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Author statement

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Cenozoic exhumation patterns in the Northern Andes: constraints from the southern Bucaramanga Fault, Eastern Cordillera, Colombia

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Abstract

The left lateral strike-slip Bucaramanga Fault exhibits a transpressional southern termination located towards the axial zone of the Eastern Cordillera of Colombia, where the Boyacá and Soapaga Faults are also identified as inversion-related structures. To unravel their exhumation history, we obtained apatite and zircon fission-track and (U-Th)/He ages from samples collected along different structural domains, along five vertical profiles. Joint Bayesian inverse modeling of these data reveals at least four different episodes of cooling. These are approximately: (i) 50 ± 5 Ma, (ii) 20 ± 5 Ma, (iii) 12 ± 3 Ma, and (iv) 5 ± 3 Ma. The earliest pulse is associated with reactivation of the Boyacá and Soapaga Faults. The second pulse is related to the age of transpressive reactivation along the southern termination of the Bucaramanga Fault and coincides with a marked increase in relief. The Miocene-Pliocene pulses are related to Bucaramanga Fault strike-slip reactivation. Older fission-track ages previously reported from other areas of the Santander Massif suggest migration of exhumation from north to south. The four cooling episodes identified in this study can be related, within a broader geodynamic context, to interaction between the Cocos, Nazca, Caribbean, and South American plates, and the accretion of large tectonic domains of different affinity (oceanic or continental) against the South American plate during the Cenozoic. Our results are consistent with previous work

reported in the Santander Massif. The ages observed in the in-situ data correspond with the ages found in modern river sediments and support a relief development from the Eocene to the present.

Keywords: Low-temperature thermochronology, thermal history modelling, transpression, strike-slip faults.

Highlights

- New thermochronologic data reported for the Eastern Cordillera of Colombia
- An exhumation pulse occurred in early Eocene time
- Significant cooling at 20 ± 5 Ma defines the onset of fault transpression and a significant increase in relief.
- Miocene-Pleistocene cooling pulses are related to Bucaramanga Fault reactivation
- Exhumation along the Bucaramanga Fault migrated from north to south
- Several structural zones exhibit significant differences in thermal and exhumation histories

1. Introduction

The axial zone of the Eastern Cordillera of Colombia is characterized by regional faults such as the Soapaga, Boyacá and the southern termination of the Bucaramanga master fault, along which crystalline basement outcrops in the Santander and Floresta massifs. The Cordillera comprises a Mesozoic basin, which was inverted tectonically during the Cenozoic (Fabre, 1983; Colletta *et al.*, 1990; Dengo and Covey, 1993; Cooper *et al.*, 1995; Sarmiento, 2001; Toro *et al.*, 2004; Sarmiento-Rojas *et al.*, 2006; Tesón *et al.*, 2013). The boundary between the Santander and Floresta massifs is not clearly defined, so the whole area is generally considered as uplifted Mesozoic basement known as the “Santander High”. Sarmiento (2001) suggested that the extension of this uplifted basement propagated from the Floresta Massif in the south to the Perijá Range in the north (Figure 1).

To the south, tectonic inversion of the Santander High occurred mainly along the Boyacá and Soapaga faults (Cooper *et al.*, 1995; Sarmiento, 2001; Toro *et al.*, 2004; Tesón *et al.*, 2013); whereas to the north, the inversion has been described along the La Salina and Suárez faults (Sarmiento, 2001; Tesón *et al.*, 2013; Caballero *et al.*, 2013). During the

Andean orogeny, Cenozoic reactivation of the Bucaramanga, Río Servitá and Baraya faults, located at the center and to the east of the current Santander Massif was significant (Kammer, 1993; Corredor, 2003; Forero-Ortega *et al.*, 2020). The origin of the Eastern Cordillera has been explained from the point of view of transpressional models by several authors (e.g., Kammer, 1999; Taboada *et al.*, 2000; Sarmiento, 2001; Sarmiento-Rojas *et al.*, 2006; Velandia *et al.*, 2020). Transpression is especially pronounced at the southern termination of the sinistral Bucaramanga Fault (Velandia and Bermúdez, 2018; Bermúdez *et al.*, 2021), the study area of this work.

Based on field observations and geo-thermochronological data, different tectonic models have been proposed to explain the evolution of the Santander and Floresta massifs (Shagam *et al.*, 1984; Parra *et al.*, 2009; Villagómez *et al.*, 2011; Tesón *et al.*, 2013; van der Lelij, 2013; van der Lelij *et al.*, 2016a, b; Amaya *et al.*, 2017; Siravo *et al.*, 2019), which record exhumation events from the Paleocene for the Eastern Cordillera, related also with the initial shortening of its central part during the late Oligocene (Villamil, 1999; Mora *et al.*, 2013; Egbue *et al.*, 2014; Horton *et al.*, 2020). Thermochronological studies in the Santander and Floresta massifs have a dispersed regional sampling approach (Shagam *et al.*, 1984; Villagómez *et al.*, 2011; van der Lelij, 2013; van der Lelij *et al.*, 2016a), or are located too far from our study area (Saylor *et al.*, 2012a,b; Parra *et al.*, 2009; Ramírez-Arias *et al.*, 2012; Amaya *et al.*, 2017, 2020). All these studies report cooling episodes, especially the Miocene-Pliocene Andean Orogeny. At the southern Bucaramanga Fault, only three thermochronological ages in the literature are from locations close to our study area: two reported by van der Lelij (2016a) in San Joaquín and Onzaga, and one by Toro (1990). These are insufficient however to understand the exhumation history of this part of the axial zone of the Eastern Cordillera, where besides compressional structures, strike-slip deformation is also reported (Velandia and Bermúdez, 2018).

Exhumation along strike-slip faults has been studied globally in several regions. Some of the processes that contribute to exhumation in these zones have been described by Cao and Neubauer (2016): (i) along transtensive and transpressive zones, (ii) overlapping of ancient strike-slip faults, (iii) reactivation of normal or reverse faults, and (iv) oblique shear with magma ascent and buoyancy by density contrasts. Exhumation along strike-slip fault terminations, some related to transpression, have been studied by Spotila *et al.* (2007a, b),

Cruz *et al.* (2007), Furlong (2007), Umhoefer *et al.* (2007), Bermúdez *et al.* (2010; 2011), and Cochran *et al.* (2017). Our research constitutes another example of exhumation along a transpressive system where tectonics is the main driver for the exhumation (García-Delgado *et al.*, 2021).

The goal of the present study is to characterize the exhumation and tectonic evolution at the southern termination of the Bucaramanga Fault, where the spatial and temporal pattern of rock exhumation is poorly constrained. For this purpose, we present new thermal history models based on low-temperature thermochronology data from bedrock along five “vertical” elevation profiles in that area. Since Velandia and Bermúdez (2018) described the structural style for the transpressive system, including the relationship with inverted faults, in this study we further elucidate the timing of the exhumation of this deformational system. A corollary of this work will be to understand the mechanism of how oblique motion is partitioned into vertical strain. Further, in the middle part of the Bucaramanga Fault a major cooling event occurring at ~25 Ma has been reported by Amaya *et al.* (2017, 2020). We will also evaluate whether such cooling extended southward to the study area, and if so, explain the implications in a regional context.

In this study we plan to address the following research questions: What is the role of the Santa Marta-Bucaramanga strike-slip fault in the study area?. How does this fault influence the exhumation patterns?. To what degree are other faults (Boyacá and Soapaga) also involved in the exhumation?. Will there be differences in terms of exhumation between the southern termination of the Bucaramanga fault and the Santander Massif or the Floresta Massif?. Is it possible to define tectonic blocks or structural domains that exhume at different rates and times?.

2. Geological setting

The core of the northern Eastern Cordillera of Colombia consists of the Floresta Massif, the Santander Massif and the Perijá Range (Figure 1), which together formed the so-called *Santander High* during Mesozoic extension (De Freitas *et al.*, 1997; Sarmiento, 2001; Sarmiento-Rojas *et al.*, 2006). In the area where the Bucaramanga, Boyacá and Soapaga faults converge, crystalline basement comprises Paleozoic to Jurassic metamorphic and igneous rocks (Figure 1). This area is bounded by folded Mesozoic sedimentary rocks,

which once covered the Santander High. Subsequently, these sediments were eroded from the central part of the mountain range during Cenozoic exhumation (Horton, *et al.*, 2010, 2020; Parra *et al.*, 2010; Amaya *et al.*, 2017), when tectonic activity and transpressive deformation were predominant (Ramírez-Arias *et al.*, 2012).

The crystalline basement of the Santander and Floresta massifs comprises diverse rock types from high-grade metamorphic rocks with sedimentary and igneous protoliths (Vargas *et al.*, 1976, 1987; Ward *et al.*, 1977 a, b). These include; Precambrian (Ward *et al.*, 1977a, b) or Paleozoic Bucaramanga Gneiss (Zuluaga *et al.*, 2017; Zuluaga and López, 2019), Early Paleozoic migmatites, Paleozoic orthogneiss, Silurian-Ordovician low-grade metamorphic (Silgará Fm.) and Silurian-Devonian metamorphic rocks (Guaca - La Virgen / Floresta Fm.) (Vargas *et al.*, 1976, 1987; Ward *et al.*, 1977 a, b; Mantilla-Figueroa *et al.*, 2016; van der Lelij *et al.*, 2016b; Zuluaga *et al.*, 2017). Sequences of siltstones, conglomerates, sandstones and limestones are also present in the massifs (Devonian Floresta and Tibet formations; Carboniferous-Permian Cuche Formation, and the Paleozoic Río Nevado Formation). In addition, Ordovician-Silurian and Jurassic intrusive rocks, Early to Middle Jurassic volcanic and volcanoclastic rocks, as well as Late Jurassic sedimentary rocks (Girón Formation) also crop out in the area (Vargas *et al.*, 1976, 1987; Ward *et al.*, 1977 a, b).

A Cretaceous marine succession overlies the Girón Group, but there is no consensus about the nature of the contact. The Early to Late Cretaceous marine sequence comprises units of varied lithology: claystones, sandstones, limestones, grouped in the Río Negro, Tibú-Mercedes, Aguardiente, Capacho, La Luna and Colón-Mito Juan formations. A Cenozoic sedimentary succession overlying this sequence includes the Catatumbo basin formations (Barco, Cuervos, Mirador and Carbonera formations) correlated in the Eastern Cordillera with the Socha sandstones, Socha siltstones, Picacho and Concentración formations toward the adjacent El Cocuy and El Tablazo sub-basins (Fabre, 1983; Jiménez *et al.*, 2014) (Figure 2). Quaternary deposits are commonly found in the northeastern block of the Soapaga and Bucaramanga faults, and basins located between the Soapaga and Boyacá faults (Figure 1). These structures played an important role in the regional tectonic framework since the early Mesozoic, which involved their activity in the half-graben systems as the Cretaceous Tablazo and El Cocuy basins (Figure 1) (Fabre, 1983; Mojica

and Kammer, 1995; Cooper *et al.*, 1995), and others as the Yariguíes or Arcabuco – Norean for the Jurassic (Velandia, 2017; Osorio-Afanador and Velandia, 2021). These structures probably originated or were reactivated from a combination of rifting and back-arc extensional activity related to the spreading of Pangea and the subduction of the Farallón Plate beneath the South and North American plates (Pindell and Dewey, 1982). The faults bounding the basins, such as the Boyacá, Bucaramanga, Soapaga or Río Servitá (Figure 1), were affected by tectonic inversion during the Cenozoic and this has also been documented in the northern Eastern Cordillera (Fabre, 1983; Colletta *et al.*, 1990; Dengo and Covey, 1993; Cooper *et al.*, 1995; Kammer and Sánchez, 2006; Tesón *et al.*, 2013). This tectonism is related to the eastern advance of the deformation, with orogenic pulses occurring during the Oligocene, Miocene and Plio–Pleistocene (Parra *et al.*, 2009; Mora *et al.*, 2013, 2015), although the compressional regime related to tectonic inversion was initiated along the western flank of the cordillera in the late Paleocene – early Eocene (Cortés *et al.*, 2005; Parra *et al.*, 2009; Nie *et al.*, 2012). In some cases, exhumation during this period was interpreted as the product of crystalline basement erosion (Shagam *et al.*, 1984; Horton *et al.*, 2010; van der Lelij *et al.*, 2016a). Structural models for the Eastern Cordillera of Colombia and Mérida Andes in Venezuela are consistent in their agreement on the role of preexisting discontinuities for controlling partition between structural domains, deformation, and the erosional exhumation of these mountain belts. A large part of these pre-existing discontinuities developed along the former passive margin of the South American plate and played an important role in the evolution of the orogen (Jacques, 2004; Mora *et al.*, 2009). The distribution of thermochronological ages and the time-temperature history arising from these data have allowed the definition of tectonic blocks with different ages and cooling rates along the Eastern Cordillera (Shagam *et al.*, 1984; Mora *et al.*, 2008, 2013, 2015; Parra *et al.*, 2009; Amaya *et al.*, 2017; Pérez-Consuegra *et al.*, 2021) and the Mérida Andes (Kohn *et al.*, 1984; Bermúdez *et al.*, 2010, 2011; van der Lelij *et al.*, 2016a).

In the Floresta Massif, two N30E oriented reverse faults of possible Jurassic origin, the Boyacá and Soapaga faults, were reactivated during the Andean orogeny. As these faults approach the strike-slip Bucaramanga Fault, trending N15W along the Eastern Cordillera, their orientation changes to the north. Most structural style models show thick and thin-skinned tectonics for the boundaries of the belt (at the southern part of the Floresta Massif),

where pure shear compression is the predominant mechanism (Colletta *et al.*, 1990; Toro, 1990; Dengo and Covey, 1993; Cooper *et al.*, 1995; Roeder and Chamberlain, 1995; Toro *et al.*, 2004, Saylor, *et al.*, 2012a, Tesón *et al.*, 2013). However, simple shear and sinistral kinematics have also been recognized along the Eastern Cordillera (Kammer, 1996, 1999; Taboada *et al.*, 2000; Sarmiento, 2001; Cediel *et al.*, 2003; Velandia, 2005; Acosta *et al.*, 2007, García-Delgado *et al.*, 2020; Velandia *et al.*, 2020; Machuca *et al.*, 2021).

The southern termination of the Bucaramanga Fault, where the present thermochronological study was carried out, is characterized as a transpressional fault system in a regional restraining bend induced by sinistral kinematics (Velandia, 2017; Velandia and Bermúdez, 2018). The main trace of the strike-slip fault defines a 5 to 8 km wide damage zone up to the Ricaurte site, from where the structure branches into two traces; the Chaguacá and Los Micos faults (Figure 1). These form the main fractures of a positive flower structure, which includes other longitudinal faults such as La Chorrera and Chicamocha, together with some minor NE transverse faults (Figure 2). Taking into account the sinistral kinematics of the major faults and dextral movement of the bounded transverse traces, the transpressional set is defined as a domino structural style. The southward advance of deformation along the transpressional system enabled the capture of the Boyacá and Soapaga faults, which constitute the main inverted structures of the axial zone of the Eastern Cordillera (Velandia and Bermúdez, 2018).

3. Methods

A total of 36 samples of crystalline basement (igneous and metamorphic rocks) were collected along the southern termination of the Bucaramanga Fault between the town of Cepitá and the Páramo (Figures 1 and 3). 21 of these samples belong to five age-elevation profiles (Figures 3 and 4), with samples collected as near as vertically as possible from the highest to the lowest part within the blocks. It is important to clarify that locally no faults cross or cut the blocks. These profile are: (i) Ricaurte profile (samples FV-55 to 58, from 1026 m to 1734 m elevation), located west of the Bucaramanga Fault; (ii) El Tendido profile (samples FV-43 to 46, from 1038 m to 1613 m elevation), located along the Bucaramanga Fault (Figure 3); (iii) Chaguacá profile (samples FV-31, 37-39, from 2415 m to 3344 m elevation), (iv) the Páramo profile (samples FV-31-35, from 3422 m and 3628 m elevation), located in the area delimited by the Chaguacá and Los Micos faults (Figure

3), and (v) San Joaquin profile (samples FV-48 to 51, from 2027 m to 2567 m elevation), located between the Bucaramanga and Lebrija faults (Figure 3).

Detailed sample information is presented in Tables 1, 2 and 3. Apatite and zircon grains were separated using conventional mineral separation techniques in three different laboratories: Servicio Geológico Colombiano (Bogotá, Colombia), Universidad EAFIT (Medellín, Colombia) and at the Université Paul Sabatier (Toulouse, France).

3.1. Fission-track analysis

The apatite and zircon fission-track (AFT and ZFT, respectively) method is based on the accumulation of fission tracks or radiation damage trails (Wagner and van den Haute, 1992; Gallagher *et al.*, 1998). The tracks result from the spontaneous fission of heavy radionuclides (with an atomic number ≥ 90 and a mass number ≥ 230). Among these elements ^{232}Th , ^{235}U and ^{238}U can be measured, but it is ^{238}U which has the abundance and half-life significant for geology (Tagami and O'Sullivan, 2005). For the AFT and ZFT two accepted age determination are used currently: i) the external detector method (EDM), and ii) the fission-track Laser Ablation Quadrupole Inductively-Coupled-Plasma Mass Spectrometer (LA-Q-ICP-MS) method. For the first method, the age can be calculated from counting spontaneous tracks in crystals (e.g. apatite or zircon) and induced tracks in an external detector (ultra-low uranium mica), held in close contact with the crystal during neutron irradiation (e.g., see Hurford and Green, 1982; Wagner and Van den Haute, 1992, Gallagher *et al.*, 1998, Donelick *et al.*, 2005, and Tagami and O'Sullivan, 2005). The LA-Q-ICP-MS spot analysis has been successfully employed for in-situ measurements in AFT dating (e.g., Hasebe *et al.*, 2004, 2013; Chew and Donelick, 2012; Vermeesch, 2018; Cogné *et al.*, 2020; Ansberque *et al.*, 2021) and ZFT dating (e.g., Hasebe *et al.*, 2013). This approach is rapid as it avoids the need for irradiation and counting of induced fission-tracks, limits the use of hazardous acids and can also yield additional information such as apatite Cl content (Chew *et al.*, 2014).

Three apatite samples (FV-07, FV-20 and FV-21) and eight zircon samples (FV-07, FV-17, FV-18, FV-20, FV-21, FV-23, FV-28 and FV-29) were prepared and processed in the fission-track laboratory of the ISTERre thermochronology laboratory in Grenoble, following the external detector method and zeta calibration procedure. Apatites were etched in HNO_3

5M, for 20 seconds at 21° C, while zircons grains were etched in a NaOH-KOH eutectic solution at 228° C for 10-20 hours. Samples were irradiated at the FRM II research reactor in Garching, Germany. After irradiation, muscovite external detectors were etched for 18 min at 20°C in 48% HF to reveal induced tracks. Samples were analyzed using a 1250× dry objective with an Olympus BH2 optical microscope and the FTStage 4.04 system in the ISTerre thermochronology laboratory.

Four more apatite samples (FV-44, FV-46, FV-49, and FV-57; Table 2) were analysed using the fission-track LA-Q-ICP-MS method at the University of Melbourne following the methodology described by Gleadow *et al.* (2015). Results for all AFT and ZFT samples are presented in Tables 1 and 2. Due to sample problems, it was only possible to obtain confined track lengths for two samples (FV-44 and FV-57; Table 2), these lengths measurements were corrected as a function of their angle to the c-axis. Aliquots of these samples were irradiated on a second mount using a ^{252}Cf source under vacuum for 140 min at the Thermochronology Laboratory at the University of Melbourne to produce more confined tracks for length measurement. Regardless of the fission-tracks method used (EDM or LA-ICPMS), Dpar was measured and used as kinetic parameter only for those samples for which confined fission-track lengths were obtained.

3.2. (U-Th)/He Analysis

(U-Th-Sm)/He thermochronology is based upon the accumulation of ^4He in minerals and rocks over geologic time by the α -decay of ^{238}U , ^{235}U , ^{232}Th , and ^{147}Sm (Farley, 2002). For detailed reviews of the apatite (U-Th-Sm)/He (or AHe) and zircon (U-Th)/He (or ZHe) methodology see Farley and Stockli (2002) and Reiners (2005), respectively. The methodology reported here was described by Gleadow *et al.* (2015). Furthermore, Durango apatite (AHe reference age = 31.02 ± 1.01 Ma, McDowell *et al.*, 2005) and Fish Canyon Tuff zircon (ZHe reference age = 28.3 ± 0.4 Ma, Gleadow *et al.*, 2015) were also analyzed as ‘unknowns’ with each batch of apatite or zircons samples run and served as an internal check on analytical accuracy (see Tables 3 and 4, respectively). AHe data for 52 single grains from 16 samples were acquired, additionally ZHe data from 121 individual grains from 32 samples were obtained, and results are presented in Tables 3 and 4. In these tables we use the age columns, since they were corrected for factors such as grain geometry, alpha radiation damage, amongst others. Different factors that can contribute in different

degrees to single-grain AHe and ZHe age dispersion include grain size, radiation damage, grain fragmentation, U and/or Th zonation, complex eU intra-grain relationships, He implantation, uncertainties in the alpha ejection factor calculation, mineral inclusions, He-rich fluid inclusions and lengthy residence in the He partial retention zone (e.g., Wildman *et al.*, 2016; Danišik *et al.*, 2017; Hueck *et al.*, 2018). Furthermore, imperfections, such as vacancy damage and crystallographic micro-voids may also affect He diffusion (Gerin *et al.*, 2017; Zeitler *et al.*, 2017). From all these factors a significant variation of compositional and crystallographic characteristics could produce an intra-sample dispersion at He ages above 50% (e.g. Wolfe and Stockli, 2010; Wildman *et al.*, 2016). It is possible to reduce a part of this possible source of error by crystal selection (Danišik *et al.*, 2017). In this study, we took into account grain size, morphology and accumulated radiation damage. The corrected age was calculated as the measured age/ F_t , where F_t is the total fraction of alpha decays (see Farley *et al.*, 1996; Fitzgerald *et al.*, 2006, and Zeitler, 2015 for more details). For data interpretation and thermal history modelling, similar to other works (e.g. Boone *et al.*, 2018), we use the effective uranium concentration $eU = U + 0.235 \times Th$ as a proxy for α -radiation damage.

4. Results

4.1 Fission/track analysis

Regarding the three AFT ages obtained using the external detector method, the late Oligocene-early Miocene age for FV-07 (Table 1) located near Cepitá town (Figure 3), is comparable with an age reported by Amaya *et al.* (2017, 2020) for the same western block of the Bucaramanga Fault. The other two samples, which are separated by the Pueblo Viejo fault and sinistral Chaguacá fault (Figure 3), yield early Miocene (FV-21 to the west) and late Miocene (FV-20 to the east) ages, which are similar to AFT ages of two samples previously reported for the area (10VDL32, and 10VDL28 in van der Lelij *et al.*, 2016a) (Figure 3). Moreover, for AFT ages determined using the LA-ICP-MS method (Table 2, Figure 3) three show an early Miocene age and one a late Miocene age.

ZFT data show the oldest ages (Lower Cretaceous) in two samples located in the southern part of study area (FV-23 and FV-28), separated by the Boyacá and Chaguacá faults (Figure 3). The two ZFT samples for Chaguacá fault (FV-21 and FV-20) show Paleocene-

Eocene ages, while three other ZFT samples yield Eocene-Oligocene ages (FV-17, FV-18, FV-29) (Table 1, Figure 3).

4.2 (U-Th)/He analysis

Single grain AHe range from 3.7 ± 0.2 to 42.5 ± 2.6 Ma (Table 3). Table 4 summarizes ZHe data for 118 individual grains from 31 samples. Except for two single grains the morphology for zircons has both terminations (2T). Single-grain ZHe ages range from 3.5 ± 0.2 Ma to 227.7 ± 14.1 Ma, and intra-sample dispersion is large in 17 samples. Before estimating weighted (U-Th)/He ages because of issues which may result in age dispersion mentioned above (section 3.2), it is necessary to justify what is considered to be an outlier in an intra-sample data set. However, in some samples ages replicate reasonably well within associated uncertainties (e.g. AHe FV-40, FV-44, FV-45, FV-54, FV-56, FV-61 or ZHe FV-31, FV-35, FV-39, FV-44, FV-45, FV-47, FV-52, FV-59, FV-60 and FV-61).

We used the following as exclusion criteria: i) Grain morphology, grains without one or both terminations were excluded; ii) seemingly lower or higher [eU] ppm outliers, compared to the remaining grains, although higher [eU] ppm could affect closure temperature and could provide some additional information on the cooling history during numerical inversion of our dataset. We tested the inclusion of these grains but did not find any significant differences in numerical models when including these ages and when considering constraint-free models. This is shown in Figure DR-1; iii) Following Fukuda *et al.* (2020), we calculated weighted mean age of samples, where more than three intra-sample analyses were used, employing IsoplotR (Vermeesch, 2018). We verified whether grain ages within the error range of $\pm 3\sigma$ were consistent with a weighted mean age ranging within $\pm 95\%$ confidence interval. When single grain ages did not overlap within the weighted mean age of a sample, the grain ages were rejected as outliers and the weighted mean age without such outliers was recalculated, and iv) based on a “quasi-plateau age” or flatline trend (e.g. Johnson *et al.*, 2017) to $\sim 20 \pm 5$ Ma. We used this “plateau” criterion, which was derived from a first-order observation. In order to understand the different factors that could produce age dispersion, a plot of [eU] versus ZHe ages is shown in Figure 5A which considers all grains including “outliers”. Although no trend is observed, it is possible to discriminate an alignment or “plateau” of significant number of individual grains ages around 20 ± 5 Ma. This plateau is observed for both high and relatively low

values of [eU] (Figures 5B and C). It is suggested that this plateau may be associated with a distinct cooling event in the study area, which is the reason why it is taken into account as a reference value when calculating the weighted mean AHe and ZHe ages for the individual grains in a sample. Using IsoplotR (Vermeesch, 2018) we calculated weighted mean ages for each sample (Tables 3 and 4).

5. Interpretation and discussion

A common approach to estimating exhumation rates is to collect and date a suite of samples within a tectonic block according to elevation, in certain cases (e.g. when there is not a combination of advection and isotherm compression, the effect of topography on near-surface isotherms, and where samples are collected across the topography or the topographic wavelength) the slope of these age-elevation relationship (AER) can be considered as the exhumation rate (Braun, 2002), where changes or breaks in slope can be related as changes in exhumation rate through time (e.g. Wagner and Reimer, 1972; Wagner *et al.*, 1977; Gleadow and Fitzgerald, 1987; Fitzgerald *et al.*, 1995; Fitzgerald and Malusà, 2019). Thus, the age-elevation approach can be considered as a 1D-interpretative approach considering the effect of the cooling age distribution at the surface, because cooling ages increase with sample elevation in proportion to the exhumation rate. This way, thermal models are frequently used to investigate exhumation rates (Huntington *et al.*, 2007).

During the exhumation/cooling process the concept of closure temperature defined by Dodson (1973) as the temperature of a mineral (e.g., apatite or zircon) at the time given by its radiometric age is very important, because the daughter product is essentially retained in a crystal below the closure temperature range but not above it. This facilitates the interpretation of thermochronological data, but often these are only valid for minerals that experienced decreasing temperatures with time (or monotonic cooling; Dodson, 1973). Closure temperature will vary depending on how quickly a sample is cooled, grain size and mineral composition. Thus, faster cooling results in higher closure temperatures and vice versa (e.g., Reiners and Brandon, 2006). Each thermochronometer has a temperature window over which the daughter product starts to be retained or annealed within the system, since it was related to the He Partial Retention Zone (HePRZ) (Wolf *et al.*, 1998) and Partial Annealing Zone (PAZ) for the fission-track method (Gleadow and Fitzgerald,

1987), respectively. In the PAZ fission-tracks lengths are shortened. ^4He can be considered as an almost open system (Wolfe and Stockli, 2010), where some He diffusion information is retained, particularly for apatite the information is partially retained between $\sim 40^\circ\text{C}$ and 70°C , and typically not retained above $\sim 80^\circ\text{C}$ (Farley, 2000, 2002). The closure temperature for He in zircon, in contrast, is typically $\sim 170\text{--}190^\circ\text{C}$ (Reiners *et al.*, 2004), and the PRZ $\sim 130\text{--}180^\circ\text{C}$ (Reiners and Brandon, 2006; Wolfe and Stockli, 2010), but these ranges may vary considerably as a function of radiation damage (e.g. Shuster *et al.*, 2006; Guenthner *et al.*, 2013). For the fission-track technique, all fission-tracks are annealed and their concentration, and thus age, is zero above $\sim 120^\circ\text{C}$ in apatite (Laslett *et al.*, 1987; Ketcham *et al.*, 1999), and $\sim 240^\circ\text{C}$ in zircon (Zaun and Wagner, 1985). Partial annealing of fission tracks typically occurs between $\sim 60^\circ\text{C}$ and 120°C in apatite, depending on apatite composition (Green *et al.*, 1989) and between $\sim 180^\circ\text{C}$ and 350°C for zircon, depending on the degree of radiation damage (Tagami, 2005). An exhumed PAZ/PRZ may be revealed in an AER when, following a period of uplift/exhumation, the form of the PAZ/PRZ is retained with a 'sharp' convex inflexion (the 'break in slope') marking the base of the exhumed PAZ/PRZ with reset samples structurally beneath (Gleadow and Fitzgerald, 1987; Fitzgerald and Gleadow, 1988, 1990; Gleadow, 1990; Stockli *et al.*, 2000; Fitzgerald and Malusà, 2019).

In order to facilitate discussion and discriminate between some trends in the data, the weighted mean ages (Tables 3 and 4) plotted versus elevation are presented in Figure 6. We show AER for both methods AHe (Figure 6A) and ZHe (Figure 6B). Based on the frequency of the ages and the errors, we discriminate some rapid cooling events, which are drawn as grey bands in this figure. In particular, the age of 20 ± 5 Ma discriminated as a 'plateau' age (Figure 4). This age and other three populations (5 ± 3 Ma, 12 ± 3 Ma, and 50 ± 5 Ma) are defined based on detrital modern river apatite fission-track ages distributions (Bermúdez *et al.*, 2021) around the Onzaga and Los Micos river (Figure 1), these two basins cover a considerable portion of our study area. We use weighted ages in this figure because it allows us to show more clearly the most important cooling events in the study area, either by the distribution of detrital ages or by important regional events reported by van der Hammen (1961) and summarized by Restrepo-Moreno *et al.* (2019).

Assuming that the isotherms corresponding to the closure temperature remained essentially parallel, and the relief did not change through exhumation, in Figure 6 the AER are used to infer “apparent” exhumation rates which could be compared with cooling rates derived from the numerical model of thermal histories. Table 5 summarizes the estimated confidence interval for exhumation rates based on AER. These “apparent” exhumation rates were calculated using the Williamson (1968) regression line, which takes into account the errors on ages. For this regression line we assume that the dependent variable (y-axis) is the (U-Th)/He age and the independent variable (x-axis) is the elevation, thus exhumation rates are calculated as the reciprocal of the slope. When the rate of exhumation is very high, or the regression line is near vertical (infinite slope) this method has the advantage of allowing the detection of variations in exhumation rates by considering errors on slopes and intercepts. Basically, in our dataset it is possible to discriminate three different trends. AER relationships for the Páramo and San Joaquín profiles indicate exhumation rates below 0.5 km my^{-1} at $50 \pm 5 \text{ Ma}$. Regardless of our assumptions for calculating apparent exhumation rates from the AER based on ZHe data, the result is negative or very high at $20 \pm 5 \text{ Ma}$. This suggests a significant change in relief for the Chaguacá and Los Micos profiles. In these areas exhumation rates are $> 1 \text{ km my}^{-1}$. This rate is in good agreement with exhumation rates calculated in these zones by Bermúdez *et al.* (2021) assuming that the topography is spatially variable using two different methods BIN2E (Braun *et al.*, 2018) and thermo-kinematic 3D modelling (PeCube; Braun, 2003; Braun *et al.*, 2012). Our results suggest that the ZHe ‘plateau’ age of $20 \pm 5 \text{ Ma}$ could be related to an important cooling phase related to significant topographic amplification. We emphasize that not all profiles have a considerable difference in elevation range (>1000 meters) and this could explain why some exhumation rates are extremely low. Exhumation rates derived from AHe ages in the 5 to 15 Ma time range for the Los Micos fault profile and Ricaurte profile are $< 0.2 \text{ km my}^{-1}$.

It should be noted that based on scarce data in Figure 6, we do speculate on the possibility of the existence of two intervals of tectonic quiescence: (i) 68 to 60 Ma (Maastrichtian to early Paleocene) and (ii) 36 to 34 Ma (late Eocene). These intervals of “apparent” tectonic quiescent allow for the separation of three long intervals where data could indicate exhumation phases: a first from 84 to 72 Ma (Santonian to Campanian), a second with a significant increase in data between 60 and 33 Ma (middle Paleocene to late Eocene) and a

final phase based on more data between 32 and 5 Ma (Oligocene-Miocene). To avoid over-interpretation of our data, numerical thermal history models have been generated for comparison.

5.1. Inverse Thermal History Modeling

For all the models, AHe, ZHe, and AFT ages of representative samples were used, however in those cases where ZFT ages existed, these were incorporated for determining time-temperature paths through inverse Bayesian transdimensional Markov chain Monte Carlo modeling using the QTQt 5.7.3 program (Gallagher *et al.*, 2009; Gallagher, 2012). This software permits thermal histories to be calculated from low temperature thermochronology data using multiple samples. Additionally, QTQt has an option for considering burial and reheating episodes scenarios (Fox and Carter, 2020). This option is useful to infer possible events associated with major fault activity. Although the software produces four different time-temperature statistical models (expected, mode, maximum-Likelihood and posterior models), here we only considered the Expected model, which corresponds to the weighted mean of the posterior distribution and provides more regular curves and variation rates, compared to other statistical outputs.

For each sample the oldest ZHe weighted age (Tables 3 and 4) and temperature ($100 \pm 100^\circ\text{C}$) ranges were used for the general prior (model space). The present-day surface temperature was set as $15 \pm 5^\circ\text{C}$. Although it appears that the constraints used in our QTQt philosophy modeling were forced, we considered four different independent constraints based on two aspects: first, the four main reported pulses thermotectonic/orogenic phases in the Eastern Cordillera of Colombia (Restrepo-Moreno *et al.*, 2019). Second, the preferred time-temperature history derived from the best PeCube model for the study area (see Figure 12c in Bermúdez *et al.*, 2021). We are interested in corroborating the timing of exhumation onset in the study area from at least 35 Ma to the present (see Figure 12C in Bermúdez *et al.*, 2021). That PeCube model (Bermúdez *et al.*, 2021) is constraint independent and the range of parameters run was quite wide, plus it was possible to corroborate equilibrium versus time-varying topography conditions. Thus, we used the following four constraints: (i) 50 ± 10 Ma with temperatures of $160^\circ \pm 40^\circ\text{C}$; (ii) 20 ± 5 Ma with temperatures of $120^\circ \pm 60^\circ\text{C}$, (iii) 12 ± 3 Ma with temperatures of $100^\circ \pm 40^\circ\text{C}$, and (iv) 5 ± 3 Ma with temperatures of $80^\circ \pm 40^\circ\text{C}$. Because models start at 50 ± 10 Ma

and all temperatures overlap for these different time intervals, the constraints used are even wider than those provided by the best PeCube model (Bermúdez *et al.*, 2021), to give some freedom to the thermal histories. QTQt generates time-Temperature paths for two different Markov chains (birth and death), where a chain is a statistical perturbation of the other (Gallagher, 2012). Our modeling strategy was designed to use the QTQt software with a dual purpose: (i) to model individual samples closer to and away from the main faults (Figure 7) and (ii) to model all samples belonging to each vertical profile separately considered in this study (Figure 8).

For two samples FV-44 (El Tendido) and FV-57 (Ricaurte) AFT age, track lengths, Dpar measurements and individual AHe, and ZHe ages were used to determine time-temperature paths (Figure 9A, B). For AFT data we selected the multi-kinetic annealing model of Ketcham *et al.* (2007b), with c- axis projected track length data (Ketcham *et al.*, 2007a). As there were AFT, AHe, ZHe ages and MTL measurements from these two samples, which belong to distinct blocks, they were modeled individually and compared with models from the different profiles.

5.1.1 Cooling histories along the Los Micos and Chaguacá faults

The time-temperature path for the Chaguacá Fault (Figure 7A) suggests an onset of cooling at ~24 Ma for all samples, and a long residence or slight heating pulse from 24 to 8 Ma closer to the apatite PAZ occurred. Between 8 and 5 Ma a cooling pulse is recorded which occurred at much faster rate than the first pulse (24 Ma). Probably in this short period the rocks reached the near-surface. Finally, from 5 Ma to the present, the cooling rate decreased or possibly there was heating due to fault activity. This last possibly could also be an artifact of the modeling to be able to adjust to the present-day temperature. Although our data do not support this assumption, when we analyzed models for the El Tendido profile, in particular, sample FV-44 the data does support the result. In this case there are individual grains (younger ages) that can support the modeled time-Temperature path for this sample. For modeling we mainly used samples where both AHe and ZHe data (FV-31 and FV-59) were available, and we also added samples FV-38 and FV-39 that only had ZHe ages (Tables 3 and 4) because they are located parallel to the Chaguacá Fault. Of all the samples used to model this area (FV31, FV-38, FV-59 and FV-60) the northernmost sample FV-59 exhibits a more complex cooling-heating history. This could be explained

by its location in a small tectonic block, where the Bucaramanga Fault bifurcates into the Chaguacá and Los Micos faults. A comparison of predicted versus observed ages is shown in the center of Figure 7A, the colors in the figure represent the elevation of the samples; note that the obtained likelihood is -13.48 which means that the differences between the observed and model-predicted ages are very small. At the base of Figure 7A the predictions of the model are shown in the form of AER.

Expected t-T models derived for each sample located along the Los Micos Fault (Figure 7B), suggest prolonged residence within the ZHe PRZ before 25 Ma. Following this time, three successive cooling phases are observed: 1) a fast pulse between ~25 to 16 Ma, 2) a slow pulse compared to the first one between ~16 and 7 Ma, and finally 3) a fast-cooling pulse between ~7 Ma to present. This last episode is consistent with AFT and AHe ages in that area (e.g. FV-20, 10VDL28 and FV-45; Figure 3). Figure 7B (central part of the panel) compares ages predicted by the model and observed ages. Again, for this model, samples FV-40, FV-54 and FV-61 were selected, which had both AHe and ZHe age data (Tables 2, 3 and 4). The comparison between observed and predicted ages in the form of AER is shown at the base of Figure 7B. At an elevation between 2000 to 2500 m, a break in the EAR slope is observed. The model allows kinetic parameters to be predicted for the AFT method, such as Dpar.

5.1.2 Cooling histories for vertical profiles

All AFT, AHe, and ZHe ages for each profile (Figure 6) were modeled jointly (Figure 8). It was not possible to incorporate ZFT ages here since such data was not available for the profiles. Figure 8 is again split into three sectors; a left panel presenting the time-Temperature paths predicted by QtQT, a central panel presenting comparisons between predicted and observed ages, and a right panel showing the central panel comparisons in the form of age-elevation relationships (AER). In general, in the interval between 60 and ~25 Ma, the different tectonic blocks experience a long residence in the ZHe PRZ (140-180 °C; Ricaurte), AFT PAZ (San Joaquín), or very slow cooling (El Tendido, Chaguacá, and Páramo). From ~25 Ma to present the blocks exhibit contrasting time-Temperature histories. The Ricaurte profile exhibits rapid cooling from 25 Ma to 12 Ma (Oligocene - Middle Miocene), slow cooling from ~12 Ma to 4 Ma, and an increased cooling rate from 4 Ma to the present. The El Tendido profile experienced a slow cooling pulse from ~50 Ma

to 25 Ma, a slight increase in cooling rates from ~18 Ma to 14 Ma (Oligocene - early Miocene), a slight reduction in cooling rate from ~16 Ma to 5 Ma and finally from ~5 Ma to the present a rapid cooling pulse. In the San Joaquin structural domain a lengthy residence in the PAZ AFT from ~60 Ma to 22 Ma appears to be followed by a relatively fast continuous (4.4 °C/Ma) cooling pulse from ~22 Ma to the present. Although mean fission-tracks lengths measurements would be required to confirm that scenario. For the Chaguacá profile only three samples with ZHe ages were used to model numerically the time-Temperature history. Thus, the time-temperature history below the ZHe PRZ cannot be interpreted. In the Páramo, slow and continuous cooling occurred through the ZHe PRZ from ~50 Ma to 16 Ma, followed by an increase in the cooling rate from ~16 Ma to 6 Ma and a slight reduction in the cooling rate from ~6 Ma to the present.

Based on the four well defined thermotectonic/orogenic pulses defined by van der Hammen (1961), supported by low temperature thermochronology (Restrepo-Moreno *et al.*, 2019) and the discrete tectonic pulses discriminated from detrital dataset and PeCube modelling (Bermúdez *et al.*, 2021) we can confirm several cooling pulses previously identified. The first pulse occurred before ~25 Ma (Oligocene) was discerned in the San Joaquín and Páramo profiles, and in the western side of the Bucaramanga Fault (Figure 1). This is also observed in the San Joaquín and Páramo profiles, with slow cooling rates (<4°C/Ma), which are located furthest away from the main strand of the Bucaramanga Fault. The similarity between both profiles may indicate that the Chaguacá Fault might not have been active at that time. In the models, most samples from the four profiles indicate the onset of a cooling pulse between ~22 to 15 Ma (Oligocene - early Miocene). This coincides with the onset of Bucaramanga Fault activity, while the most recent pulse recorded between ~6 to 2 Ma for samples in the El Tendido, Chaguacá and Ricaurte profiles is associated with subsequent recent activity of the Bucaramanga Fault and its subsidiary branches in that area. The Ricaurte and El Tendido profiles exhibit complex thermal histories, possibly related to reactivation of the Los Micos and Bucaramanga faults.

For samples FV-44 (El Tendido) and FV-57 (Ricaurte) weighted AHe and ZHe ages, AFT ages, fission-track lengths and Dpar measurements, were used as input for determining time- temperature paths (Figure 9A and B) using QTQt. El Tendido shows a very slow

cooling rate ($2^{\circ}\text{C}/\text{Ma}$) from ~ 50 Ma to 8 Ma with temperatures ranging between $\sim 200^{\circ}\text{C}$ to 125°C . From 8 Ma to the present this sample exhibited a fast cooling rate ($\sim 13^{\circ}\text{C}/\text{Ma}$). The histogram located at the right of the Figure 9A represent the fission-track length distribution. The values in this figure correspond to observed (O) and predicted (P) data.

Figure 9B shows the predicted t-T path for the Ricaurte profile, the Expected model suggests lengthy residence in the zircon PRZ, with heating, possibly due to burial episode between ~ 22 Ma to 16 Ma, whereas a faster cooling episode ($\sim 21^{\circ}\text{C}/\text{Ma}$) began from ~ 16 Ma to 12 Ma. From ~ 12 Ma to 2.5 Ma the cooling rate decreased to $\sim 0.1^{\circ}\text{C}/\text{Ma}$ and the sample remained within the AHe PRZ. From ~ 2.5 Ma to present the cooling rate appears to have increased, although this should be confirmed through the use of other more strategically located samples.

5.2 Relationship between cooling/heating pulses and fault reactivation

In most of the profiles cooling episodes are recorded between ~ 25 to 15 Ma. For the San Joaquin, and Páramo profiles (Figure 8) cooling events prior to ~ 25 Ma could be not associated with the Bucaramanga Fault reactivation, instead, these were probably related to reactivation of the Boyacá and Soapaga faults at two different times, $\sim 50 \pm 5$ Ma and $\sim 36 \pm 3$ Ma (Ricaurte and Páramo; Fig. 7C), i.e. in early and late Eocene time, respectively. The late Eocene pulse is comparable with the onset of cooling between ~ 40 and 30 Ma for the Floresta Massif (Figure 1), based on AFT data reported by Parra *et al.* (2009). These pulses are related to displacement of the Soapaga Fault, whose onset in turn extends to ~ 50 Ma, similarly to ages reported in the present work. In contrast, heating is observed in the Chaguacá Fault (Figure 7A) and in sample FV-57 from the Ricaurte profiles (Figure 9B). These apparent heating "pulses" are possibly related to local advection of isotherms resulting from fault activity, or associated phenomena resulting from either shear heating or fluid flow, which could perturb the AHe ages (Reiners *et al.*, 2005).

Our modeled ages indicate that mountain building mainly occurred during the Cenozoic, with significant exhumation, especially in the southern and western Santander High. Eocene exhumation is a well-defined pulse observed in the detrital dataset (Bermúdez *et al.*, 2021) and this was probably controlled by early activity of the Boyacá fault. The low Oligocene exhumation rates are in concordance with the phase of orogen stabilization

reported by Mora *et al.* (2010, 2015) for this time in the northeastern Eastern Cordillera. This differs from ages reported in other sectors around the study area, particularly to the east of the Soapaga Fault (Figure 1). We note that this sector, located on the hanging wall (west part) of the fault, exhibits an apparent tectonic quiescence or slow exhumation between ~36 and 22 Ma. The reported range of ages here is similar to those reported by Saylor *et al.* (2012a) suggesting that to the south, in the Floresta Massif, the exhumation of the Soapaga Fault occurred after that related to activity of the Boyacá Fault (between 3~9 and 36 Ma), suggesting a migration of deformation to the east, preceding activity of the Bucaramanga Fault.

A strong regional exhumation pulse during the early Miocene (between 20 ± 5 Ma, and 12 ± 3 Ma) suggests an important role of the Bucaramanga Fault. Similar ages are also reported in AFT samples from this work (FV-17 and FV-21, Figure 3) and from Shagam *et al.* (1984), van der Lelij *et al.* (2016b) and Amaya *et al.* (2017, 2020) in the Cepitá sector, in addition to Parra *et al.* (2009) in the Massif of Floresta, where Toro (1990) also reports an AFT age of 22.3 ± 4 Ma. Villagómez (2010) using a sparse AFT age distribution on the west side of the Santander Massif suggests that cooling occurred between 23 and 16 Ma (early Oligocene-Miocene). The timing of ~25 to 20 Ma that Amaya *et al.* (2017) report for cooling in the Cepitá zone (Figure 3) may indicate that the pulse had migrated to the east and in that case, the onset of the tectonic activity of the Bucaramanga Fault and associated exhumation may have migrated from north to south. Van der Lelij *et al.* (2016b) suggest that the fault was already active at 40 Ma (37 Ma for Amaya *et al.*, 2017) and that exhumation was variable along it. However, at least to the south (in our study area), the ~35 Ma exhumation pulse (Bermúdez *et al.*, 2021) is more related to the late Eocene pulse that exhumed the western part of the Floresta Massif due to the inversion of the Boyacá Fault, whose prolonged activity to the north could also have had some influence on Santander Massif tectonism.

The last cooling pulses from ~5 Ma in the El Tendido profile and ~2 Ma in the Ricaurte profile coincide with exhumation events reported by Shagam *et al.* (1984) and Amaya *et al.* (2017, 2020) with similar AFT ages of 5 Ma, in samples located closer to secondary faults associated with the Bucaramanga Fault (Figure 3). This pulse is of relevance for some sectors across the Eastern Cordillera and can be related to an increase in tectonic

activity between ~6 and 3 Ma as evidenced by data from the Guaicáramo Fault system in the piedmont (Bayona *et al.*, 2008) and sedimentation of a thick late Miocene to Pliocene facies for the Los Llanos basin reported by Parra *et al.* (2010). Miocene-Pliocene tectonic-exhumation events have also been reported from across the entire Maracaibo block boundaries (Shagam *et al.*, 1984; Kohn *et al.*, 1984; Audemard and Audemard, 2002; Audemard, 2003; Bermúdez *et al.*, 2019).

5.3 Relief change, exhumation history, sedimentary record and geodynamic context

A decrease in relief leads to a further overestimate of the exhumation rate from the AER (Braun, 2002). Thus, a significant decrease in relief could lead to a negative slope. Such a negative AER is observed in Figure 6B for the El Tendido, Ricaurte, Los Micos Fault and Chaguaca profiles (Figure 3) around the interval $\sim 20 \pm 5$ Ma. Based on the previous information, the calculation of exhumation rates from age-elevation profiles should not be carried out, but rather we did the exercise for the purpose of comparison with exhumation rates derived from detrital thermochronological data for the same study area by Bermúdez *et al.* (2021). Assuming steady-state topography and spatially variable topography over time for the Chaguacá and Onzaga river catchments (Figure 1), Bermúdez *et al.* (2021) using 3D thermos-kinematic modeling (PeCube; Braun, 2003; Braun *et al.*, 2012) reproduced the distributions of detrital apatite and zircon fission-track ages. The best fits between the predicted and observed cumulative density function (CDF) are achieved when the amplification factor for topography or relief variation is assumed to be changing over time. These results suggest that prior to ~40 Ma some 10 to 50% of the present-day topography existed, with the balance being created in the interval between ~40 and 20 Ma. The PeCube modelling of Bermúdez *et al.* (2021) suggests that exhumation rates in the study area evolved from $\sim 2 \text{ km my}^{-1}$ between ~40 and 30 Ma, decreasing to values $< 0.1 \text{ km my}^{-1}$ from ~30 to 25 Ma, and again increased to 0.5 km my^{-1} from ~20 Ma to the present. In Table 5, numbers in italics show that despite the possible overestimation of AER ratios, the estimated rates are very close to those reported by Bermúdez *et al.* (2021).

The late Miocene cooling pulse recorded in our study area can be related to higher exhumation rates resulting in coarse-grained geological units in adjacent basins to the study area (El Cocuy and El Tablazo; Fabre, 1983; Jiménez *et al.*, 2014 – Figures 1, and 2).

In these basins during the late Miocene pulse there is important stratigraphic evidence for erosion such as the Tilatá Formation, which outcrops in the axial zone of the Cordillera.

The latest exhumation pulse that commenced between ~5 and 2 Ma (Plio-Pleistocene, Figure 7) can be linked to exhumation observed along the Bucaramanga Fault, that is associated with the El Tendido shutter ridge in the northern part of the transpressive southern termination of the structure (Velandia and Bermúdez, 2018) and the subsequent impoundment of the Chicamocha River, suggested by Galvis (2016) to be associated with the origin of a Pleistocene lake reported by Villarroel *et al.* (2001) in that area. Further, geomorphological evidence for current tectonic activity along the Bucaramanga Fault is provided by Diederix *et al.* (2009), e.g. eight Holocene earthquakes of magnitude M_s 6.6 to 7.0 spanning from 8300 to 930 yr BP and morphometric indices pointing to fault activity as a leading contributor to regional hillslope instability (García-Delgado *et al.*, 2019, 2020).

Similar to the Venezuelan Andes (e.g., Kohn *et al.*, 1984; Colletta *et al.*, 1997; Audemard and Audemard, 2002; Bermúdez *et al.*, 2010), the evolution of the Eastern Cordillera of Colombia has been controlled by the reactivation of preexisting faults (Corredor 2003; Cortés *et al.*, 2005; Mora *et al.*, 2009; Parra *et al.*, 2009). As observed in other transpressional mountain belts (e.g., Spotila *et al.*, 2007a), these faults delimit tectonic blocks characterized by contrasting exhumation histories. Unlike the Venezuelan Andes, the signal of early (pre- Miocene) exhumation across the Eastern Cordillera is significant. These tectonic blocks at the southern Bucaramanga Fault termination responded in different ways to tectonic events that occurred in this zone, which were driven by the triple convergence of the South American, Caribbean and Farallon/Nazca plates. In Paramo of Güina and San Joaquín, older weighted mean ZHe ages ranging from ~80 to 50 Ma are similar to AFT and ZFT ages reported by different authors for other sectors of the Eastern and Central Cordillera (Vinasco *et al.*, 2006; Montes *et al.*, 2010; Cardona *et al.*, 2010; Mora *et al.*, 2017; Restrepo-Moreno *et al.*, 2019) and at the Sierra Nevada de Santa Marta (Patiño *et al.*, 2019) suggesting widespread and significant exhumation at that time. This exhumation could be related to accretion of the Caribbean Plate on northwestern South America. A significant phase of mountain building with changes in exhumation rates occurring closer to $\sim 20 \pm 5$ Ma has been discerned in other sectors of the Colombian

Andes, such as: the Central Cordillera, Eastern Cordillera, Garzón Massif and Sierra Nevada de Santa Marta (Amaya *et al.*, 2017, 2020; Patiño *et al.*, 2019; Restrepo-Moreno *et al.*, 2019), but also from the Caparo and Trujillo blocks of the Venezuelan Andes (Bermúdez *et al.*, 2010). This period of significant relief growth coincides with important sediment deposition in the Maracaibo basin (Lugo and Mann, 1995; Guzmán and Fisher, 2006; Erickson *et al.*, 2012; Bermúdez *et al.*, 2017).

An exhumation phase at $\sim 12 \pm 3$ Ma coincides with the main surface uplift of the Venezuelan Andes (Bermúdez *et al.*, 2011) and events reported for the Perijá (Shagam *et al.*, 1984) and Santa Marta (Villagómez *et al.*, 2011). Finally, a more recent episode between ~ 5 to 2 Ma is similar to that reported by Kohn *et al.* (1984) for the El Carmen block in the Venezuelan Andes. This last event is associated with an increase in oblique convergence between the Maracaibo block and South American plate, which resulted in transpression and exhumation of the central part of the Venezuelan Andes (Kohn *et al.*, 1984; Audemard and Audemard, 2002; Bermúdez *et al.*, 2010) and other sectors at the circum-Maracaibo block (e.g. Shagam *et al.*, 1984; Kohn *et al.*, 1984; Bermúdez *et al.*, 2017; 2019; Restrepo-Moreno *et al.*, 2019). This episode starting at ~ 5 Ma continues to the present day, particularly in our study area where this event is observed in some regions: circum Chaguacá Fault (Figure 7A), El Tendido, Chaguacá and Ricaurte profiles, but not in all sectors. Convergence between the Maracaibo block and South American plate is also consistent with the current stress field in the northern Andes as resolved from fault striations, earthquake focal mechanisms and GPS data (Taboada *et al.*, 2000; Audemard and Audemard, 2002; Colmenares and Zoback, 2003; Audemard *et al.*, 2005; Cortés and Angelier, 2005; Audemard and Castilla, 2016; Pérez *et al.*, 2018; Mora-Páez *et al.*, 2019; Velandia *et al.*, 2020).

The timing of the four main cooling episodes reported here is in accordance with tectonic events reconstructed from coarse facies (Van der Hammen, 1961). These last four major events are known as the Laramic, Pre-Andina, Proto-Andina, and Eu-Andina orogenic events and occurred during the Late Cretaceous-Early Paleocene, the middle Eocene, the Late Oligocene, and the Miocene-Pleistocene, respectively (Van der Hammen, 1961). These events are the results of the complex interactions between Nazca, Cocos, Caribbean and South American plate, which control the accretion of continental and/or oceanic

tectonic realms as Cauca-Patía, Chocó, Gorgona, Baudó and Maracaibo (Cediel *et al.*, 2003; Restrepo-Pace and Cediel, 2019).

6. Conclusions

Numerical models based on low temperature thermochronology data suggest contrasting thermal histories between tectonic blocks prior to transpressional Bucaramanga Fault reactivation in the Eastern Cordillera of Colombia. Some blocks experienced slow cooling through the PAZ and PRZ, but some heating pulses occurred prior to the fault displacement, after that, short and fast cooling pulses are discerned, possibly as a result of Bucaramanga Fault activity.

Although Eocene exhumation of the Eastern Cordillera has been recorded in different works, in this study numerical models of elevation profiles show that in the study area the main cooling pulses occurred at the beginning of the Eocene ($\sim 50 \pm 5$ Ma). These episodes are probably related to activity of the Boyacá and Soapaga faults during tectonic inversion of the study area.

The onset of the most evident exhumation pulse occurred at $\sim 20 \pm 5$ Ma (late Oligocene-early Miocene) and is characterised by high cooling rates associated with the onset of Bucaramanga Fault transpressive activity along its southern termination, including one of its main splays: the Chaguacá Fault. Older ages reported within the region of the Santander Massif may indicate that exhumation across the Bucaramanga Fault has migrated from north to south.

An exhumation phase closer to $\sim 12 \pm 3$ Ma is identified as being associated with a regional event that coincided with the main surface uplift of the Venezuelan Andes, Perijá Range and Sierra Nevada de Santa Marta. Another important exhumation pulse is identified during the early Plio-Pleistocene (5-2 Ma) also with a high cooling rate, which is considered to be mainly associated with reactivation of the Bucaramanga Fault.

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FIGURES CAPTIONS

Figure 1. Geological map of the axial zone of the Eastern Cordillera of Colombia. Red boxes indicate the studied area (modified from Gómez *et al.*, 2015).

Figure 2. A. Chronostratigraphic compilation in basins adjacent to the Santander and Floresta massifs. Dark grey = mainly coarse clastic units, light grey = fine-grained textures (modified from Jiménez *et al.*, 2014). **B.** Thermo-tectonic/orogenic phases from based on a compilation of in-situ (Restrepo-Moreno *et al.*, 2019) and detrital (Bermúdez *et al.*, 2021) low-temperature thermochronology data.

Figure 3. Map of the main geological faults and sample location in the studied area. The southern termination of the Bucaramanga Fault is characterized by a transpressive system, including the Chaguacá and Los Micos faults. The figures include location of samples analyzed in this work (AFT, ZFT, AHe and ZHe), as well as those from previous work by Shagam *et al.* (1984), Toro (1990), van der Lelij *et al.* (2016a), and Amaya (2016). Only those samples enclosed in red ellipses belonging to vertical profiles were considered for the modeling of thermal histories. Samples in red triangles were used to model the thermal history of the Los Micos and Chaguacá faults.

Figure 4. Panoramic views and Google Earth images of sample locations for vertical profiles. A, Ricaurte. B, El Tendido. C, San Joaquín. D, Páramo. E, Chaguacá. F. Photograph of the valley controlled by the sinistral, transpressive Chaguacá Fault.

Figure 5. Comparisons between [eU] ppm versus individual ZHe grain age for (A) all samples. (B) and (C) correspond to a close-up of panel (A). In these figures all individual grain ages have been considered without making any exclusions.

Figure 6. Weighted (U-Th)/He age-elevation relationships: (A) AHe ages and (B) ZHe ages. AFT data has also been added in panel (B) for comparison (unfilled diamonds whose outline colors follow the same nomenclature of the different profiles or areas). Grey bands are considered significant regional geological events derived from detrital thermochronology (Bermúdez *et al.*, 2021) and other Colombian regions (Restrepo-Moreno *et al.*, 2019). By contrast, based on scarce ages, we relate white bands with period of “apparent” tectonic quiescence. Superscripts 1 and 2 refer to profile or fault, respectively.

Figure 7. Time-Temperature expected paths predicted from QTQt software (Gallagher, 2012) along the (A) Los Micos Fault and (B) Chaguacá Fault. Selected samples for the Los Micos Fault are shown in red, while selected samples for the Chaguacá Fault models are shown in blue. Green and transparent triangles correspond to samples from other blocks, which were not considered for modelling.

Figure 8. (Left panel) Thermal history models for the different profiles across the southern Bucaramanga Fault samples determined using the QTQt software (Figure 5). The dashed rectangles correspond to the four time-Temperature constraints: (i) 50 ± 10 Ma, (ii) 20 ± 5 Ma, (iii) 12 ± 3 Ma, and 5 ± 3 Ma with temperatures of $160^\circ \pm 40^\circ\text{C}$, $120^\circ \pm 60^\circ\text{C}$, $100^\circ \pm 40^\circ\text{C}$, and $80^\circ \pm 40^\circ\text{C}$, respectively. (Central panel) Observed versus predicted thermochronology ages (note that He ages are displayed with resampling errors). (Right panel) Age-elevations relationships (AER) showing comparisons between predicted and observed age and/or kinematic parameter (Dpar or Mean Track-Length). In these models the AFT ages, mean track lengths, weighted ZHe and AHe ages were integrated. For AFT data the multikinetic annealing model of Ketcham *et al.* (2007b), with c-axis projected track length data (Ketcham *et al.*, 2007a) was used. For the radiation damage accumulation and annealing model, we used the Gautheron *et al.* (2009) model for AHe and the Guenther *et al.* (2013) model for ZHe ages, respectively.

Figure 9. (A) Individual time-Temperature path for samples FV-44 (El Tendido profile) and (B) FV-57 (Ricaurte profile). In these models we integrated AFT ages, mean track lengths, weighted ZHe and AHe ages. For AFT data the multikinetic annealing model of Ketcham *et al.* (2007b), with c-axis projected track length data (Ketcham *et al.*, 2007a) was used. For the radiation damage accumulation and annealing model, we used the Gautheron *et al.* (2009) model for AHe and the Guenther *et al.* (2013) model for ZHe ages, respectively. (O) = observed and (P) = predicted data.

TABLE CAPTIONS

Table 1. Apatite and zircon fission-track data from the Bucaramanga Fault southern termination using the External Detector Method (EDM).

Table 2. Apatite fission-track data from the Bucaramanga Fault southern termination using the LA-ICP-MS method. In this table, n: number of analyzed crystals. Ns: number of spontaneous tracks counted. RhoS: spontaneous track density. ^{238}U : average uranium concentration. SD: Standard deviation of the track length distribution. Dpar: long axis of track etch pit. MTL: mean confined track length and SE: standard error. NL: number of confined track lengths (TINTs) measured. Single apatite fission track ages were calculated using an absolute calibration based on primary constants (aggregate $\xi = 2.176 \times 10^{-3}$). Pooled ages were calculated according to Hasebe *et al.* (2004). Central ages, as well as dispersion, were calculated using the RadialPlotter program (Vermeesch, 2009).

Table 3. Apatite (U-Th-Sm)/He bedrock data from the Bucaramanga Fault southern termination.

Table 4. Zircon (U-Th)/He bedrock data from the Bucaramanga Fault southern termination.

Table 5. Average exhumation rates and confidence intervals estimated from Age-Elevation Relationships (AER) for the different profiles. Exhumation rates were calculated using the York method (Williamson, 1968) considering the 1σ error on the age. See text for further details.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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