010.htm; copies can also be obtained by e-mail to gsatoday@geosociety.org.

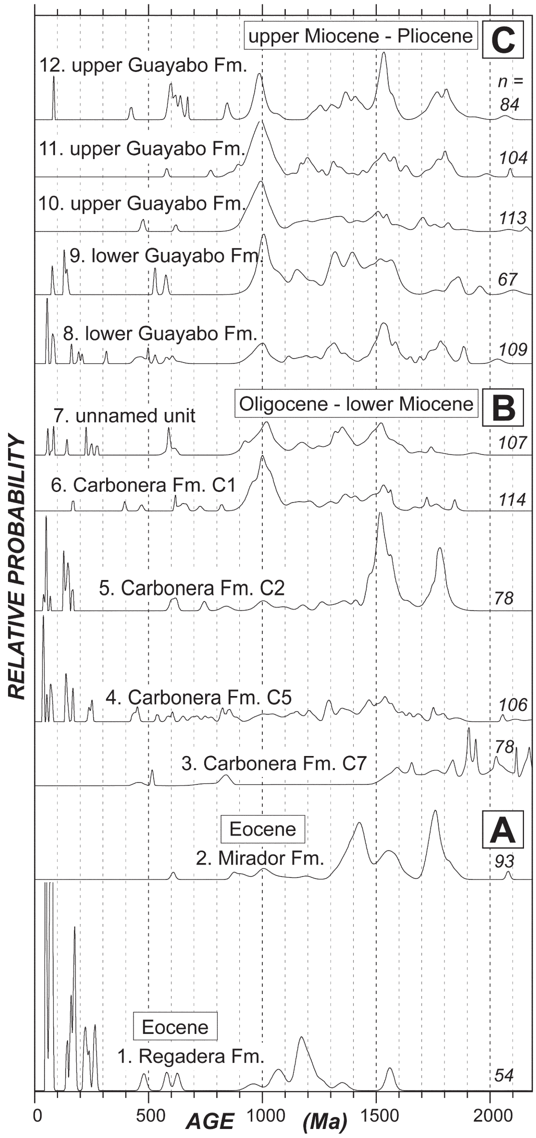

Figure 4. Detrital zircon U-Pb ages for Cenozoic strata in the proximal Llanos basin (samples 2–6 and 8–12) and axial Eastern Cordillera (samples 1 and 7). Age probability plots arranged in stratigraphic order.

samples contain the same area. Interpretations are based on age peaks defined by three or more grains.

Results and Interpretations

An Eocene sample from the upper Mirador Formation (Fig. 3) in the proximal Llanos basin is characterized by Precambrian age peaks of 1850–1350 Ma (Fig. 4A). In contrast, a sample from the Mirador-equivalent Regadera Formation in the axial Eastern Cordillera shows principally Phanerozoic ages, with peaks at 85–75, 65–55, and 190–170 Ma (Fig. 4A). We ascribe the Llanos age distributions to a dominant eastern source of Proterozoic rocks in the Guyana shield, consistent with previous studies (Cooper et al., 1995; Villamil, 1999; Roure et al., 2003). Age spectra for the axial Eastern Cordillera, however, signify exhumation of Jurassic-Paleogene magmatic-arc rocks from a western source region in the Central Cordillera or Magdalena Valley region (Fig. 2). During Paleocene to Oligocene time, the Eastern Cordillera and proximal Llanos basin likely formed a single integrated basin with sediment supplied from the east and west (Dengo and Covey, 1993; Cooper et al., 1995; Villamil, 1999) and potentially from localized structural highs (Gómez et al., 2005a; Bayona et al., 2008).

Five Oligocene to lower Miocene samples (Fig. 4B) reveal a major provenance shift. A basal sample of the Oligocene C7 member of the Carbonera Formation (Fig. 3) shows exclusively Precambrian age peaks older than 1500 Ma, indicating a cratonic signature. Upsection, the four lower Miocene samples from the C5, C2, and C1 members and an unnamed equivalent unit in the Eastern Cordillera exhibit Precambrian age peaks (1850–1300, 1050–950 Ma) and a collection of Phanerozoic ages (65–45, 90–80, 155–135, 175–170 Ma) that include the first appearance in the Llanos basin of Jurassic-Paleogene zircons, grains that must originate in the west. Although such Phanerozoic zircons could be first-cycle grains from magmatic-arc rocks of the Central Cordillera and Magdalena Valley, the presence of a Grenville age peak at 1050–950 Ma and Paleoproterozoic to Mesoproterozoic grain ages at 1850–1300 Ma (Fig. 4B) suggests recycling of sediments originally derived from the easternmost Andes and/or Guyana shield (e.g., Horton et al., 2010). We attribute the U-Pb ages to initial unroofing of the Upper Cretaceous–Paleogene stratigraphic succession along the axis and eastern flank of the Eastern Cordillera during latest Oligocene–early Miocene time. Unroofing of this cover section produced composite age spectra reflecting recycled contributions from arc-derived Paleogene strata (e.g., Regadera; Fig. 4A), craton-derived Paleogene strata (e.g., Mirador; Fig. 4A), and craton-derived Cretaceous strata.

Five upper Miocene–Pliocene samples from the lower and upper Guayabo Formation (Fig. 3) exhibit age spectra (1850–1300, 1050–950 Ma) comparable to Proterozoic basement in the Guyana shield, with limited Phanerozoic and few Jurassic-Paleogene ages (Fig. 4C). Paleocurrent data and conglomerate clast compositions show that these deposits were derived from western Andean sources rather than the Guyana shield in the east (Parra et al., 2010). We ascribe the U-Pb results to continued unroofing of the Eastern Cordillera, with recycling of principally Cretaceous strata originally sourced from the Guyana shield. Notably, for the upper Miocene–Pliocene upper Guayabo Formation, the conspicuous absence of Jurassic-Paleogene age populations that typified the underlying lower Miocene section (Fig. 4B) rules out the western magmatic arc as a potential source and suggests nearly complete erosional stripping of the arc-derived Paleogene section in the Eastern Cordillera (e.g., Regadera; Fig. 4A). Further, continued erosional recycling of craton-derived Cretaceous strata accounts for the upsection increase in Grenville-aged (1050–950 Ma) detritus at the expense of Jurassic-Paleogene ages (compare Figs. 4B and 4C). Removal of most of the ~2–3-km-thick Paleogene section during early to middle Miocene time suggests an average one-dimensional exhumation rate of ~0.2–0.3 mm/yr, a rate comparable to values estimated from low-temperature thermochronometry (Parra et al., 2009b).

(U-Th)/He THERMOCHRONOMETRY

Zircon (U-Th)/He thermochronometry is an established technique involving a closure temperature of ~180–200 °C (e.g.,

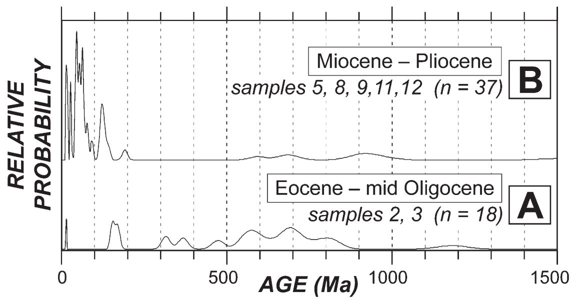

Figure 5. Detrital zircon (U-Th)/He ages for Cenozoic strata in the proximal Llanos basin. Age probability plots arranged in stratigraphic order.

Reiners, 2005) and a partial retention zone of ~120–180 °C (Stockli, 2005). Detrital (U-Th)/He age determinations were carried out following laboratory procedures described in Biswas et al. (2007). All ages were calculated using Fish Canyon and Durango zircon age standards and alpha-ejection corrections based on morphometric analyses (Farley et al., 1996). Reported age uncertainties reflect the reproducibility of replicate analyses of the two standards, with estimated analytical uncertainties of ~8% (2σ) for zircon (U-Th)/He ages (Reiners, 2005; Biswas et al., 2007).

We report 55 (U-Th)/He ages from seven of the aforementioned samples (see supplemental data Table DR2 [footnote 1]). Results are plotted on normalized relative age probability diagrams (Fig. 5). Detrital zircon (U-Th)/He ages for Eocene to mid-Oligocene sandstones of the Mirador and lowermost Carbonera Formations show a strong component of Neoproterozoic ages (11 of 18 grains in the 850–550 Ma range) with subordinate Paleozoic and Jurassic ages (Fig. 5A). In sharp contrast, Miocene-Pliocene sandstones of the middle-upper Carbonera and Guayabo Formations are dominated by Cretaceous-Cenozoic age signatures (28 of 37 grains younger than 150 Ma), with a minor 1000–850 Ma subpopulation of possible Grenville origin (Fig. 5B).

The (U-Th)/He results indicate a substantial shift in detrital age signatures during lower Carbonera deposition that coincides with the provenance shift expressed in the U-Pb data. However, rather than crystallization ages, the detrital zircon (U-Th)/He results provide insight into the integrated cooling history of the sediment source areas. In this case, we interpret the dominantly Precambrian cooling signatures of the Eocene to mid-Oligocene sandstones as the product of extremely long residence time at shallow burial depths (<5–10 km) in the stable cratonic interior of the Guyana shield. The significantly younger (U-Th)/He ages identified in the Miocene-Pliocene sandstones are considered to be the product of Cretaceous-Cenozoic exhumation in the Andean orogenic belt and/or possible contribution from igneous sources. Similar to the U-Pb data, these (U-Th)/He results reveal a pronounced shift in provenance from the ancient Guyana shield in the east to the Andean orogenic belt in the west.

CLAST COMPOSITIONS AND ACCUMULATION RATES

The new detrital zircon data are compatible with the unroofing record suggested by conglomerate clast compositions and sediment accumulation rates in the proximal Llanos basin. Clast composition data for the Eocene to upper Miocene succession (Fig. 6A) record the first appearance of large proportions of sandstone clasts followed by increased amounts of distinctive clasts of glauconite-bearing quartzose sandstones (Fig. 6B). Reworked microfossils (pollen, dinoflagellates, and foraminifera; Bayona et al., 2008) suggest a Paleocene or older age for these sandstone clasts. This history indicates late Oligocene–early Miocene unroofing of Paleocene-Eocene sandstones and widespread middle to late Miocene exposure of glauconitic sandstones that are diagnostic of specific mid- to Upper Cretaceous units (Une, Chipaque, and Guadalupe units).

An Eocene to late Miocene sediment accumulation history (Fig. 6C) for the proximal Llanos basin has been constructed on the basis of stratigraphic sections temporally calibrated by detailed palynological assemblages (Parra et al., 2010). The data show a major increase in accumulation rates, starting ca. 26–23 Ma, from ~100 to ~460 m/m.y. Although this stratigraphic transition shows only modest changes in lithofacies or paleocurrents, it corresponds with the abrupt change in detrital zircon age signatures (Figs. 4 and 5) discussed in previous sections.

DISCUSSION AND IMPLICATIONS

Coeval shifts in U-Pb and (U-Th)/He zircon age spectra, clast composition, and sediment accumulation rates in the Llanos

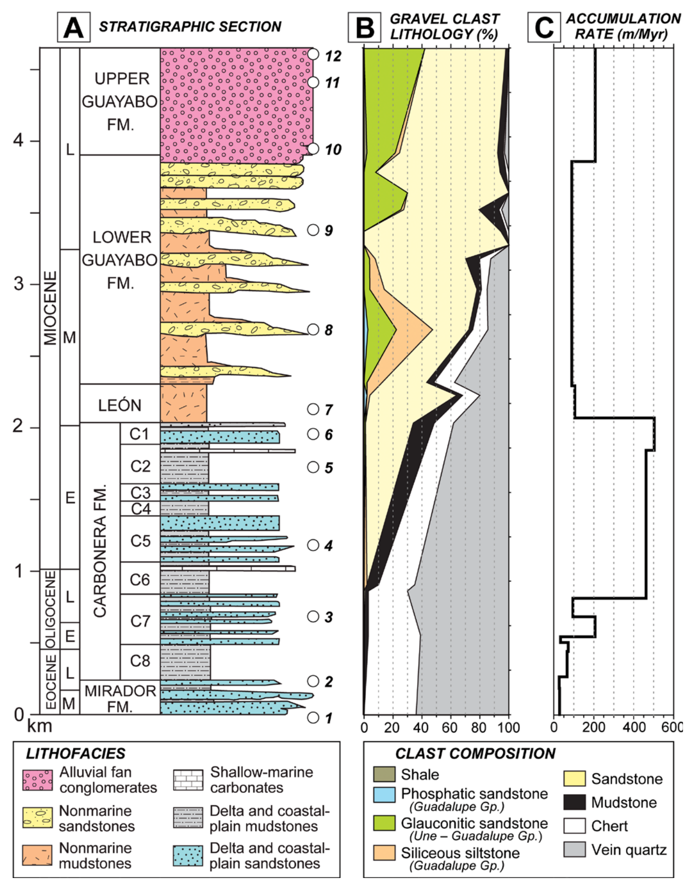

Figure 6. (A) Stratigraphic log of ~4.7-km succession showing approximate levels of 12 samples (circles); (B) corresponding conglomerate clast compositions; and (C) sediment accumulation rates derived from one-dimensional decompacted thicknesses for Eocene-Miocene deposits of the proximal Llanos basin at ~5°N (after Parra et al., 2009a, 2010).

foreland basin can be attributed to initial uplift of the eastern flank of the Eastern Cordillera (Fig. 2) during latest Oligocene time, consistent with zircon fission-track cooling histories (Parra et al., 2009b). Eastern Cordillera uplift is considered fundamental to the genesis and/or reorganization of the largest drainages in northern South America (Fig. 1). Therefore, initial deformation by ca. 26–23 Ma suggests that precursors of the Amazon, Orinoco, and Magdalena river systems may have originated >10–20 m.y. earlier than envisioned (e.g., Hoorn et al., 1995; Díaz de Gamero, 1996; Campbell et al., 2006). Evidence for protracted drainage histories should be preserved in the depositional records of the respective river deltas and submarine fans (e.g., Dobson et al., 2001; Harris and Mix, 2002), recognizing that changes in sediment accumulation rates could also be the product of climatic effects (Molnar, 2004). We speculate that reduced sediment accumulation rates in the Amazon fan during the early and middle Miocene (Dobson et al., 2001) may be the product of enhanced loading during Eastern Cordillera uplift and a corresponding increase in flexural accommodation and proximal storage of sediment in the Llanos foreland basin (e.g., Bayona et al., 2008; Parra et al., 2009a).

As the principal orographic barrier to easterly air masses, surface uplift of the Eastern Cordillera has influenced the paleogeography and biodiversity of South America's neotropical rainforests (e.g., Hooghiemstra and Van der Hammen, 1998; Albert et al., 2006). We hypothesize that aridification in the intermontane Magdalena Valley of Colombia (Fig. 2) represents the leeward orographic response to Eastern Cordillera uplift (e.g., Strecker et al., 2007). Although critical threshold elevations were likely reached in late Miocene to Pliocene time (Mora et al., 2008), paleoprecipitation estimates based on mammal faunal assemblages (Kay and Madden, 1997) are consistent with a sediment provenance reversal (Guerrero, 1997) suggesting that initial aridification due to an emerging orographic barrier may have been under way by middle Miocene time.

A further intriguing implication of latest Oligocene uplift along the eastern flank of the Eastern Cordillera is an apparent long-term reduction in the average rate of thrust front advance over the past ~25 m.y., the period of maximum shortening and surface uplift. This seeming contradiction underscores the potential importance of precipitation-driven erosion and inherited mechanical properties on structural evolution of the orogenic wedge in the humid northern Andes.

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