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► **To cite this version:**

Francisco Velandia, Mauricio Bermúdez, Barry Kohn, Matthias Bernet, Carlos Zuluaga, et al.. Cenozoic exhumation patterns in the northern Andes: Constraints from the southern Bucaramanga Fault, Eastern Cordillera, Colombia. *Journal of South American Earth Sciences*, 2021, 111, pp.103473. 10.1016/j.jsames.2021.103473 . insu-03466312

**HAL Id: insu-03466312**

**<https://insu.hal.science/insu-03466312v1>**

Submitted on 2 Mar 2022

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# Journal Pre-proof

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PII: S0895-9811(21)00320-5

DOI: <https://doi.org/10.1016/j.jsames.2021.103473>

Reference: SAMES 103473

To appear in: *Journal of South American Earth Sciences*

Received Date: 24 November 2020

Revised Date: 8 July 2021

Accepted Date: 9 July 2021

Please cite this article as: Velandia, F., Bermúdez, M.A., Kohn, B., Bernet, M., Zuluaga, C.A., Brichau, S., Cenozoic exhumation patterns in the northern Andes: Constraints from the southern Bucaramanga Fault, Eastern Cordillera, Colombia, *Journal of South American Earth Sciences* (2021), doi: <https://doi.org/10.1016/j.jsames.2021.103473>.

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**Author statement**

**Velandia:** methodology, conceptualization, funding acquisition, software, formal analysis, writing, reviewing and editing. **Bermúdez:** methodology, conceptualization, software, validation, formal analysis, writing, reviewing and editing. **Kohn:** methodology, conceptualization, software, validation, formal analysis, writing, reviewing and editing. **Bernet:** methodology, conceptualization, writing and reviewing. **Zuluaga:** methodology, conceptualization and writing. **Brichau:** methodology, conceptualization and writing.

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

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24 **Abstract**

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

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

45

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

48

#### 49 **Highlights**

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

#### 58 **1. Introduction**

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

69

70 To the south, tectonic inversion of the Santander High occurred mainly along the Boyacá  
71 and Soapaga faults (Cooper *et al.*, 1995; Sarmiento, 2001; Toro *et al.*, 2004; Tesón *et al.*,  
72 2013); whereas to the north, the inversion has been described along the La Salina and  
73 Suárez faults (Sarmiento, 2001; Tesón *et al.*, 2013; Caballero *et al.*, 2013). During the

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

82

83 Based on field observations and geo-thermochronological data, different tectonic models  
84 have been proposed to explain the evolution of the Santander and Floresta massifs  
85 (Shagam *et al.*, 1984; Parra *et al.*, 2009; Villagómez *et al.*, 2011; Tesón *et al.*, 2013; van  
86 der Lelij, 2013; van der Lelij *et al.*, 2016a, b; Amaya *et al.*, 2017; Siravo *et al.*, 2019),  
87 which record exhumation events from the Paleocene for the Eastern Cordillera, related also  
88 with the initial shortening of its central part during the late Oligocene (Villamil, 1999;  
89 Mora *et al.*, 2013; Egbue *et al.*, 2014; Horton *et al.*, 2020). Thermochronological studies in  
90 the Santander and Floresta massifs have a dispersed regional sampling approach (Shagam  
91 *et al.*, 1984; Villagómez *et al.*, 2011; van der Lelij, 2013; van der Lelij *et al.*, 2016a), or are  
92 located too far from our study area (Saylor *et al.*, 2012a,b; Parra *et al.*, 2009; Ramírez-  
93 Arias *et al.*, 2012; Amaya *et al.*, 2017, 2020). All these studies report cooling episodes,  
94 especially the Miocene-Pliocene Andean Orogeny. At the southern Bucaramanga Fault,  
95 only three thermochronological ages in the literature are from locations close to our study  
96 area: two reported by van der Lelij (2016a) in San Joaquín and Onzaga, and one by Toro  
97 (1990). These are insufficient however to understand the exhumation history of this part of  
98 the axial zone of the Eastern Cordillera, where besides compressional structures, strike-slip  
99 deformation is also reported (Velandia and Bermúdez, 2018).

100

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

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

111

112 The goal of the present study is to characterize the exhumation and tectonic evolution at  
113 the southern termination of the Bucaramanga Fault, where the spatial and temporal pattern  
114 of rock exhumation is poorly constrained. For this purpose, we present new thermal history  
115 models based on low-temperature thermochronology data from bedrock along five  
116 “vertical” elevation profiles in that area. Since Velandia and Bermúdez (2018) described  
117 the structural style for the transpressive system, including the relationship with inverted  
118 faults, in this study we further elucidate the timing of the exhumation of this deformational  
119 system. A corollary of this work will be to understand the mechanism of how oblique  
120 motion is partitioned into vertical strain. Further, in the middle part of the Bucaramanga  
121 Fault a major cooling event occurring at ~25 Ma has been reported by Amaya *et al.* (2017,  
122 2020). We will also evaluate whether such cooling extended southward to the study area,  
123 and if so, explain the implications in a regional context.

124

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

132

## 133 **2. Geological setting**

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

140 which once covered the Santander High. Subsequently, these sediments were eroded from  
141 the central part of the mountain range during Cenozoic exhumation (Horton, *et al.*, 2010,  
142 2020; Parra *et al.*, 2010; Amaya *et al.*, 2017), when tectonic activity and transpressive  
143 deformation were predominant (Ramírez-Arias *et al.*, 2012).

144

145 The crystalline basement of the Santander and Floresta massifs comprises diverse rock  
146 types from high-grade metamorphic rocks with sedimentary and igneous protoliths (Vargas  
147 *et al.*, 1976, 1987; Ward *et al.*, 1977 a, b). These include; Precambrian (Ward *et al.*, 1977a,  
148 b) or Paleozoic Bucaramanga Gneiss (Zuluaga *et al.*, 2017; Zuluaga and López, 2019),  
149 Early Paleozoic migmatites, Paleozoic orthogneiss, Silurian-Ordovician low-grade  
150 metamorphic (Silgará Fm.) and Silurian-Devonian metamorphic rocks (Guaca - La Virgen  
151 / Floresta Fm.) (Vargas *et al.*, 1976, 1987; Ward *et al.*, 1977 a, b; Mantilla-Figueroa *et al.*,  
152 2016; van der Lelij *et al.*, 2016b; Zuluaga *et al.*, 2017). Sequences of siltstones,  
153 conglomerates, sandstones and limestones are also present in the massifs (Devonian  
154 Floresta and Tibet formations; Carboniferous-Permian Cucho Formation, and the Paleozoic  
155 Río Nevado Formation). In addition, Ordovician-Silurian and Jurassic intrusive rocks,  
156 Early to Middle Jurassic volcanic and volcanoclastic rocks, as well as Late Jurassic  
157 sedimentary rocks (Girón Formation) also crop out in the area (Vargas *et al.*, 1976, 1987;  
158 Ward *et al.*, 1977 a, b).

159

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



173 and Kammer, 1995; Cooper *et al.*, 1995), and others as the Yariguíes or Arcabuco –  
174 Norean for the Jurassic (Velandia, 2017; Osorio-Afanador and Velandia, 2021). These  
175 structures probably originated or were reactivated from a combination of rifting and back-  
176 arc extensional activity related to the spreading of Pangea and the subduction of the  
177 Farallón Plate beneath the South and North American plates (Pindell and Dewey, 1982).  
178 The faults bounding the basins, such as the Boyacá, Bucaramanga, Soapaga or Río Servitá  
179 (Figure 1), were affected by tectonic inversion during the Cenozoic and this has also been  
180 documented in the northern Eastern Cordillera (Fabre, 1983; Colletta *et al.*, 1990; Dengo  
181 and Covey, 1993; Cooper *et al.*, 1995; Kammer and Sánchez, 2006; Tesón *et al.*, 2013).  
182 This tectonism is related to the eastern advance of the deformation, with orogenic pulses  
183 occurring during the Oligocene, Miocene and Plio–Pleistocene (Parra *et al.*, 2009; Mora *et*  
184 *al.*, 2013, 2015), although the compressional regime related to tectonic inversion was  
185 initiated along the western flank of the cordillera in the late Paleocene – early Eocene  
186 (Cortés *et al.*, 2005; Parra *et al.*, 2009; Nie *et al.*, 2012). In some cases, exhumation during  
187 this period was interpreted as the product of crystalline basement erosion (Shagam *et al.*  
188 1984; Horton *et al.*, 2010; van der Lelij *et al.*, 2016a). Structural models for the Eastern  
189 Cordillera of Colombia and Mérida Andes in Venezuela are consistent in their agreement  
190 on the role of preexisting discontinuities for controlling partition between structural  
191 domains, deformation, and the erosional exhumation of these mountain belts. A large part  
192 of these pre-existing discontinuities developed along the former passive margin of the  
193 South American plate and played an important role in the evolution of the orogen (Jacques,  
194 2004; Mora *et al.*, 2009). The distribution of thermochronological ages and the time-  
195 temperature history arising from these data have allowed the definition of tectonic blocks  
196 with different ages and cooling rates along the Eastern Cordillera (Shagam *et al.*, 1984;  
197 Mora *et al.*, 2008, 2013, 2015; Parra *et al.*, 2009; Amaya *et al.* 2017; Pérez-Consuegra *et*  
198 *al.*, 2021) and the Mérida Andes (Kohn *et al.*, 1984; Bermúdez *et al.*, 2010, 2011; van der  
199 Lelij *et al.*, 2016a).

200

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

206 where pure shear compression is the predominant mechanism (Colletta *et al.*, 1990; Toro,  
207 1990; Dengo and Covey, 1993; Cooper *et al.*, 1995; Roeder and Chamberlain, 1995; Toro  
208 *et al.*, 2004, Saylor, *et al.*, 2012a, Tesón *et al.*, 2013). However, simple shear and sinistral  
209 kinematics have also been recognized along the Eastern Cordillera (Kammer, 1996, 1999;  
210 Taboada *et al.*, 2000; Sarmiento, 2001; Cediel *et al.*, 2003; Velandia, 2005; Acosta *et al.*,  
211 2007, García-Delgado *et al.*, 2020; Velandia *et al.*, 2020; Machuca *et al.*, 2021).

212

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

226

### 227 **3. Methods**

228 A total of 36 samples of crystalline basement (igneous and metamorphic rocks) were  
229 collected along the southern termination of the Bucaramanga Fault between the town of  
230 Cepitá and the Páramo (Figures 1 and 3). 21 of these samples belong to five age-elevation  
231 profiles (Figures 3 and 4), with samples collected as near as vertically as possible from the  
232 highest to the lowest part within the blocks. It is important to clarify that locally no faults  
233 cross or cut the blocks. These profile are: (i) Ricaurte profile (samples FV-55 to 58, from  
234 1026 m to 1734 m elevation), located west of the Bucaramanga Fault; (ii) El Tendido  
235 profile (samples FV-43 to 46, from 1038 m to 1613 m elevation), located along the  
236 Bucaramanga Fault (Figure 3); (iii) Chaguacá profile (samples FV-31, 37-39, from 2415 m  
237 to 3344 m elevation), (iv) the Páramo profile (samples FV-31-35, from 3422 m and 3628  
238 m elevation), located in the area delimited by the Chaguacá and Los Micos faults (Figure

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

241

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

246

### 247 **3.1. Fission-track analysis**

248 The apatite and zircon fission-track (AFT and ZFT, respectively) method is based on the  
249 accumulation of fission tracks or radiation damage trails (Wagner and van den Haute,  
250 1992; Gallagher *et al.*, 1998). The tracks result from the spontaneous fission of heavy  
251 radionuclides (with an atomic number  $\geq 90$  and a mass number  $\geq 230$ ). Among these  
252 elements  $^{232}\text{Th}$ ,  $^{235}\text{U}$  and  $^{238}\text{U}$  can be measured, but it is  $^{238}\text{U}$  which has the abundance and  
253 half-life significant for geology (Tagami and O'Sullivan, 2005). For the AFT and ZFT two  
254 accepted age determination are used currently: i) the external detector method (EDM), and  
255 ii) the fission-track Laser Ablation Quadrupole Inductively-Coupled-Plasma Mass  
256 Spectrometer (LA-Q-ICP-MS) method. For the first method, the age can be calculated  
257 from counting spontaneous tracks in crystals (e.g. apatite or zircon) and induced tracks in  
258 an external detector (ultra-low uranium mica), held in close contact with the crystal during  
259 neutron irradiation (e.g., see Hurford and Green, 1982; Wagner and Van den Haute, 1992,  
260 Gallagher *et al.*, 1998, Donelick *et al.*, 2005, and Tagami and O'Sullivan, 2005). The LA-  
261 Q-ICP-MS spot analysis has been successfully employed for in-situ measurements in AFT  
262 dating (e.g., Hasebe *et al.*, 2004, 2013; Chew and Donelick, 2012; Vermeesch, 2018;  
263 Cogné *et al.*, 2020; Ansberque *et al.*, 2021) and ZFT dating (e.g., Hasebe *et al.*, 2013). This  
264 approach is rapid as it avoids the need for irradiation and counting of induced fission-  
265 tracks, limits the use of hazardous acids and can also yield additional information such as  
266 apatite Cl content (Chew *et al.*, 2014).

267

268 Three apatite samples (FV-07, FV-20 and FV-21) and eight zircon samples (FV-07, FV-  
269 17, FV-18, FV-20, FV-21, FV-23, FV-28 and FV-29) were prepared and processed in the  
270 fission-track laboratory of the ISTERre thermochronology laboratory in Grenoble, following  
271 the external detector method and zeta calibration procedure. Apatites were etched in  $\text{HNO}_3$

272 5M, for 20 seconds at 21° C, while zircons grains were etched in a NaOH-KOH eutectic  
273 solution at 228° C for 10-20 hours. Samples were irradiated at the FRM II research reactor  
274 in Garching, Germany. After irradiation, muscovite external detectors were etched for 18  
275 min at 20°C in 48% HF to reveal induced tracks. Samples were analyzed using a 1250×  
276 dry objective with an Olympus BH2 optical microscope and the FTStage 4.04 system in  
277 the ISTerre thermochronology laboratory.

278

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

290

### 291 **3.2. (U-Th)/He Analysis**

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

305 degrees to single-grain AHe and ZHe age dispersion include grain size, radiation damage,  
306 grain fragmentation, U and/or Th zonation, complex eU intra-grain relationships, He  
307 implantation, uncertainties in the alpha ejection factor calculation, mineral inclusions, He-  
308 rich fluid inclusions and lengthy residence in the He partial retention zone (e.g., Wildman  
309 *et al.*, 2016; Danišik *et al.*, 2017; Hueck *et al.*, 2018). Furthermore, imperfections, such as  
310 vacancy damage and crystallographic micro-voids may also affect He diffusion (Gerin *et*  
311 *al.*, 2017; Zeitler *et al.*, 2017). From all these factors a significant variation of  
312 compositional and crystallographic characteristics could produce an intra-sample  
313 dispersion at He ages above 50% (e.g. Wolfe and Stockli, 2010; Wildman *et al.*, 2016). It  
314 is possible to reduce a part of this possible source of error by crystal selection (Danišik *et*  
315 *al.*, 2017). In this study, we took into account grain size, morphology and accumulated  
316 radiation damage. The corrected age was calculated as the measured age/ $F_t$ , where  $F_t$  is the  
317 total fraction of alpha decays (see Farley *et al.*, 1996; Fitzgerald *et al.*, 2006, and Zeitler,  
318 2015 for more details). For data interpretation and thermal history modelling, similar to  
319 other works (e.g. Boone *et al.*, 2018), we use the effective uranium concentration  
320  $eU=U+0.235\times Th$  as a proxy for  $\alpha$ -radiation damage.

321

## 322 4. Results

### 323 4.1 Fission/track analysis

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

333

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

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

339

#### 340 **4.2 (U-Th)/He analysis**

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

350

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

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

375

## 376 **5. Interpretation and discussion**

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

390

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

403 1987), respectively. In the PAZ fission-tracks lengths are shortened.  $^4\text{He}$  can be considered  
404 as an almost open system (Wolfe and Stockli, 2010), where some He diffusion information  
405 is retained, particularly for apatite the information is partially retained between  $\sim 40^\circ\text{C}$  and  
406  $70^\circ\text{C}$ , and typically not retained above  $\sim 80^\circ\text{C}$  (Farley, 2000, 2002). The closure  
407 temperature for He in zircon, in contrast, is typically  $\sim 170\text{--}190^\circ\text{C}$  (Reiners *et al.*, 2004),  
408 and the PRZ  $\sim 130\text{--}180^\circ\text{C}$  (Reiners and Brandon, 2006; Wolfe and Stockli, 2010), but these  
409 ranges may vary considerably as a function of radiation damage (e.g. Shuster *et al.*, 2006;  
410 Guenther *et al.*, 2013). For the fission-track technique, all fission-tracks are annealed and  
411 their concentration, and thus age, is zero above  $\sim 120^\circ\text{C}$  in apatite (Laslett *et al.*, 1987;  
412 Ketcham *et al.*, 1999), and  $\sim 240^\circ\text{C}$  in zircon (Zaun and Wagner, 1985). Partial annealing  
413 of fission tracks typically occurs between  $\sim 60^\circ\text{C}$  and  $120^\circ\text{C}$  in apatite, depending on  
414 apatite composition (Green *et al.*, 1989) and between  $\sim 180^\circ\text{C}$  and  $350^\circ\text{C}$  for zircon,  
415 depending on the degree of radiation damage (Tagami, 2005). An exhumed PAZ/PRZ may  
416 be revealed in an AER when, following a period of uplift/exhumation, the form of the  
417 PAZ/PRZ is retained with a 'sharp' convex inflexion (the 'break in slope') marking the base  
418 of the exhumed PAZ/PRZ with reset samples structurally beneath (Gleadow and  
419 Fitzgerald, 1987; Fitzgerald and Gleadow, 1988, 1990; Gleadow, 1990; Stockli *et al.*,  
420 2000; Fitzgerald and Malusà, 2019).

421

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

434



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

461

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

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

471

### 472 **5.1. Inverse Thermal History Modeling**

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

485

486 For each sample the oldest ZHe weighted age (Tables 3 and 4) and temperature ( $100 \pm$   
487  $100^\circ\text{C}$ ) ranges were used for the general prior (model space). The present-day surface  
488 temperature was set as  $15 \pm 5^\circ\text{C}$ . Although it appears that the constraints used in our QTQt  
489 philosophy modeling were forced, we considered four different independent constraints  
490 based on two aspects: first, the four main reported pulses thermotectonic/orogenic phases  
491 in the Eastern Cordillera of Colombia (Restrepo-Moreno *et al.*, 2019). Second, the  
492 preferred time-temperature history derived from the best PeCube model for the study area  
493 (see Figure 12c in Bermúdez *et al.*, 2021). We are interested in corroborating the timing of  
494 exhumation onset in the study area from at least 35 Ma to the present (see Figure 12C in  
495 Bermúdez *et al.*, 2021). That PeCube model (Bermúdez *et al.*, 2021) is constraint  
496 independent and the range of parameters run was quite wide, plus it was possible to  
497 corroborate equilibrium versus time-varying topography conditions. Thus, we used the  
498 following four constraints: (i)  $50 \pm 10$  Ma with temperatures of  $160^\circ \pm 40^\circ\text{C}$ ; (ii)  $20 \pm 5$   
499 Ma with temperatures of  $120^\circ \pm 60^\circ\text{C}$ , (iii)  $12 \pm 3$  Ma with temperatures of  $100^\circ \pm 40^\circ\text{C}$ ,  
500 and (iv)  $5 \pm 3$  Ma with temperatures of  $80^\circ \pm 40^\circ\text{C}$ . Because models start at  $50 \pm 10$  Ma

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

509

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

517

### 518 **5.1.1 Cooling histories along the Los Micos and Chaguacá faults**

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

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

540

541 Expected t-T models derived for each sample located along the Los Micos Fault (Figure  
542 7B), suggest prolonged residence within the ZHe PRZ before 25 Ma. Following this time,  
543 three successive cooling phases are observed: 1) a fast pulse between ~25 to 16 Ma, 2) a  
544 slow pulse compared to the first one between ~16 and 7 Ma, and finally 3) a fast-cooling  
545 pulse between ~7 Ma to present. This last episode is consistent with AFT and AHe ages in  
546 that area (e.g. FV-20, 10VDL28 and FV-45; Figure 3). Figure 7B (central part of the panel)  
547 compares ages predicted by the model and observed ages. Again, for this model, samples  
548 FV-40, FV-54 and FV-61 were selected, which had both AHe and ZHe age data (Tables 2,  
549 3 and 4). The comparison between observed and predicted ages in the form of AER is  
550 shown at the base of Figure 7B. At an elevation between 2000 to 2500 m, a break in the  
551 EAR slope is observed. The model allows kinetic parameters to be predicted for the AFT  
552 method, such as Dpar.

553

### 554 **5.1.2 Cooling histories for vertical profiles**

555 All AFT, AHe, and ZHe ages for each profile (Figure 6) were modeled jointly (Figure 8).  
556 It was not possible to incorporate ZFT ages here since such data was not available for the  
557 profiles. Figure 8 is again split into three sectors; a left panel presenting the time-  
558 Temperature paths predicted by QtQT, a central panel presenting comparisons between  
559 predicted and observed ages, and a right panel showing the central panel comparisons in  
560 the form of age-elevation relationships (AER). In general, in the interval between 60 and  
561 ~25 Ma, the different tectonic blocks experience a long residence in the ZHe PRZ (140-  
562 180 °C; Ricaurte), AFT PAZ (San Joaquín), or very slow cooling (El Tendido, Chaguacá,  
563 and Páramo). From ~25 Ma to present the blocks exhibit contrasting time-Temperature  
564 histories. The Ricaurte profile exhibits rapid cooling from 25 Ma to 12 Ma (Oligocene -  
565 Middle Miocene), slow cooling from ~12 Ma to 4 Ma, and an increased cooling rate from  
566 4 Ma to the present. The El Tendido profile experienced a slow cooling pulse from ~50 Ma

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

578

579 Based on the four well defined thermotectonic/orogenic pulses defined by van der  
580 Hammen (1961), supported by low temperature thermochronology (Restrepo-Moreno *et*  
581 *al.*, 2019) and the discrete tectonic pulses discriminated from detrital dataset and PeCube  
582 modelling (Bermúdez *et al.*, 2021) we can confirm several cooling pulses previously  
583 identified. The first pulse occurred before ~25 Ma (Oligocene) was discerned in the San  
584 Joaquín and Páramo profiles, and in the western side of the Bucaramanga Fault (Figure 1).  
585 This is also observed in the San Joaquín and Páramo profiles, with slow cooling rates  
586 (<4°C/Ma), which are located furthest away from the main strand of the Bucaramanga  
587 Fault. The similarity between both profiles may indicate that the Chaguacá Fault might not  
588 have been active at that time. In the models, most samples from the four profiles indicate  
589 the onset of a cooling pulse between ~22 to 15 Ma (Oligocene - early Miocene). This  
590 coincides with the onset of Bucaramanga Fault activity, while the most recent pulse  
591 recorded between ~6 to 2 Ma for samples in the El Tendido, Chaguacá and Ricaurte  
592 profiles is associated with subsequent recent activity of the Bucaramanga Fault and its  
593 subsidiary branches in that area. The Ricaurte and El Tendido profiles exhibit complex  
594 thermal histories, possibly related to reactivation of the Los Micos and Bucaramanga  
595 faults.

596

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

600 cooling rate ( $2^{\circ}\text{C}/\text{Ma}$ ) from  $\sim 50$  Ma to 8 Ma with temperatures ranging between  $\sim 200^{\circ}\text{C}$  to  
601  $125^{\circ}\text{C}$ . From 8 Ma to the present this sample exhibited a fast cooling rate ( $\sim 13^{\circ}\text{C}/\text{Ma}$ ). The  
602 histogram located at the right of the Figure 9A represent the fission-track length  
603 distribution. The values in this figure correspond to observed (O) and predicted (P) data.

604

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

612

## 613 **5.2 Relationship between cooling/heating pulses and fault reactivation**

614 In most of the profiles cooling episodes are recorded between  $\sim 25$  to 15 Ma. For the San  
615 Joaquin, and Páramo profiles (Figure 8) cooling events prior to  $\sim 25$  Ma could be not  
616 associated with the Bucaramanga Fault reactivation, instead, these were probably related to  
617 reactivation of the Boyacá and Soapaga faults at two different times,  $\sim 50 \pm 5$  Ma and  $\sim 36 \pm$   
618  $3$  Ma (Ricaurte and Páramo; Fig. 7C), i.e. in early and late Eocene time, respectively. The  
619 late Eocene pulse is comparable with the onset of cooling between  $\sim 40$  and 30 Ma for the  
620 Floresta Massif (Figure 1), based on AFT data reported by Parra *et al.* (2009). These pulses  
621 are related to displacement of the Soapaga Fault, whose onset in turn extends to  $\sim 50$  Ma,  
622 similarly to ages reported in the present work. In contrast, heating is observed in the  
623 Chaguacá Fault (Figure 7A) and in sample FV-57 from the Ricaurte profiles (Figure 9B).  
624 These apparent heating "pulses" are possibly related to local advection of isotherms  
625 resulting from fault activity, or associated phenomena resulting from either shear heating  
626 or fluid flow, which could perturb the AHe ages (Reiners *et al.*, 2005).

627

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

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

642

643 A strong regional exhumation pulse during the early Miocene (between  $20 \pm 5$  Ma, and  $12$   
644  $\pm 3$  Ma) suggests an important role of the Bucaramanga Fault. Similar ages are also  
645 reported in AFT samples from this work (FV-17 and FV-21, Figure 3) and from Shagam *et*  
646 *al.* (1984), van der Lelij *et al.* (2016b) and Amaya *et al.* (2017, 2020) in the Cepitá sector,  
647 in addition to Parra *et al.* (2009) in the Massif of Floresta, where Toro (1990) also reports  
648 an AFT age of  $22.3 \pm 4$  Ma. Villagómez (2010) using a sparse AFT age distribution on the  
649 west side of the Santander Massif suggests that cooling occurred between 23 and 16 Ma  
650 (early Oligocene-Miocene). The timing of ~25 to 20 Ma that Amaya *et al.* (2017) report for  
651 cooling in the Cepitá zone (Figure 3) may indicate that the pulse had migrated to the east  
652 and in that case, the onset of the tectonic activity of the Bucaramanga Fault and associated  
653 exhumation may have migrated from north to south. Van der Lelij *et al.* (2016b) suggest  
654 that the fault was already active at 40 Ma (37 Ma for Amaya *et al.*, 2017) and that  
655 exhumation was variable along it. However, at least to the south (in our study area), the  
656 ~35 Ma exhumation pulse (Bermúdez *et al.*, 2021) is more related to the late Eocene pulse  
657 that exhumed the western part of the Floresta Massif due to the inversion of the Boyacá  
658 Fault, whose prolonged activity to the north could also have had some influence on  
659 Santander Massif tectonism.

660

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

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

672

### 673 **5.3 Relief change, exhumation history, sedimentary record and geodynamic context**

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

694

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



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

700

701 The latest exhumation pulse that commenced between ~5 and 2 Ma (Plio-Pleistocene,  
702 Figure 7) can be linked to exhumation observed along the Bucaramanga Fault, that is  
703 associated with the El Tendido shutter ridge in the northern part of the transpressive  
704 southern termination of the structure (Velandia and Bermúdez, 2018) and the subsequent  
705 impoundment of the Chicamocha River, suggested by Galvis (2016) to be associated with  
706 the origin of a Pleistocene lake reported by Villarroel *et al.* (2001) in that area. Further,  
707 geomorphological evidence for current tectonic activity along the Bucaramanga Fault is  
708 provided by Diederix *et al.* (2009), e.g. eight Holocene earthquakes of magnitude Ms 6.6  
709 to 7.0 spanning from 8300 to 930 yr BP and morphometric indices pointing to fault activity  
710 as a leading contributor to regional hillslope instability (García-Delgado *et al.*, 2019,  
711 2020).

712

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

731 Andes, such as: the Central Cordillera, Eastern Cordillera, Garzón Massif and Sierra  
732 Nevada de Santa Marta (Amaya *et al.*, 2017, 2020; Patiño *et al.*, 2019; Restrepo-Moreno *et*  
733 *al.*, 2019), but also from the Caparo and Trujillo blocks of the Venezuelan Andes  
734 (Bermúdez *et al.*, 2010). This period of significant relief growth coincides with important  
735 sediment deposition in the Maracaibo basin (Lugo and Mann, 1995; Guzmán and Fisher,  
736 2006; Erickson *et al.*, 2012; Bermúdez *et al.*, 2017).

737

738 An exhumation phase at  $\sim 12 \pm 3$  Ma coincides with the main surface uplift of the  
739 Venezuelan Andes (Bermúdez *et al.*, 2011) and events reported for the Perijá (Shagam *et*  
740 *al.*, 1984) and Santa Marta (Villagómez *et al.*, 2011). Finally, a more recent episode  
741 between  $\sim 5$  to 2 Ma is similar to that reported by Kohn *et al.* (1984) for the El Carmen  
742 block in the Venezuelan Andes. This last event is associated with an increase in oblique  
743 convergence between the Maracaibo block and South American plate, which resulted in  
744 transpression and exhumation of the central part of the Venezuelan Andes (Kohn *et al.*,  
745 1984; Audemard and Audemard, 2002; Bermúdez *et al.*, 2010) and other sectors at the  
746 circum-Maracaibo block (e.g. Shagam *et al.*, 1984; Kohn *et al.*, 1984; Bermúdez *et al.*,  
747 2017; 2019; Restrepo-Moreno *et al.*, 2019). This episode starting at  $\sim 5$  Ma continues to the  
748 present day, particularly in our study area where this event is observed in some regions:  
749 circum Chaguacá Fault (Figure 7A), El Tendido, Chaguacá and Ricaurte profiles, but not  
750 in all sectors. Convergence between the Maracaibo block and South American plate is also  
751 consistent with the current stress field in the northern Andes as resolved from fault  
752 striations, earthquake focal mechanisms and GPS data (Taboada *et al.*, 2000; Audemard  
753 and Audemard, 2002; Colmenares and Zoback, 2003; Audemard *et al.*, 2005; Cortés and  
754 Angelier, 2005; Audemard and Castilla, 2016; Pérez *et al.*, 2018; Mora-Páez *et al.*, 2019;  
755 Velandia *et al.*, 2020).

756

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

764 tectonic realms as Cauca-Patía, Chocó, Gorgona, Baudó and Maracaibo (Cediel *et al.*,  
765 2003; Restrepo-Pace and Cediel, 2019).

766

## 767 **6. Conclusions**

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

774

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

780

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

787

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

793

## 794 **Acknowledgments**

795 This work is part of the doctoral thesis of Francisco Velandia at the Universidad Nacional  
796 de Colombia, supported by Colciencias-Colfuturo grant (PDBC 6172) and a study

797 commission given by the Universidad Industrial de Santander. We are indebted to María  
798 Isabel Marín and Wilton Echavarría (Universidad EAFIT), Héctor Enciso, Francisco  
799 Santaella, Sergio Amaya and Mary Luz Peña (laboratories of the Servicio Geológico  
800 Colombiano). We are grateful to Sergio Restrepo-Moreno for remarks on the first version  
801 of this work. Thanks to the School of Geology, Universidad Industrial de Santander,  
802 especially Juan Diego Colegial and Giovanny Jiménez for facilitating samples delivery,  
803 and also to Nicolás Villamizar and Milton Galvis for accompanying the first field trip.  
804 Bermúdez acknowledges support from the Institut de Recherche pour le Développement  
805 (IRD) for the BEST Project and the convention between Universidad de Ibagué and IRD  
806 which allowed to stay in GET lab at Toulouse, France, where apatite and zircon were  
807 separated, also to Universidad de Ibagué (Project 15-377-INT) and Universidad  
808 Pedagógica y Tecnológica de Colombia (UPTC), DIN SGI Project 3104. The University of  
809 Melbourne thermochronology laboratory receives support under the AuScope program of  
810 the National Collaborative Research Infrastructure Strategy (NCRIS). Finally, we thanks to  
811 the editor Franck Audemard, Melanie Noury and an anonymous reviewer for their valuable  
812 comments and suggestions.

### 813 FIGURES CAPTIONS

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

816  
817 **Figure 2. A.** Chronostratigraphic compilation in basins adjacent to the Santander and Floresta  
818 massifs. Dark grey = mainly coarse clastic units, light grey = fine-grained textures (modified from  
819 Jiménez *et al.*, 2014). **B.** Thermo-tectonic/orogenic phases from based on a compilation of in-situ  
820 (Restrepo-Moreno *et al.*, 2019) and detrital (Bermúdez *et al.*, 2021) low-temperature  
821 thermochronology data.

822  
823 **Figure 3.** Map of the main geological faults and sample location in the studied area. The southern  
824 termination of the Bucaramanga Fault is characterized by a transpressive system, including the  
825 Chaguacá and Los Micos faults. The figures include location of samples analyzed in this work  
826 (AFT, ZFT, AHe and ZHe), as well as those from previous work by Shagam *et al.* (1984), Toro  
827 (1990), van der Lelij *et al.* (2016a), and Amaya (2016). Only those samples enclosed in red ellipses  
828 belonging to vertical profiles were considered for the modeling of thermal histories. Samples in red  
829 triangles were used to model the thermal history of the Los Micos and Chaguacá faults.

830  
831 **Figure 4.** Panoramic views and Google Earth images of sample locations for vertical profiles. A,  
832 Ricaurte. B, El Tendido. C, San Joaquín. D, Páramo. E, Chaguacá. F. Photograph of the valley  
833 controlled by the sinistral, transpressive Chaguacá Fault.

834  
835 **Figure 5.** Comparisons between [eU] ppm versus individual ZHe grain age for (A) all samples. (B)  
836 and (C) correspond to a close-up of panel (A). In these figures all individual grain ages have been  
837 considered without making any exclusions.

838 **Figure 6.** Weighted (U-Th)/He age-elevation relationships: (A) AHe ages and (B) ZHe ages. AFT  
 839 data has also been added in panel (B) for comparison (unfilled diamonds whose outline colors  
 840 follow the same nomenclature of the different profiles or areas). Grey bands are considered  
 841 significant regional geological events derived from detrital thermochronology (Bermúdez *et al.*,  
 842 2021) and other Colombian regions (Restrepo-Moreno *et al.*, 2019). By contrast, based on scarce  
 843 ages, we relate white bands with period of “apparent” tectonic quiescence. Superscripts 1 and 2  
 844 refer to profile or fault, respectively.

845  
 846 **Figure 7.** Time-Temperature expected paths predicted from QTQt software (Gallagher, 2012)  
 847 along the (A) Los Micos Fault and (B) Chaguacá Fault. Selected samples for the Los Micos Fault  
 848 are shown in red, while selected samples for the Chaguacá Fault models are shown in blue. Green  
 849 and transparent triangles correspond to samples from other blocks, which were not considered for  
 850 modelling.

851  
 852 **Figure 8.** (Left panel) Thermal history models for the different profiles across the southern  
 853 Bucaramanga Fault samples determined using the QTQt software (Figure 5). The dashed rectangles  
 854 correspond to the four time-Temperature constraints: (i)  $50 \pm 10$  Ma, (ii)  $20 \pm 5$  Ma, (iii)  $12 \pm 3$   
 855 Ma, and  $5 \pm 3$  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  $80^\circ \pm 40^\circ\text{C}$ ,  
 856 respectively. (Central panel) Observed versus predicted thermochronology ages (note that He ages  
 857 are displayed with resampling errors). (Right panel) Age-elevations relationships (AER) showing  
 858 comparisons between predicted and observed age and/or kinematic parameter (Dpar or Mean  
 859 Track-Length). In these models the AFT ages, mean track lengths, weighted ZHe and AHe ages  
 860 were integrated. For AFT data the multikinetic annealing model of Ketcham *et al.* (2007b), with c-  
 861 axis projected track length data (Ketcham *et al.*, 2007a) was used. For the radiation damage  
 862 accumulation and annealing model, we used the Gautheron *et al.* (2009) model for AHe and the  
 863 Guenther *et al.* (2013) model for ZHe ages, respectively.

864  
 865  
 866 **Figure 9.** (A) Individual time-Temperature path for samples FV-44 (El Tendido profile) and (B)  
 867 FV-57 (Ricaurte profile). In these models we integrated AFT ages, mean track lengths, weighted  
 868 ZHe and AHe ages. For AFT data the multikinetic annealing model of Ketcham *et al.* (2007b), with  
 869 c- axis projected track length data (Ketcham *et al.*, 2007a) was used. For the radiation damage  
 870 accumulation and annealing model, we used the Gautheron *et al.* (2009) model for AHe and the  
 871 Guenther *et al.* (2013) model for ZHe ages, respectively. (O) = observed and (P) = predicted data.

872  
 873

## 874 TABLE CAPTIONS

875

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

878

879 **Table 2.** Apatite fission-track data from the Bucaramanga Fault southern termination using the LA-  
 880 ICP-MS method. In this table, n: number of analyzed crystals. Ns: number of spontaneous tracks  
 881 counted. RhoS: spontaneous track density.  $^{238}\text{U}$ : average uranium concentration. SD: Standard  
 882 deviation of the track length distribution. Dpar: long axis of track etch pit. MTL: mean confined  
 883 track length and SE: standard error. NL: number of confined track lengths (TINTs) measured.  
 884 Single apatite fission track ages were calculated using an absolute calibration based on primary  
 885 constants (aggregate  $\xi = 2.176 \times 10^{-3}$ ). Pooled ages were calculated according to Hasebe *et al.*  
 886 (2004). Central ages, as well as dispersion, were calculated using the RadialPlotter program  
 887 (Vermeesch, 2009).

888

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

890

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

892

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

896

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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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