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# Early-subduction-related orogeny in the northern Andes: Turonian to Eocene magmatic and provenance record in the Santa Marta Massif and Rancheria Basin, northern Colombia

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## ABSTRACT

**The timing of orogeny in the northern Andes and the mechanism driving it are still debated. We have studied the age, composition and provenance of granitoids and sandstones of the Santa Marta Massif and Rancheria Basin, northern Colombia, to relate deep-seated and surface tectonic processes attending the Late Cretaceous–Palaeogene history of the northern Andes. Our results indicate the development of five tectonic episodes: (1) collision of northwestern South America with a 92–80 Ma Caribbean arc (70 Ma); (2) late-collisional to early-subduction metamorphism and magmatism (65 Ma); (3) distal accumulation of a thick siliciclastic sequence (60–58 Ma); (4) renewed arc magmatism (58–50 Ma); and (5) magmatic quiescence and block uplift (post-50 Ma). The first episodes are related to the onset of subduction, and the last episode is related to shallow subduction and oblique convergence. Similar events in Colombia and Ecuador reveal that the Late Cretaceous–Eocene orogeny of the northern Andes was influenced by the collision and subduction of the Caribbean oceanic plate.**

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## Introduction

Subduction is the major force driving crustal growth and recycling of continental crust. Even though evidence for the earlier stages of subduction remains elusive (House *et al*., 2002; Stern, 2004; Kimura *et al*., 2005), complex tectonic responses have been predicted when the newly subducted plate contains thick oceanic crust (Cloos, 1993; Gutscher *et al*., 2000; Mann and Taira, 2004; Van Hunen *et al*., 2004). Basin analysis, petrological studies and regional geological and geophysical considerations have suggested that the Late Cretaceous to early Cenozoic tectonic evolution of the northern South American margin was controlled by its interaction with the margins of an allochthonous (Pacific-derived) and anomalously thick Caribbean oceanic plate and its associated arc (Burke, 1988; Kerr *et al*., 1997; Pindell *et al*., 1998; Montes *et al*., 2005; Spikings *et al*., 2005; Luzieux *et al*., 2006; Vallejo *et al*., 2006; Maresh *et al*., 2009; Weber *et al*., 2009).

Subsequent Palaeogene orogenic phases have been linked to regional variations in plate convergence in a subduction setting or to oceanic accretions (Pindell *et al*., 1998; Parra *et al*., 2009; Restrepo-Moreno *et al*., 2009; Vallejo *et al*., 2009; Jaillard *et al*., 2010).

In this article, we present information on the composition and U–Pb crystallization and detrital ages of Turonian and Palaeogene granitoids and sedimentary rocks from the Sierra Nevada de Santa Marta and the adjacent Rancheria Basin in northern Colombia (Figs 1 and 2). The spatiotemporal and compositional features of these granitoids, along with shifts in the detrital zircon provenance of the sandstones, suggest that both collisional tectonics and the early subduction of the Caribbean plate exerted first-order control on the northern Andean orogeny.

## Geological setting

Post-Eocene strike-slip and escape tectonics have facilitated block displacement and isolation along the Caribbean margin of northern South America (Pindell *et al*., 1998, 2005; Montes *et al*., 2010). The Sierra de Santa Marta is a displaced fault-bounded block in northern Colombia, which is isolated from the continuous Andean ranges by thick middle to late Cenozoic basins (Fig. 1). Tomographic and seismological analyses show a subducted Caribbean slab beneath this region, dipping 17° to the south-east down to 250 km depth (Kellogg, 1984; Van der Hilst and Mann, 1994; Taboada *et al*., 2000; Miller *et al*., 2009).

The geology of the Santa Marta Massif includes three belts (Fig. 1): (1) Jurassic magmatic rocks with remnants of 1.16–0.9 Ga high-grade metamorphic inliers (Tschanz *et al*., 1974; Cordani *et al*., 2005); (2) Palaeozoic schists and amphibolites with 270–250 Ma orthogneisses (Cardona-Molina *et al*., 2006; Cardona *et al*., 2010b); and (3) allochthonous Late Cretaceous amphibolites and schists, which formed after metamorphism of volcano-sedimentary Cretaceous volcanic arc rocks (MacDonald *et al*., 1971; Tschanz *et al*., 1974; Bustamante *et al*., 2009; Cardona *et al*., 2009a, 2010c).

Two main types of granitoid units are found in the northwestern Santa Marta Massif: a poorly exposed orthogneissic unit, enclosed within

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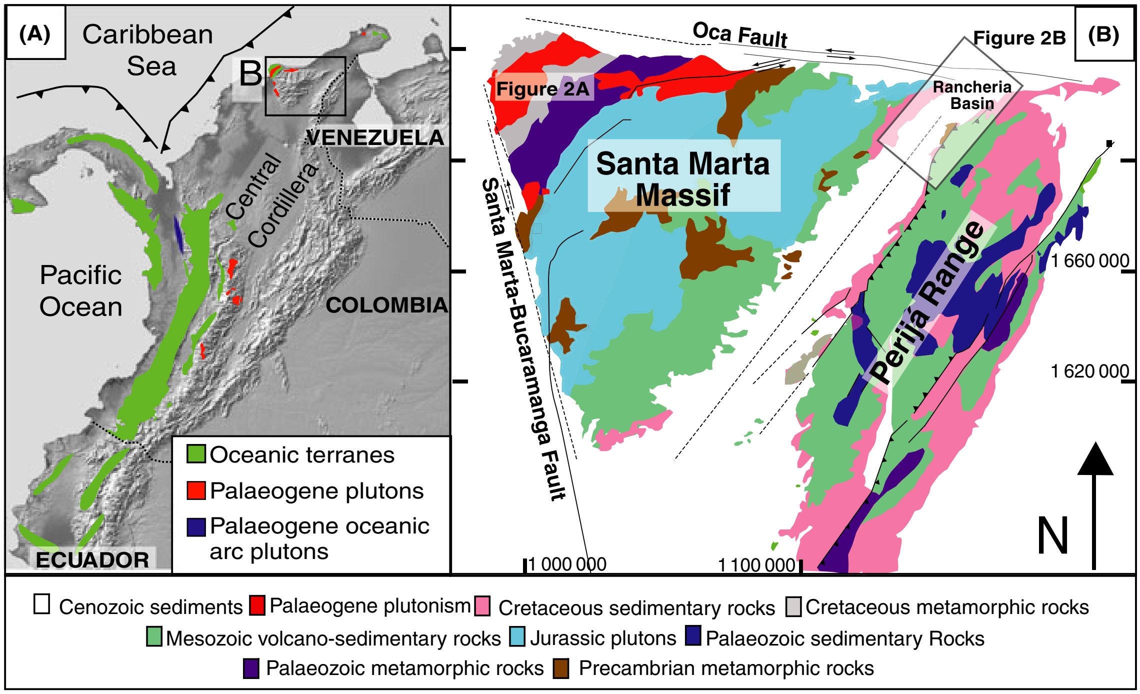


**Fig. 1** (A) Digital elevation map of northern South America with Cretaceous oceanic terranes and Palaeogene granitoids (Aspden *et al.*, 1987; Kerr *et al.*, 1997). (B) Geologic map of the Santa Marta and Perijá Massifs (Tschanz *et al.*, 1974).

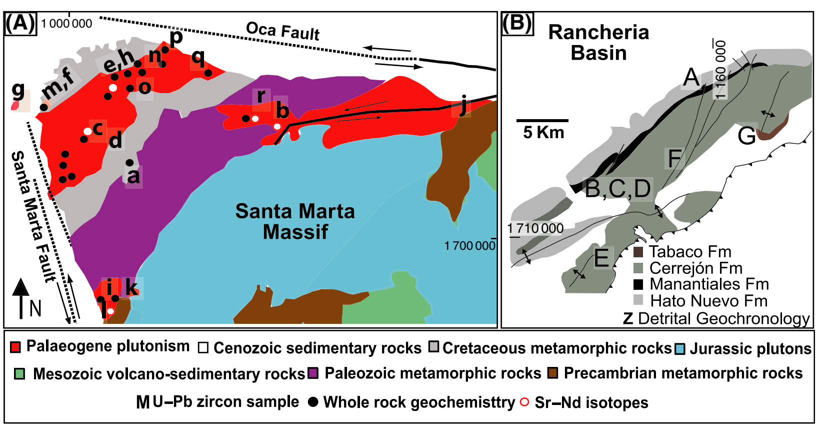


**Fig. 2** (A) Regional geology of the Santa Marta granitoids (Tschanz *et al.*, 1974). Lowercase letters are U/Pb LA-MC-ICP-MS analysed samples. (B) Geology of the Rancheria Basin (Bayona *et al.*, 2007); letters indicate sample locations. Coordinates are from the Bogota Observatory datum.

the Cretaceous volcanic-arc-derived amphibolites and schists, and widely exposed massive granitoid bodies. The latter include tonalites, granodiorites, micaceous granites and mafic enclaves forming the coastal Santa Marta batholiths and a series of smaller inland plutons all intruding Late Cretaceous, Palaeozoic and Grenvillian metamorphic rocks (Figs 1 and 2).

The southeastern foothills of the Santa Marta Massif are bounded by the Cesar and Rancheria Basins (Figs 1 and 2B). Evolution of the Rancheria Basin reached a passive-margin stage by the Aptian with deposition of the Cogollo Group and the La Luna Formation (Martinez and Hernandez, 1992). An initial Maastrichtian regression is recorded by the neritic to prodeltaic mudstone facies of the Colón Formation. Regression continued with the lower Palaeocene shallow marine to marginal shales and sandy limestones of the Hato Nuevo and Manantial Formations (Etayo-Serna, 1979). The overlying 1000 m Cerrejón Formation includes a deltaic sequence with sandstones, mudstones and coal that were deposited in $<2$ Ma (Bayona *et al.*, 2007; Jaramillo *et al.*, 2007). This sequence is unconformably covered by 75 m of sandstones of the early Eocene Tabaco Formation. To the south-east, the Sierra de Perijá Massif is thrust over the Rancheria Basin (Fig. 1; Kellogg, 1984). This massif consists of Jurassic and Palaeozoic igneous and sedimentary rocks (Kellogg, 1984). Overlying Cretaceous to Palaeogene sedimentary rocks indicate a former connection with the Rancheria Basin (Bayona *et al.*, in press).

## Results

### Geochemistry of plutonic rocks

Whole-rock major and trace element analyses of 21 granitoid samples from the massive Santa Marta batholith and several inland plutons are presented in Table S1 and in Fig. 3A,B.

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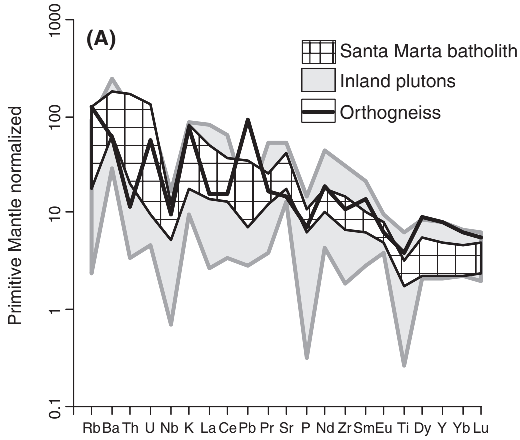


**Fig. 3** (A) Mantle-normalized multielement diagram (Sun and McDonough, 1989). (B) Rare earth elements chondrite-normalized diagram (Nakamura, 1974). Samples from the Palaeocene–Eocene granitoids were divided into Santa Marta and inland granitoids just for geographic purposes.

Chemically, the rocks are characterized by high $Al_2O_3$ and $Na_2O$ (15.05–20.74% and 2.44–4.89%) and by enrichment in Ba and Sr (199–1693 and 274–1145 p.p.m.; Fig. 3A). They are also enriched in large ion lithophile elements and depleted in the high field strength elements; there is variable enrichment in light rare earth elements (LREE) ($La/Yb_N$ = 3.3–16.5), and there are negative Nb–Ta anomalies, characteristic of arc granitoids formed by prominent melting of metabasaltic sources (Fig. 3A,B; Pearce *et al.*, 1984; Petford and Atherton, 1996).

The orthogneiss within the metamorphosed Cretaceous volcanic-arc-derived amphibolites and schists lacks the $Al_2O_3$ and $Na_2O$ enrichment. It is enriched in K, Rb and Th and depleted in Nb and Ta (Fig. 3A). LREE are also slightly enriched [$(La/Yb)_N$ = 2.27] with a well-defined Eu anomaly ($Eu/Eu^*$ = 0.50; Fig. 3B). These features are characteristic of typical subduction-related magmatism (Pearce *et al.*, 1984).

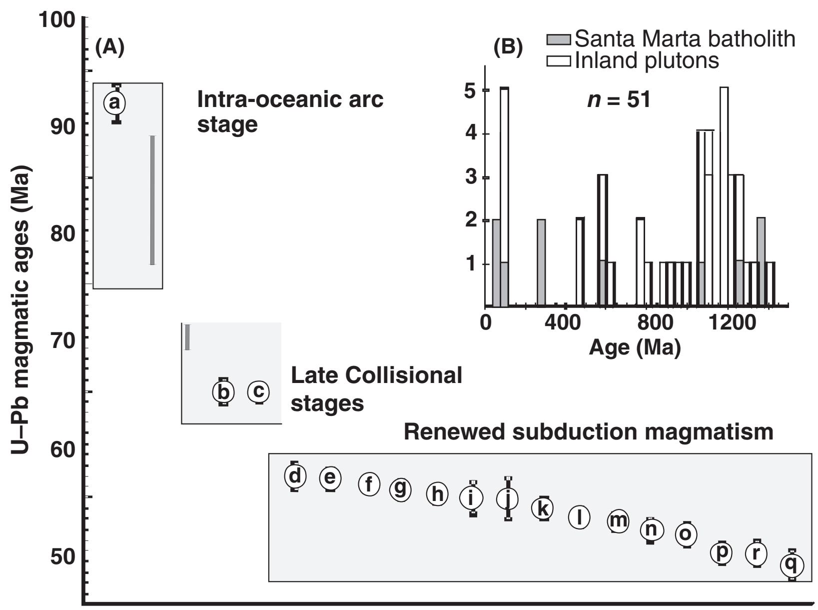


**Fig. 4** (A) Major plutonic events defined by U–Pb zircon geochronology in the northwestern Santa Marta Massif. Letters a–r indicate the locations of samples in Fig. 2; (B) inherited zircons from the analysed granitoids. Sample locations are those from Fig. 2. Other data (grey lines) from Late Cretaceous metavolcano-sedimentary rocks and late-collisional granitoids after Cardona *et al.* (2009b, 2010c).

## Geochronology and isotope geology

Analysed granitoid samples are presented in Fig. 2B and Supporting information. $^{206}Pb/^{238}U$ ages from seventeen granitoid samples reveal two major peaks of magmatic activity, one at *c.* 65 Ma and another more prominent peak at 58–50 Ma (Fig. 4A). Inherited Phanerozoic and Proterozoic zircons are abundant (Fig. 4B) and are similar to those that characterize their host rocks (Cardona *et al.*, 2010a,b,c). In contrast, magmatic zircons from the orthogneiss sample record magmatic crystallization at 92.0 ± 1.7 Ma (Fig. 4A), indicating the existence of an older Turonian arc. Nd–Sr results from the massive granitoids, including those from published data (Mejía *et al.*, 2008), show unradiogenic to highly radiogenic values, with εNd varying between −10.31 and 2.39 and $^{87}Sr/^{86}Sr$ varying from 0.70470 to 0.71096 (Fig. 5). These patterns can be modelled by a single mixing scenario between Atlantic sediments/South American continental crust and a metabasaltic source similar to the accreted Caribbean arc (Fig. 5).

## U/Pb detrital zircon provenance

Figure 2B shows the distribution of Palaeogene sandstones in the Rancheria Basin. Palaeocurrent analysis has

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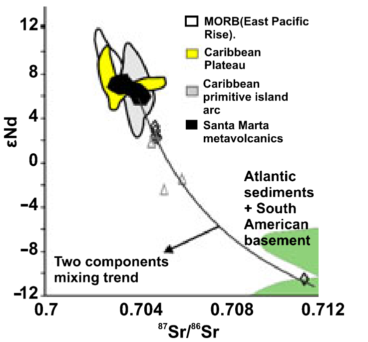


**Fig. 5** Sr–Nd isotopes from the Santa Marta and inland Palaeogene granitoids (data from this work = ◇, published data after Mejía *et al*., 2008 = △). Trend supports two-component single mixing of Cretaceous intra-oceanic rocks from Santa Marta and Atlantic sediments (White *et al*., 1985; Cardona *et al*., 2010a,b,c). Data for two-component single mixing calculations include Caribbean accreted intra-oceanic arc from Santa Marta (Cardona *et al*., 2010a,b,c), MORB (White and Hofman, 1982) and Atlantic sediments (White *et al*., 1985). The Atlantic sediments field overlaps with the field of Precambrian crust from northern South America (Cordani *et al*., 2005). Equations are after Faure and Mensing (2005). Compositional fields for Caribbean magmatic provinces and MORB are after Kerr *et al*. (2003), Thompson *et al*. (2004) and Jolly *et al*. (2006).

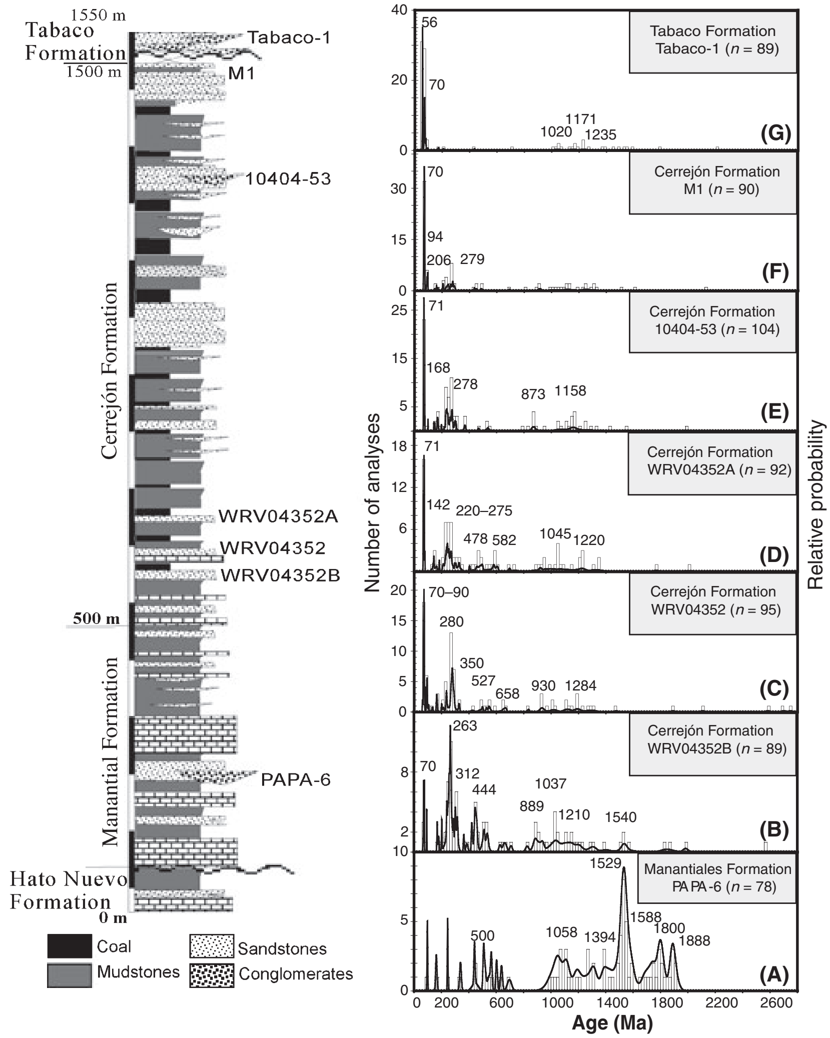


**Fig. 6** Stratigraphic column after Bayona *et al*. (2007) and detrital zircon U–Pb age frequency distribution plots from the Rancheria Basin. (A) Manantial Formation (Fm.). (B–E) Middle Cerrejón Fm. (F) upper Cerrejón Fm. (G) Tabaco Fm.

shown that Palaeocene siliciclastics of the Rancheria Basin were supplied from the northwestern Santa Marta Massif. In the Eocene, input also occurred from the Sierra de Perijá Massif to the southeast (Bayona *et al*., 2007). An age plot showing the frequency distribution of the detrital zircons is presented in Fig. 6. The lower Palaeocene Manantial Formation (170–400 m) yields Proterozoic zircons with peaks between 1058 and 1888 Ma (Fig. 6A). These ages are similar to those of the Grenvillian inliers of the northern Andes, such as those found in the Santa Marta region (Cordani *et al*., 2005; Cardona *et al*., 2010a), and to reworked Late Cretaceous passive-margin sediments (Ayala-Calvo *et al*., 2010; Weber *et al*., 2010). Five samples distributed along the 1 km thick middle and upper Cerrejón Formation include age clusters of 94–67, 328–220 and 530–420 Ma, with some Proterozoic peaks at *c*. 1.2 and 1.0 Ga (Fig. 6B–F). The 90–65 Ma ages correlate with the crystallization age of the orthogneiss, the Cretaceous metavolcano-sedimentary rocks of northwestern Santa Marta and plutonic rocks drilled in the adjacent coast (Fig. 1; Cardona *et al*., 2009b, 2010c). The Triassic to Carboniferous zircons are similar in age to metamorphosed granitoids and detrital zircons from Cretaceous metasedimentary rocks from north-west Santa Marta (Cardona *et al*., 2010b). Finally, the overlying Eocene Tabaco Formation is characterized by 70 and 60–55 Ma peaks (Fig. 6G) and limited 1000–1500 Ma zircons. Whereas the younger peaks correlate with the plutonic ages reported here, the Precambrian sources are linked to reworked sedimentary rocks and Grenvillian highs in the Santa Marta and Perijá Massifs.

## Tectonic implications

The spatio-temporal distribution of the magmatic rocks records major shifts in the tectonic setting of the continental margin. A crystallization age of the orthogneiss of *c*. 92 Ma combined with *c*. 80 Ma peaks in detrital zircons from intra-oceanic metavolcano-sedimentary rocks indicates that older arc magmatism was active during this time interval (Cardona *et al*., 2009b, 2010c). This arc was formed at the margins of the

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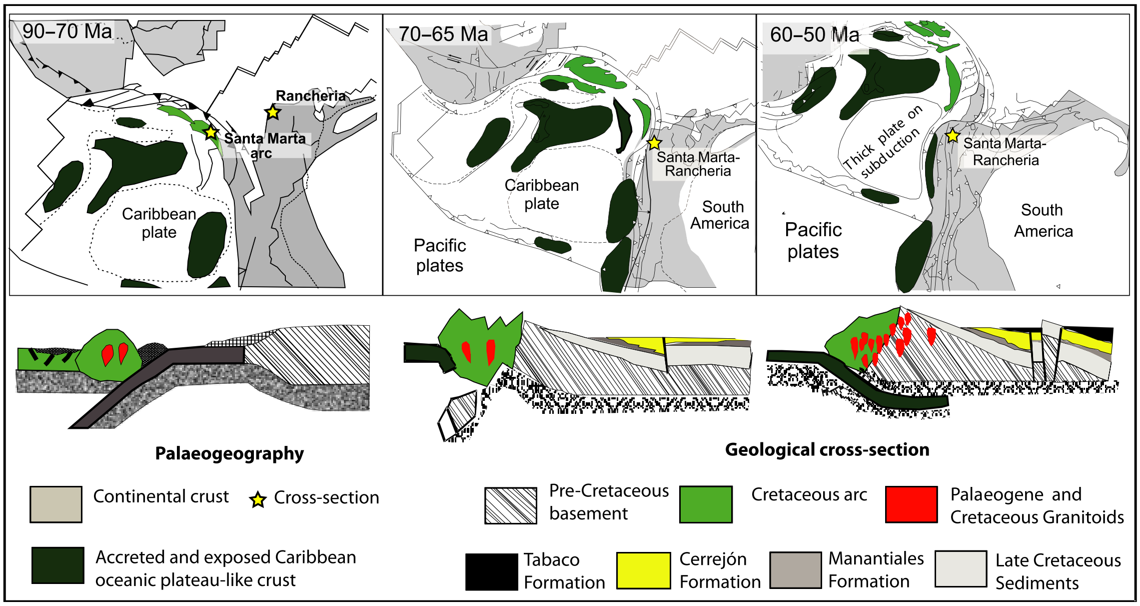


**Fig. 7** Tectonic model for the northern Andes and Caribbean region (after Pindell *et al.*, 2005). 90–70 Ma: Intra-oceanic arc evolution; *c.* 92 Ma emplacement of arc granitoids. This intra-oceanic arc magmatism persisted until *c.* 76 Ma (Weber *et al.*, 2009). 70–65 Ma: Accretion of Great Caribbean Arc in northwestern South America and Caribbean oceanic plateau at its eastern margin (Vallejo *et al.*, 2006, 2009; Cardona *et al.*, 2009b). Late-collisional magmatism and metamorphism associated with slab break-off, polarity flip and the initiation of subduction. 60–50 Ma: Active subduction zone with associated magmatism, uplift and basin filling.

allochthonous (Pacific-derived) Caribbean oceanic plate (Fig. 7A). Mesozoic magmatic activity intruding the South American active margin in the Santa Marta region ended in the Early Cretaceous (Tschanz *et al.*, 1974; Pindell and Kennan, 2009). Correlatable accreted intra-oceanic arc remnants are found within adjacent massifs in the Guajira region of northeastern Colombia and in Bonaire (Thompson *et al.*, 2004; Weber *et al.*, 2009, 2010).

On the other hand, sedimentation within the Rancheria Basin indicates limited subsidence and a passive-margin setting (Martinez and Hernandez, 1992; Bayona *et al.*, in press), suggesting a contrasting tectonic setting. Hence, the Rancheria Basin and the allochthonous Late Cretaceous arc probably approached each other during the interval 80–65 Ma, as a likely consequence of the eastward progress of the latter.

By 70 Ma, arc–continent collision was in progress, as suggested by the resetting of Ar–Ar ages in the Palaeozoic basement (Cardona-Molina *et al.*, 2006) and late tectonic granitoids and by Ar–Ar cooling ages from high-pressure rocks in Guajira (Cardona *et al.*, 2009b; Weber *et al.*, in press). We relate the older *c.* 65 Ma plutonic peak in Santa Marta and contemporaneous Barrovian metamorphism in the allochthonous volcanic-arc-derived amphibolites and schists (Bustamante *et al.*, 2009; Cardona *et al.*, 2009a) to this collisional event, which eventually led to subduction of the Caribbean plate under the northwestern South American margin after flipping of the subduction polarity and strong compression during the early phase of renewed subduction (Fig. 7B; Shemenda, 1992; Davies and von Blanckenburg, 1995; Teng *et al.*, 2000; House *et al.*, 2002; Regard *et al.*, 2008; Nikolaeva *et al.*, 2010).

From 58 to 50 Ma, arc-related granitoids show that subduction occurred at the continental margin (Fig. 7C). Their high contents of $Al_2O_3$, $Na_2O$ and Sr, their REE patterns and their Sr–Nd isotopes are compatible with melting of metabasaltic rocks and continental crust/subducted sediments (Fig. 5; Kay and Kay, 1991; Rapp and Watson, 1995; Petford and Atherton, 1996). These sources are compatible with the melting of Caribbean oceanic crust and continental crust tectonically underplated during the arc–continent collision and initiation of subduction (Arculus *et al.*, 1999; Draut *et al.*, 2002; Saito *et al.*, 2007).

Some of the Eocene granitoids intrude accreted back-arc and oceanic rocks (Cardona *et al.*, 2010c), which suggests an emplacement proximal to their related palaeotrench (Fig. 7C). This spatial feature and the geochemistry of the granitoids are attributed to abnormal shallow melting facilitated by mantle upwelling during early subduction (Peacock *et al.*, 1994; Keleman, *et al.* 2003; Gorczyk *et al.*, 2007). Tomographic analyses have shown the existence of a subducted Caribbean slab beneath the Santa Marta region, dipping 17° down to 250 km depth (Van der Hilst and Mann, 1994; Miller *et al.*, 2009). Assuming convergence rates as low as 3.7–6.5 mm $a^{-1}$ (Müller *et al.*, 1999), subduction must have begun by *c.* 65 Ma, in agreement with the magmatic record.

Shifts in the detrital record provide additional tectonic constraints. The Palaeocene Manantial Formation in the Rancheria Basin includes Protero-

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zoic zircons and metamorphic and sedimentary lithics (Bayona *et al.*, 2007), which we relate to the erosion of passive-margin deposits exposed during arc–continent collision (Ayala *et al.*, 2010; Weber *et al.*, 2010). The thick 60–58 Ma Cerrejón Formation contains zircons with ages of 90–65 and 290–220 Ma, recording the erosion of the northwestern basement and the accreted arc and the late-collisional magmatism (Fig. 1B). This distal filling sourced from the northwest overlaps the initiation of magmatism and reflects the localized uplift and subsidence that characterized initial subduction stages (House *et al.*, 2002; Nikolaeva *et al.*, 2010).

The final record includes early Eocene erosion of the Palaeogene arc recorded in the Tabaco Formation, a magmatic hiatus after *c.* 50 Ma, angular unconformity and block uplift in the adjacent Cesar Basin and Perijá Massif (Fig. 7C; Tschanz *et al.*, 1974; Kellogg, 1984; Bayona *et al.*, in press). These events can be related to the shallow subduction and increase in convergence obliquity of the thick Caribbean plate under South America (Mauffret and Leroy, 1997; Pindell *et al.*, 1998; Müller *et al.*, 1999; Van Hunen *et al.*, 2004; Gerya *et al.*, 2009; Royden and Husson, 2009).

## Andean orogeny

Palaeogene palinspastic restorations link the Santa Marta Massif and Rancheria Basin to the continuous northern Andean chain (Fig. 1; Pindell *et al.*, 1998; Gomez *et al.*, 2005; Montes *et al.*, 2010). The northern Andes in Colombia and Ecuador experienced several diachronous exhumation events at 73–65, 65–55 and 45–30 Ma (Spikings *et al.*, 2001; Gomez *et al.*, 2005; Vallejo *et al.*, 2006; Martin-Gombojav and Winkler, 2008; Villagómez *et al.*, 2008; Parra *et al.*, 2009; Restrepo-Moreno *et al.*, 2009). There is also evidence of Eocene plutonism and of a late Eocene–Oligocene magmatic hiatus (Aspden *et al.*, 1987), and tomographic imaging reveals a remnant Caribbean slab over the Nazca plate (Van der Hilst and Mann, 1994; Taboada *et al.*, 2000).

Tectonic models of the Caribbean plate suggest that it was formed in the Pacific by the growth of several Cretaceous oceanic volcanic plateaus (Duncan and Hargraves, 1984; Burke, 1988; Pindell and Barrett, 1990; Kerr *et al.*, 2003). As this plate migrated from the Pacific, its diachronous interaction with the northwestern margin of South America began in the late Albian (Pindell *et al.*, 2005; Maresh *et al.*, 2009). Whereas the Late Cretaceous orogenic events in the northern Andes can be related to the collision of the arc and plateau plate margins of the Caribbean plate (Fig. 7B; Pindell *et al.*, 2005; Vallejo *et al.*, 2006; Jaillard *et al.*, 2010), we suggest that the late Palaeocene to Eocene events are related to the early subduction of the thick Caribbean plate.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Table S1.** Whole-rock geochemical analyses from of the analysed granitoids.

**Table S2.** U–Pb zircon geochronologic analyses from the Santa Marta granitoids.

**Table S3.** U–Pb geochronologic analyses from detrital zircons of the Rancheria Basin.

**Table S4.** Whole-rock Sr–Nd isotope results.

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