Drainage reorganization during mountain building in the river system of the Eastern Cordillera of the Colombian Andes

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ABSTRACT

The Eastern Cordillera of Colombia is a thick-skinned thrust-fold belt that is characterized by two topographic domains: (1) the axial zone, a high altitude plateau (the Sabana de Bogotá, 2500 m asl) with low local relief and dominated by longitudinal rivers, and (2) the Cordillera flanks, where local relief exceeds 1000 m and transverse rivers dominate. On the basis of an analysis of digital topography and river parameters combined with a review of paleodrainage data, we show that the accumulation of shortening and crustal thickening during the Andean orogeny triggered a process of fluvial reorganization in the Cordillera. Owing to a progressive increase of the regional slope, the drainage network evolves from longitudinal to transverse-dominated, a process that is still active at present. This study provides the idea of progressive divide migration toward the inner part of the mountain belt, by which the area of the Sabana de Bogotá plateau is decreasing, the flanks increase in area, and ultimately transverse rivers will probably dominate the drainage of the Cordillera.

Keywords: drainage network; fluvial capture; drainage evolution; Eastern Cordillera of Colombia

1. Introduction

In the internal, thickened, and uplifting parts of the orogens, rivers are expected to follow the regional slope and flow perpendicular to the structural trend of mountain ranges, a pattern always matched by numerical models of continental-scale surface processes (e.g., Koons, 1995; Kooi and Beaumont, 1996; Willett et al., 2001; Goren et al., 2014). However, during mountain building, active folds and thrusts can deviate rivers from the regional slope (e.g., Van der Beek et al., 2002). Conceptually, the ability or not of preexisting reaches to incise uplifting structures controls the number of diversions, and by extension it determines the drainage organization, a phenomenon confirmed by modeling (Koons, 1994, 1995; Tomkin and Braun, 1999; Humphrey and Konrad, 2000; Champel, 2002; Van der Beek et al., 2002; Sobel et al., 2003). Additional factors such as bedrock lithology determine spatial changes in strength and erodibility, and climate may control changes in weathering and discharge.

Babault et al. (2012) showed in the High Atlas Mountains of Morocco (a thrust-fold belt formed by tectonic inversion of a continental rift) an evolution from early fold- and fault-controlled longitudinal rivers to a transverse-dominated drainage network during mountain building and crustal thickening in response to a progressive increase in regional slope. This may be a common transient mechanism of fluvial network evolution in mountain belts (Babault et al., 2013).

A fluvial capture implies changes in flow direction, that is, the flow/discharge of the captured drainage basin (victim) is deviated toward the neighbor captor basin with higher erosion potential caused by either higher local precipitation, erodibility, and/or slope (e.g., Brookfield, 1998). Unlike models that show progressive divide migration and small-scale capture events during mountain building (Willett et al., 2001; Pelletier, 2004; Bonnet, 2009; Castelltort et al., 2012; Perron et al., 2012; Goren et al., 2014), the model of evolution from longitudinal- to transverse-dominated drainage network implies captures of large longitudinal drainages and substantial modifications of sedimentary outflux into adjacent basins, potentially influencing clastic systems and petroleum reservoirs. Captures of longitudinal rivers by transverse rivers are episodic and initially localized, whereas the integrated long-term effect of the episodic capture events may be a major drainage reorganization as discussed in this work.

The aim of this study is to characterize the fluvial network and the drainage dynamics in the central segment of the Eastern Cordillera of the Colombian Andes, as a case for drainage reorganization. Like the High Atlas, the Eastern Cordillera of Colombia is an example of a thrust-fold belt formed by the inversion of a former continental rift and shows similarities in the fluvial network, with a high-elevation axial area dominated by low-energy longitudinal rivers and with flanking belts of high-relief transverse valleys debouching into the forelands. By means of field observations, morphometric analysis, and a review of published palaeodrainage data, we first document that a longitudinal- to transverse-pattern of fluvial evolution also applies to the Eastern Cordillera and then discuss a main mechanism that may have enhanced drainage reorganization (and captures), together with the potential implications for the downstream basin sediment supply.

2. Regional setting

2.1. Geological setting

The northern Andes in Colombia are divided into three belts: the Western, the Central, and the Eastern Cordilleras. While the Western and Central Cordilleras are mainly composed of crystalline rocks, including Precambrian to Paleozoic basement and Mesozoic intrusives and ophiolites, the Eastern Cordillera is an inverted continental rift constituted by a thick sequence of Mesozoic and Cenozoic sedimentary rocks (Julivert, 1970; Colleta et al., 1990; Cooper et al., 1995) (Fig. 1A).

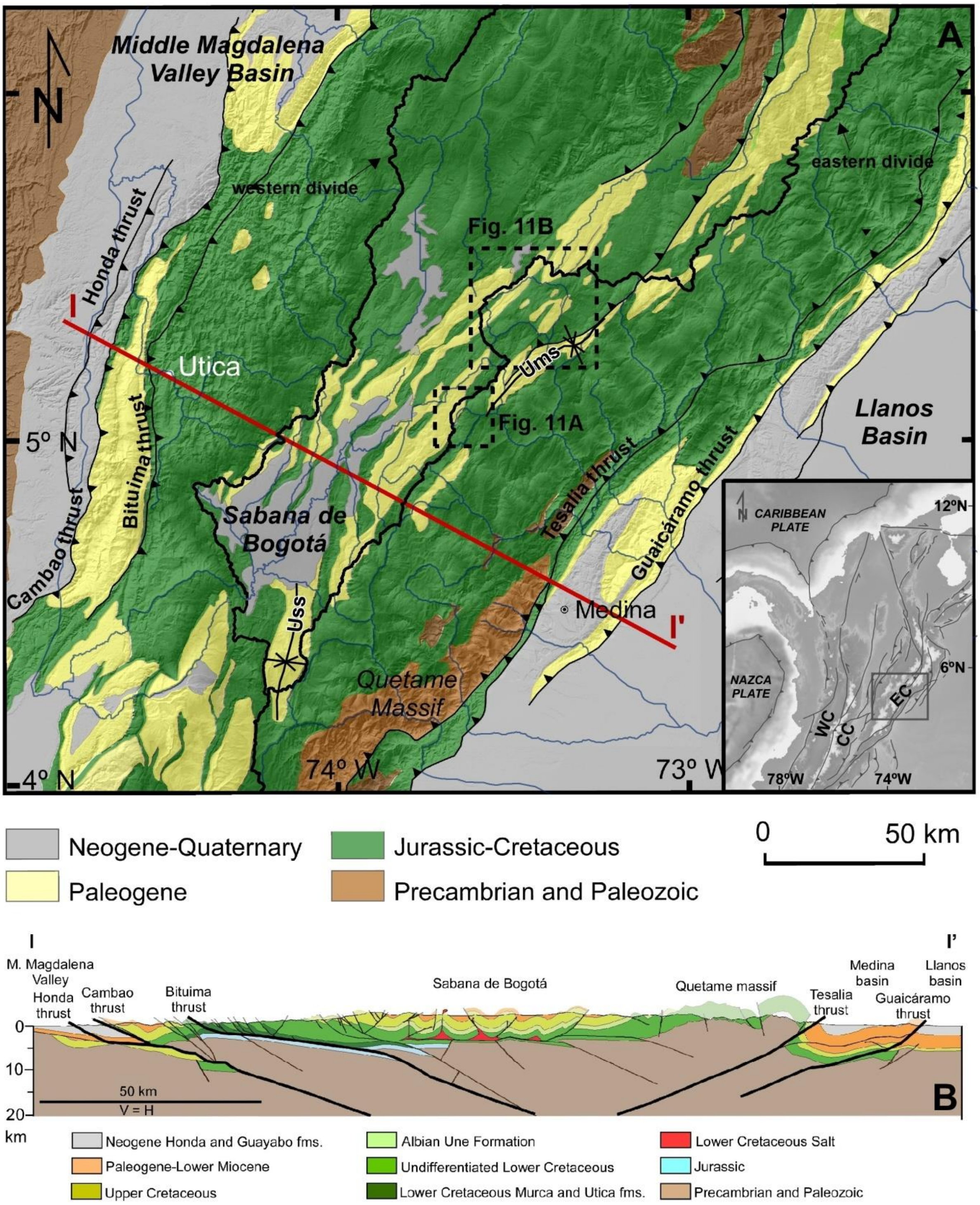

Fig. 1. (A) Geological sketch map of the study area in the Eastern Cordillera of Colombia. Thick black lines represent the western and eastern drainage divides, and thin blue lines correspond to the river network (modified from Babault et al., 2013). Inset shows a map of the northern Andes showing the location of the Eastern (EC), Central (CC), and Western (WC) Cordilleras of Colombia. (B) Structural cross section of the central part of the Eastern

Cordillera (location in Fig.1A). The main thrust faults in thick black lines are from west to east the Honda, Cambao, Bituima, Tesalia (here including the Servitá-Lengupá and Tesalia ss. faults) and Guaicáramo thrusts (modified from Teixell et al., 2015)

The Eastern Cordillera is a doubly-verging thrust system (Fig.1B) with a long convergence history, but whose main episode of shortening and thickening began during the Miocene as a response to the accretion of the Panama arc against the western margin of Colombia (Duque-Caro, 1990; Kellogg and Vega, 1995; Rolon et al., 2004; Taboada et al., 2000). Many of the thrust faults observed are derived from the reactivation of former extensional faults of early Cretaceous age, belonging to the main episode of rifting in a back-arc tectonic setting (Cooper et al., 1995; Mora et al., 2006, 2008; Tesón et al., 2013). Since the mid-late Miocene, no major fault activity is recorded in the central or axial part of the orogen; the main deformation was concentrated in the flanks (Mora et al., 2008; Hermeston and Nemcok, 2013; Teixell et al., 2015). Evidence for active faulting along the foothill thrust system, composed by the Servitá-Lengupá, Tesalia, Guaicáramo, and Yopal thrusts, is provided by deformed terraces and fault scarps in Quaternary alluvial deposits (Taboada et al., 2000; Mora et al., 2010; Hermeston and Nemcok, 2013; Veloza et al., 2015).

From a topographic point of view (Fig. 2), the Eastern Cordillera can be divided into (I) a plateau area of ~4300 km^2 at high altitude (~2500 m) in the axial zone, called the Sabana de Bogotá; and (II) the Cordillera flanks and foothills, where deep incisions locally exceed 1000 m (e.g., middle-lower part of the Guayuriba River). The boundary between the plateau and the flanks is defined by two main drainage divides.

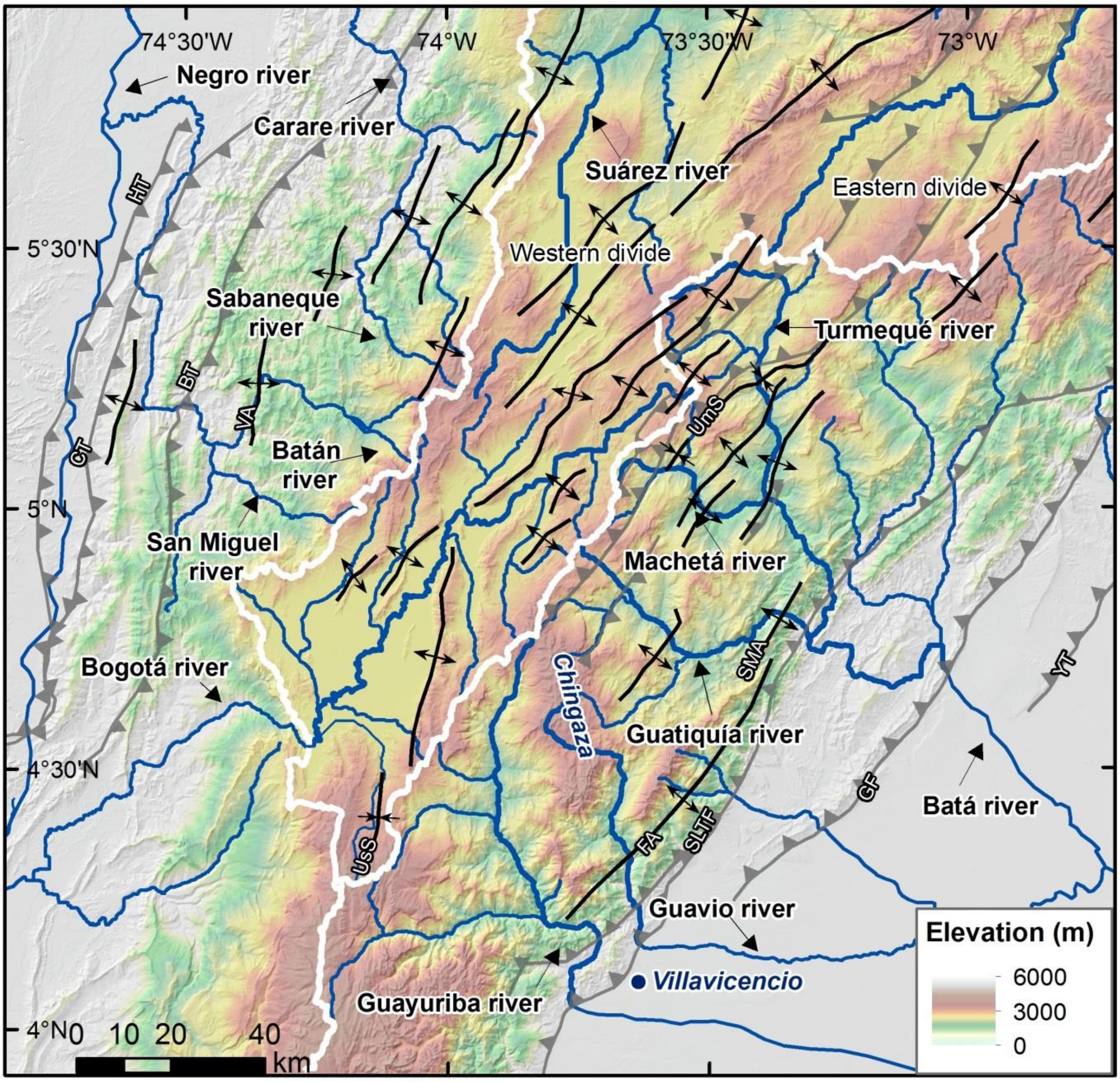

Fig. 2. Main tectonic elements and rivers of the central part of Eastern Cordillera superimposed over digital topography. Thick white lines represent the western and eastern drainage divides between the axial plateau and flanks, and rivers are in blue (the main rivers highlighted by thicker lines). Grey barbed lines represent the main thrusts, and black lines represent the main folds. Rivers in the Sabana de Bogotá run parallel to the main folds, and rivers located in the flanks are transverse to the main tectonic structures. SLTF: Servitá-Lengupá, Tesalia faults; GF: Guaicáramo fault; YT: Yopal thrust; FA: Farallones anticline; SMA: Santa Maria anticline; VA: Villeta anticlinorium; BT: Bituima thrust; CT: Cambao thrust; HT: Honda thrust; UsS: Usme syncline; UmS: Umbita syncline.

The Sabana de Bogotá is dominated by Cenozoic sandstone and shale formations with upper Cretaceous sandstone outcrops in anticlinal cores (Fig.1). The flanks of the Cordillera are characterized by lower and upper Cretaceous sandstone and shale formations and isolated Precambrian to Paleozoic basement massifs. Despite the basement outcrops, no overall difference exists in bedrock strength between the Sabana de Bogotá and the flanks, as both are dominated at the surface by sandstone and shale formations. The Eastern Cordillera is flanked on both sides by foreland basins dominated by Neogene and Quaternary alluvial deposits that correspond to the middle Magdalena Valley basin in the west and the Llanos basin in the east, at elevations of ~200-300 m asl.

Most of the tectonic shortening of the Eastern Cordillera is concentrated in the orogen flanks, especially in the eastern margin (Fig. 1B). In the eastern thrust belt, basement rocks are uplifted by thick-skinned thrust faults and exposed at the surface in the rugged Quetame Massif (Toro et al., 2004; Mora et al., 2006, 2008). The western thrust belt does not expose basement to the surface but is still characterized by large thrust displacements (Gómez et al., 2003; Restrepo-Pace et al., 2004; Cortés et al., 2006). In contrast, the interior of the Eastern Cordillera is constituted by the simple fold belt of the Sabana de Bogotá (Figs. 1A, B) with low, rather homogeneous structural relief and without major thrusting (e.g., Julivert, 1963; Mora et al., 2008; Teixell et al., 2015). As a whole, the Eastern Cordillera was mostly uplifted by the major thrusts on the mountain flanks of the belt (Fig. 1B).

The amount of orogenic shortening in the Cordillera is still in debate and depends on the mode of thrusting adopted and on the role of the pre-orogenic extensional faults. Values of 150-200 km (up to 50%) of shortening have been calculated in thin-skinned models (e.g., Dengo and Covey, 1993; Roeder and Chamberlain, 1995), whereas smaller values of 70-100 km (25-30%) are reported in thick-skinned models (e.g., Colletta et al., 1990; Cooper et al., 1995; Tesón et al., 2013; Teixell et al., 2015).

2.2. Fluvial drainage in the Eastern Cordillera

Rivers in the Sabana de Bogotá run approximately NNE-SSW, parallel to fold axes, and preferentially located in synclines (Fig. 2). Synclinal valleys are wide and flat, and ridges in between correspond to anticline cores (Fig. 3A). The main river draining the plateau is the Bogotá River, which ultimately incises into the western flank and drains to the Magdalena River. The Bogotá River when draining in the plateau lengths 220 km; and its tributaries flow to the SSW, parallel to the structural trend (Fig. 2). Rivers in the Sabana typically show a general meandering pattern (Fig. 3C), gentle slopes, and low runoff velocity in accordance with the smooth topography.

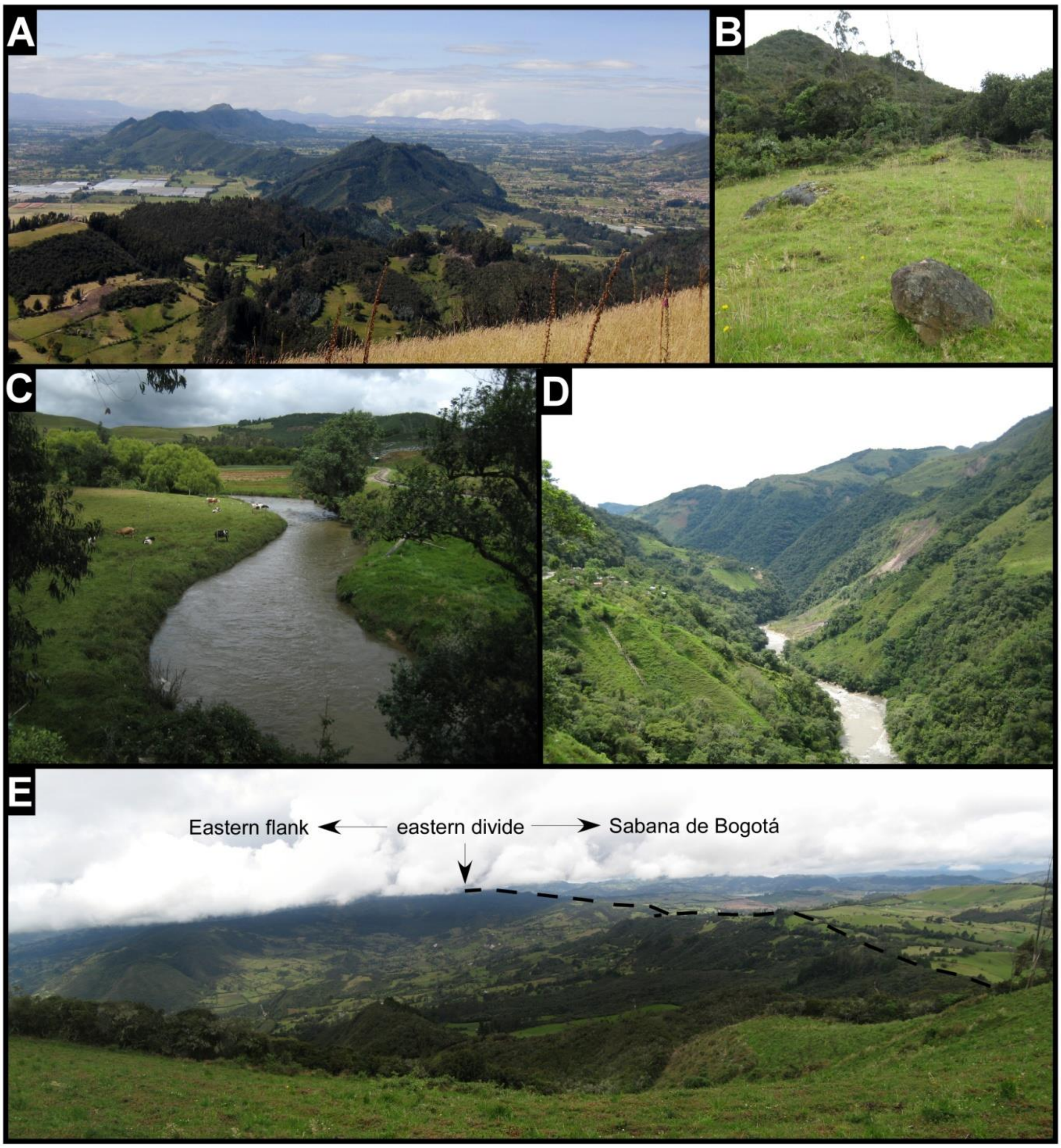

Fig. 3. (A) Field photograph of the Sabana de Bogotá showing the sandstone anticlinal ridge of the Chía Range (middle) and low slopes in adjacent synclinal areas. (B) Rock boulders product of a rockfall located on the eastern divide of the Cordillera, in the Machetá River capture zone (location in Fig. 9). (C) View of the longitudinal river Bogotá flowing in the plateau. (D) View of the transverse river Guayuriba in the eastern flank of the Cordillera with greater slopes and local relief, and common landslides in the hillslopes linked to the high slope angles. (E) Field image of the two topographic domains of the Eastern

Cordillera: the Sabana de Bogotá and the upstream part of the Machetá transverse river in the eastern flank (field of view 4 km, view to the south).

In the eastern flank of the Cordillera, the main rivers from south to north are Guayuriba (Fig. 3D), Guatiquía, Guavio, and Batá rivers, draining to the Orinoco River in the Llanos basin. These rivers range between 70 and 170 km long in the flank and flow perpendicular to the structural grain, i.e., transverse to the trend of the Eastern Cordillera.

In the western flank of the Eastern Cordillera, the main rivers are the Río Negro and Minero-Carare draining to the Magdalena River at the middle Magdalena Valley (108 ±46 m of elevation in this region). These rivers are 150 and 110 km long, respectively, and flow mainly in an E-W direction, transverse to the general trend of the Cordillera and perpendicular to the main tectonic structures (Fig. 2). However, they also show sharp changes in flow direction with longitudinal reaches separated by transverse reaches in the medium and lower part of the western flank, displaying a gridiron-like drainage organization which is common in fold-and-thrust belts (e.g., Gupta, 1997).

2.2.1. *Paleogene drainage in the Eastern Cordillera from paleocurrent data*

Paleocurrent and sediment provenance data of the early Cenozoic deposits of the Eastern Cordillera indicate a western and southwestern sediment source and a drainage network controlled by emerging folds and thrust sheets following a regional slope to the NNE (Laverde et al., 1989; Cooper et al., 1995; Diaz and Serrano, 2001; Gómez et al., 2005a; Bayona et al., 2008; Horton et al., 2010; Nie et al., 2010, 2012; Saylor et al., 2011; Bande et al., 2012; Caballero et al., 2013; Silva et al., 2013).

In Paleocene-early Eocene times, there was a longitudinal drainage pattern (Fig. 4), parallel to the structural grain (Brown et al., 1991; Gómez et al., 2005b,c; Bayona, 2008; Bayona et al., 2008; Saylor et al., 2011; Mora et al., 2013; Silva et al., 2013). Paleocene fluvial sediments in the Sabana de Bogotá region record paleocurrents to the NNE (Laverde et al., 1989; Bayona, 2008; Bayona et al., 2008; Saylor et al., 2011).

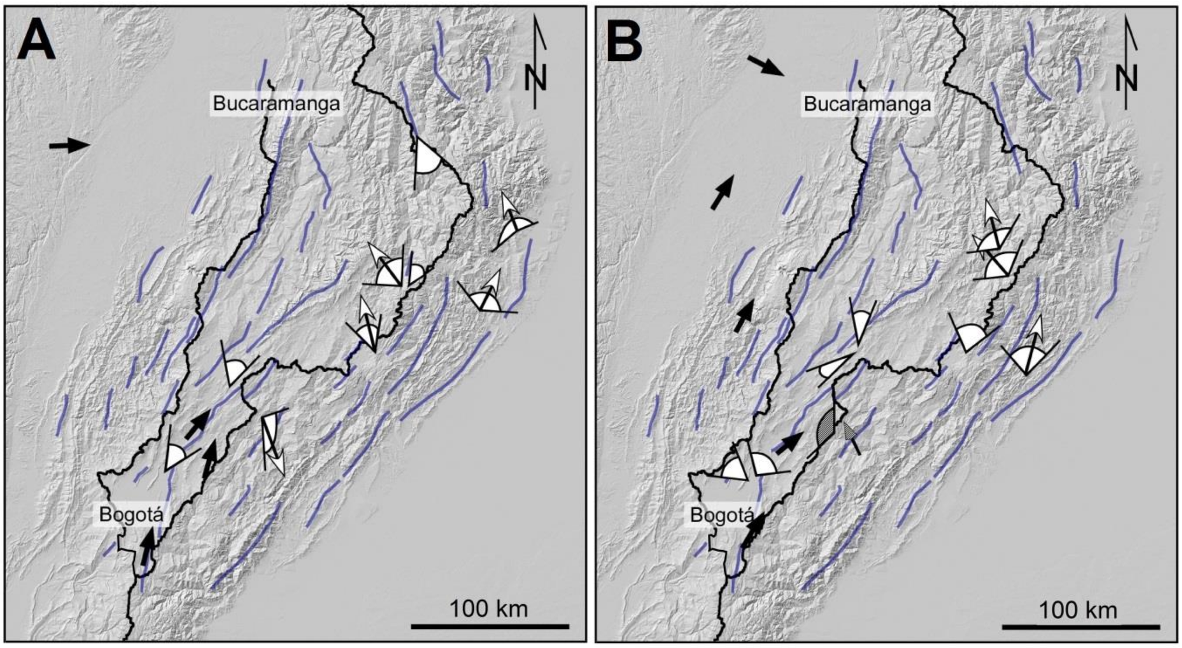

Fig. 4. Summary of paleocurrent data from Paleocene (A) to Eocene (B) in the Eastern Cordillera compiled from Gómez et al. (2005b) (black arrows), Bayona et al. (2008) (white arrows), and Bayona (2008) (line-filled arrows).

The late Eocene-Oligocene still records a mean northward drainage in the current Sabana de Bogotá area and in the Magdalena Valley (Diaz and Serrano, 2001; Gómez et al., 2005a; Silva et al., 2013). In the late Oligocene to mid-Miocene interval, important changes occurred in the middle Magdalena Valley basin (MMVB): owing to deformation in the northern part of the basin, the base level started to rise and forced rivers to divert toward the Llanos Basin across the Eastern Cordillera (Gómez et al., 2005a,b). During the mid-late and late Miocene, the MMVB paleodrainage returned to the north in relation with continued rising of the Cordillera. In the eastern foreland of the Cordillera, a transverse, eastward paleocurrent direction is observed in the entire Miocene succession (Parra et al., 2010).

2.3. Summary of climate features

Climate can be a major control on the evolution of drainage network (e.g., Schumm, 1979; Bull, 1991; Whitfield and Harvey, 2012). A mean annual precipitation map (Fig. 5) was compiled for the years 1998-2009 using TRMM data (Bookhagen and Strecker, 2008) following the methodology of Bookhagen and Burbank (2010).

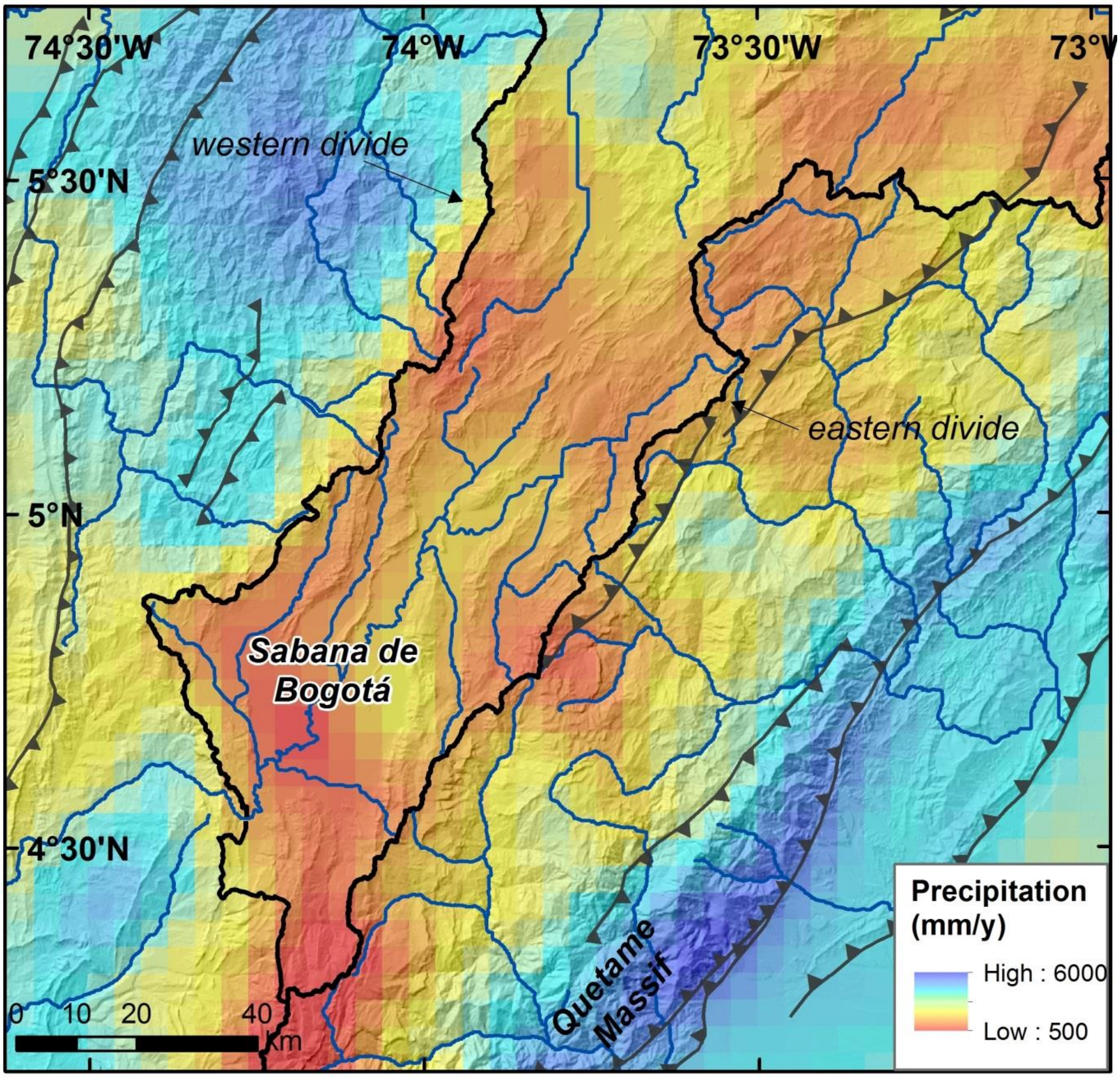

Fig. 5. Precipitation map of the Eastern Cordillera of Colombia compiled for the years 1998-2009 (after Bookhagen and Strecker, 2008).

The map shows a strong gradient of precipitation in the vicinity of the western divide, by which rainfall increases markedly in the western flank of the Cordillera. In contrast, a similar gradient is not observed across the eastern divide, as the distribution of annual precipitation is approximately homogeneous in the plateau and upper eastern flank. Precipitation is higher in the eastern foothills and Quetame Massif.

The Sabana de Bogotá presents a sparse record of glaciation during the last 50 ka at altitudes higher than 3500 m (Helmens, 1988, 1990; Helmens and Kuhry, 1995; Helmens et al., 1997). On the basis of moraine deposits, glaciers are described as very small and poorly developed valley glaciers or ice caps, ranging from 0.5 to 8 km^2 and were deglaciated at ca. 12.5 ka (Helmens, 2004). U-shaped valley forms have never been reported (Mark and Helmens, 2005).

2.4. Summary of the deformation and uplift history of the Eastern Cordillera

During the late Cretaceous and early Tertiary, the Eastern Cordillera was the foreland basin system of the Central Cordillera (Cooper et al., 1995; Gómez et al., 2005a). Progressive growth of the Eastern Cordillera structures since the late Maastrichtian or early Paleogene disrupted and compartmentalized the foreland basin and ultimately subdivided it into the Magdalena Valley and the Llanos basins (Gómez et al., 2003; Parra et al., 2009a,b; Horton et al., 2010; Mora et al., 2013).

Based on subsidence and exhumation analysis (Parra et al., 2009a,b; Mora et al., 2010) and detrital sediment provenance (Horton et al., 2010), the main emergence of the major thrust faults in the flanks of the Eastern Cordillera started during late Oligocene to early Miocene times. The disappearance of Meso-Cenozoic detrital zircons (which indicate a Central Cordillera provenance) in the eastern foothills (Horton et al., 2010) indicates that the Eastern Cordillera had already become an effective topographic barrier that separated the Central Cordillera from the Llanos basin by the mid-late Miocene. This is marked by a contemporaneous conglomeratic influx of the Honda and Guayabo formations (upper Miocene to Pliocene) into the middle Magdalena Valley and Llanos basins (Hoorn et al., 1995; Gómez et al., 2003; Parra et al., 2009a).

After a sedimentary hiatus that comprises most of the Oligocene and Miocene, the Sabana de Bogotá accumulated ca. 600 m of fluviolacustrine deposits (Tilatá and Sabana formations; Julivert, 1963; Andriessen et al., 1993; Torres et al., 2005), which partially filled synclinal depressions and contributed to smooth the relief of the plateau as we see it today. In spite of this, Van der Hammen et al. (1973) and Hooghiemstra et al. (2006) inferred low altitudes for the Sabana until the late Miocene and a rapid surface uplift of 1500 ± 500 m between 6 and 3 Ma ago, based on the palynological content of the late Neogene deposits using the nearest living relatives method. However, these data may not be reliable enough because Gregory-Wodzicki (2000) reported errors in paleoaltimetry estimates for the Andes of ±1500 m, implying that the proposed paleoelevation changes of the Sabana de Bogotá may not be accurately resolved by the nearest living relatives method. For this reason, a continuous crustal thickening and surface uplift since the onset of mountain building is not discarded (Babault et al., 2013), as shortening was accumulating in a progressive way (e.g., Moreno et al., 2013; Teixell et al., 2015) and explains the current high elevation of the Eastern Cordillera.

3. Digital topographic analysis

Comparison of the paleodrainage data summarized above and the present-day fluvial network of the Eastern Cordillera of Colombia suggests that drainage has experienced a process of reorganization over geologic time. We undertook an analysis of the spatial distribution of the local and mean slopes, of the drainage network organization, and of the longitudinal profiles of the main rivers of the Cordillera with the aim of characterizing the river dynamics and the signal of reorganization in the current network. According to Bishop (1995), drainage rearrangement in mountain belts can be produced by beheading during progressive divide migration and by discrete events of capture, which are mechanisms of drainage expansion that result from headward erosion (Fig. 6A) The beheading process results in the nonpreservation of early drainages, and thus capture elbows (sharp changes in the river channel direction) and wind gaps (dry valleys with fluvial deposits) in the divide are not preserved. However, low-elevation zones (anomalous depressions) in the topographic profile of a divide may be the topographic expression of the migration of a divide originally located at the crest and later reaching the bottom of an adjacent valley, as reproduced in numerical models (e.g., Willett et al., 2001). Stream capture (piracy) can be identified by distinctive geomorphic features (e.g., Fig. 6B). These include the preservation of the early lines of the drainage network, elbows, and knickpoints (Small, 1978; Bishop, 1995). Elbows and knickpoints cannot be used separately as a diagnostic for captures because changes in rock uplift and river diversion may also produce them. Other features potentially indicating capture events are hanging depressions (wind gaps) or discrete jumps (or reentrants) of a drainage divide, but they are seldom preserved in rapidly eroding settings like active orogenic belts (e.g., Clark et al., 2004; Prince et al., 2011; Brocard et al., 2012). Wind gaps correspond to segments of captured rivers where water no longer flows and show a width that is impossible to relate with the actual basin drainage area upstream (suggesting that they were created in past times with larger drainage areas). Stratigraphic evidence for captures include abandoned river terrace tracts and the existence of fluvial sediments with larger grain size than the current channel can transport or with lithologies linked to source areas that are now disconnected from the basin.

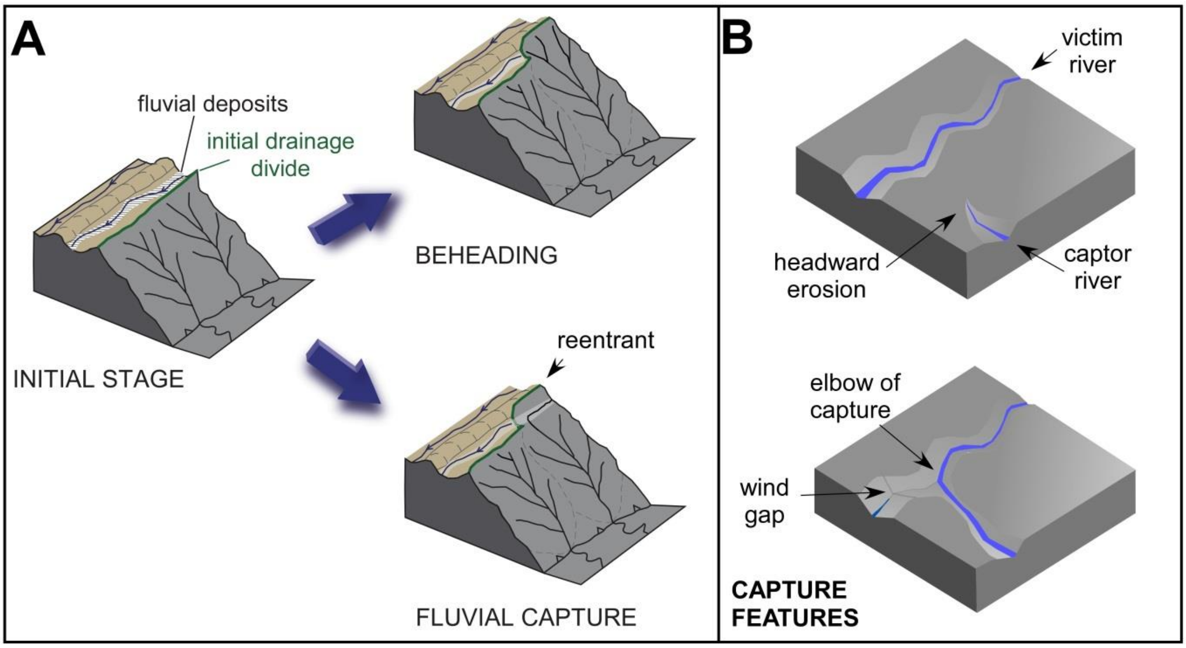

Fig. 6. (A) Diagram showing the process of beheading and fluvial capture from the same initial stage. (B) Fluvial capture processes preserve the initial drainage lines and produce elbows and fluvial deposits in the divide (wind gap). These features do not occur in beheading.

3.1. Methods

In this study we analyzed the topography in the search of geomorphologic evidence for divide migration and captures as previously mentioned. Beheading and stream captures occur if disequilibrium of erosion exists between two catchments. We highlighted potential disequilibrium of erosion by quantifying morphological differences between the axial plateau of the Sabana de Bogotá and the steep Cordillera flanks between latitudes 5º30’N and 4º10’N (Fig. 2). We used the 90-m-resolution digital elevation model (DEM) SRTM90v4 (Jarvis et al., 2008) in the analysis. However, in areas where the fluvial channel is narrow (<90 m), the SRTM90 DEM leads to overestimated elevations in gorges, providing wrong data for river parameter extraction. Such errors were corrected using elevations from Instituto Geográfico Agustín Codazzi (IGAC) 1:100,000 topographic maps and then modifying the raster elevation matrix (DEM) pixel by pixel. Morphometric analysis and calculation of the geomorphologic parameters described in the following sections was carried out by using the D8 flow routine (eight-flow direction matrix; O’Callaghan and Mark, 1984; Tarboton, 1997; Mudd et al., 2014).

We compared the current drainage network geometry with the regional slope obtained by calculating the local slopes of the mean elevations. The mean elevations have been calculated with a moving window of 30 km of diameter. We compared the frequencies of elevations, the local slopes, and the channel slopes between the plateau and the western and eastern flanks of the Cordillera to highlight their topographic difference. In the supplementary data we provide longitudinal river profiles of the main rivers draining the Sabana de Bogotá and the Cordillera flanks.

River erosion depends at least on bedrock erodibility, water flow, and slope (e.g., Howard and Kerby, 1983). Analysis of slope-area relationships is often used to reveal spatial trends of erosion and/or rock uplift in channel networks by the mean of the channel steepness index or Ksn (e.g., Kirby and Whipple, 2001; Kirby, 2003; Snyder et al., 2003; Wobus et al., 2006; DiBiase et al., 2010). However, scatters in local slope data in regions of noisy and low-resolution DEM such as the Eastern Cordillera prevent accurate estimates of normalized channel steepnesses. Therefore, for the measurement of the normalized channel slopes we preferred an alternative methodology, the χ (chi) gradient (*Mx*) approach, where the river profile elevation (instead of the slope data) is the dependent variable that is plotted against the integral of the drainage area (χ) as the independent variable, giving more accurate results (Perron and Royden, 2013; Mudd et al., 2014). The value of the channel slope in χ-elevation space (*Mx*) depends on the concavity, and we determined the best concavity with AICc-collinearity tests and χ-plots following the method developed by Mudd et al. (2014). Assuming that rock uplift is balanced by erosion (steady-state condition) and that uplift, erosion, and erodibility are constant in time and space, the stream power theory predicts that river profile will have a linear χ plot and *Mx* is proportional to erosion rates (Royden and Perron, 2013; Mudd et al., 2014). However, transient states where uplift rates change spatially or temporally can lead to piecewise (stepped) channel profiles. In this case, we used the collinearity test to identify the concavity (*m/n* ratio) for each river basin that best collapses the tributaries in χ-plots (Mudd et al., 2014).

We generated topographic elevation profiles of the eastern and western main divides, and we calculated their mean elevation using an adjacent-averaging smoothing method (over 900 and 550 km distance for the eastern and western divide, respectively). Smoothing with the adjacent-averaging method calculates the average of elevations around each point and replaces the actual elevation of the point with the average value. The location of the divide depressions (low-elevation segments) was compared with the geometry and characteristics of the current drainage network. A fluvial capture leaves depressed zones or gaps in the drainage divide where water does not actually flow (wind gaps). These depressed zones can have fluvial sediments relict of the old fluvial drainage network.

3.2. Analysis and results

The differentiation between the topographic domains of the Eastern Cordillera is evidenced by the results of the morphometric analysis. A first differentiation is based on hypsometric and slope frequency curves (Fig.7). The plateau region shows a high frequency in elevation around 2500 m, corresponding to the average elevation of the Sabana plains (Figs. 7B and D). This region is also characterized by a high frequency (21%) of slopes of < 3° and secondary maxima close to 8º (14%) (Fig. 7C). On the other hand, the flanks of the Cordillera show a wider range of elevation. The eastern flank shows the highest frequency values close to 2300 m, whereas in the western flank they are close to 1300 m. The Cordillera flanks also show a higher local relief, with local slopes greater than 10º. Greater local slope values (>30º) are located in the external parts of the flanks coinciding with the frontal fold-thrust structures (Servitá, Lengupá and Tesalia faults and Farallones anticline in the eastern flank; Bituima fault and Villeta anticlinorium in the western flank; Fig. 2).

The Sabana de Bogotá plateau shows a short range of elevation, giving a high frequency in 2500 m. The Cordillera flanks are characterized by a wider range of elevation values.

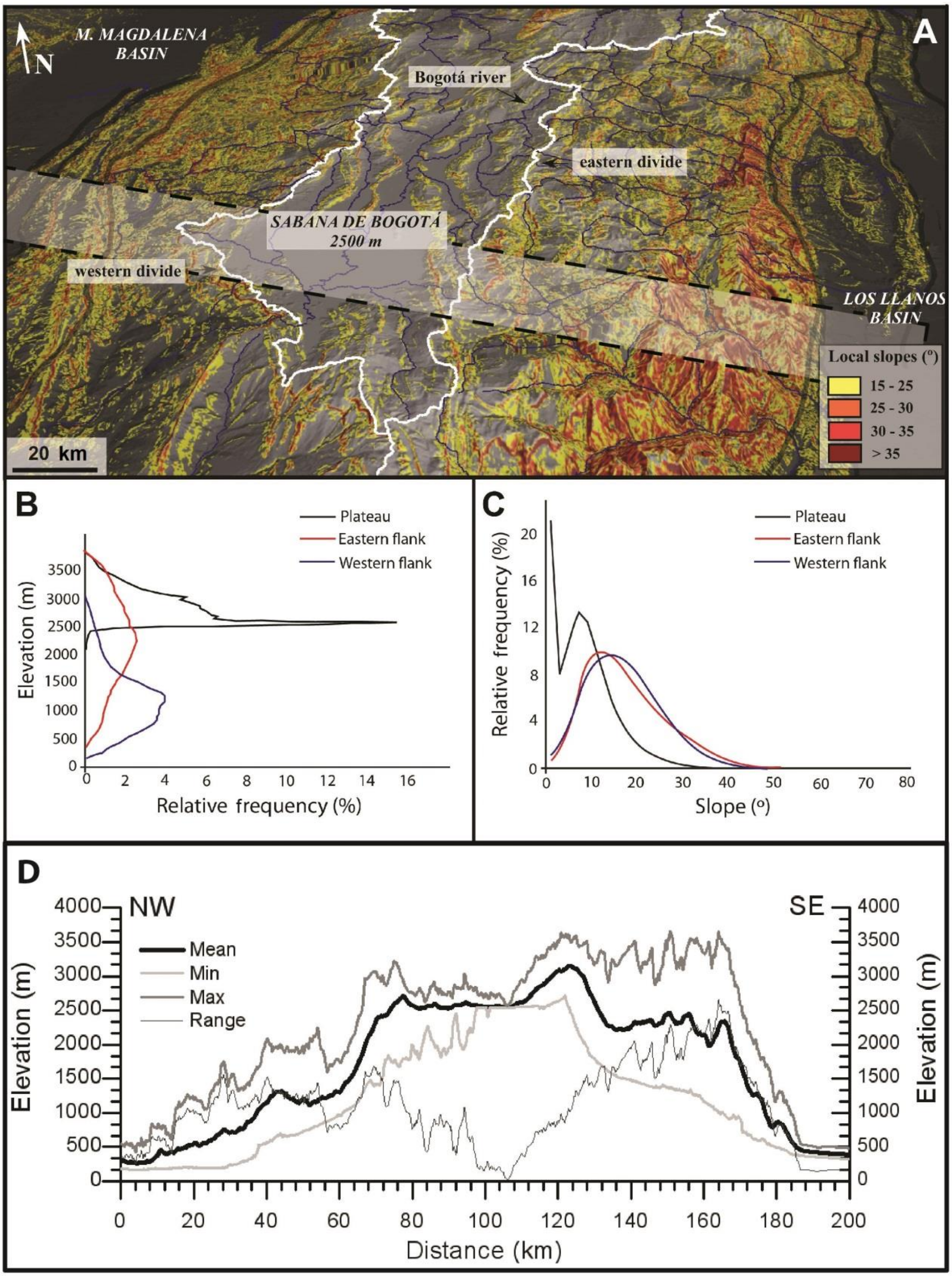

Fig. 7. (A) Oblique view of the Eastern Cordillera indicating local slopes (in colors). The transparent white band indicates the location of the 30-km swath used for the elevation profiles in (D). (B) Plot of the relative frequency of elevations that characterize each topographic domain defined for the Eastern Cordillera. (C) Plot of relative frequency of slopes in each domain. (D) Orogen-transverse topographic profiles of the Eastern Cordillera

along the swath indicated in (A), including maximum, minimum, and mean elevations and the elevation range (difference between maximum and minimum).

The contrast between the plateau and the eastern flank is illustrated in Fig. 8, where we plot the long profile of the Guayuriba River in the eastern flank and the profile of the Siecha-Bogotá River in the plateau, including the projections of lateral divides and local relief for each one. The plateau area, represented in Fig. 8 by the Siecha-Bogotá river, is characterized by a low-elevation lateral divide and a very low local relief (500 m maximum). In contrast, the Guayuriba basin, in the eastern flank, is characterized by a higher-elevation lateral divide, as well as by a greater local relief (up to 2750 m).

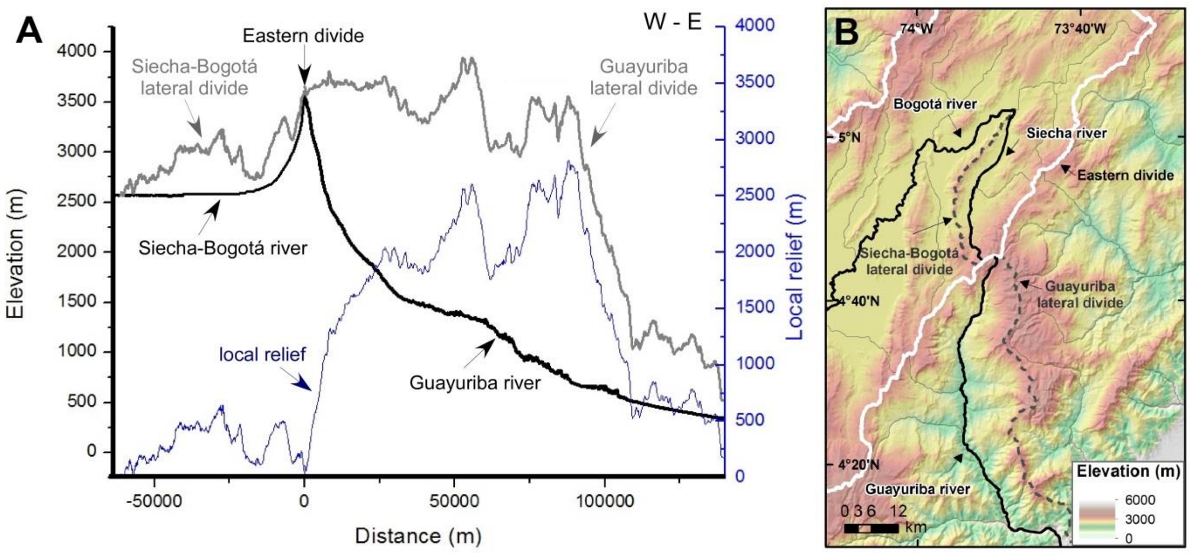

Fig. 8. (A) Longitudinal profiles of the Siecha-Bogotá (Sabana de Bogotá plateau) and Guayuriba (eastern flank) rivers, compared with a projection of their lateral divides and the local relief (difference between maximum and minimum elevations) between rivers and divide ridges. (B) Location map of the rivers and divides shown in (A).

Mean regional slopes in the Eastern Cordillera illustrate that the Sabana de Bogotá plateau is characterized by a very low mean regional slope of 1º (Fig. 9) and rivers follow the main structures longitudinally. Rivers in the eastern flank follow the regional slope, that is, to the east. The eastern flank shows greater mean slope values than the plateau, which becomes greatest in the lower part of the flank (mean values of 2.5º and, 4.5º respectively; Fig. 9). The western flank shows high values of regional slope (mean value of 4.5º) immediately west of the western divide where the main rivers are also transverse.

Significant variations in channel slope (expressed by *Mx*, the slope in χ-elevation plots) are not only observed between the Sabana and the flanks. Relevant variations in channel slope occur either along the same river or between different rivers in each domain (see supplementary data, SD1). The *Mx* values were calculated in function of the best concavity for all basins analyzed. We found a 0.45 concavity as the best value based on the AICc-collinearity test and χ-plots (see supplementary data, SD2 and SD3).

The map distribution of the *Mx* index of major rivers (Fig. 9) shows generally low values (*Mx* 0-3) in the plateau area, coinciding with the lower regional slope and consistently with the results of digital analysis of local slopes and with field observations: rivers in the plateau show a meandering morphology (Fig. 3C) as well as lower slope and runoff velocity than those in the flanks (Fig. 3D). The eastern flank shows *Mx* average values between 5 and 12, with peaks of 20-27. The greatest values are located in areas of recent tectonic uplift (e.g., Farallones and Santa Maria anticlines in the eastern flank; Mora et al., 2008) or in rivers with a drastic slope increase where they leave high-elevation, low-relief upstream areas like the Chingaza region (see Fig. 2). The *Mx* values in the higher parts of the western flank (bordering the divide), where rivers are transverse, range around 5-12, and the *Mx* values decrease in the lower part of the flank where rivers are longitudinal (*Mx* 1-4).

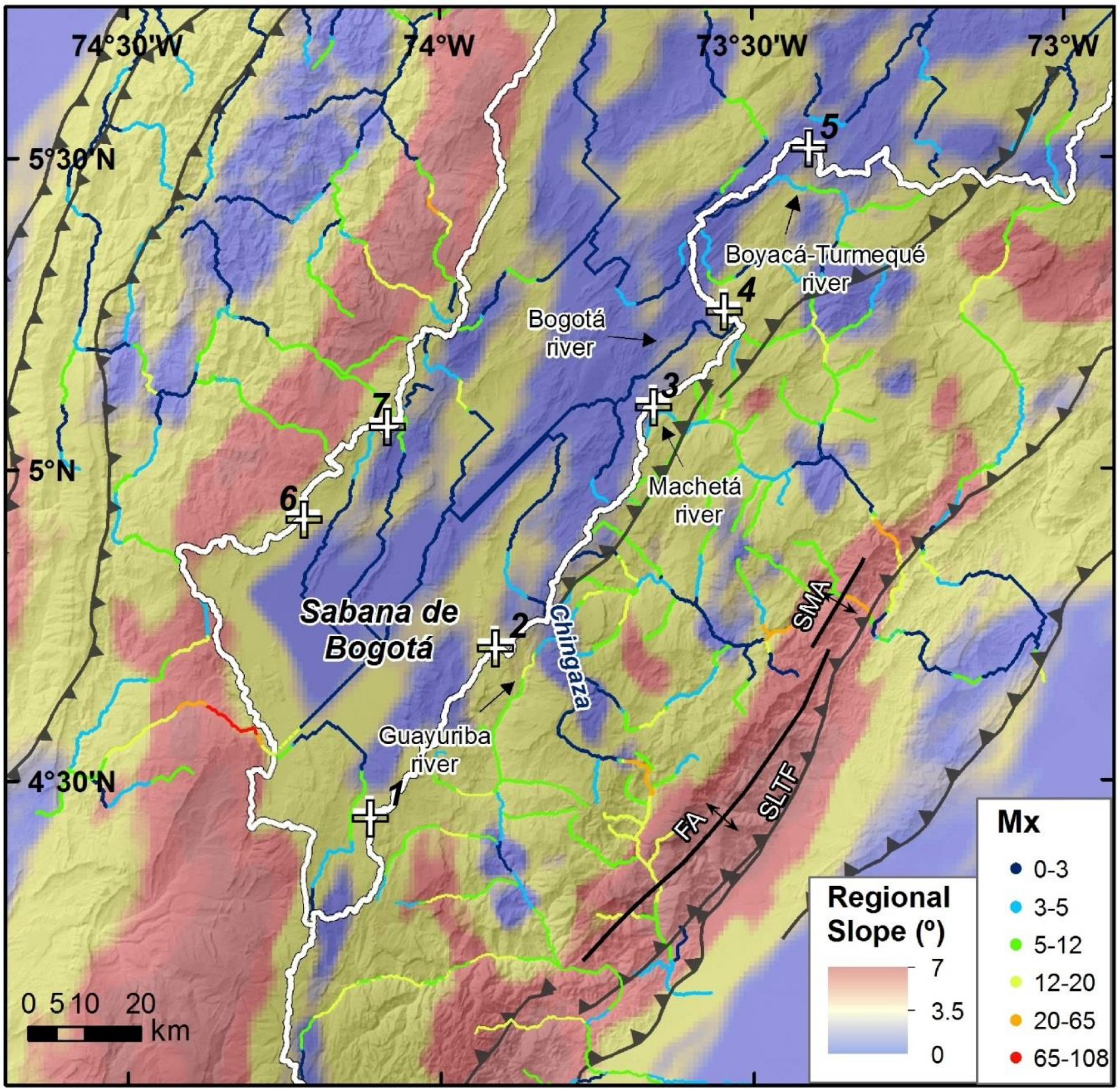

Fig. 9. Map of *Mx* (slope in χ-elevation plots) values for the analyzed rivers and regional slope (º) calculated with a mobile window of 30 km diameter. The eastern and western divides are indicated by white lines. Note low *Mx* values in the Sabana de Bogotá and high values in the flanks of the Cordillera. Depressions in the divide ridges are indicated by white crosses and labeled with numbers from 1 to 7 (see text for discussion). FA: Farallones anticline; SMA: Santa Maria anticline; SLTF: Servitá-Lengupá-Tesalia fault.

Topographic profiles of the two drainage divides separating the axial plateau of the Sabana de Bogotá from the eastern and western flanks (Fig. 10) show a series of depressions (low-elevation segments in the divide) several hundreds of meters deep below the average elevation of the divide ridges. Depressions usually coincide with reentrants of the divide trace into the plateau (Figs. 9 and 10), i.e., segments of the divide that diverge from the main orientation and project toward the axial plateau of the orogen.

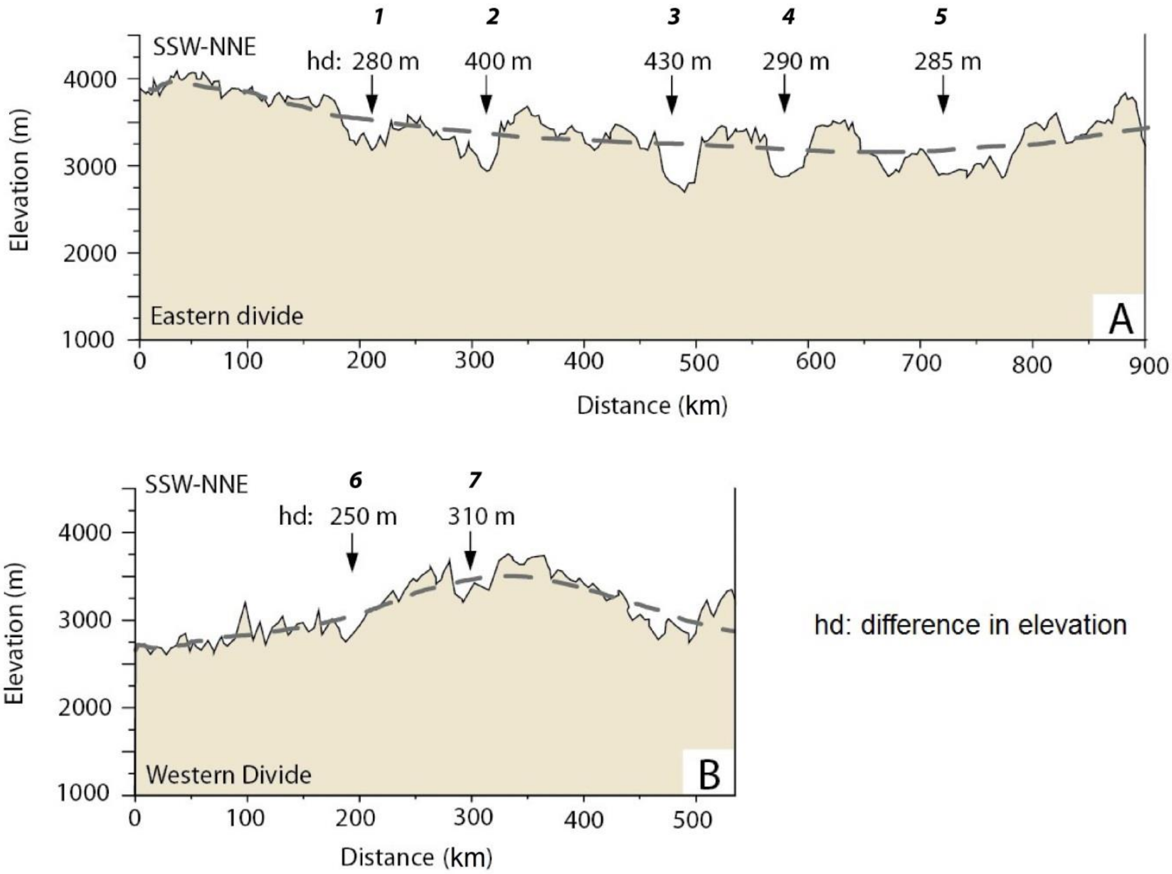

Fig. 10. Profiles of the eastern (A) and western (B) drainage divides that bound the Sabana de Bogotá plateau showing the location of depressions (numbers in *italic* refer to Fig. 9). Additionally, we indicate the difference in elevation between the lower part of the divide (depressed area) and the mean elevation of the divide (dashed line).

An illustrative example of a divide depression is observed between the Machetá and Bogotá rivers (see Fig. 2 for location). In the headwater of the east-flowing Machetá River, the elevation low in the divide (2700 m) rises only 50 m above the longitudinal river in the Sabana (2750 m) (Fig. 11A). Local slopes are higher to the east of the divide (15°) than to the west in the plateau (5°) (Fig. 3E). Farther north, the depression in the eastern divide between the Boyacá-Turmequé and Bogotá rivers is only 80 m above the latter (Fig. 11B).

As in the case of the Machetá River, local slopes are higher to the east (20º) than in the plateau (10º). In addition, the *Mx* of rivers is higher in the flanks than in the plateau (Fig.9), in agreement with the distribution of local slopes. The depressions are associated with elbow geometries with knickpoints in the downstream part of the longitudinal reach in the flank rivers, and we do not observe spatial correlations with the trace of active faults nor with easily erodible bedrock lithologies (Figs. 11C and D). Neither of these areas correspond to zones of fold plunge (which could in principle provide low resistance to incision and favor capture localization). This lack of correlation between divide depressions or reentrants and tectonic structures or specific lithologies is observed all along the eastern and western divides of the Eastern Cordillera.

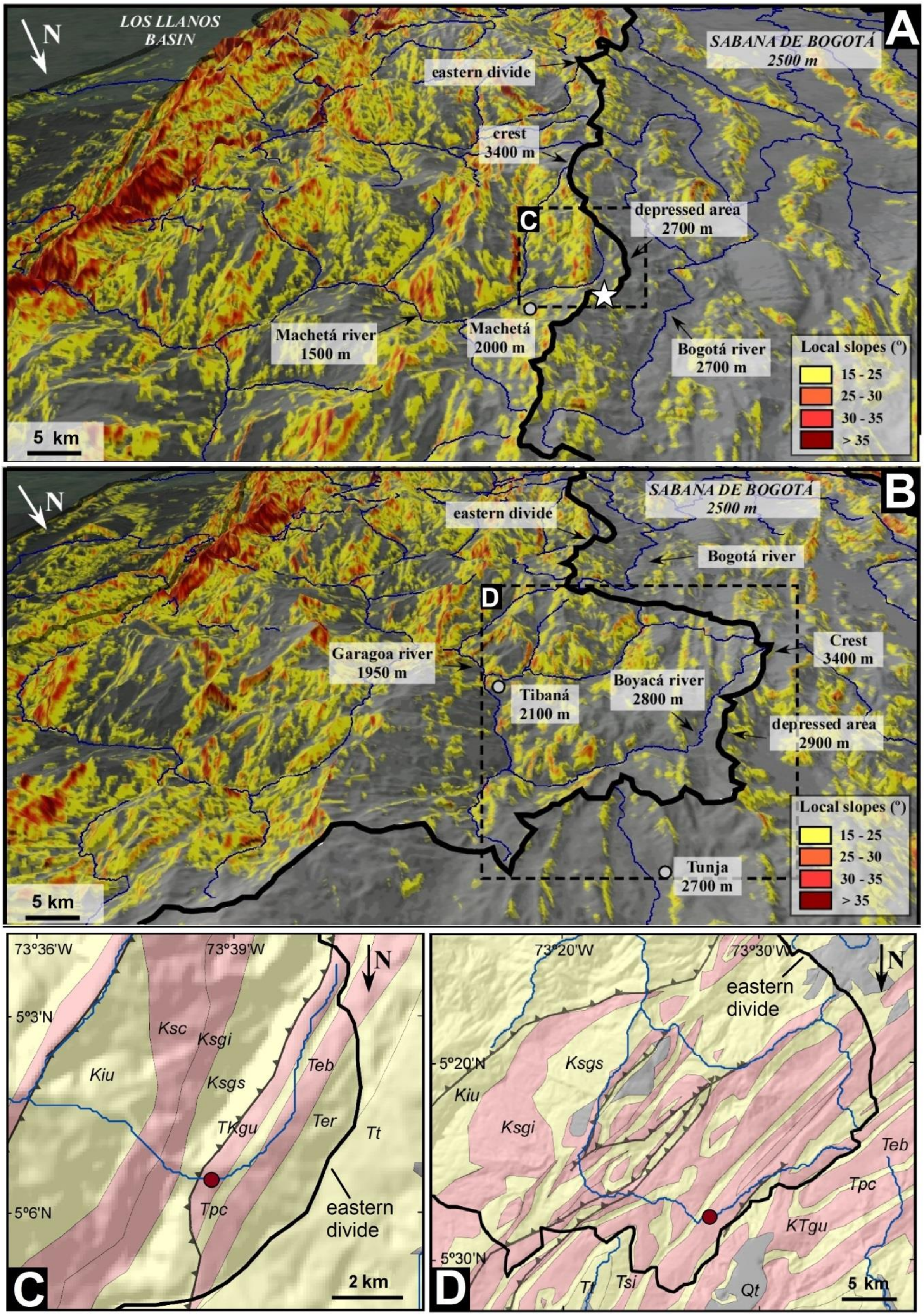

Fig. 11. *Local slope and lithology distribution at the Eastern Cordillera of Colombia. Note that they are oriented with North to the bottom of the page for a better appreciation of the*

topography and drainage. (A) Oblique view showing local slopes in the Eastern Cordillera. A reentrant in the divide associated to a depressed area is indicated in Figs. 9 and 10, testifying to processes of fluvial capture with a difference in elevation of 430 m between the mean altitude of the divide and the bottom of the depression. The occurrence of rounded rockfall deposits (Fig. 3B) is marked by a white star (see text for discussion). (B) Oblique view indicating local slopes in the plateau and in the upstream part of the Boyacá-Turmequé transverse river. The reentrant area is indicated in Fig. 9 and corresponds to a depression in the elevation profile of the divide (see Fig. 10), with a difference in elevation of 285 and 290 m. (C) and (D) Lithologic maps of the depressed divide in (A) and (B), respectively, showing no lithologic or tectonic control on the divide depression and on its trace. Red polygons are shale formations and yellow polygons sandstone formations. The red circle shows the location of a knickpoint. Cretaceous and Tertiary sandstone formations: Kiu (Une Fm), Ksgs (Guadalupe Superior Fm), Tpc (Cacho Fm), Ter (Regadera Fm), Tt (Tilatá Fm), Tsi (Socha inferior Fm). Cretaceous and Tertiary shale formations: Ksc (Chipaque Fm), Ksgi (Guadalupe Inferior Fm), KTgu (Guaduas Fm), Teb (Bogotá Fm) (modified from Toro et al., 2004; Parra et al., 2009b, Mora et al., 2010; and unpublished maps by ICP-Ecopetrol).

3.3. River capture and evidence for drainage divide migration

At present, the main rivers flowing in the Sabana de Bogotá plateau are longitudinal and follow synclines constituted by Cenozoic strata, mostly terrestrial in origin. In the Cordillera flanks, the main rivers are transverse to the chain and they are deeply incised across Cretaceous and Paleogene folded series. As summarized above, during Paleocene-Oligocene times, the drainage network was controlled by the emerging folds and thrusts and followed a gentle regional slope to the NNE (Gómez et al., 2005a; Silva et al., 2013).

Incised transverse rivers that cut across the Paleogene folded series in the eastern flank are evidence of a strong contrast between the current flow drainage organization and the paleodrainage deduced from the Paleogene strata. The northern flow direction from palaeocurrent data in these Paleogene series are now incised by an eastern transverse flow. This is the case of the Tertiary Umbita and Usme synclines (Fig. 1). The Usme syncline, with a N-S orientation parallel to the mean trend of the orogen, records an Oligocene paleoflow in the same direction. Nevertheless, part of this syncline has been captured by a river of the eastern flank and now drains to the east, which indicates a migration of the main eastern divide toward the inner part of the Cordillera (the plateau) after the Oligocene. The Umbita syncline records a western flow in Paleocene times (see location in Figs. 1 and 4). This syncline is actually in the eastern flank and dominated by a transverse drainage flowing to the east (Figs. 11A and C). Paleogene strata are not preserved in the western flank of the Cordillera, and this line of evidence cannot be applied.

Captures usually leave gaps/depressions in drainage divides (e.g., Bishop, 1995). The topographic profiles of the main divides of the Eastern Cordillera show low-elevation tracts (Figs. 9 and 10). These depressed tracts coincide with map-view reentrants of the divide trace toward the plateau, suggesting a drainage area transfer from the plateau to the Cordillera flanks, as explained above. In addition, elbows with knickpoints at or above the elbow can be observed in these areas (see Figs. 11C and D), and the channel slope map (*Mx* values) (Fig. 9) also illustrates a strong topographic contrast across the main divides separating the Sabana plateau from its flanks. On the other hand, rounded rockfall deposits are locally found on the eastern divide into the Sabana plateau (Figs. 3B and 11A), where none of the current debris flow corridors observed in the slopes of the surrounding peaks lead to the rockfall deposit. This suggests that the missing crest that fed these boulders must have been eroded away, indicating divide migration toward the plateau.

On the assumption that erosion balances the local base level fall, the Mx value relates to the ratio between erosion rate and erodibility (Royden and Perron, 2013; Mudd et al., 2014). Therefore, the high *Mx* values observed in the Eastern Cordillera flanks suggest greater erosion rates than in the plateau. This may have favored the progressive divide migration toward the plateau and captures of longitudinal rivers previously flowing in the plateau by expanding transverse rivers in the flanks, thus providing an explanation for the contrast between the Eocene paleodrainage organization recorded in the Usme and Umbita synclines, and the current river network. We observe the same distribution of local slopes and channel slopes (*Mx*) between the western flank and the axial plateau, suggesting a similar migration in the western divide toward the centre of the Eastern Cordillera.

In summary, the depressions in the main divides, the occurrence in the flanks of knickpoints in the upstream parts of the longitudinal river profiles (e.g., Chingaza area), the existence of rock landslides with no source near the divide (Figs. 3B and 11), the observation of elbows in the rivers of the eastern flank with knickpoints upstream, and the contrast between the local slopes and the channel slopes of the main rivers support the view that the drainage network of the Eastern Cordillera reorganizes by progressive divide migration toward the inner part of the chain and by discrete events of capture. This is in agreement with the reorganization inferred from the contrast between the palaeocurrent data of the geological record and the present-day drainage network. The case of the Umbita and Usme synclines (where youngest strata are Oligocene in age) indicates that in those areas such reorganization did not start before the Miocene. As the main divides converge toward the centre of the Eastern Cordillera, and given the scarcity of Cenozoic strata in the Eastern Cordillera flanks, we cannot rule out that reorganization may have started earlier in the external parts of the eastern and western flanks.

4. Causes and implications of drainage reorganization

4.1. Mechanism causing drainage reorganization

Our observations suggest that the drainage network in the Eastern Cordillera evolves from longitudinal-dominated to transverse-dominated, with rivers turning into the direction of the regional slope. The steep transverse rivers must have higher rates of incision than the gentle longitudinal rivers in the plateau to expand their catchment. At least four potential mechanisms that could explain differential erosion between the plateau rivers and rivers in the flanks can be considered.

First, a gradient of precipitation perpendicular to the trend of an orogen can result in divide migration toward the dry side, as has been observed in numerical models (e.g., Willett, 1999; Bonnet, 2009). Figure 5 shows the annual precipitation for the period 1998-2009 in the Eastern Cordillera, where no precipitation gradient is observed across the eastern main divide. On the basis of evidence as stable isotope geochemistry from fossil and present-day growth bands in mollusks, from palynology, and from macroscopic paleoflora, Mora et al. (2008) suggested that the influence of the erosion processes by global climate change was negligible since the Pliocene in the region. The precipitation pattern appears to have remained similar at least since middle Miocene time (Mora et al., 2008, and references herein), coinciding with the early topographic growth causing the topographic asymmetry of the orogen (Mora et al., 2008). Moreover, an eastward gradient in moisture could not explain the similar contrast of morphology between the western flank and the plateau. Therefore, the reorganization of longitudinal to transverse drainage may not be attributed to an asymmetric precipitation pattern across the eastern divide.

Second, erodibility differences associated with lithological changes can explain spatial variations in erosion rates (e.g., Safran et al., 2005) and can produce local changes in the organization of drainage. In the Eastern Cordillera of Colombia, the depressions along the main divides are not located on less-resistant lithologies, and they occur indistinctly over shale or sandstone formations, from which we can conclude that the reorganization of the drainage is not controlled by lithology.

Third, in some mountain settings at mid-latitudes, different intensity of glacial erosion by valley or cirque glaciers may produce a divide migration toward the hillslopes receiving less insolation (Brocklehurst and Whipple, 2002). The Eastern Cordillera of Colombia is close to the equator so that the reorganization of drainage cannot be controlled by glacial erosion as eastern and western slopes receive the same amount of insolation. Indeed, we see unlikely that the small and poorly developed valley glaciers deduced for the Eastern Cordillera during the Quaternary (Helmens, 2004) contributed to an important difference in erosion between the flanks and the plateau, especially in view of the abundant fluvial geomorphologic features that point for drainage reorganization.

Fourth, longitudinal drainage largely coincides with areas where the regional slopes are low, whereas transverse rivers are related to higher regional slopes. The marked slope contrast between the flanks and the plateau appears to be the sole factor responsible for the higher erosional activity on the flanks. Consequently, we propose that the reorganization of the drainage network in the Eastern Cordillera is the result of increased regional slope. We interpret that the regional slope increase was acquired during orogenic shortening and crustal thickening of the mountain belt. The slope contrast between the axial plateau and the flanks associated with orogenic building promotes fluvial capture of the initial longitudinal drainage area by the transverse drainage system. The longitudinal-to-transverse drainage evolution thus deduced may represent a transient stage in mountain building, as previously discussed for the High Atlas Mountains of Morocco by Babault et al. (2012, 2013). Moreover, the occurrence of precipitation in the eastern flank will enhance the eastern divide migration toward the central part of the Cordillera.

The dynamics of drainage network described here is currently active in the Eastern Cordillera, and we can expect future captures to occur in areas where steep transverse rivers flow close to low-gradient longitudinal rivers located in the plateau, especially if they are separated by a low-elevation stretch of the main divide. As an illustrative example, the Batán river in the western flank threatens to capture the Frío River in the Plateau (zone 7 in Fig. 9).

4.2. Implications for sediment supply into the adjacent basins

Changes in the sediment supply, sedimentation rate and detrital composition are often considered to be caused by climatic and/or tectonic variations (e.g., Molnar and England, 1990; Stokes et al., 2002; Allen, 2008). Drainage reorganization can exert, alternatively, a control on the sedimentation rates (e.g., Mather, 2000; Stokes et al., 2002; Prince et al., 2011; Antón et al., 2012; Willett et al., 2014). Capture processes involve sudden changes in the drainage areas of the captor river and of the victim river. The captor river gains drainage area and therefore the erosion rate increases connecting an elevated catchment to a lower base level. The remnant drainage basin, the victim, experiences an erosion rate decrease as it loses headwaters and drainage area. These variations must affect the clastic fluxes at the outlets, and modify the spatial and temporal localization of the proximal clastic bodies at the toe of the thrust front. Therefore, with the reorganization of the drainage network in the Eastern Cordillera related to the increase of the regional slope, the transverse rivers located in the flanks increased their drainage areas against the rivers located in the Sabana. In this way, erosion of the captured areas may have enhanced sedimentation rates in the Llanos and Magdalena basins.

Previous works interpreted the distribution of maximum sediment thickness of the late Oligocene to Miocene Carbonera to Guayabo formations (which are coarse-clastic foreland basin deposits derived from the Eastern Cordillera) as associated with the orogenic loads (Parra et al., 2009a,b; Hermeston and Nemcok, 2013; Jimenez et al., 2013). We propose that the migration of the orogenic load is not the only mechanism to explain sedimentation rate increases, coarse-clastic inputs, and depocenter migration in the basins adjacent to the Eastern Cordillera. The process of fluvial drainage reorganization in the source areas of the mountain belt may have exerted an additional control.

5. Conclusions

The Eastern Cordillera of Colombia presents a clear differentiation into two topographic domains: an axial plateau dominated by gentle longitudinal rivers, with low local relief and local slopes, and the flanks with high local relief and slope dominated by steep transverse rivers. These domains are separated by two main drainage divides in the eastern and western sides of the Sabana de Bogotá plateau.

In the eastern flank of the Cordillera, the change in flow direction between the Paleogene palaeodrainage toward the NNE, parallel to the early tectonic structures, and the current drainage toward the SE, incising across folded Paleogene strata near the eastern divide, argues for drainage reorganization. This work highlights the convenience of morphological analysis to characterize drainage reorganization and supports models of evolution of relief in mountain belts. Morphometric analysis and field observations show depressions and map-view reentrants in the main divides, debris flow deposits with no source near the divide, elbows with knickpoints upstream, and an evident contrast of the local and river slopes across the divides. This evidence indicates that the drainage network reorganizes by progressive divide migration toward the inner part of the chain by discrete events of capture.

We interpret that fluvial reorganization from longitudinal to transverse-dominated drainage in the Eastern Cordillera was triggered by the increase of the orogen regional slope by the progressive accumulation of crustal shortening and thickening. This pattern of drainage evolution is comparable to the drainage evolution described in other orogenic belts such as the Moroccan High Atlas. The evolution from longitudinal to transverse drainage in the Eastern Cordillera of Colombia may lead to a progressive area reduction and eventually a disappearance of the high plateau of the Sabana de Bogotá.

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