Vertical tectonics at a continental crust-oceanic plateau plate boundary zone: Fission track thermochronology of the Sierra Nevada de Santa Marta, Colombia

VILLAGOMEZ DIAZ, Diego, et al.

Abstract

The topographically prominent Sierra Nevada de Santa Marta forms part of a faulted block of continental crust located along the northern boundary of the South American Plate, hosts the highest elevation in the world (∼5.75 km) whose local base is at sea level, and juxtaposes oceanic plateau rocks of the Caribbean Plate. Quantification of the amount and timing of exhumation constrains interpretations of the history of the plate boundary, and the driving forces of rock uplift along the active margin. The Sierra Nevada Province of the southernmost Sierra Nevada de Santa Marta exhumed at elevated rates (≥0.2 Km/My) during 65–58 Ma in response to the collision of the Caribbean Plateau with northwestern South America. A second pulse of exhumation (≥0.32 Km/My) during 50–40 Ma was driven by underthrusting of the Caribbean Plate beneath northern South America. Subsequent exhumation at 40–25 Ma (≥0.15 Km/My) is recorded proximal to the Santa Marta-Bucaramanga Fault. More northerly regions of the Sierra Nevada Province exhumed rapidly during 26–29 Ma (∼0.7 Km/My). Further northward, the Santa Marta Province [...]
Vertical tectonics at a continental crust-oceanic plateau plate boundary zone: Fission track thermochronology of the Sierra Nevada de Santa Marta, Colombia

Diego Villagómez,1 Richard Spikings,1 Andrés Mora,2 Georgina Guzmán,3 Germán Ojeda,2 Elizabeth Cortés,4 and Roelant van der Lelij1

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[1] The topographically prominent Sierra Nevada de Santa Marta forms part of a faulted block of continental crust located along the northern boundary of the South American Plate, hosts the highest elevation in the world (~5.75 km) whose local base is at sea level, and juxtaposes oceanic plateau rocks of the Caribbean Plate. Quantification of the amount and timing of exhumation constrains interpretations of the history of the plate boundary, and the driving forces of rock uplift along the active margin. The Sierra Nevada Province of the southernmost Sierra Nevada de Santa Marta exhumed at elevated rates (≥0.2 Km/My) during 65–58 Ma in response to the collision of the Caribbean Plateau with northwestern South America. A second pulse of exhumation (≥0.32 Km/My) during 50–40 Ma was driven by underthrusting of the Caribbean Plate beneath northern South America. Subsequent exhumation at 40–25 Ma (≥0.15 Km/My) is recorded proximal to the Santa Marta-Bucaramanga Fault. More northerly regions of the Sierra Nevada Province exhumed rapidly during 26–29 Ma (~0.7 Km/My). Further northward, the Santa Marta Province exhumed at elevated rates during 30–25 Ma and 25–16 Ma. The highest exhumation rates within the Sierra Nevada de Santa Marta progressed toward the northwest via the propagation of NW verging thrusts. Exhumation is not recorded after ~16 Ma, which is unexpected given the high elevation and high erosive power of the climate, implying that rock and surface uplift that gave rise to the current topography was very recent (i.e., ≤1 Ma?), and there has been insufficient time to expose the fossil apatite partial annealing zone.


1. Introduction

[2] The Maracaibo Block represents a major crustal fragment of the northern South American Plate, forms part of the broad, right lateral boundary between the Caribbean and South American plates and hosts the highest mountain range on Earth (Sierra Nevada de Santa Marta; 5775 m), whose topographic baseline is located directly at sea level (Figure 1). We aim to use apatite fission track data collected along several vertical profiles and transects to quantify the thermal histories of surface rocks of the northwest verging thrust belt of the Sierra Nevada de Santa Marta (SNSM; see Figure 1), which defines the northwestern corner of the fault bounded Maracaibo Block and was deformed and uplifted in the Tertiary. The structural architecture of the block formed in response to the multiple plate boundaries that have interacted to drive accretion along the Pacific margins of Ecuador and Colombia and dextral strike-slip tectonics along the northern boundary of the South American Plate during the dextral migration of the Caribbean Plate [Pindell, 1993; Colletta et al., 1997; Taboada et al., 2000], since ~75 Ma. Variations in sedimentary successions and sharp changes in elevation within the Maracaibo Block suggests that faulted regions responded differently to plate interaction during the Tertiary and have highly varied exhumation, surface uplift and burial histories. Clearly, any tectonic reconstructions of this hydrocarbon rich region must account for these variations.

[3] Low-temperature thermochronology is essential for quantifying upper crustal tectonics and surficial processes. Within this crustal level, temperature can be used as a proxy...
for depth and thermal histories are a proxy for rock displacement relative to the Earth’s surface, provided paleogeothermal gradients are known. Apatite fission track thermochronology is a broadly used thermochronometer that is sensitive to temperatures of <120° ± 10°C to <60°C in common apatites (e.g., Cl < 1wt%), which constrains exhumation within the upper 3–5 km of the crust [e.g., Kohn et al., 2005]. Previous thermochronological data from the SNSM are sparse and are usually not interpretable, which has hampered tectonic interpretations in that region. Thermal histories for the SNSM have been combined with previous radiometric data and the surrounding sedimentary record to quantify exhumation and propose a tectonic synthesis for the evolution of the crystalline rocks.

The SNSM is bound to the north by the right lateral Oca Fault, which separates it from underthrusting Caribbean oceanic crust and continental crust of the Guajira Peninsula (Figure 2). The eastern boundary of the fault block that hosts the SNSM is faulted against the Perijá Range, which, along with the Maracaibo Basin and the Mérida Andes (Figure 1) form the Maracaibo Block [Kellogg, 1984]. The Santa Marta-Bucaramanga fault (Figure 1) defines the western boundary of the SNSM block, and extends southward toward central Colombia (Figure 1). Collectively, the interactions of these major fault systems have driven rock uplift and exhumation leading to a peak elevation of ∼5.75 km within the SNSM block, located ∼40 km from the coast, and quantification of that record may enable us to (1) assess the tectonic relationship between the cordillera of the SNSM and surrounding structural zones within the Maracaibo Block and (2) determine the relative roles played by tectonic forces that originated at the Pacific and Caribbean margins since the Late Cretaceous.

2. Geological Framework

The SNSM massif resides within a triangular faulted block in northern Colombia and reaches a peak elevation of ∼5.75 km within ∼40 km of the coastline (Figures 1 and 2). The northern margin of the SNSM block is truncated by the right lateral Oca fault, which is displacing Cretaceous and older continental crust of the Guajira Peninsula to the east that was deformed and laterally displaced during the Tertiary [Macellari, 1995; Cardona et al., 2009] (Figure 2). The western margin of the triangular block is defined by the Santa Marta-Bucaramanga Fault (Figure 1), which separates crystalline rocks in the east from the Oligo-Miocene Lower Magdalena Basin to the west, which is believed to be floored by Triassic rocks similar to those exposed in the SNSM [Montes et al., 2010]. The Santa Marta-Bucaramanga Fault extends toward the SSE for a distance of several hundred kilometers, where it defines the western margin of elevated...
Paleozoic and older gneisses of the Santander Massif within the Colombian Eastern Cordillera (Figure 1). Pervasive brittle deformation adjacent to the east of the Santa Marta–Bucaramanga fault is observed within a ∼20-km-wide zone where ubiquitous NW verging thrust faults bend southward to join the major strike slip fault (Figure 2) [Ingeominas, 2007a, 2007b]. The eastern margin of the cordillera of the SNSM is marked by the burial of Jurassic granites beneath the Paleocene–Miocene Cesar Basin, which resides within the SNSM block, and the structural limit of the fault block of the SNSM can be considered to be the Cerrejón Fault, which separates the Cesar Basin from the Perijá Range (Figure 2).

The recognition of major geological units and detailed geological mapping was compiled in the work of Tschanz et al. [1969]. The present study follows the geological subdivisions of the SNSM proposed by Tschanz et al. [1969, 1974], which were recently structurally revised by Ingeominas [2007a, 2007b] and better geochronologically constrained by Cardona et al. [2008a, 2010a, 2010b]. The cordillera of the SNSM is divided into three NW verging thrusted provinces, which host rocks of distinctly different ages and lithologies (Figure 2). Proterozoic granulites, anorthosites and gneisses [Cordani et al., 2005; Cardona et al., 2006] in the southeast of the SNSM are intruded by undeformed Jurassic granites, which collectively define the Sierra Nevada Province (Figure 2). These rocks define the largest province within the SNSM, form the highest elevations of 5775 m and may represent part of a larger Grenvillian province that is exposed in the Garzón and Santander Massifs of the Eastern Cordillera [Restrepo-Pace et al., 1997, Ordóñez-Carmona et al., 2006] (Figure 1). These rocks overthrust the Sevilla Province to the northwest, and the main structural boundary is referred to as the Sevilla Lineament (Figure 2), which has been resolved into individual fault traces by Ingeominas [2007a, 2007b], which show a thrust vergence toward the northwest. The Sevilla Province consists of Paleozoic orthogneisses and schists, which were intruded by Permian–Late Triassic syntectonic granitoids [Cardona et al., 2006] and the Paleogene Buritaca granite [Tschanz et al., 1974; Ingeominas, 2007a]. These rocks have been correlated with the Macuira Schist Belt in the Guajira Peninsula [Cardona et al., 2006]. The Sevilla Province overthrusts metamorphosed Upper Cretaceous–Paleogene intrusive, volcanic and sedimentary rocks of the Santa Marta Province (Figure 2), toward the north-
west. The bounding fault has been assigned numerous names [Ingeominas, 2007a, 2007b], and it is referred to here as the La Aguja Fault (Figure 2). Within the Santa Marta Province, Upper Cretaceous low-grade metamorphic rocks to the northwest are separated from amphibolites in the southeast by undeformed Paleogene granitoids of the Santa Marta Batholith (K/Ar ages of 58–44 Ma [Tschanz et al., 1974]; zircon U-Pb ages of 57–50 Ma [Cardona et al., 2008a]) (Figure 2). The batholith yields a Maastrichtian–early Paleocene minimum age for the timing of metamorphism within the Santa Marta Province [Cardona et al., 2010b]. The outermost coastal metamorphic rocks probably extend offshore toward the Caribbean Plate [MacDonald et al., 1971], and correlate with similar lithologies found along the northern Guajira Peninsula.

[7] Recent paleomagnetic studies [Bayona et al., 2006, 2010] have shown that Jurassic rocks exposed in the southern border of the Sierra Nevada Province displaced northward (from 9°S to 4°N) with respect to cratonic South America, and rotated clockwise (17° ± 13°C) between the Middle-Late Jurassic and Early Cretaceous. This rotational event may have occurred during the opening of the Early Cretaceous Colombian marginal back-arc basin [Pindell, 1993]. Bayona et al. [2010] report that the pre-Early Cretaceous units of the SNSM were at their current latitude by the Albanian. Vertical axis clockwise rotation of up to 30°C during the Cenozoic has been proposed to accommodate simultaneous contractual and extensional deformation in the Cesar and Lower Magdalena basins [Montes et al., 2010].

3. Previous Thermochronological Studies of the Sierra Nevada de Santa Marta

[8] Several high-temperature (>300°C) radiometric analyses were performed on rocks of the SNSM during the period 1969–1997, which utilized the potentially inaccurate Rb/Sr and K/Ar methods. Those ages relate to (1) Precambrian crystallization or isotopic disturbance during the Precambrian [MacDonald and Hurley, 1969; Restrepo-Pace et al., 1997], (2) Jurassic magmatic crystallization [e.g., Tschanz et al., 1974], (3) Late Cretaceous–Early Tertiary metamorphism of rocks of the Santa Marta Province [MacDonald et al., 1971], and (4) Paleocene–Eocene arc activity (Santa Marta Batholith [Tschanz et al., 1969]). More recently, Cardona et al. [2006] utilized the oldest individual step-ages from discordant hornblende and biotite 40Ar/39Ar age spectra, obtained from a paragneiss of the Paleozoic Sevilla Complex (minimum zircon U-Pb age of 529 ± 10 Ma [Cardona et al., 2006]) (Figure 2), to suggest it experienced heating and cooling during the Triassic-Jurassic. However, Ar isotope homogenizing, dehydration reactions during in-vacuo heating of ferromagnesian phases suggests the form of the age spectra does not reflect the original distribution of 40Ar, implying that their conclusions cannot be regarded as robust. Clearly, these high-temperature studies provide no information to constrain the exhumation history of the Sierra Nevada de Santa Marta during the Late Cretaceous–Recent, and no fission track studies have been performed on the Sierra Nevada de Santa Marta.

[9] Cardona et al. [2008b] obtained zircon and apatite (U-Th)/He ages of 20–27 Ma and 5–24 Ma, respectively, from crystalline rocks exposed along a NW-SE traverse within the northwestern region of the Santa Marta Province. They assumed a high geothermal gradient of 50°C/km to propose moderate exhumation rates of 0.16 km/Ma during the late Oligocene, and 0.33 km/Ma since the middle-late Miocene.

4. Sampling Strategy and Methods

[10] Apatite fission track data have been acquired from 27 samples of Precambrian-Paleogene intrusive and metamorphic rocks and a single rhyolite collected from several traverses within the SNSM that span a total elevation range of 20–2720 m (Table 1). Zircon and apatite fission track data have been obtained from two Jurassic granitoids that form part of the Santander Massif (Figure 1) to assess the regional influence of the Santa Marta-Bucaramanga fault, south of the SNSM.

[11] Fourteen samples of Jurassic granitoids and Precambrian gneiss were collected in discrete regions of the Sierra Nevada Province, along the eastern, southeastern and southwestern slopes of the cordillera (Figure 2), the westernmost of which have experienced brittle deformation associated with displacement of the Santa Marta-Bucaramanga fault [Ingeominas 2007a, 2007b]. One sample of the Paleogene Buritaca granodiorite and one granitoid with an undetermined age were collected north of the Sevilla Lineament, within the eastern Sevilla Province. The remaining 11 samples of Paleocene-Eocene granitoids of the Santa Marta Batholith and Upper Cretaceous metasedimentary rocks of the Santa Marta Schist were collected along a single traverse that is oriented approximately perpendicular to the Aguja Fault within the Santa Marta Province (Figure 2). This traverse spans an elevation range of 24–2340 m, and hence represents a useful elevation profile for reconstructing quantitative exhumation information.

[12] Whole rock samples were crushed and apatite was recovered using conventional heavy liquid and magnetic methods. Apatite grains were mounted in epoxy, polished and etched using 5.5 M HNO3 for 20 s at 21.0 ± 0.5°C in a temperature-calibrated water bath, and spontaneous track densities were obtained with a Zeiss Axiosimager optical microscope and used as a proxy for the number of 238U fission decay events. Only those grains that were mounted with the c-axis parallel to the microscope stage were counted. Identical regions of each apatite grain where the spontaneous track counts were recorded were subsequently analyzed by either (1) the LA-ICP-MS method [e.g., Hasebe et al., 2004; Parra et al., 2009a] for 27 samples collected from the SNSM (Appendix A) or (2) the external detector method [Gleadow, 1981] for 2 samples collected from the Santander Massif, to determine the 238U content of the apatites. Separate grain mounts were irradiated with 252Cf fission fragments to generate ~107 tracks/cm2 in a vacuum chamber to enhance the number of confined track-in-tracks available for length measurement [e.g., Donelick and Miller, 1991; Donelick et al., 2005], after etching in 5.5N HNO3 for 20.0 s at 21.0 ± 0.5°C. Despite this approach, fewer than half of the samples yielded a statistically useful quantity (i.e., >30) of measureable, confined fission track lengths due to the presence of numerous mineral and fluid inclusions. A mean Dpar value was deter-
Table 1. Apatite Fission Track Data, Sierra Nevada de Santa Marta

| Sample | Lithology | Elevation (m) | UTM X (m) | UTM Y (m) | Grains | Nsi | U (ppm) | Pi* | *43Ca | *238U | Dpar ± | MTL ± SD (μm) | Dpar ± 2σ | MTL ± SD (μm) | Dpar ± 2σ | MTL ± SD (μm) | Dpar ± 2σ | MTL ± SD (μm) | Dpar ± 2σ | MTL ± SD (μm) | Dpar ± 2σ |
|--------|-----------|--------------|----------|----------|--------|-----|--------|-----|--------|--------|--------|----------------|----------|----------------|--------|----------------|----------|----------------|--------|----------------|----------|----------------|----------|----------------|--------|----------------|
| SN3    | Granodiorite | 10055 | 101774 | 167941 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN25  | Diorite | 100978 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN26  | Diorite | 100702 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN28  | Gneiss | 100278 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN29  | Gneiss | 100278 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN30  | Gneiss | 100278 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN31  | Granodiorite | 10055 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |
| SN32  | Granodiorite | 10055 | 170045 | 30 | 177 | 1.03 ± 0.29 | 5.85 ± 0.02 | 1.17 ± 0.02 | 11.22 ± 5.0 | 20.7 ± 3.6 | 13.96 ± 0.51 | 5.0 | 5.85 ± 0.02 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 | 7.38 ± 0.29 | 5.75 ± 0.13 | 11.00 ± 5.0 |

*Data for all samples is from Zeta MS for all samples is 12.4756 ± 0.368.

Note: MS for all samples is 12.4756 ± 0.368.
mined for each sample to assess the variation of track annealing kinetics between samples. Further methodological details are provided in Appendix A.

5. Results

[13] Maximum long etch pit diameter (Dpar) values in apatite within the studied region range between 1.89 and 1.00 µm (Table 1) without any particular trend (Figure 3) relative to apatite FT age, which suggests that the compositional influence on fission track age distribution and fission track annealing is insignificant. P(γ2) values for all modeled samples range between 5.0% and 96.7% (Table 1), suggesting that the apatite fission track ages obtained by the LA-ICP-MS method define single FT age populations. All apatite fission track age errors are reported at the 2σ level.

5.1. South of the Sevilla Lineament (Sierra Nevada Province)

5.1.1. Rocks From Southern and Eastern Regions of the Sierra Nevada Province

[14] The oldest apatite fission track ages within the Sierra Nevada de Santa Marta were obtained from the southern and eastern Sierra Nevada Province. Six Jurassic granitoids and a single rhyolite that are located furthest inland (Figure 2 and Table 1) and are proximal to the Cesar Lineament yield apatite fission track ages between ~60 Ma and ~40 Ma. These rocks form part of the Andean-wide, Jurassic continental arc that extends along the western South American margin. Despite the fact that these samples reside in three or more distinct faulted blocks (Figure 2), all of the apatite fission track ages are indistinguishable over an elevation range of 400–2700 m, with the exception of granite SN43 (Figure 4). Two of these samples yielded intermediate mean track lengths of 12.55 ± 1.81 µm and 12.72 ± 1.19 µm suggesting they are partially annealed, and Dpar values range between 1.09–1.12 µm (Figure 3 and Table 1).

5.1.2. Rocks Located Within the Deformation Zone Associated With the Santa Marta–Bucaramanga Fault

[15] Apatite fission track data have been acquired from deformed Jurassic arc rocks and gneisses of their host Precambrian sequence (the Los Mangos granulite), located within 10 km of the Santa Marta-Bucaramanga Fault, within the Sierra Nevada Province. Seven samples span an elevation range of 290–1620 m, and yield indistinguishable pooled apatite fission track ages between 23 and 30 Ma (Figure 4), which are clearly younger than less deformed regions of the same province to the east. However, Dpar values range between 1.00 and 1.39 µm, and are thus similar to those yielded by rocks exposed further east. Mean apatite fission track lengths range between 12.21 ± 1.70 µm and 13.96 ± 0.17 µm (Table 1), suggesting the tracks are partially annealed.

5.2. North of the Sevilla Lineament: Santa Marta and Sevilla Provinces

[16] Twelve Paleogene granitoids (Santa Marta Batholith; K/Ar age 58–44 Ma [Tschanz et al., 1974]; zircon U-Pb age 57–50 Ma [Cardona et al., 2008a]) and Upper Cretaceous schists from the region north of the Sevilla Lineament, defined by the Santa Marta and Sevilla provinces yielded the youngest apatite fission track ages within the Sierra Nevada de Santa Marta, ranging between 16 Ma and 29 Ma (Figures 3 and 4). An exception to this group is mica schist SN6, which gave an imprecise apatite fission track age of 41.0 ± 9.6 Ma, and will be considered separately. Dpar values range between 1.21 and 1.54 µm and mean apatite fission track lengths range between 12.62 ± 1.71 µm and 13.83 ± 1.05 µm (Table 1), suggesting the tracks are partially annealed.

5.3. Santander Massif

[17] Two samples of Jurassic granites exposed in the Santander Massif (Figures 1 and 5), which form part of the Andean-wide Jurassic continental arc yielded pooled apatite fission track ages of 16.7 ± 3.2 Ma (sample BU140) and...
23.3 ± 3.8 Ma (sample BU142) Ma, although insufficient confined tracks were found to generate a meaningful length distribution. P(χ2) values are >5% suggesting that these ages define single fission track age populations (Table 2). The ages are similar to those obtained from the SNSM in the vicinity of the Santa Marta-Bucaramanga Fault. Granite BU140 yielded a zircon fission track age of 28.1 ± 3.2 Ma, which is distinguishably older than its apatite fission track age.

6. Periods of Cooling

[18] Apatite fission track ages are a function of thermal history and annealing kinetics of individual apatite grains. A comparison of apatite fission track age and the long etch-pit diameter (Dpar), which is considered to be a reliable proxy for variations in track annealing [Donelick, 1993; Carlson et al., 1999] reveals no clear relationship (Figure 3) and therefore we consider that intersample variations in fission track data in this study are dominated by differences in thermal histories.

[19] A comparison of apatite fission track age and mean track length (Figure 3) from nine samples dispersed across the sampled region shows that the longest mean lengths (13.83–13.96 μm) are associated with ages between 30 and 20 Ma, implying that cooling rates were most rapid during the late Oligocene-early Miocene. However, the partially annealed nature of these tracks precludes a more precise estimate of the timing of cooling through the apatite partial annealing zone. To quantify the timing and amount of cooling experienced by the current land surface between ~120–60°C we modeled the apatite fission track data following the approach described by Ketcham [2005] using the quantitative description of apatite annealing kinetics of Ketcham et al. [2007a] and the software HeFTy v 1.6.7 [Ketcham, 2009]. The modeling procedure predicts fission track parameters for various thermal history paths and compares them with the observed fission track age and length data. A controlled random search procedure identifies those thermal histories that most closely match the fission track analytical data. The paucity of fission track length measurements restricted the acquisition of useful thermal history solutions, which were only acquired from nine samples (Figure 6) from the SNSM. Those solutions have been compared with the relationship between fission track age and elevation to reconstruct the thermal histories of the samples.

6.1. South of the Sevilla Lineament (Sierra Nevada Province)

6.1.1. Rocks Located in Central and Eastern Regions of the Sierra Nevada Province

[20] Undeformed granitoids (SN42 and SN44) and a rhyolite (SN43) located far from the Santa Marta-Bucaramanga fault zone yield apatite fission track ages older than 40 Ma.
Figure 2), although an insufficient quantity of confined track lengths were recorded to perform thermal history modeling. Two quartz monzonites (SN35 and SN39) also yielded apatite fission track ages older than 40 Ma, and sufficient track length data to generate thermal history solutions using inverse modeling. Considering only the good fit solutions (Figure 6), quartz monzonite SN39, located within 15 km of the Cesar Lineament cooled from ≥120°C to ∼75°C during 65–58 Ma, at rates ∼6°C/My, with subsequent significantly slower rates toward the surface, despite a poorly constrained possible increase at ∼35 Ma. Quartz monzonite SN35, located 7 km northward and separated from sample SN39 by an ∼east-west trending strike-slip fault (Tierra Nueva Fault [Ingeominas, 2007b]) (Figure 2) experienced a slightly younger cooling history with cooling from ≥120°C to ∼70°C between 50 and 40 Ma, at an average cooling rate of ∼5°C/My.

No clear relationship exists between the fission track ages and elevation of Jurassic granitoids (samples SN42 and SN43) and a Jurassic rhyolite (Figure 4; sample SN44) located close to the Oca Fault, implying the samples probably reside in distinct fault blocks (Figure 2).

Table 2. Apatite Fission Track Data From the Santander Massif, Obtained Using the External Detector Methoda

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>Stratigraphic Age</th>
<th>Elevation (m)</th>
<th>UTM-X</th>
<th>UTM-Y</th>
<th>Grains</th>
<th>RhoS ×10^5 Track/cm²</th>
<th>RhoI ×10^5 Track/cm²</th>
<th>RhoD ×10^5 Track/cm²</th>
<th>U (ppm)</th>
<th>P((c^2))</th>
<th>Pooled Fission Track Age ± 2σ (Ma)</th>
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<tr>
<td>BU140</td>
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<td>Jurassic</td>
<td>1275</td>
<td>710320</td>
<td>788226</td>
<td>19</td>
<td>1.452(122)</td>
<td>24.107(2025)</td>
<td>16.322 (18044)</td>
<td>17</td>
<td>98.97</td>
<td>16.7 ± 3.2</td>
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<tr>
<td>BU142</td>
<td>granite</td>
<td>Jurassic</td>
<td>1896</td>
<td>715252</td>
<td>787848</td>
<td>20</td>
<td>2.186(73)</td>
<td>25.689(858)</td>
<td>16.138 (18044)</td>
<td>18</td>
<td>56.28</td>
<td>23.3 ± 3.8</td>
</tr>
<tr>
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<td>Jurassic</td>
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<td>788226</td>
<td>15</td>
<td>40.206(780)</td>
<td>45.206(877)</td>
<td>5.341 (7728)</td>
<td>284</td>
<td>22.65</td>
<td>28.1 ± 3.2</td>
</tr>
</tbody>
</table>

Values in parentheses indicate the number of tracks counted. Samples counted by D. Villagómez (zeta: 340.83 ± 8.02, CN5 glass, apatite; 118.52 ± 3.08, CN1 glass, zircon).
Figure 6
track length data renders the fission track ages uninterpretable. However, three granitoids (SN35, SN36 and SN37) located in the central part of the Sierra Nevada Province yield indistinguishable apatite fission track ages over an elevation range spanning 1927–2721 m, suggesting they may reside in a single fault block, corroborating the fault distribution shown on Figure 2. Their weighted mean age of ~43 Ma overlaps with the timing of elevated cooling rates of quartz monzonite SN35, obtained from inverse modeling (Figure 6; 50–40 Ma).

6.1.2. Rocks Located Within the Deformation Zone Associated With the Santa Marta–Bucaramanga Fault

[22] Post-Eocene apatite fission track ages are restricted to rocks located north of the Sevilla Lineament, and in the vicinity of the Santa Marta–Bucaramanga Fault within the Sierra Nevada Province. This latter group yields ages between 30 and 23 Ma, with partially annealed mean track lengths. Two Precambrian gneisses (SN29 and SN30) yield almost identical thermal history solutions, which reveal elevated cooling rates during 40–25 Ma, with cooling from ≥120°C to 80–60°C (Figure 6), at an average rate of ≥4°C/My. Subsequent cooling occurs in both samples at slower rates, toward the present day. The thermal history solution for Jurassic granodiorite SN23 located close to the Sevilla Lineament, which gave the longest mean track length in the data set (13.96 ± 0.17 µm), yields a period of rapid cooling during 29–26 Ma between ≥120°C to ≤60°C at a high average rate of ≥20°C/My (Figure 6).

[23] The relationship between fission track age and elevation (Figure 4) for all samples located proximal to the Santa Marta–Bucaramanga Fault can be described as linear, and ages overlap at 30–25 Ma over elevations spanning 288–1620 m (Figure 4), suggesting they share a common, exhumation induced cooling event. However, considering the differences in the thermal history solutions (Figure 6) and the spatial distribution of samples (Figure 2), we suggest that with the exception of granite SN23, all samples proximal to the Santa Marta–Bucaramanga Fault cooled within the same fault block during 40–30 Ma, at a rate slow enough to allow the partial annealing of tracks in apatite, and hence a reduction in their apatite fission track ages. Subsequent cooling during 29–26 Ma, may have affected all samples located proximal to the Santa Marta–Bucaramanga Fault, although cooling was more rapid in the Jurassic granitoid (SN23) that is located proximal to the Sevilla Lineament (Figure 6), and may reside within a distinct, faulted block.

6.2. North of the Sevilla Lineament

[24] Apatite fission track ages from Paleogene granitoids and Upper Cretaceous schists from the region north of the Sevilla Lineament range between 29 and 16 Ma, and define a slightly younger group than samples from south of the lineament (Figures 3 and 4). Mica schist SN6 yields an older apatite fission track age of 41.0 ± 9.6 Ma and its low precision reflects its extremely low U content (~3 ppm; see Table 1). Four samples, which are located in three different faulted blocks (Figures 2 and 6), yielded a statistically useful quantity of confined track lengths and have been used to generate plausible thermal history solutions.

[25] The good fit models for mica schist SN3 reveal elevated cooling commencing at 25–16 Ma, which proceeds at an almost constant average rate of ~4°C/My until 10–0 Ma. Similarly, aplite SN18 experienced high cooling rates of 8–9°C/My during 25–18 Ma from ≥120°C to <60°C, which subsequently decelerated toward the present day. In contrast, aplite SN15 was cooling rapidly during 30–25 Ma from ≥120°C to 100°C, followed by slower cooling until the present day (Figure 6).

[26] The good fit envelope for quartz diorite SN4 (incorporating zircon and apatite (U-Th)/He ages of 26.8 ± 1.1 Ma and 13.3 ± 1.9 Ma, respectively; taken from A. Cardona et al., manuscript in preparation) reveals two potential cooling periods, which occurred during 30–25 Ma from ≥200°C to <80°C at rates of ~24°C/My, and during 20–15 Ma at a rate of ~10°C/My, from 70°C to the surface (Figure 6).

[27] Summarizing, the most rapid periods of cooling north of the Sevilla Lineament occurred either in the late Oligocene (30–25 Ma, samples SN4 and SN15), or in the early to middle Miocene (25–16 Ma, samples SN3 and SN18), and the solutions for SN4 reveal evidence for both cooling periods. The age v elevation profile reveals no obvious trend (Figure 4), which is probably a consequence of vertical displacements along faults that separate the samples (Figure 2). However, when considered as a whole, the age range is restricted to 30–15 Ma over an elevation range of more than 2 km, suggesting the fission track ages originate from rapid cooling events that occurred during the late Oligocene-middle Miocene, corroborating the thermal history solutions.

6.3. Santander Massif

[28] The lack of track length data precludes an accurate assessment of the timing of cooling of the Santander Massif. However, both apatite fission track ages span a similar range (23–16 Ma; see Figure 5) to those obtained from the Santa Marta–Bucaramanga Fault.
Marta Province of the SNSM, suggesting it may have also cooled during the Oligocene-early Miocene. The zircon fission track age (28.1 ± 3.2 Ma) of Jurassic granite BU140 is distinguishably older than its apatite fission track age (16.7 ± 3.2 Ma), precluding rapid cooling of the massif from temperatures >200°C during the middle Miocene.

7. Exhumation of Rocks Within the Sierra Nevada de Santa Marta

[29] The thermal history solutions reveal periods of elevated cooling rates at (1) 65–58 Ma and 50–40 Ma (Jurassic granitoids), in the central Sierra Nevada Province; (2) 40–25 Ma (Precambrian gneisses) proximal to the Santa Marta-Bucaramanga Fault with higher rates at 29–26 Ma (Jurassic granitoid) close to the Sevilla Lineament, in the western Sierra Nevada Province; and (3) 30–25 Ma (Paleogene quartz diorite and aplite) and 25–16 Ma (Paleogene aplite and quartz diorites and Upper Cretaceous schist) north of the Sevilla Lineament. We consider these cooling events to be a consequence of exhumation because (1) they broadly correlate with high gradients on the age v elevation plot (Figure 4), (2) they are not coeval with and do not immediately postdate proximal magmatic activity, and (3) they are contemporaneous with sedimentation in the neighboring basins (Cesar and Lower Magdalena basins; see Figure 7).

[30] Public domain heat flow data from rocks in Colombia is sparse, and current estimates of the geothermal gradient are restricted to 20–25°C/km in the Llanos foreland basin [Bachu et al., 1995], and a similar value of 22°C/km from...
the continental shelf adjacent to the Santa Marta-Barraquilla region [López and Ojeda, 2006] (Figure 1). Given the paucity of data, we are forced to estimate a value for the geothermal gradient throughout the Tertiary. Mancktelow and Grasemann [1997] demonstrated that high exhumation rates lead to narrowing of isotherms and higher geothermal gradients due to rock advection, and thus we have assumed a constant Tertiary geothermal gradient of 30°C/km, which is similar to the gradient used in thermochronological studies of the foreland basin of Colombia [e.g., Mora et al., 2008, 2010] and the cordilleras of Ecuador [e.g., Spikings et al., 2000].

[31] Exhumation rates can be estimated by (1) the rate of change of elevation with fission track age and (2) direct measurements taken from the best fit thermal history solutions. However, it is likely that the apatite partial annealing zone was laterally perturbed by variations in surface relief, and therefore any slopes obtained from Figure 4, will yield maximum exhumation rates [Braun et al., 2006].

7.1. The Sierra Nevada Province

[32] The Sierra Nevada Province experienced cooling periods during 65–40 Ma. Jurassic granitoid SN39, located in a distinct fault block (Figure 2) cooled most rapidly during 65–58 Ma at rates of ~6°C/My, which is equivalent to a slow exhumation rate of ≥0.2 km/My. Subsequently, granitoid SN35, which is located in an adjacent faulted unit toward the north cooled during 50–40 Ma at an average rate of 5°C/My (Figure 6), yielding an average exhumation rate of 0.2 km/My. Jurassic granitoids SN35, SN36 and SN37 reside within the same fault block (Figure 2), span an elevation range of 794 m and yield indistinguishable apatite fission track ages, with a best fit linear regression line that yields a slope of ~0.32 km/My (Figure 4). Combining both estimates of exhumation rate obtained from the elevation profile and the thermal history solutions, we propose that these Jurassic granitoids exhumed at rates of 0.32–0.2 km/My during 50–40 Ma.

[33] The gneisses and granitoids sampled proximal to the Santa Marta-Bucaramanga fault probably reside in the western section of the same faulted block that hosts Jurassic granitoids SN35, SN36 and SN37 (Figure 2). Consequently, it is plausible to suggest that these rocks exhumed through the crust within the same, northwest vergent transpressive fault slice and experienced a similar quantity of rock uplift, implying that along-structural strike variations in fission track ages are simply a function of variable amounts of erosional exhumation. Thermal history models indicate that gneiss SN30 and SN29 cooled during 40–25 Ma at an average rate of 24°C/My, via exhumation at a rate of ~0.15 km/My, and are exposed at lower elevations than the granitoids located further east (Figure 4). Assuming that this analysis is accurate, the relationship between age and elevation (gray line on Figure 4) for samples taken from this particular faulted block reflects elevated, albeit moderate exhumation rates at 40–25 Ma and 50–40 Ma. Clearly, the reduction in apatite fission track ages of these rocks relative to the time of cooling is reflected by the partially annealed track lengths (Table 1). Thermal history solutions have not been obtained from Jurassic granitoids SN24, SN25 and SN26, although they intersect the same trend line (Figure 4), suggesting they exhumed within the same fault block.

[34] Jurassic granodiorite SN23, located in a distinct thrust slice in the western Sierra Nevada Province [Ingeominas, 2007a, 2007b], proximal to the Sevilla Lineament (Figure 2), yields a high cooling rate of ~20°C/My during 29–26 Ma, and an exhumation rate of 0.6–0.7 km/My. Clearly, this thrust slice was exhumed more after 30 Ma than regions located more distal to the Sevilla Lineament within the Sierra Nevada Province, which may reflect the progradation of thrusts toward the northwest during the Eocene-late Oligocene.

7.2. The Santa Marta and Sevilla Provinces

[35] Thermal history modeling suggests that thrusted units of Paleogene granitoids and Upper Cretaceous schists of the Santa Marta province cooled at elevated rates of 4–10°C/My during 25–16 Ma (Figure 6), and the highest cooling rate in the Sierra Nevada de Santa Marta of 24°C/My during 25–30 Ma, yielding exhumation rates of 0.14–0.3 km/My and ~0.8 km/My, respectively. The rocks were sampled along a traverse that ascends from a low coastal elevation of 24 m to 2341 m toward the southeast, although the traverse crosses numerous thrust faults whose displacements clearly gave rise to variations in thermal and exhumation histories (Figure 6), and are responsible for the nonlinear relationship between fission track age and elevation (Figure 4). No clear geographic trends of the timing of elevated exhumation rates can be observed within the Santa Marta Province, suggesting that any thrust displacement occurred out of sequence.

[36] Granitoids SN31 and SN32 are the only samples taken from the Sevilla province, although they did not yield a useful quantity of confined fission tracks in apatite, precluding the generation of thermal history solutions via numerical modeling.

7.3. Trends in Exhumation Across the Sierra Nevada de Santa Marta

[37] The southern Sierra Nevada Province exhumed at elevated rates during 65–40 Ma, with a younger pulse at 40–25 Ma occurring proximal to the Santa Marta-Bucaramanga Fault. More northeasterly regions of the Sierra Nevada Province located proximal to the Sevilla Lineament, exhumed by greater amounts and more rapidly during 29–26 Ma. North of the Sevilla Lineament, the densely thrusted Santa Marta Province exhumed at elevated rates during 30–25 and 25–16 Ma, without any clear correlation between the timing of exhumation and location. This general pattern shows that the location of the region of highest exhumation rates gradually progressed toward the northwest within the Sierra Nevada province. The diachronous trend in exhumation toward the northwest, combined with mapped northwest vergent thrust faults (Figure 2) [Ingeominas, 2007a, 2007b] suggests that northwest directed thrust propagation may have been responsible for the temporal trends in exhumation throughout the Tertiary.

8. Regional Correlations and Discussion

8.1. Early Eocene: 65–50 Ma

[38] A clear coincidence can be found linking the inception of sedimentation proximal to the SNSM and exhumation of the SNSM, supporting our interpretation that cooling was a consequence of erosional exhumation.
[39] Inception of the foreland Cesar Basin, located along the southeastern border of the cordillera of the SNSM (Figure 2) occurred during the earliest Tertiary with high subsidence rates and the deposition of terrigenous, red-bed, coarse siliciclastic rocks of the Manantial Fm, during 65–61 Ma [Montes et al., 2010] (Figure 7), precisely matching the timing of elevated exhumation in the southern Sierra Nevada Province of the SNSM. The Manantial Fm. hosts clasts of granulite and schist, and dense minerals such as garnet indicating that it was derived from the Sierra Nevada Province [Montes et al., 2010]. The conformably overlying mudstones of the Cerrejón Formation (58–55 Ma [Jaramillo et al., 2007; Montes et al., 2010]), which were deposited in a relatively low energy environment, approximately temporally correlate with a reduction in exhumation rates within the present-day cordillera of the SNSM. Analyses of the dense mineral assemblages of these basal sequences of the Cesar Basin confirms that they were dominantly sourced from rocks of the SNSM [Bayona et al., 2007; Ayala, 2009]. The region now occupied by the SNSM, Cesar Basin, Perijá Range and the Maracaibo Basin was buried beneath extensive Cretaceous siliciclastic and carbonate sequences that terminate at 65 Ma (Figure 7). Consequently, it is clear that the first phase of orogenic growth of the SNSM occurred at 65 Ma, although exhumation was slow (0.2 km/My) compared to thrust belts that evolve at plate margins such as the Himalayas (in the area of K2: 3–6 km/My [Foster et al., 1994]). An exhumation rate of 0.2 km/My is comparable to values proposed for intracontinental orogenesis in Australia (0.4 km/My [Shaw et al., 1992]), and may be typical for crust responding to increased compression originating at a distal plate margin.

[40] Several authors have shown that the allochthonous Caribbean Plateau and overlying island arc collided with the Pacific margin of northern South America, approximately north of 5°S (present-day coordinates) at 75–70 Ma [Spikings et al., 2000; Villagómez et al., 2008; Vallejo et al., 2009], resulting in (1) a sudden onset of high exhumation rates (>1 km/My) along the continental margin, which is represented by the Central Cordillera in Colombia and the Eastern Cordillera in Ecuador (Figure 1); (2) initiation of a foreland setting east of the Central Cordillera in Colombia (the Middle Magdalena Basin [Villamil, 1999; Gómez et al., 2005] and Ecuador (Oriente Basin)); and (3) inversion of the preforeland basin sequence of the Amazon Foreland Basin [Baby et al., 1990]. However, platform continental sedimentation persisted across northern Colombia (north of 8°N; present-day coordinates; see Figure 7) covering the region of the present-day SNSM until 65 Ma, implying the region did not respond to the initial collision event. More recently, van der Lelij et al. [2010] have shown that the plateau-continent collision event did not occur until 65 Ma along the northernmost zone of collision, near to the northwestern corner of the continental plate, implying that the collision was diachronous, becoming younger to the northeast. We propose that the onset of exhumation in the Sierra Nevada Province and the associated early Paleocene inception of the foreland Cesar Basin was a direct response to increased transpressive stress originating from oblique ocean plateau-continent collision along the northwestern corner of South America. Surface uplift caused the marine platform that covered the northern region of Colombia to retreat, and the foreland was placed into a continental environment (Manantial, Cerrejón and Tabaco Fms [Toussaint, 1999] (Figure 7). Previous thermochronological studies of the Late Cretaceous Pacific margin of Colombia and Ecuador have shown that elevated exhumation events persisted during 75–45 Ma and 75–55 Ma, respectively [Spikings et al., 2000, 2010; Villagómez, 2010], possibly due to a combination of a long period of elevated stress, and rock uplift driven by isostatic rebound. Therefore, we also suggest that the elevated exhumation rates in the Sierra Nevada province that persisted until ~58 Ma also represent continued exhumation beyond the timing of collision at 65 Ma.

[41] The western flank of the Eastern Cordillera of Colombia (an inverted Mesozoic rift), south of the Santander Massif (between 4°S–6°S) started exhuming as a response to contractual shortening at some time during ~56–43 Ma [Parra et al., 2009a] (Figure 7) and Mora et al. [2010] report that shortening and exhumation within the Eastern Cordillera in response to collision of the Caribbean Plateau was minor. The diachronous response of the SNSM and rocks of the Eastern Cordillera suggests the SNSM may have formed an along-strike extension of the rocks of the Central Cordillera of Colombia (Figure 1) during the late Cretaceous-Early Paleocene, which was exhuming rapidly at 70–60 Ma [Villagómez, 2010].

8.2. Middle Eocene: 50–40 Ma

[42] The onset of deposition of the terrigenous Tabaco formation in the Cesar Basin during continuous subsidence slightly predates an increase in exhumation rates within the Sierra Nevada province during 50–40 Ma (Figure 7), suggesting the SNSM may not have been the sole source of detritus, with some sediment being derived from the Perijá Range [Shagam et al., 1984].

[43] The ocean plateau-continent collision event during the early Paleocene was followed by dextral displacement of the Caribbean Plate and the onset of a new shallow, southeast dipping subduction zone offshore of the SNSM, whose present-day surficial trace corresponds to the southwestern Caribbean plate boundary zone (Figure 1). Subduction of the Caribbean slab [e.g., Gorney et al., 2007] and the onset of a continental arc commenced in the late Paleocene [Pindell and Barrett, 1990; Müller et al., 1999] and lasted until the early Eocene [MacDonald et al., 1971], which produced the Santa Marta Batholith (K/Ar ages of 58–44 Ma [Tschanz et al., 1974]; zircon U-Pb ages of 57–50 Ma [Cardona et al., 2008a]) as a consequence of increased NE-SW convergence between the South and North American plates [Müller et al., 1999]. We propose that the elevated exhumation rates in the Sierra Nevada Province were driven by the same compressive forces, and ultimately reflect convergence between the North and South American plates. Coeval local occurrences include (1) the initiation of surface uplift of the Perijá Range during the middle Eocene [Bayona et al., 2007] (Figure 7) as a response to displacement along the Cerrejón Fault (CF; see Figure 2) and (2) southeastward younger onset of continental deposition in the Late Paleocene-Early Eocene in the region of the Maracaibo Basin [Mann et al., 2006], reflecting tilting upward of its northwestern sector (Figure 7). Eocene arc shut-off in the Santa Marta
Province may have been triggered by the onset of flattening of the subducted slab beneath the SNSM.

### 8.3. Late Eocene–Early Oligocene: 40–30 Ma

[44] Precambrian gneisses and Jurassic granitoids of the Sierra Nevada Province located proximal to the Santa Marta-Bucaramanga Fault were exhuming at elevated rates during 40–30 Ma. The thermal history models suggest that exhumation rates in more easterly regions of the Sierra Nevada province may have also increased slightly during ~35–30 Ma (sample SN39). This spatial distribution of elevated exhumation rates during 40–30 Ma suggests they were related to displacement along the Santa Marta-Bucaramanga Fault. This time period coincides with a hiatus in both the Cesar and Maracaibo basins, and predates the earliest preserved sedimentary rocks in the Lower Magdalena Basin (Figure 7), suggesting either (1) surface uplift in the basins rendered them topographically prominent, (2) the depocenters were starved of sediment, or (3) the sedimentary rocks were reworked prior to sedimentation in the Oligocene. We are unable to distinguish between these possibilities, although previous authors have utilized seismic data to suggest that there is a late Eocene–early Oligocene, regional unconformity present in the Cesar and the Lower Magdalena basins [Mora and García, 2006]. We propose that cooling during 40–30 Ma is unequivocal evidence of exhumation, although the detritus was mainly distributed offshore, and may still exist as unrecognized remnants within the surrounding basins. A zircon fission track age of 28.1 ± 3.2 Ma (Table 2; Jurassic granite) from the Santander Massif, which is bound to the west by the Santa Marta-Bucaramanga fault suggests that the region has undergone extensive exhumation since 30 Ma, precluding a determination of the regional influence of the fault prior to 30 Ma.

[45] A lack of regionally distributed exhumation during 40–30 Ma renders it difficult to confidently assign a driving force, although we speculate that exhumation was caused by flattening of the subducted Caribbean slab, leading to reactivation of faults and the rapid drainage of sediments toward the continental shelf, accounting for hiatuses distributed across the region (Figure 7). It is likely that the slab was composed of buoyant, oceanic plateau rocks [Taboada et al., 2000], which provided support for an elevated upper plate.

#### 8.4. Late Oligocene–Miocene: 30–16 Ma

[46] The highest exhumation rates within the cordillera of the SNSM during 30–16 Ma occurred during 29–26 Ma proximal to the Santa Marta-Bucaramanga Fault in the western Sierra Nevada Province, and 30–25 Ma and 25–16 Ma in the Santa Marta Province. These time periods correlate closely with conglomerates and sandstones (Real Fm. [Toussaint, 1999]) in the Cesar Basin and basal tuffaceous strata of the Lower Magdalena Basin (Figure 7), bolstering our interpretation that cooling of the SNSM was a consequence of erosional exhumation. Kellogg and Bonini [1982] document intense folding and thrusting and elevated exhumation in the northwestern SNSM during the late Oligocene based on field mapping and gravity data, corroborating our interpretations. Post-middle Oligocene tectonic events recorded in the SNSM were coeval with events recorded in basins located on the South American Plate (e.g., Lower Magdalena, Cesar, Maracaibo and Llanos basins of Colombia and Venezuela [e.g., Mann et al., 2006; Parra et al., 2009a, 2009b; Horton et al., 2010; Mora et al., 2010; Nie et al., 2010]). In contrast, thermochronological analyses of the Leeward Antilles islands suggest they have been tectonically quiescent since ~40–35 Ma [van der Lelij et al., 2010]. Therefore, we suggest that the SNSM was already mainly decoupled from the Caribbean by 30 Ma and has responded to a South American tectonic regime since then. East-west dextral vertical faults located south of the Southern Caribbean Plate Boundary Zone (Figure 1; e.g., Oca Fault) formed after the tectonic emplacement of the Santa Marta Province [Pinell and Barrett, 1990] and have only been active since the late Miocene [Pindell and Kennan, 2009] by absorbing a component of lateral displacement within the Southern Caribbean Plate Boundary Zone [Taboada et al., 2000].

[47] Zircon and apatite fission track ages that span 28–16 Ma in the Santander Massif (Table 2) suggest the region was also cooling and exhuming at elevated rates during the late Oligocene–Miocene. Mora et al. [2010] show that the southern termination of the Santa Marta-Bucaramanga fault (Figure 1) was active at that time. Similarly, coeval exhumation of the Perijá Range is recorded in the Maracaibo Basin, where a thick clastic wedge fills the basin from the west [Shagam et al., 1984; Mann et al., 2006] (Figure 7).

[48] We propose that sinistral displacement of the Santa Marta-Bucaramanga fault was responsible for the deformation and elevated exhumation rates found in the SNSM during 30–16 Ma, in addition to surface uplift within the Perijá Range. The Santa Marta-Bucaramanga fault is believed to be an old paleosuture, which has been reactivated several times, culminating with displacement in the Miocene that uplifted the Santander Massif, caused thickening in the Perijá Range [Cediel et al., 2003] and may be linked to the exhumation of parts of the Merida Andes of Venezuela [Bermúdez et al., 2010]. Prolonged sinistral transpressional movement extended all along the Santa Marta-Bucaramanga fault toward its northern tip, where displacement was impeded by the presence of oceanic plateau rocks of the Caribbean Plate, favoring northwest verging thrusting. The westernmost part of the Sierra Nevada province thrust above the Sevilla Province along the Sevilla Lineament at ~30 Ma (see thermal history solution for SN23; Figure 6). Faulted blocks linked with the Santa Marta-Bucaramanga fault were also exhumed at a similar time. As transpression proceeded northwestern, the Santa Marta Province was thrust, uplifted and exhumed during 25–16 Ma.

[49] This period (30–16 Ma) was coincident with a period of elevated exhumation rates during the late Oligocene–early Miocene throughout the Northern Andes [Spikings et al., 2000, 2001, 2010; Parra et al., 2009a, 2009b; Mora et al., 2010], including the Eastern Cordillera of Colombia (Figure 7). The Farallón Plate fragmented into the Cocos and Nazca plates at ~25 Ma, and the Nazca Plate vector changed from ESE to E with an accompanying sudden increase of its convergence rate with the South American Plate [Pilger, 1984; Pardo-Casas and Molnar, 1987]. Müller et al. [1999] report increased convergence rates between the South and North American plates during the early Miocene, which could have underthrust Caribbean oceanic crust below.
the South American margin, increasing the regional compressive stress.

9. Why is the Sierra Nevada de Santa Marta Currently at 5775 m?

[50] The SNSM reaches a maximum height of 5775 m, which is unexpected considering that (1) it yields an unexpectedly high gravity anomaly (208 mGal, Complete Bouguer Anomaly [Kellogg and Bonini, 1982; Cerón, 2008]), indicating the region is not in isostatic equilibrium [Case et al., 1982, 1990; Cerón, 2008]; (2) the youngest period of exhumation detected within the sensitivity realm of the apatite fission track method, which we assume to be a proxy for rock uplift is ~16 Ma; and (3) the prevailing climate is tropical-subtropical with an annual rainfall of 1000–2000 mm/yr [Arias and Morales, 1999] in the foothills of the massif, which should provide significant erosive power.

[51] Given the high elevation of the SNSM, coupled with the highly erosive climate of northern Colombia, we would expect rock uplift and therefore exhumation to have been more recent than 16 Ma. For example, fission track analyses of other prominent topographic regions such as the Cordillera Blanca in Peru, and K2 in the Pakistan Karakoram, yielded ages of 10–7 Ma (zircon U-Th/He [Garver et al., 2005]) and 4–2 Ma (apatite fission track [Foster et al., 1994]), respectively. This comparison suggests that the high peaks of the SNSM formed when the present surface was at temperatures lower than 60°C, and there has been insufficient erosion (approximately <1.5 km) to expose late Miocene and younger apatite partial annealing zones. Therefore, we suggest that this is indicative of very recent, rapid rock uplift, leaving insufficient time for erosion to expose rocks that cooled through the apatite partial annealing zone after ~16 Ma. This analysis suggests that (1) there have been significant alterations to the relief since the surface cooled through the apatite partial annealing zone, rendering our exhumation rates to be maximum values, and (2) the lower-temperature apatite (U-Th)/He thermochronometer should be applied to help constrain the timing of exhumation through near-surface temperatures to resolve between the various driving forces that could have generated, and may be currently maintaining the high elevations of the SNSM.

[52] Cerón [2008] proposes that the dynamic topography of the SNSM and isostatic disequilibrium may be maintained by a rigid, underthrusted Caribbean oceanic lithosphere. If this underthrust slab is composed of oceanic plateau rocks [Taboada et al., 2000], then its high buoyancy compared to MORB may be sufficient to support high elevations at the margins of the continental lithosphere even though it has no deep continental roots. Alternatively, Hernandez [2006] and Cerón [2008] show that geodetic measurements and the gravity anomaly can be satisfied by a Moho that bulges upward, providing dynamic support. This hypothesis is supported by high heat flow (>40 m W/m² [Hamza et al., 2005]) revealed by elevated geothermal gradients of ~40°C/km within crystalline rocks located to the northwest of the SNSM [Lopez et al., 2005]. Levander et al. [2008] imaged an undulating Moho beneath western Venezuela with a wavelength of ~150 km, which is similar to the width of the cordillera of the SNSM. Finally, the subduction of buoyant oceanic heterogeneities such as aseismic ridges is known to drive rock uplift and exhumation in the continent via increased horizontal stress (e.g., Carnegie Ridge [Spikings et al., 2001, 2010]). The Caribbean Plate mainly consists of oceanic plateau material, and hosts abundant seamounts.

[53] We are unable to distinguish between the potential driving forces for the most recent phase of rock uplift within the SNSM using the apatite fission track data. Subduction of the Caribbean Plateau beneath the region of the SNSM may have started as early as the Paleocene [e.g., Pindell and Barrett, 1990]. Therefore, while the Caribbean Plate provided a driving force for periods of exhumation throughout the Tertiary, it is not immediately clear why it should have driven the most recent phase of rock uplift, unless it provided lateral forces due to the very recent subduction of seamounts. If an upwelling Moho was responsible for the current topography of the SNSM, flexure of the Moho must have occurred extremely rapidly, within the previous 1–2 My.

10. Conclusions

[54] 1. Elevated exhumation rates in the Sierra Nevada Province during 65–58 Ma represent the initial phase of rock uplift and exhumation within the SNSM, and were driven by the later stages of diachronous accretion of the Caribbean Plateau to the Pacific margin of the South American Plate, and the initiation of a foreland basin setting in the Cesar Basin.

[55] 2. Convergence between the North and South American plates at ~50 Ma [e.g., Pindell et al., 2005] underthrust the Caribbean Plate beneath the northern South American Plate, and was probably responsible for a second pulse of exhumation within the Sierra Nevada Province during 50–40 Ma, which corresponds with terrigenous deposition in the foreland Cesar Basin, and south-eastward trending regression of continental deposition in the Maracaibo Basin.

[56] 3. Precambrian gneisses and Jurassic granitoids located proximal to the Santa Marta-Bucaramanga fault exhumed at elevated rates during 40–30 Ma. Similar lithologies located further east within the same fault block within the Sierra Nevada province may have also been exhumed during the same period although their fission track record has since eroded. Coeval sedimentary rocks have not been preserved in the surrounding basins, suggesting they may have been reworked. A lack of regionally distributed exhumation during 40–30 Ma renders it difficult to confidently assign a driving force, although we speculate that exhumation was caused by flattening of the subducted Caribbean slab, leading to reactivation of faults, and the rapid drainage of sediments toward the continental shelf.

[57] 4. The highest exhumation rates within the cordillera of the SNSM occurred during 29–26 Ma proximal to the Santa Marta-Bucaramanga fault in the western Sierra Nevada Province, and 30–25 Ma and 25–16 Ma in the Santa Marta Province. Interactions between the SNSM and the Caribbean Plate were minor during the late Oligocene-Miocene, and exhumation was a consequence of compression originating at the Pacific margin of South America. Sinistral displacement of the Santa Marta-Bucaramanga fault pushed the SNSM against the thick oceanic plateau of the Caribbean.
Plate during 30–16 Ma, and also gave rise to rock uplift and exhumation in the Santander Massif and the Perijá Range. Fragmentation of the Farallón Plate and increased convergence rates at the Pacific margin were probably responsible for increased compressive stress in northern South America, which was partly accommodated by transpression along the Santa Marta–Bucaramanga fault.

The data reveal northwest directed propagation of exhumation within the SNSM that is probably linked to progressive thrust displacement. The displacing thrusts intersect the Santa Marta–Bucaramanga Fault, whose sinistral displacement probably provides the local driving force for the advance of exhumation within the SNSM.

The high peaks of the SNSM (5775 m) formed when the present surface was at temperatures lower than 60°C, and there has been insufficient erosion (approximately < 1.5 km) to expose late Miocene and younger apatite partial annealing zones. Given the high erosional power of the climate in northern Colombia, this is indicative of very recent, rapid rock uplift, leaving insufficient time for erosion to expose rocks that cooled through the apatite partial annealing zone after ~16 Ma.

Appendix A

[60] Apatites were mounted in epoxy resin and polished using 3.0 μm and 0.3 μm Al2O3 slurry at Apatite to Zircon Inc. Natural fission tracks crossing the polished apatite grains surface were etched for counting using: 5.5 N HNO3 for 20.0 (±0.5) s at 21.0(±0.5)°C. Monts were scanned to search for the best apatite grains for age dating and grain location and pictures were digitally recorded at the University of Geneva (Microscope Zeiss Axio–Imager.z1m, 3 axis motorized stage, Autoscan System Pty. Ltd.). Grain localities were revisited using the Laser ablation inductively coupled plasma–mass spectrometer (LA–ICP–MS apparatus housed at the GeoAnalytical Laboratory, Washington State University, Pullman, Washington, U.S.A.) in order to determine 238U concentrations by measuring the ratio of 238U to 43Ca in apatite grains from the same regions of individual grains from which the spontaneous tracks were obtained [see Hasebe et al., 2004; Donelick et al., 2005; Parra et al., 2009a]. We assumed that Ca occurs in stoichiometric amounts in all of the analyzed apatite grains, and 43Ca is assumed to be directly proportionally to the volume of apatite ablated. Samples were ablated in He to induce condensation and elemental fractionation. Spot analyses were performed with the laser centered on a fixed point. A total of 30 scans for 238U, 232Th, 147Sm, and 43Ca were performed for each spot. The first 10 scans were performed while the laser was blocked from contacting the grain surface, allowing the background measurements to be recorded. Subsequently, a cylindrical pit was excavated to a depth beyond which uranium did not contribute fission tracks to the etched grain surface. The depths of a representative number of the pits were measured and 238U/43Ca was calculated for the entire pit based on the weighted mean of 238U/43Ca values for individual scans relative to the depths from which the ablated material was derived. Fission track ages and errors were calculated using (1) the ratio of the density of natural fission tracks present in the grain to the amount of 238U present and (2) a modified version of the radioactive decay equation that includes a LA–ICP–MS zeta calibration factor [Donelick et al., 2005]. The zeta calibration factor was determined for each sample analyzed by measuring the U/Ca ratio in standard Durango (31.44 ± 0.09 Ma) apatite at the beginning and end of each LA–ICP–MS session.

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