Factors controlling selective abandonment and reactivation in thick-skin orogens: a case study in the Magdalena Valley, Colombia

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Abstract: The initial stages of tectonic inversion and the mechanisms of selective reactivation and abandonment of pre-existing normal faults during contractional orogenesis are explored in a partially buried Cenozoic thrust belt in the Andes of Colombia. A multidisciplinary approach that includes subsurface structural mapping, multimethod thermochronometry and detrital zircon U–Pb geochronology reveals the extent of a Palaeogene thrust belt buried underneath the Cenozoic strata of the Middle Magdalena Valley Basin. A less oblique orientation with respect to compressive stress and shorter traces in faults of the Middle Magdalena Valley Basin with respect to faults in the western part of the Eastern Cordillera, apparently acted as deformation inhibitors of the Magdalena faults in advanced Neogene stages of inversion. Protracted Cenozoic eastwards tilting of the Central Cordillera and the tectonic load from the uplifting Eastern Cordillera favoured the accumulation of a thick Cenozoic sedimentary sequence in an, at least episodically, closed basin. All the above-mentioned conditions helped to block deformation in the Magdalena Basin, favouring deformation to be taken up by structures in the western Eastern Cordillera. These relationships underscore the importance of buried structural records in elevated hinterland basins, in which the low-relief stratigraphic cover overlies a complex subsurface record, potentially including large magnitudes of deformation during early orogenesis.

Supplementary material: Tables and figures on the laboratory methods for the thermochronometrical and geochronometrical analyses are available at http://www.geolsoc.org.uk/SUP18601.

Continental areas that have an earlier history of extension develop weaker zones that are susceptible to reactivate in contraction (Cooper & Williams 1989; Letouzey 1990; Lowell 1995; McClay 1995). Subsequent changes in the stress field from tensional to compressional in these areas can potentially lead to positive inversion (Cooper & Williams 1989; Letouzey 1990; Grier et al. 1991; Lowell 1995).

The mechanical and kinematic evolution of thrust belts has been studied through theoretical and analogue models (Einsenstadt & Withjack 1995). In some models, the orogenic front evolves as a non-cohesive, frictional, Coulomb wedge, without involvement of the basement (Sibson 1985; Hansen 1986; McClay 1995). In other models, thrust belts evolve out of an intracontinental rift system, inverted by the reactivation of normal faults (Colletta et al. 1990; Hilley et al. 2005; Nemčok et al. 2005). In this case, while some older normal faults are reactivated, others with similar attitude are not (Davis et al. 1983; Sibson 1995). This is controlled by: (1) the principle σ1 stress orientation with respect to pre-existing faults (Gries 1982; Hansen 1986; Stone 1989, 1993; Letouzey 1990; Lowell 1995; Teixell et al. 2003; Marshak et al. 2010); (2) the frictional resistance and cohesion along the faults to be inverted (Byerlee 1978; Sibson 1985; Lowell 1995); and (3) the modification in the wedge’s dynamic equilibrium due to the effects of syn-orogenic erosion and deposition (Davis et al. 1983; Dahlen & Barr 1989; Horton 1999).

The Middle Magdalena Valley (MMV) Basin is an intermountane basin in the Northern Andes of Colombia (Fig. 1). Initial shortening in the MMV was associated with Paleocene–middle Eocene inversion tectonics over an area of Mesozoic rifting (Restrepo-Pace et al. 2004; Cortés et al. 2005; Moretti et al. 2010; Parra et al. 2012). Although it has been documented that reactivation of pre-existing extensional faults configured a Late Cretaceous–early Eocene thrust belt front, which was later covered by east-dipping post-middle Eocene strata as subsequent deformation was taken up by the reactivation of the rift system of the Eastern Cordillera, it remains to be determined why reverse slip along Mesozoic normal faults in the MMV was abandoned and when this abandonment occurred.

The existence of robust subsurface data allow the evaluation of the factors that control the
abandonment and the deformation shift to the Eastern Cordillera. By using previously unavailable subsurface seismic and well data, sedimentological characterization of outcropping Cenozoic strata, low-temperature thermochronology and provenance data, including both conventional and detrital zircon U–Pb data, this study determines the deformation timing of this buried thrust belt. Our thermochronology and detrital U–Pb data refine previous estimates of the onset of erosion of the Central Cordillera and constrain the spatial distribution of sediments provided by this denudation event. We identify which Mesozoic faults are reactivated, discuss the mechanisms of selective extensional fault reactivation and explain why they were subsequently abandoned. With the aid of thermochronological data, we track the exhumation style of the western flank of the Eastern Cordillera and its influence on the survival of the long and west-verging faults along this flank. Finally, by integrating all datasets, we present a Late Cretaceous–late Miocene development model of the study area.

Geological setting

The approximately 560 km long and 80 km wide intermountane MMV Basin is located between the NNE-striking Central and Eastern cordilleras of Colombia. It is limited to the west by the monoclinal structure of the Central Cordillera and to the west by the thrust belt of the western margin of the Eastern Cordillera (Fig. 1).

Precambrian–Mesozoic

The basement of the Central Cordillera consists mainly of Palaeozoic low- to medium-grade...
metamorphic rocks (McCourt et al. 1984; Ordoñez-Carmona et al. 2006; Vinasco et al. 2006) and, along the eastern flank, Grenvillian-age basement (Cordani et al. 2005; Cardona et al. 2010). These rocks are intruded by the Ibagué (160 ± 3 Ma) and Antioquia (94.5 ± 1.7 Ma) batholiths, and the Cordoba (79.3 ± 1.5 Ma) and Buga (90.6 ± 1.2 Ma) granitoids (Aspden 1986; Villagómez 2010; Villagómez et al. 2011). Basement and intrusive rocks are overlain by strata of marine origin.

The basement of the Eastern Cordillera is composed of metamorphic rocks of Grenvillian age (Forero-Suarez 1990). These rocks were intruded by Cambrian–Ordovician plutonic rocks in the Quetame and Floresta massifs (Horton et al. 2010a, b), and by Palaeozoic and Jurassic plutonic rocks in the Santander Massif (Ward et al. 1973). To the east, the Guyana Shield is the easternmost stable craton with Proterozoic-age basement.

In the Eastern Cordillera, the Grenvillian rocks are unconformably overlain by Cambrian–Ordovician metamorphic rocks. Crystalline basement and metamorphic rocks are unconformably overlain by Devonian–Carboniferous sedimentary rocks (Forero-Suarez 1990). A Triassic–Jurassic sedimentary sequence of red beds, comprising the Jordan and Giron formations, unconformably overlay the Palaeozoic rocks. These rocks were deposited concomitant to the development of plutonism and volcanism in Mesozoic rifts located in the Central Cordillera and Magdalena Valley rift basins (Maze 1984; Clavijo et al. 2008).

West of the Eastern Cordillera, thick sequences of continental Triassic–Jurassic and marine Cretaceous rocks were deposited in the extensional Tablazo–Magdalena and San Lucas basins during their phases of rifting and subsequent thermal subsidence (Etayo-Serna et al. 1969; Sarmiento-Rojas 2001; Clavijo et al. 2008). More than 6 km of marine sediments covered most of the nowadays Eastern Cordillera. Less than 4 km and approximately 2 km remain below the Cenozoic cover in the Magdalena Valley and Llanos basins, respectively (Morales 1958; Fabre 1983; Mora, A. et al. 2009; Mora, C. et al. 2009) (Fig. 2).

**Late Cretaceous—early Eocene**

Uplift of the Central Cordillera (Gomez et al. 2003; Villagómez 2010) started a process of foreland basin construction to the east (Cooper et al. 1995; Gomez et al. 2005a). In the SW Middle Magdalena Valley Basin, the initial non-marine deposition is recorded by the eastwards-sourced Maastrichtian...

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Fig. 2. Generalized chronostratigraphical chart of Cretaceous and Cenozoic strata along the Middle Magdalena Valley Basin, from approximately 4°N to 7.7°N.
Cimarrona Formation (Gómez et al. 2003) and its lateral equivalent, the coastal Seca Formation, to the east (Cooper et al. 1995; Villamil 1999; Gómez et al. 2003).

During the Paleocene, NW South America was characterized by a compressive stress field with east–west- to WSW–ENE-orientated principal stress δ1 that, in the MMV Basin, reactivated NE–SW Mesozoic subvertical normal faults as right-lateral and wrench faults in the south (Cortés et al. 2006) and reverse faults in the north (Restrepo-Pace et al. 2004; Gómez et al. 2005b; Parra et al. 2012). Paleocene–early Eocene sediment accumulation in the MMV Basin took place in alluvial, fluvial and coastal environments (Gómez et al. 2003). In the southern sector of the basin, the Hoyón Formation corresponds to alluvial fans sourced in the Central Cordillera. These facies change to the east and NE to fluvial facies of the upper strata of the Seca Formation (e.g. Bayona et al. 2013), and, further to the north, to coastal and deltaic facies of the Lisama Formation (Moreno et al. 2011) (Fig. 2).

Middle Eocene–Miocene

In the early–middle Eocene, the protracted crustal shortening that started during the Late Cretaceous was associated with a NW–SE to WNW–ESE δ1 stress (Colmenares & Zoback 2003; Cortés et al. 2005). The configuration was that of a frontal thrust belt, east of the Central Cordillera, that advanced to the east, incorporating a prestrained region with several pre-existing grabens, including the San Lucas and the Tablazo–Magdalena basins (Morales 1958; Cooper et al. 1995; Sarmiento-Rojas 2001; Gómez et al. 2003, 2005a; Restrepo-Pace et al. 2004; Cortés et al. 2005; Mora, A. et al. 2006, 2009; Clavijo et al. 2008; Moretti et al. 2010; Parra et al. 2012). Subsurface data from the MMV (Parra et al. 2012) show that a crustal shortening phase occurred mostly prior to sediment accumulation of lower–middle Eocene non-marine strata above the MMV substratum, in what has configured a regional unconformity (the Late Cretaceous–Cenozoic unconformity (LKCU) of Gómez et al. 2003).

Thermochronological data (Parra et al. 2012) in the Eastern Cordillera have been used to infer the age of the pre-middle Eocene deformation event that is recorded in the LKCU. Post-middle Eocene–Recent deformation is associated with an episode of continuous deformation (Parra et al. 2009; Mora et al. 2010a), with thrust-induced denudation that has migrated from the axial Floresta and Aracabuco anticlines toward both the eastern and western thrust systems. In the southern MMV Basin, the sedimentary provenance feeding the upper Eocene–Oligocene, fluvial, San Juan de Rio Seco Formation records initial uplift of the western flank of the Eastern Cordillera (Gómez et al. 2003). The middle Miocene fluvial and alluvial Santa Teresa and Honda formations record the inversion event of the Bituima Fault in the Eastern Cordillera (Gómez et al. 2003; Sassi et al. 2007; Parra et al. 2009; Moretti et al. 2010). In the northern MMV Basin, middle–upper Eocene alluvial to fluvial La Paz and Esmeraldas formations host the sedimentary record of the initial uplift of the western flank of the Eastern Cordillera. Subsequent inversion and unroofing of the range through folding and uplift above the La Salina Fault are registered in the Oligocene–Miocene alluvial Mugrosa, Colorado and Real formations. (Gómez et al. 2005b; Caballero et al. 2010; Moreno et al. 2011) (Fig. 3).

Methods

Subsurface data enabled us to map the geological configuration below and above the unconformity in the MMV Basin (Fig. 4). A previously published seismic profile from the northern sector of the basin (Parra et al. 2012) (Fig. 3) and two profiles located at the northern and southern ends of the basin were analysed to determine the configuration of the MMV Basin (Figs 1, 3 & 5).

With the aim of determining the timing of deformation and uplift in the Central Cordillera, the MMV Basin and the western flank of the Eastern Cordillera, we present a new bedrock apatite fission-track (AFT) thermochronology from 16 surface samples taken from the NE flank of the Central Cordillera and the western flank of the Eastern Cordillera, and seven subsurface samples retrieved from three boreholes along the basin (Fig. 3; Tables 1 & 2). In addition, we conducted four zircon fission-track (ZFT) analyses (Table 3), as well as 85 individual zircon (U–Th)/He (ZHe) analyses from 19 samples collected from the Upper Jurassic and Cretaceous strata exposed in the more deeply exhumed areas in the western flank of the Eastern Cordillera. These analyses were complemented with 106 detrital (ZHe) ages obtained from analyses performed on 27 samples from early Eocene–upper Miocene strata from the Caguí and Cocuyo well, in the northern MMV.

We guided our interpretations of thermochronometrical data in terms of fully v. partially reset ages using maximum burial temperatures derived from new vitrinite reflectance (R0) data acquired in three new organic-rich samples from the Cagui well, plus published palaeothermometrical data (Table 4). Temperature equivalents for R0 data were calculated employing the kinetic model of Burnham & Sweeney (1989) with heating rates of 1–5 °C Ma−1. Integration of thermochronometrical and
palaeothermometrical data was conducted using the modelling software HeFTy (Ketcham 2005). The study of spatial and temporal evolution of exhumed areas was complemented with sedimentary provenance analyses in the upper Mesozoic and Cenozoic strata of the MMV Basin, using detrital zircon U–Pb geochronology. We present 3823 new individual U–Pb ages obtained in 37 samples, including units straddling the eastern margin of the basin (Fig. 3).

Details on the laboratory methods for both thermochronometrical and U–Pb geochronometrical

![Fig. 3. Detailed geological map of the Middle Magdalena Valley Basin and the Eastern Cordillera. It shows the main tectonic elements, the location of samples referred in the text and the main thermochronological results.](image-url)
analyses, as well as for inverse modelling of thermochronometrical and $R_0$ data, are included in Supplementary material.

Results

Pre-middle Eocene basin configuration

The subcrop map of the MMV Basin below the LCKU defines the early Eocene tectonic configuration. Two areas with different degrees of faulting are observed below the unconformity. In the northern sector, Jurassic igneous and sedimentary rocks and Cretaceous–Paleocene strata were exhumed along short south–north-, NNW–SSE- and SW–NE-striking reverse faults with opposite vergence, as in the prominent example of the La Cira High (Fig. 4a). In contrast, to the south, a master east-verging reverse fault juxtaposes pre-Cretaceous igneous rocks, mostly represented by the Jurassic Ibague batholith, and Jurassic sedimentary rocks in the hanging wall over Cretaceous and Paleocene strata in its footwall (Fig. 4a).

Unconformably overlying this substratum in the eastern sector of the basin appears a sedimentary cover that includes the middle Eocene La Paz Formation, the overlying upper Eocene Esmeraldas and the Oligocene Mugrosa formations, which progressively onlap onto the unconformity to the west and north (Fig. 4b).

Recently published subsurface data along a composite west–east-directed seismic profile across the Cagüi area in the northern MMV Basin illustrate an eastwards-tilted sequence of mildly folded post-middle Eocene strata, progressively north and eastwards lapping on a thrust belt composed of the Jurassic–Paleocene units (Parra et al. 2012, see their fig. 2). The subcrop map above the unconformity allows this two-dimensional view to be extrapolated across the entire MMV Basin. Only Mesozoic normal faults located at the eastern margin of the basin have cut through the LKCU, whereas shorter, more obliquely striking faults in the central part of the basin are fossilized beneath the Cenozoic strata (Fig. 4b). In the same area of the northern MMV Basin, at 7°40’N, a
SSW–NNE-orientated seismic profile (Fig. 5a) images the erosional truncation of Paleocene and older strata under the unconformity, and the middle Eocene and younger strata lapping on the Cachira High. Similarly, a seismic profile throughout the southern part of the Upper Magdalena Valley, at 3°40′N (Fig. 5b), shows Oligocene–Miocene units southwards lapping on the El Patá and Natagaima basement highs; thus, portraying a mirror image of what is observed in the northern sector of the basin.

Thermochronology data in the eastern flank of the Central Cordillera

The AFT analyses in Jurassic volcanic and Permi–Triassic metamorphic units of the San Lucas range (a–g in Fig. 3) yield two sets of cooling ages, one ranging from 50.6 ± 2.1 to 59.8 ± 12 Ma and another ranging from 107.6 ± 16 to 118.7 ± 15.8 Ma, with older ages found in the easternmost and structurally shallower units of the range (Table 1). A sample from the Triassic Segovia Diorite (González & Londoño 2002), which was retrieved from few metres below the unconformity with the overlying Jurassic Morrocoyal Formation, yields an AFT age of 113.5 ± 10.5 Ma with relatively long tracks (mean track length (MTL) 13.01 ± 1.0 μm). Further to the SW, a Triassic gneiss (Santa Isabel Gneiss: Restrepo et al. 2005) from the Cajamarca complex yielded an age of 50.6 ± 2.1 Ma (a, c in Fig. 3). The inverse HeFTy modelling of both samples shows time–temperature paths indicating a rapid Paleocene–middle Eocene cooling that has decelerated since the late Eocene.

In the Cocuyo well, 64 detrital ZHe ages obtained from sandstones of the early–middle Eocene Cantagallo and Oligocene Mugrosa formations exhibit a dominant age cluster of 60–100 Ma (Fig. 6; see Fig. 3 for the location).

Uplift timing of the Central Cordillera

The Early Cretaceous AFT ages and the relatively long tracks of the Segovia Diorite (sample code 1018-28) are consistent with partially reset ages due to the protracted residence within the shallower portion of the partial annealing zone (PAZ) after the accumulation of overlying sediments. Such insufficient post-Jurassic burial renders the ages inadequate to resolve Cenozoic cooling paths, and probably reveal early folding and deformation of the eastern flank of the Central Cordillera, concomitant to burial and sediment accumulation further to the east, in the MMV Basin. From the pattern of ages and the available thermal models, we interpret that AFT ages near 60 Ma from western and structurally deepest areas are reset ages and indicate the timing of exhumation in the Central Cordillera. The style of exhumation of the Central Cordillera shows rapid Paleocene–middle Eocene cooling followed by slow cooling rates since the late Eocene (Villagómez 2010).

Based on the depositional geometry of a sandstone wedge, spatially restricted to the west of the La Cira–Infantas High (see the location in Fig. 4a) and onlapping eastwards onto it, the Cantagallo sandstones have been interpreted as being sourced from the Central Cordillera (Suarez 1997; Gómez et al. 2005a). Detrital zircon U–Pb signatures of this unit further validate provenance from the eastern flank of the Central Cordillera. Thus, we regard the dominant cluster of ZHe ages of 60–100 Ma in Eocene and Oligocene sandstones of the Cantagallo and Mugrosa formations (Fig. 6) in the Cocuyo well as further evidence of the Late Cretaceous–Paleocene rapid exhumation of the Central Cordillera.

Thermochronology data in the Middle Magdalena Valley Basin

In the Caguí well (h in Fig. 3), an AFT analysis of the Lower Cretaceous Rosablanca Formation (1063-25) yields an age of 66.7 ± 7.8 Ma. Inverse modelling of AFT data and a $R_o$ value of 1.23% (temperature of c. 158 °C) from this unit shows a time–temperature path with an onset of cooling in the Late Cretaceous and reheating since the late Eocene. Inverse modelling of AFT data and a $R_o$ value of 0.53% from the late Eocene Esmeraldas Formation (1063-21) results in a time–temperature path that shows a high cooling rate between 60 and 40 Ma in the source area, followed by accumulation, burial and heating to the present. In the same well, inverse modelling of AFT and $R_o$ data of the overlying lower Miocene Colorado Formation (1063-20: 35.0 ± 4.3 Ma, MTL 12.1 ± 1.6 μm, $R_o$ 0.43%) shows a different pattern, characterized by slow cooling rate in the source area until early Eocene and subsequent rapid cooling between 45 Ma and deposition at approximately 20 Ma. (Tables 1 & 4).

Forty-two ZHe ages in 10 Eocene–Miocene samples in the Caguí well (Fig. 7) reveal: (a) an approximately 60 Ma cooling age in zircons from upper Eocene units; (b) a wider distribution of ages, including some Jurassic cooling ages, in the Oligocene and lower Miocene units; and (c) a tight distribution, with ZHe cooling ages ranging from 15 to 50 Ma in middle–upper Miocene units.

In the Sonero well (i in Fig. 3), a sandstone of the Jurassic Girón Formation (1082-12), has an AFT age of 70.4 ± 9.8 Ma (Table 1). Time–temperature
Table 1. Apatite fission-track data acquired with the external-detector method

| Sample code | Longitude (°W) | Latitude (°N) | Elevation (m) | Stratigraphic age (Ma) | #Gr U (ppm) | Rho-S* (NS) (×10^5 tracks cm^-2) | Rho-I* (NI) | Rho-D† (ND) (×10^5 tracks cm^-2) | P(χ^2) (%) | Age§ (Ma) | ±1σ error | Dpar (μm) | ±1σ (Cl % wt) | ±1σ Length (μm) | ±1σ SD (μm) | ±1σ #Length |
|-------------|----------------|---------------|---------------|------------------------|-------------|---------------------------------|-------------|---------------------------------|-------------|-----------|-----------|----------|---------------|-----------------|-------------|--------------|
| Eastern flank, Central Cordillera | | | | | | | | | | | | | | | |
| 1018-21 | 74.46159 | 6.53497 | 190 Triassic | 250–200 | 22 | 3.640 | 1.86 (66) | 4.34 (3.93) | 14.436 (8201) | 92.56 | 107.8 | 16.8 | 1.18 | 0.14 | N.D. | N.D. | – | – | – | – | – |
| 1018-22 | 74.44827 | 6.78799 | Granite | 150–200 | 10 | 36.950 | 7.47 (134) | 34.005 (610) | 14.574 (8201) | 11.88 | 55.9 | 5.50 | 1.32 | 0.14 | N.D. | N.D. | – | – | – | – | – |
| 1018-23 | 74.66667 | 6.82382 | Tonalite | 150–200 | 23 | 4.550 | 2.449 (85) | 5.273 (183) | 14.713 (8201) | 98.50 | 118.7 | 15.8 | 1.41 | 0.18 | N.D. | N.D. | – | – | – | – | – |
| 1018-24 | 74.09351 | 7.02408 | Giron | 150–200 | 12 | 25.080 | 7.208 (104) | 33.197 (479) | 14.851 (8201) | 2.31 | 56.3 | 6.02 | 1.46 | 0.12 | N.D. | N.D. | – | – | – | – | – |
| 1018-25 | 74.09351 | 7.07722 | Segovia | 200–150 | 20 | 4.100 | 2.132 (175) | 5.031 (413) | 15.406 (8201) | 55.72 | 113.5 | 15.80 | 1.41 | 0.23 | N.D. | N.D. | – | – | – | – | – |
| 1018-26 | 74.09351 | 7.59633 | Cajamarca | 289 | 22 | 9.700 | 1.51 (77) | 12.77 (650) | 15.08 (2353) | 89.60 | 35 | 4.3 | 0.31 | 0.12 | N.D. | N.D. | – | – | – | – | – |
| 1018-27 | 74.09351 | 7.59633 | Colorado | 23–16 | 20 | 7.900 | 1.51 (77) | 12.77 (650) | 15.08 (2353) | 89.60 | 35 | 4.3 | 0.31 | 0.12 | N.D. | N.D. | – | – | – | – | – |
| 1018-28 | 74.09351 | 7.59633 | Esmeraldas | 48–33 | 10 | 43.100 | 6.70 (120) | 56.86 (1009) | 15.05 (2353) | 40.1 | 35.1 | 3.50 | 0.24 | 0.34 | N.D. | N.D. | – | – | – | – | – |
| 1018-29 | 74.09351 | 7.59633 | Rosablanca | 140–130 | 11 | 12.500 | 3.74 (95) | 16.33 (415) | 14.93 (2353) | 30.80 | 66.7 | 7.80 | 0.14 | 0.08 | N.D. | N.D. | – | – | – | – | – |
| Caguá area, well-1, northern Middle Magdalena Valley Basin | | | | | | | | | | | | | | | |
| 1063-20 | 73.57646 | 7.68093 | Colorado | 23–16 | 20 | 7.900 | 1.51 (77) | 12.77 (650) | 15.08 (2353) | 89.60 | 35 | 4.3 | 0.31 | 0.12 | N.D. | N.D. | – | – | – | – | – |
| 1063-21 | 73.57646 | 7.68093 | Esmeraldas | 48–33 | 10 | 43.100 | 6.70 (120) | 56.86 (1009) | 15.05 (2353) | 40.1 | 35.1 | 3.50 | 0.24 | 0.34 | N.D. | N.D. | – | – | – | – | – |
| 1063-25 | 73.57646 | 7.68093 | Rosablanca | 140–130 | 11 | 12.500 | 3.74 (95) | 16.33 (415) | 14.93 (2353) | 30.80 | 66.7 | 7.80 | 0.14 | 0.08 | N.D. | N.D. | – | – | – | – | – |
| Sonoro area, well-2, Middle Magdalena Valley Basin | | | | | | | | | | | | | | | |
| 1082-01 | 73.921 | 7.399 | Real | 11–5 | 20 | 27.900 | 8.30 (257) | 35.95 (1113) | 14.56 (2357) | 12.5 | 64.1 | 4.70 | 0.29 | 0.24 | N.D. | N.D. | – | – | – | – | – |
| 1082-12 | 73.92100 | 7.399 | Giron | 145–179 | 20 | 4.100 | 1.34 (66) | 5.45 (269) | 15.16 (2357) | 71.80 | 70.4 | 9.80 | 0.51 | 0.27 | N.D. | N.D. | – | – | – | – | – |
| Saltaren area, well-3, Upper Magdalena Valley Basin | | | | | | | | | | | | | | | |
| 474-64 | 75.03957 | 3.25254 | Real | 115–150 | 23 | 4.13 | 0.67 (56) | 3.54 (296) | 35.77 (4057) | 17.25 | 34.5 | 6.60 | 0.33 | 0.33 | N.D. | N.D. | – | – | – | – | – |
| 474-74 | 75.03957 | 3.25254 | Saldaña | 235–160 | 25 | 12.24 | 1.54 (115) | 10.01 (749) | 36.75 (4057) | 25.08 | 32 | 3.3 | 0.15 | 0.15 | N.D. | N.D. | – | – | – | – | – |

* Rho-S and Rho-I are the spontaneous and induced track density measured, respectively (×10^5 tracks cm^-2). NS and NI are the number of spontaneous and induced tracks counted for estimating RhoS and RhoI, respectively.

† Rho-D is the induced track density measured in the external mica detector attached to CN2 dosimetry glass (×10^5 tracks cm^-2). ND is the number of induced tracks counted in the mica for estimating RhoD.

χ² (%) is the chi-square probability (Galbraith 1981; Green 1981). Values greater than 5% are considered to pass this test and represent a single population of ages. Pooled (central) age reported for ages that pass (fail) the χ² test.

#Gr, Number of grains with tracks analyzed for each sample. Dpar, Major diameter of the solution cavity of a fission track.

#Length, Number of track lengths counted in the grains analyzed.

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Table 2. Apatite fission-track data from samples analysed with laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS)

| Sample code | Longitude (°W) | Latitude (°N) | Unit | Stratigraphic age (Ma) | # Gr | NS* | \(\Sigma (\text{PD})^\parallel (\text{cm}^2)\) | \(1\sigma \Sigma (\text{PD}) (\text{cm}^2)\) | \(\bar{c}_{\text{MS}}\) | \(1\sigma \bar{c}_{\text{MS}}\) | \(^{40}\text{Ca}^{39}\text{Ar}^{39}\text{Ar}\) | P(\(\chi^2\)) | Age (Ma) \(\pm 1\sigma\) error | \(D_{\text{par}}\) (μm) | SD (μm) | # | Length (μm) | Error (μm) | SD (mm) | # | Reference |
|-------------|----------------|--------------|------|------------------------|------|-----|------------------------|------------------------|--------|----------------|------------------------|------------------------|------------------------|------------------------|--------|------|------------------------|------------------------|--------|------|------------------------|------------------------|--------|------|------------------------|------------------------|--------|------|------------------------|------------------------|--------|------|------------------------|------------------------|--------|------|
| 1072-18     | 73.8852        | 6.3847       | Esmeraldas | 48–34 20              | 62   | 1.70E–05 6.41E–07 16.238 0.305 0.026 0.018 0.71 | 29.5 ± 3.9 1.76 0.14 | 62 | 11.28 0.37 1.66 | 21 This work |
| 1072-17     | 73.8647        | 6.3698       | Mugrosa    | 34–23 39              | 47   | 1.35E–05 2.46E–07 16.102 0.303 0.024 0.350 0.31 | 27.8 ± 4.1 2.38 0.57 | 88 | 11.9 0.27 2.23 | 69 This work |
| 1072-20     | 73.8937        | 6.3839       | Colorado   | 23–15 8              | 38   | 1.34E–06 9.02E–07 16.324 0.306 0.019 0.016 0.23 | 9.4 ± 4.7 1.45 0.84 | 13 | 11.96 0.56 1.26 | 6 This work |
| 1072-19     | 73.9012        | 6.3793       | Mugrosa    | 34–23 15              | 5    | 1.34E–06 9.02E–07 16.324 0.306 0.019 0.016 0.23 | 9.4 ± 4.7 1.45 0.84 | 13 | 11.96 0.56 1.26 | 6 This work |
| 1072-93     | 74.2601        | 5.9547       | Upper Mugrosa | 34–23 36              | 500  | 1.22E–04 3.28E–06 16.428 0.331 0.036 0.002 0.00 | 33.6 ± 1.7 1.76 0.20 | 118 | 11.41 0.16 1.91 | 152 Moreno et al. (this volume, in press) |
| 1072-94     | 74.2435        | 5.9438       | Upper Mugrosa | 34–23 39              | 495  | 1.55E–04 2.56E–06 16.426 0.333 0.033 0.002 0.00 | 36.6 ± 1.6 1.81 0.21 | 136 | 12.14 0.12 1.64 | 202 Moreno et al. (this volume, in press) |
| 1072-92     | 74.2853        | 5.9393       | Esmeraldas | 50–34 13              | 152  | 4.65E–05 2.78E–06 16.430 0.329 0.037 0.072 0.00 | 26.8 ± 2.3 1.57 0.15 | 38 | 10.62 0.3 1.83 | 37 Moreno et al. (this volume, in press) |
| 1072-91     | 74.3058        | 5.9425       | La Paz     | 56–50 36              | 451  | 1.31E–04 3.92E–06 16.430 0.329 0.038 0.003 0.00 | 28.2 ± 1.5 1.62 0.21 | 126 | 11.54 0.21 2.36 | 124 Moreno et al. (this volume, in press) |
| 1072-118    | 74.7668        | 5.1876       | Seca       | 59–70 10              | 21   | 5.32E–03 1.84E–07 16.413 0.348 0.321 0.055 0.00 | 30.1 ± 0.6 1.98 0.42 | 13 | 13.19 1.27 2.16 | 12 Moreno et al. (this volume, in press) |
| 1072-123    | 74.5477        | 5.0259       | Umir       | 83–65 32              | 24   | 1.43E–05 7.12E–07 11.467 0.248 0.017 0.006 0.99 | 9.6 ± 2.0 1.61 0.31 | 39 | 12.49 0.57 1.88 | 12 Moreno et al. (this volume, in press) |
| 1072-124    | 74.5207        | 5.0208       | Socotá     | 121–112 7              | 8    | 1.48E–05 2.11E–06 14.386 0.284 0.017 0.002 0.03 | 3.9 ± 1.4 1.67 0.15 | 8  | 12.76 0.81 1.82 | 6 Moreno et al. (this volume, in press) |
| 1072-125    | 74.4795        | 5.0798       | La Naveta  | 140–130 14             | 12   | 2.30E–05 1.98E–06 14.464 0.286 0.027 0.003 0.02 | 3.8 ± 1.1 1.52 0.23 | 15 | 14.27 0.46 1.44 | 11 Moreno et al. (this volume, in press) |
| 1072-126    | 74.4876        | 5.0805       | La Naveta  | 140–130 27             | 16   | 2.19E–05 2.30E–06 11.548 0.249 0.015 0.181 0.01 | 4.2 ± 1.1 1.44 0.21 | 31 | 11.86 0.68 2.25 | 12 Moreno et al. (this volume, in press) |
| 1072-127    | 74.4154        | 5.1182       | Trinchera  | 130–121 18            | 8    | 3.25E–06 3.20E–07 14.588 0.289 0.021 0.242 0.00 | 17.9 ± 6.4 1.42 0.23 | 20 | 12.44 1.89 2.68 | 3 This work |
| 1072-128    | 74.3801        | 5.1006       | Trinchera  | 130–121 8             | 7    | 6.42E–06 1.22E–06 11.397 0.249 0.016 0.003 0.14 | 4.8 ± 1.8 1.54 0.33 | 8  | 10.86 0.56 0.97 | 4 This work |

*Number of spontaneous fission tracks counted over area Ω.

| Sum of R*W, for all grains evaluated; R is \((238\text{U})/^{40}\text{Ca})\) for apatite grain i; W is the area over which NS and \(R_i\) are evaluated.

\(|c|^2\)-calibration factor based on the LA-ICP-MS of fission-track age standards.

| Background-corrected \(^{40}\text{Ca}\) (dimensionless).

| Background-corrected \((238\text{U})\) (dimensionless).

| \(\chi^2\) probability. Values greater than 5% are considered to pass this test and represent a single population of ages.

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Table 3. Zircon fission-track data from samples analysed with laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS)

| Sample code | Longitude ('W) | Latitude ('N) | Unit | Stratigraphic age (Ma) | # Gr | U (ppm) | Th (ppm) | Sm (ppm) | (NS) | 1σ ∑Rho | 1σ ∑Rho | P(χ²)‡ | ZFT age | ± 1σ | ζ§ | 1σ |
|-------------|----------------|---------------|------|------------------------|------|---------|---------|----------|------|----------|----------|---------|---------|-------|-----|-----|
| 1072-126    | 74.48764       | 5.08047       | La Naveta | 112–125                | 30   | 145.5307 | 9.23E + 01 | 2.01E + 01 | 2003.000 | 3.163E–05 | 2.167E–06 | 0.000E + 00 | 150.42 | 12.32 | 2.40 | 0.07 |
| 1072-115    | 73.36350       | 6.57161       | Giron    | 145–179                | 30   | 114.3194 | 9.09E + 01 | 2.31E + 01 | 2151.000 | 3.261E–05 | 1.097E–06 | 0.000E + 00 | 215.34 | 13.88 | 2.40 | 0.07 |
| 1072-112    | 73.46631       | 6.30631       | Giron    | 145–179                | 30   | 112.6829 | 8.01E + 01 | 2.85E + 01 | 1821.000 | 1.742E–05 | 1.063E–06 | 0.000E + 00 | 246.51 | 18.6  | 2.40 | 0.07 |
| 1072-101    | 74.02161       | 5.83603       | Arcabuco | 100–145                | 21   | 272.62 | 2.21E + 02 | 2.09E + 01 | 654.000 | 3.311E–05 | 1.806E–06 | 8.000E – 03 | 47.30  | 3.8   | 2.40 | 0.07 |

*Number of spontaneous fission tracks counted.
†Density of spontaneous fission tracks counted (tracks cm⁻²).
‡χ² probability. Values greater than 5% are considered to pass this test and represent a single population of ages.
§ζ-calibration factor based on the LA-ICP-MS of fission-track age standards.
paths obtained from inverse modelling allow initial cooling to occur as early as the Late Cretaceous. The upper Miocene Real Formation (1082-01), above the unconformity, has a detrital AFT age of $64.1 \pm 4.7$ Ma. Inverse modelling of these data resulted in a time–temperature path that shows rapid cooling in the source area during the Paleocene and slower cooling thereafter.

**Inversion timing in the Middle Magdalena Valley Basin**

In the Cagüi area, AFT and $R_o$ results from the Lower Cretaceous Rosablanca Formation document that the onset of cooling related to inversion and thrusting can be as early as the Late Cretaceous ($70–75$ Ma). This corroborates previous age determinations for initial rift inversion in the MMV Basin (Parra et al. 2012). AFT ages are partially reset above the unconformity, as documented by depositional and AFT ages, which overlap in the Esmeraldas and Colorado formations, and by a $R_o$ value of 0.53% equivalent to a maximum burial temperature of approximately $91$ °C. Based on the contrasting style of cooling of these units, we attribute a source in the Central Cordillera for the upper Eocene Esmeraldas Formation and in the Eastern Cordillera for the lower Miocene Colorado Formation, which is in agreement with determinations based on sandstone and conglomerate petrology (Caballero et al. 2010).

The cluster of ZHe ages at around $60$ Ma, in the upper Eocene Esmeraldas Formation in the Cagüi area (Fig. 7), suggests a source in the Central Cordillera. A broader age distribution in Oligocene and lower Miocene units would have resulted from erosion of the upper crustal levels composed of strata of Cenozoic and Late Cretaceous age in the Eastern Cordillera. These levels contain a wide distribution of unreset ZHe ages (Horton et al. 2010a, b; Bande et al. 2012; Saylor et al. 2012). The tighter distribution observed in the upper Miocene Real Group suggests the erosion and denudation of deeper crustal levels with reset ZHe ages in the Eastern Cordillera, in agreement with sandstone petrography and U–Pb data available (Caballero et al. 2010; Nie et al. 2010).

Adjacent to the Central Cordillera, the inverse modelling of track lengths and ages from the Jurassic Giron Formation in the Sonero well is consistent with a Late Cretaceous onset of cooling related to inversion and thrusting, as our bedrock data show. Cooling of this age has also been widely documented for basement rocks from the Central Cordillera (Gómez et al. 2003; Villagómez 2010). Finally, rapid Paleocene cooling followed by slower Eocene and Oligocene cooling for the source area of the Real Formation is consistent with the time–temperature histories of the Central Cordillera.

### Table 4. Vitrinite reflectance ($R_o$) data

| Sample code | Unit       | Longitude (°W) | Latitude (°N) | Random† $R_o$ (%) | Maximum‡ $R_o$ (%) | Temperature§ (°C) | Source                  |
|-------------|------------|----------------|---------------|------------------|-------------------|------------------|-------------------------|
| Ro210110-27 | Lower La Paz | 73.85824       | 6.34495       | 0.63              | 0.66              | 109              | Moreno et al. (this volume, in press) |

Guaduas area

- 1072-123: Unir 74.54424 5.01997 1.24 ± 0.29 1.40 ± 0.25 166 Moreno et al. (this volume, in press)
- 10GU65: Socota 74.36832 5.03310 4.53 ± 0.57 5.38 ± 0.59 311 Moreno et al. (this volume, in press)
- 10GU48: Trincheras 74.45371 5.10288 1.13 ± 0.15 1.27 ± 0.08 160 Moreno et al. (this volume, in press)
- 10GU57: Trincheras 74.38134 5.10682 1.72 ± 0.35 1.98 ± 0.33 192 Moreno et al. (this volume, in press)
- 10GU46: Naveta 74.49943 5.11421 1.09 ± 0.17 1.22 ± 0.11 157 Moreno et al. (this volume, in press)

Rio Ermitaño–Penón Arcabuco anticlines

- 10BY07: Tablazo 73.58989 5.90954 >3.0 >3.5 243 Mora et al. (2013)
- 10BY10A: Paja 73.45152 5.76631 >3.0 >3.5 243 Mora et al. (2013)
- 10BY35: Paja 73.70881 5.99741 3.4 ± 0.3 4.0 ± 0.3 263 Mora et al. (2013)
- 10BY34: Paja 73.73049 6.03491 3.8 ± 0.2 4.5 ± 0.2 290 Mora et al. (2013)

Cagüi area, well-1

- GC1063-20: Colorado 73.5765 7.6809 – 0.43 ± 0.052 74 This study
- GC1063-21: Esmeraldas 73.5765 7.6809 – 0.53 ± 0.073 91 This study
- GC1063-25 ST: Rosablanca 73.5765 7.6809 – 1.23 ± 0.07 158 This study

*After Burnham & Sweeney (1989).
†$R_o$ value calculated by thermal alteration index of the organic matter.
‡$R_o$ value obtained by measurements of vitrinite reflectance.
and, thus, document the Miocene denudation in this range and sediment transport to the eastern MMV Basin.

**Thermochronology data in the western flank of the Eastern Cordillera**

New data in the northernmost section studied, at approximately 6° 50’N at the western margin of the Eastern Cordillera, consist of two new zircon fission track (ZFT) ages from the Jurassic Giron Formation samples 1072-112 and 1072-115, exposed along the core of the southern Los Cobardes Anticline (p7 and p8 in Fig. 3). ZFT ages are 246 ± 18 and 215 ± 14 Ma (Table 3), respectively.

Further to the SW, in the Opon Syncline at about 6° 25’N (see Fig. 3 for the location) along the footwall of the La Salina thrust, the upper Eocene Esmeraldas (1072-18), Oligocene Mugrosa (1072-17) and lower Miocene Colorado (1072-19 and 1072-20) formations have AFT ages ranging from 9.4 ± 4.7 to 41.9 ± 2.4 Ma, which are approximately equal to or older than the stratigraphic ages (Table 2). This pattern and the $R_o$ value of 0.66% from the underlying lower Eocene La Paz Formation, corresponding to a temperature of about 109 °C (Table 4), illustrate that the samples are partially reset and host information on the cooling of the source areas. The inverse modeling of AFT data reveals a rapid Paleocene–early Eocene cooling for the source area of the Esmeraldas Formation, and slower Eocene–Oligocene cooling for the source areas of the Mugrosa and Colorado formations.
Further to the south, at approximately 6°8'N in the Rio Ermitaño Syncline (see Fig. 3 for the location), upper Eocene–Miocene units (samples 1072-91, 1072-92, 1072-93 and 1072-94) exhibit a similar pattern of AFT ages in the range of 28.2 +1.5–36.6 +1.6 Ma, approximately overlapping with depositional ages (Table 2). Inverse modelling of track lengths and ages results in time–temperature paths consistent with rapid cooling during the Paleocene and early Eocene for the source area of the La Paz Formation, rapid cooling during middle Eocene in the source area of the Esmeraldas Formation, and slower cooling during the Eocene and Oligocene in the source area of the Mugrosa and Colorado formations. Further to the east along the same latitude, in the El Peñón and Arcabuco anticlines (Fig. 3), a zircon (U–Th)/He analysis of 10 samples from the Upper Jurassic and the Lower Cretaceous units yields ZHe ages of about 15–19 Ma in units exposed at the core of the El Peñón Anticline, and approximately 30–31 Ma at the core of the Arcabuco Anticline (j, k and o, p in Fig. 3). Upper Cretaceous units exposed along the limbs of these folds yield older ages, in the range of about 54–55 Ma for the El Peñón Anticline and approximately 39–54 Ma for the Arcabuco Anticline (l, m, n and q, r, s in Fig. 3). In addition, a ZFT age of 47.3 ± 3.8 Ma from the Upper Jurassic sandstones of the units in the core of the El Peñón Anticline (1072–101, t in Fig. 3; Table 3) and a $R_o$ value of 3.5% (temperature c. 245 °C) for the Lower Cretaceous units were obtained.

Further to the south, at about 5°N in the eastern flank of the Guaduas Syncline, one sample from the middle–upper Paleocene Hoyo Ñ Formation (1072-117) and one from the Maastrichtian–lower Paleocene Seca Formation (1072-118) yielded AFT ages of 30.1 +6.6 and 8.5 ± 0.6 Ma, respectively (u and v in Fig. 3; Table 3). Reported $R_o$ values are between 0.50 and 0.64% for these units (Gómez 2001), and 0.43–0.49% for the Maastrichtian Umir Formation (Moretti et al. 2010). A new ZFT analysis in sandstones of the Aptian La Naveta Formation (1072–126) (w in Fig. 3; Table 3) yields a discordant partially reset age of 150.42 ± 12.3 Ma.

Fig. 6. Distribution of ZHe ages of the Cantagallo Formation (dark grey) and the Real Group (light grey) in a well of the Cocuyo area (see the location in Fig. 3). A cluster of ZHe ages between 60 and 100 Ma in the middle Eocene Cantagallo Formation is enlarged in the inset. Unreset cooling ages of 60–90 Ma resemble that of the Central Cordillera following recent thermochronometrical work in this area after Villagómez (2010).

Further to the south, at approximately 6°N in the Rio Ermitaño Syncline (see Fig. 3 for the location), upper Eocene–Miocene units (samples 1072-91, 1072-92, 1072-93 and 1072-94) exhibit a similar pattern of AFT ages in the range of 28.2 ± 1.5–36.6 ± 1.6 Ma, approximately overlapping with depositional ages (Table 2). Inverse modelling of track lengths and ages results in time–temperature paths consistent with rapid cooling during the Paleocene and early Eocene for the source area of the La Paz Formation, rapid cooling during middle Eocene in the source area of the Esmeraldas Formation, and slower cooling during the Eocene and Oligocene in the source area of the Mugrosa and Colorado formations. Further to the east along the same latitude, in the El Peñón and Arcabuco anticlines (Fig. 3), a zircon (U–Th)/He analysis of 10 samples from the Upper Jurassic and the Lower Cretaceous units yields ZHe ages of about 15–19 Ma in units exposed at the core of the El Peñón Anticline, and approximately 30–31 Ma at the core of the Arcabuco Anticline (j, k and o, p in Fig. 3). Upper Cretaceous units exposed along the limbs of these folds yield older ages, in the range of about 54–55 Ma for the El Peñón Anticline and approximately 39–54 Ma for the Arcabuco Anticline (l, m, n and q, r, s in Fig. 3). In addition, a ZFT age of 47.3 ± 3.8 Ma from the Upper Jurassic sandstones of the units in the core of the El Peñón Anticline (1072–101, t in Fig. 3; Table 3) and a $R_o$ value of 3.5% (temperature c. 245 °C) for the Lower Cretaceous units were obtained.

Further to the south, at about 5°N in the eastern flank of the Guaduas Syncline, one sample from the middle–upper Paleocene Hoyo Ñ Formation (1072-117) and one from the Maastrichtian–lower Paleocene Seca Formation (1072-118) yielded AFT ages of 30.1 ± 6.6 and 8.5 ± 0.6 Ma, respectively (u and v in Fig. 3; Table 3). Reported $R_o$ values are between 0.50 and 0.64% for these units (Gómez 2001), and 0.43–0.49% for the Maastrichtian Umir Formation (Moretti et al. 2010). A new ZFT analysis in sandstones of the Aptian La Naveta Formation (1072–126) (w in Fig. 3; Table 3) yields a discordant partially reset age of 150.42 ± 12.3 Ma.

Further to the south, at approximately 6°N in the Rio Ermitaño Syncline (see Fig. 3 for the location), upper Eocene–Miocene units (samples 1072-91, 1072-92, 1072-93 and 1072-94) exhibit a similar pattern of AFT ages in the range of 28.2 ± 1.5–36.6 ± 1.6 Ma, approximately overlapping with depositional ages (Table 2). Inverse modelling of track lengths and ages results in time–temperature paths consistent with rapid cooling during the Paleocene and early Eocene for the source area of the La Paz Formation, rapid cooling during middle Eocene in the source area of the Esmeraldas Formation, and slower cooling during the Eocene and Oligocene in the source area of the Mugrosa and Colorado formations. Further to the east along the same latitude, in the El Peñón and Arcabuco anticlines (Fig. 3), a zircon (U–Th)/He analysis of 10 samples from the Upper Jurassic and the Lower Cretaceous units yields ZHe ages of about 15–19 Ma in units exposed at the core of the El Peñón Anticline, and approximately 30–31 Ma at the core of the Arcabuco Anticline (j, k and o, p in Fig. 3). Upper Cretaceous units exposed along the limbs of these folds yield older ages, in the range of about 54–55 Ma for the El Peñón Anticline and approximately 39–54 Ma for the Arcabuco Anticline (l, m, n and q, r, s in Fig. 3). In addition, a ZFT age of 47.3 ± 3.8 Ma from the Upper Jurassic sandstones of the units in the core of the El Peñón Anticline (1072–101, t in Fig. 3; Table 3) and a $R_o$ value of 3.5% (temperature c. 245 °C) for the Lower Cretaceous units were obtained.

Further to the south, at about 5°N in the eastern flank of the Guaduas Syncline, one sample from the middle–upper Paleocene Hoyo Ñ Formation (1072-117) and one from the Maastrichtian–lower Paleocene Seca Formation (1072-118) yielded AFT ages of 30.1 ± 6.6 and 8.5 ± 0.6 Ma, respectively (u and v in Fig. 3; Table 3). Reported $R_o$ values are between 0.50 and 0.64% for these units (Gómez 2001), and 0.43–0.49% for the Maastrichtian Umir Formation (Moretti et al. 2010). A new ZFT analysis in sandstones of the Aptian La Naveta Formation (1072–126) (w in Fig. 3; Table 3) yields a discordant partially reset age of 150.42 ± 12.3 Ma.

Fig. 7. Distribution of (a) ZHe ages and (b) lag times for Cenozoic units in the Caguüí area. Lag time is the difference between the cooling age and the depositional age, indicated with oblique dotted lines. A broad spectrum of Late Cretaceous–Paleocene ZHe ages in middle–upper Eocene strata (black) indicates provenance from the Central Cordillera. A wider distribution of ZHe ages in Oligocene samples (dark grey) suggests denudation of supracrustal strata from the Eastern Cordillera, which include unreset ZHe ages. A narrow distribution of ages younger than 40 Ma in lower Miocene samples (medium grey) and middle–upper Miocene (light grey) indicates the erosion of ZHe-reset rocks from the Eastern Cordillera (see the location in Fig. 3).
Further to the east along this latitude, five reset AFT ages in Cretaceous units from the Villeta Anticline range from 3.8 ± 1.1 to 9.6 ± 2.0 Ma and exhibit a positive correlation with respect to the relative stratigraphic position, with younger units exhibiting older ages (Fig. 8). Likewise along this section, the distribution of 36 ZHe ages in Cretaceous units with respect to the relative stratigraphic position (samples 1072-123, 1072-124, 1072-125, 1072-126, 1072-127, 1072-128, 1072-130, 1072-131 and 1072-132) reveals an up-section transition from a clustering of Oligocene–Miocene ZHe ages in Lower Cretaceous units to a spread distribution including unreset Palaeozoic ZHe ages in Upper Cretaceous units (Fig. 8). Here, the Upper Cretaceous Umir Formation (1072-123) has a $R_o$ value of 1.4% (Table 4), corresponding to a maximum burial temperature of 166 °C.

### Uplift timing along the western flank of the Eastern Cordillera

Palaeozoic ZFT ages obtained in samples from the Los Cobardes Anticline in the NW sector of the Eastern Cordillera are unreset ages that corroborate regional considerations based on published palaeothermometrical data (Parra et al. 2012) and do not add further information to the exhumation history documented for this area.

Further to the south, AFT and $R_o$ data from the Opo´n and the Rio Ermitaño synclines (Fig. 3) indicate that Cenozoic samples are partially reset. We attribute rapid Paleocene–early Eocene cooling in middle–upper Eocene samples 1072-18, 1072-91 and 1072-92 to a provenance from the Central Cordillera, based on the results of our bedrock thermochronology and available thermochronometrical data (Villagómez 2010). Likewise, slower palaeogene cooling found in thermal models of the detrital Oligocene and middle Miocene samples (1072-17, 1072-19, 1072-20, 1072-93 and 1072-94) are reminiscent of cooling paths of the Eastern Cordillera (Parra et al. 2012), and thus we suggest that the source area for Oligocene–middle Miocene samples was probably located there, as other provenance studies also document (Caballero et al. 2010; Nie et al. 2010, 2012; Saylor et al. 2011).

Maximum burial temperatures of approximately 245 °C for the Lower Cretaceous Tablazo Formation in the El Peñón and Arcabuco anticlines (Fig. 3; Table 4) indicate that ZHe ages from Jurassic and Lower Cretaceous units in this area are reset. The maximum ZHe ages of 55–51 Ma from the flanks of the El Peñón and Arcabuco anticlines, thus, indicate that these structures were already exhumed by the Late Paleocene. This result is further confirmed by a reset ZFT age of around 48 Ma in Hauterivian sandstones, which indicates an approximately 8–10 km-scale burial of this unit needed to reset the ZFT system. The discordant, approximately 150 Ma ZFT age in sandstones of Aptian age (1072-126) reflects that this age is not reset, and that the base of the exhumed ZFT partial annealing zone in El Peñón lies between the Hauterivian and Aptian units.

Further to the south, in the Guaduas Syncline (Fig. 3), in spite of AFT ages from the middle–upper Paleocene Hoyo´n (1072-117) and Maastrichtian–lower Paleocene Seca (1072-118) being younger than the stratigraphic age, the $R_o$ values reported, equivalent to 77–105 °C, suggest that these samples never attained high enough temperatures to reset the AFT system and that these ages are, thus, partially reset. The inverse modelling of these two samples, with a $R_o$ of 0.6%, suggests that the exhumation due to slip along the Cambao Thrust may have commenced between 20 and 10 Ma. Further to the east at this latitude, in the Villeta Anticline, the passage from a clustering of Oligocene–Miocene ZHe ages in the Lower Cretaceous units to a spread distribution of unreset Palaeozoic ZHe ages in the Upper Cretaceous units suggests that the base of the exhumed ZHe partial retention zone is roughly located within the Albian units, between samples 1072-130 and 1072-131. The $R_o$ value of 1.4% (temperature $c.$ 166 °C) from the uppermost Cretaceous Umir Formation (1072-123: Table 4) agrees with this unit having been exhumed from within the ZHe partial retention zone (Fig. 8). ZHe ages of 21–41 Ma below the base of the partial retention zone

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**Fig. 8.** Distribution of AFT ages (black circles) and ZHe ages (grey circles) with respect to the relative stratigraphic position in the Villeta Anticline. Stratigraphic ages of samples are represented by dark grey triangles. The lower limit of the ZHe partial retention zone occurs where ZHe ages in all measured aliquots are younger than the stratigraphic age, and is defined between samples 1072-130 and 1072-131. An age of approximately 41–21 Ma in younger (i.e. shallower) reset samples is thus suggested as the age of the onset of exhumation in the Villeta Anticline.

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provide an approximate age for the onset of exhumation of the Villeta Anticline. This is in agreement with published zft ages from lower Cretaceous strata from the core of the Villeta Anticline, which have reset ages of 19.4 ± 1.1 and 24 ± 1.4 Ma (Parra et al. 2009).

**Thermochronology data in northern Upper Magdalena Valley**

We present AFT data from two subsurface samples of the Jurassic volcanioclastic Saldaña Formation obtained from drill cuttings of the Saltarén well located in the northern Upper Magdalena Valley Basin at about 3°15′N (Fig. 1). Both samples yield concordant AFT ages of 34.5 ± 6.6 and 32.0 ± 3.3 Ma, with long tracks (MTL values of 14.55 ± 1.48 and 13.20 ± 1.41 µm, respectively: Table 1). Thermal modelling based on a sufficient amount of track lengths (125 and 46: Table 1) shows that cooling must have commenced before 40 Ma, indicating that the onset of uplift of the Nagaima and El Patá archs took place by the middle-late Eocene. These data, as well as the onlap of Oligocene units southwards onto El Patá and Nagaima basement highs, constitute the evidence that the MMV Basin was a closed basin after Eocene time.

**U–Pb geochronology data**

Characterization of detrital zircon U–Pb populations in the Guaduas Syncline is based on data from 13 samples ranging in age from Late Cretaceous to middle Miocene (Fig. 9). U–Pb ages in Cenomanian–Campanian units (samples 1072-131 and 1072-132) comprise mainly Proterozoic age populations of 1300–1850 Ma and older age peaks. In contrast, the upper Maastrichtian–Miocene units show major age peaks younger than 200 Ma, with a Grenvillian age population of 1100–1200 Ma appearing in the middle Eocene sample (HM-528) (Fig. 9a).

Unlike in the Guaduas Syncline, Maastrichtian units in the Opón Syncline have only Precambrian age peaks of 1300–1850 Ma and even older populations, albeit with a minimal proportion (less than 3%) of zircons younger than 100 Ma (samples 1072-28 and 1072-14). In this syncline, the first appearance of a statistically significant zircon population younger than 150 Ma occurs in the Paleocene sample 1072-31. Upsection, all Paleocene–Eocene units exhibit major age peaks younger than 150 Ma, as well as a population of Permian and Triassic ages of between 200 and 300 Ma. Oligocene–middle Miocene units in the La Cira oil field (Fig. 3) show age peaks of Permian–Triassic age (200–300 Ma: Fig. 10c). Here all the units include Grenvillian (900–1200 Ma) age peaks and a Proterozoic population older than 1500 Ma, and only the upper Miocene Real Formation includes a population of detrital zircons younger than 150 Ma.

Further to the SW of the Nuevo Mundo Syncline, the Oligocene–middle Miocene units in the La Cira Oil field (Fig. 3) show age peaks of Permian–Triassic age (200–300 Ma: Fig. 10c). Here all the units include Grenvillian (900–1200 Ma) age peaks and a Proterozoic population older than 1500 Ma, and only the upper Miocene Real Formation shows age peaks younger than 300 Ma and only minor age peaks younger than 100 Ma (Fig. 10d).

**Timing of deformation and sediment dispersal**

The new bedrock AFT data from the Central Cordillera and the Sonero well, as well as the detrital ZHe data in Cenozoic units from the MMV and the western Eastern Cordillera, document cooling and exhumation of the Central Cordillera between about 90 and 60 Ma. In addition, thermal modelling corroborates recent estimates of rapid Late Cretaceous–Paleocene and slower Neogene cooling in the Central Cordillera (Villagómez 2010).

Modelling of AFT and R, data from samples beneath the sub-Eocene unconformity in the MMV Basin constrains the onset of inversion of the Mesozoic rift basin to 60–70 Ma. These ages are almost synchronous with those of the initial exhumation in the NW flank of the Eastern Cordillera along the Los Cobardes Anticline and the Mesas Region (Parra et al. 2012).
Our detrital zircon U–Pb data refine previous estimates of the onset of erosion of the Central Cordillera (Gómez et al. 2003; Nie et al. 2010; Saylor et al. 2011). They provide a first regional account of the spatial distribution of sediments delivered during this denudation event (Figs 11 & 12). The spatial distribution of samples with distinct detrital zircon U–Pb signatures in coeval strata reveals the patterns of sediment dispersal. The Upper Cretaceous rocks with zircons unambiguously assigned to sources in the Central Cordillera, defined here as those containing at least 3% of zircons younger than 180 Ma, are restricted to the Guaduas Syncline in the southern MMV Basin (Fig. 11a). A location closer to the Central Cordillera mountain front, favoured by the oblique NNE-striking trend of the

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**Fig. 9.** Normalized detrital zircon U–Pb ages of Late Cretaceous and Cenozoic units of the synclines in the SW flank of Eastern Cordillera thrust belt. (a) Guaduas Syncline. (b) Opón Syncline. (c) Río Ermitaño Syncline.
Eastern Cordillera, or an earlier uplift of the Central Cordillera in the south may have controlled such localized appearance.

Early Paleocene units record the widespread appearance of detrital zircons derived from the Central Cordillera in all but one of the localities sampled along the western flank of the Eastern Cordillera (Fig. 11b). In the eastern limb of the Nuevo Mundo Syncline, the strata of the lower Lisama Formation do not show the distinct population of young zircons derived from the Central Cordillera. We attribute this absence to the proximity of the sampled section to the Los Cobardes Anticline and the Mesas Region to the NE, where thermochronometrical data indicate contemporaneous uplift (Parra et al. 2012). Such localized uplift in the

Fig. 10. Normalized detrital zircon U–Pb ages Cenozoic units of the Nuevo Mundo Syncline and northern areas of the Middle Magdalena Valley Basin. (a) west limb of the Nuevo Mundo Syncline; (b) east limb of the Nuevo Mundo Syncline (from Nie et al. 2010); (c) Cagüi area; (d) La Cira area.
western sector of the Eastern Cordillera could have acted as a local source for adjacent Paleocene deposits, preventing magmatic-arc-derived zircons from reaching this part of the basin (Fig. 12). A NNW palaeoflow direction in the Lisama Formation (Moreno et al. 2011) is consistent with this interpretation.

A second pattern that emerges in Paleocene strata is the northwards decrease in the abundance of magmatic-arc zircons along the MMV Basin (Fig. 11b). This pattern, persistent in strata deposited further east in the axial Eastern Cordillera, is suggestive of a main source of sediments located in the Central Cordillera to the south. It also points to the existence of an axial, SW–NE-trending, sediment-dispersal pattern that would be favoured by the uplift of the Los Cobardes and El Peñon anticlines to the north, in the western Eastern Cordillera and the palaeo-highs within the MMV Basin exposing Upper Cretaceous rocks (Fig. 11b, c).

In agreement with such a sediment-dispersal pattern, the sedimentary depositional environments change from proximal to distal in the NE direction. In the western limb of the Guaduas Syncline, an eastwards-thinning package of alluvial fan conglomerates of the lower and middle Hoyón Formation has an ENE flow direction, and towards the eastern limb of the syncline the unit thins and interfingers with floodplain mudstones and sandstones of the Seca Formation (Gómez et al. 2003; Bayona et al. 2013). Further to the north, in the Opón and the Nuevo Mundo synclines, fluvial environments with mainly floodplain mudstones and sandstones in the lower Lisama Formation transitionally change to coastal plain facies of the upper Lisama Formation. Continuing further to the NE, the Lisama Formation passes transitionally to the coastal plain deposits with local marine influence (Moreno et al. 2011) of the Barco and Los Cuervos formations in the Catatumbo Basin.

![Fig. 11. Map distribution of analysed detrital zircon U–Pb samples from Late Cretaceous–Late Miocene strata in the Middle Magdalena Valley Basin and the western flank of the Eastern Cordillera. Numbers indicate the percentage of grains with ages younger than 150 Ma, which are assigned to sources in the Central Cordillera. An internally drained basin, separated from the main foreland basin, was configured between the Oligocene and middle Miocene in the MMV Basin.](image-url)
In spite of the active deformation, the Paleocene pattern of facies and sediment distribution in the basin persists until early-middle Eocene, when deposition occurred in a more restricted, highly confined alluvial valley, which had already been formed in the Paleocene (Fig. 11d). A westwards-thinning, wedge-like geometry of conglomerate facies of the La Paz Formation (Caballero et al. 2010) in the Nuevo Mundo Syncline and the upper Hoyon Formation in the Guaduas Syncline (Gómez et al. 2003) suggests that tectonic activity along the eastern front of the Central Cordillera and western flank of the Eastern Cordillera, respectively, was very active. As indicated by our new thermochronological data, the onset of the exhumation of the western flank of the Eastern Cordillera is diachronous, with younger ages towards the south, being early Eocene (c. 54–39 Ma) in the El Peñon and Arcabuco anticlines, and late Eocene–Oligocene (41–21 Ma) in the Villeta Anticlinorium to the south. Our data also provide an estimate of between 20 and 10 Ma for the westwards advance of deformation from the Eastern Cordillera into the MMV through the activation of the Cambao Fault.

The onlap of mildly folded post-middle Eocene strata onto a thrust belt across the MMV (Fig. 5) (see also fig. 2 in Parra et al. 2012) suggests that the tectonic activity during the late Eocene was less severe, and the basin broadened, prograded and covered in onlap the LKCU of the MMV Basin. The units deposited in this epoch are the San Juan de Rio Seco Formation in the Guaduas Syncline (Gómez et al. 2003; Bayona et al. 2013) and the Esmeraldas Formation in the Nuevo...
Mundo Syncline (Caballero 2012), where the accumulation of the Los Corros fossil horizon with organic fine-grained facies indicates a lacustrine environment (Fig. 11e). During the late Eocene, the Santander Massif became a new source of sediment and a barrier to the NE-directed fluvial transport of sediment (Caballero et al. 2010). In this way, a possible outlet of the ancestral Magdalena River towards the east or a closed basin would have resulted from the simultaneous uplift of the Central Cordillera, Eastern Cordillera and the Santander Massif during late Eocene (Fig. 11e).

In Oligocene and early Miocene time, the distribution of zircon U–Pb ages, the thermochronological constraints and the distribution of facies (Caballero et al. 2010) indicate that the Magdalena Valley Basin was an internally drained basin (Fig. 11f, g). AFT and ZHe data document ongoing uplift of the Santander Massif and the western flank of the Eastern Cordillera. Oligocene and Miocene units onlap the El Patá and Natagaima highs in the southern Magdalena Valley (Fig. 5b). The Oligocene Mugrosa and early Miocene Colorado formations in the northern MMV Basin have facies associations containing gypsum layers, calccrete palaeosoils and certain fossil horizons like the Mugrosa and La Cira, which indicate deposition under restricted circulation and arid conditions (Caballero 2010). Similar facies occur in the Upper Magdalena Valley (e. 3°40′N). There, the Barsaloza Formation contains abundant gypsum layers, and the Santa Teresa Formation includes several lacustrine shell fossil horizons indicative of restricted and arid conditions (Acosta et al. 2002). Such sedimentological observations and seismic stratigraphic patterns suggest that the Magdalena Valley Basin may have had a configuration similar to that of an internally drained basin.

Discussion

In this section we analyse and compare the role of each factor controlling the preferential abandonment or reactivation of faults. The factors include the stress orientation with respect to the pre-existing structural grain, the friction and cohesion along the faults to be inverted, and syn-orogenic erosion and deposition.

The role of stress orientation

It has been suggested that during the Paleocene–early Eocene time, the NW border of South America had a dominant east–west to WSW–ENE compressive stress field (Cortés et al. 2005; Mora et al. 2010b). The normal fault strikes of the Mesozoic rift system (San Lucas and western sector of the Magdalena–Tablazo) are north–south to NNW–SSE and SW–NE (Fig. 4). The north–south to NNW–SSE strikes and the $\delta_t$ stress orientation are nearly perpendicular. Andersonian laws of faulting suggest that it is harder to invert in pure compression than in transpression (Lowell 1995). The oblique configuration between the SW–NE fault system and the WSW–ENE stress direction were prone to inversion in transpression, as is common in other regions such as the Lomas de Olmedo Region of the Salta Province in Argentina (Grier et al. 1991; Comínguez & Ramos 1995).

After the early Eocene, the tectonics of NW South America were characterized by a compressive stress field with NW–SE to WNW–ESE-trending $\delta_t$ (Colmenares & Zoback 2003; Cortés et al. 2005; Mora et al. 2010b; Tesón et al. 2013). This $\delta_t$ stress orientation has been almost perpendicular to the main NE–SW trend of faults and folds in the Eastern Cordillera, and, thus, pure contractional strain should have been in place during the inversion of the main Mesozoic graben of the Magdalena Tablazo (Dengo & Covey 1993; Cooper et al. 1995; Mora, A. et al. 2009).

From the above discussion we can see that, if differential reactivation were conditioned only by the orientation of the faults, NW–SE faults would have been active during very distinct phases in comparison to the other faults (e.g. north–south). However, this is not the case, as it can be deduced from Figure 4. Therefore, other factors for differential reactivation should be analysed.

The western half of the basin, north of about 6°N, consisted of several half-grabens limited by short segmented faults in contrast to the eastern half, which is constituted by longer, less segmented faults. It has been observed that larger or longer faults have more displacement on them than smaller or shorter faults. The maximum displacement, $D$, of an inverted fault has a linear relationship to the fault-trace length, $L$, following the relation $D = cL^n$, where $c$ is a constant, and $n$ is between 1 and 1.5 (Watterson 1986; Walsh & Watterson 1988; Cowie & Scholtz 1992). According to sand-box modelling for normal listric faults, which are later inverted, the relationship between displacement and length ($d/L$) for inversion is consistently lower than that for extension (McClay 1995). The above results give an advantage to longer, less segmented faults, which could accommodate more deformation than shorter faults. For example, the La Salina Fault was originally one of the master bounding faults of the Early Cretaceous depocentre (Sarmiento-Rojas 2001, 2006; Mora et al. 2010a; Tesón et al. 2013). As a contractional structure, it has one of the largest displacements in the MMV Basin and a length of approximately 180 km. An
analogue example towards the south is the Bituima Fault, which is about 120 km long (Moretti et al. 2010) (Fig. 3).

The role of syn-orogenic erosion and deposition

During the early Paleocene, thermochronology and provenance data support the existence of topography in the Los Cobardes Anticline, which was enough to isolate the MMV Basin from the main foreland basin to the east (Fig. 12b).

From the early–middle Eocene onwards, the provenance data and the eastwards sediment thickening indicate a rapid generation of accommodation space towards the eastern margin of the MMV Basin. This space could be generated by a combination of eastwards tilting of the uplifting Central Cordillera and the tectonic loading driven by the uplift of the western flank of the Eastern Cordillera (Fig. 12c).

The sediment wedge deposited at this time could also generate a sedimentary load contributing to the total load and foreland construction towards the western flank of the Eastern Cordillera. The activity termination of short, east-verging inverted faults and the survival of the west-verging system (e.g. the La Salina Fault) cutting through the unconformity is the most important reason for the isolation of the MMV Basin, which occurred at the beginning of the Oligocene.

Role of friction and cohesion

For a fault to be reactivated, the total stress exerted from the advancing orogen must overcome the frictional resistance to sliding. The friction between the hanging wall and the footwall along a fault plane depends on the normal component of the overburden weight loading the fault plane and the pore fluid pressure. When an extensional regime passes to a compressional regime, the compression decreases the volume of the rock mass, causing the fluid expulsion from the existing pore space. If fluids cannot escape, the pore fluid pressure increases (Hubbert & Rubey 1959; Sibson 1995; Hilley et al. 2005). The increased pressure of entrapped fluids acts against the overburden weight loading the fault plane. However, we could not prove the role of the pore pressure because we do not have data on this phenomenon for the San Lucas and Magdalena Tablazo sub-basins.

Abandonment: reactivation and evolution of a hinterland basin

The abandonment of deformation in the San Lucas Graben and part of the Magdalena Graben was a consequence of several factors. The segmented and shorter faults in the graben allowed only limited accommodation of deformation. The decreasing tectonic rates by the end of the early Eocene, coeval with a high deposition rate over the trust wedge during the middle Eocene, imposed high values of normal stress over the fault planes. This blocked the activity of shorter faults and led to the advantage of the westernmost longer and fully linked faults of the La Salina system. This pattern resulted in tectonic inversion of the Eastern Cordillera and thin-skinned deformation along the western foothills adjacent to the MMV Basin (Fig. 12).

Conclusions

Subsurface data presented here document the existence of a buried thrust belt under the present-day MMV Basin. It is a paradox that most of the contractional deformation has ceased to be accommodated along the MMV Basin since the middle Eocene. We hypothesize that sediment accumulation rates in the MMV Basin must have surpassed the tectonic uplift rates so that faults became progressively buried. In contrast, protracted deformation along the western margin of the Eastern Cordillera resulted in Cenozoic exhumation of strata as old as Jurassic.

The seismic profiles and maps illustrate the inversion of half-grabens, the abandonment of short, east-verging inverted faults and the subsequent prevalence of the west-vergent La Salina Fault system cutting through the unconformity (Fig. 4). What conceivably seems to have exerted a dominant control is a longer, more rectilinear trace of the La Salina Fault with respect to the shorter, more segmented faults of the MMV Basin.

The progressive westwards onlap of Cenozoic units onto the Central Cordillera, shown in the sequentially restored cross-section (e.g. fig. 3 in Parra et al. 2012), illustrates a mechanism that controlled the subsidence and space for the accommodation of sediment derived from the Central Cordillera since the Eocene. In addition, our data show that burial was also favourably by tectonic subsidence due to the loading by the Eastern Cordillera (Fig. 12).

In addition, the middle Eocene–Oligocene uplift of structural highs in the northern sector of the Upper Magdalena Valley Basin, evident in seismic stratigraphical relationships and new thermochronometrical data in the Saltarén area well 3, favours a model of an Oligocene internally drained basin.

The Middle Magdalena Basin is, thus, an example of the establishment of internally drained conditions that enhanced sedimentary load in a
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