Tectonic controls on sedimentation in an intermontane hinterland basin adjacent to inversion structures: the Nuevo Mundo syncline, Middle Magdalena Valley, Colombia

VÍCTOR CABALLERO1*, ANDRÉS MORA1, ISAID QUINTERO1, VLADIMIR BLANCO1, MAURICIO PARRA1, LUIS ERNESTO ROJAS1, CRISTINA LOPEZ1, NELSON SÁNCHEZ1, BRIAN K. HORTON2, DANIEL STOCKLÍ3 & IAN DUDDY4

1Instituto Colombiano del Petróleo-Ecopetrol, km 7 Via a Piedecuesta, Bucaramanga, Colombia
2Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78712, USA
3Department of Geology, University of Kansas, Lawrence, KS 66045 USA
4Geotrack International Pty. Ltd., 37 Melville Rd, Brunswick West, Victoria 3055 Australia

*Corresponding author (e-mail: victor.caballero@ecopetrol.com.co).

Abstract: A combination of new surface and subsurface structural data, new stratigraphic data on conventional provenance, facies and palaeocurrents, low-temperature thermochronology and detrital zircon U–Pb provenance data provides a comprehensive account of the timing of deformation in the intermontane Middle Magdalena basin of the Central Colombian Andes, and allows evaluation of the style of foreland basin deformation associated with tectonic inversion. This robust dataset enabled documentation of focused tectonic activity in two competing low-relief basement structures to the east and west of the present Middle Magdalena Valley during the Palaeogene, earlier than previously recognized. Cenozoic sediment accumulation of a sedimentary pile up to 7 km thick in the Middle Magdalena Basin created a large original taper angle in this part of the north Andes. At that time, when the detachment rocks were deeply buried, the original larger taper angle facilitated the forelandward advance of deformation instead of promoting its stagnation.

Supplementary material: Raw data results from geochronometrical analyses are available at: http://www.geolsoc.org.uk/SUP18627

Inversion tectonics has been the topic of intense studies during recent decades (Colletta et al. 1990; Cooper et al. 1995; Cooper & Williams 1989; Mora et al. 2006; Williams & Cooper 1989). The geographic scale of most studies has been highly variable, although a majority analysed inversion in individual half-grabens and associated footwall shortcuts (Leeder & Gawthorpe 1987; Schlische 1991). However, those studies were generally focused on the geometries of the ancient rift and inversion structures and less often on syn-rift sedimentation and how it controls the subsequent contractional reactivation. In this context, there are few studies on the geometries and sediment distribution, associated with syn-inversion sedimentary packages (Morley 1989). Understanding these factors is crucial because there is a risk to applying conventional foreland-basin models in prestrained areas. In conventional foreland basins, typical sedimentary wedge geometries or facies can be predicted according to well-tested observations and inferences (Jordan 1981; Jordan et al. 1988; DeCelles & Giles 1996; Zoetemeijer 2002). However, in areas where tectonic inheritance plays an important role, its impact on syn-inversion sedimentary packages can modify conventional thrust-belt and foreland basin stratal geometries. This last idea has not been rigorously tested.

In this paper we present data on the Nuevo Mundo syncline area located in the Colombian Middle Magdalena intermontane basin. We show that, to further understand the relationship between syn-inversion stratal geometries and inversion tectonics, it is necessary to infer the age of the tectonic events, the age and rates of sedimentation, and the controls on the distribution of syn-kinematic facies. Based on multiple data sets we propose a model where a specific structural style is associated with a pattern of stratal geometries during the Cenozoic inversion of the Nuevo Mundo–Los...
Cobardes syncline–inversion anticline pair. Our observations are based on four datasets: (1) structural data derived from maps, wells and seismic lines; (2) sedimentation data such as conventional provenance, facies and palaeocurrents; (3) low-temperature thermochronology; and (4) detrital zircon U–Pb provenance data. This robust dataset enables us to hypothesize that the periods of pronounced thinning and wedge-shape geometry of the units coincide with focused tectonic activity in either of two competing low-relief structures to the east and west of the main synclinal structure in the study area during the Palaeogene. This deformation created a thick sedimentary package with a large original taper angle in the Neogene. At that time, when the detachment rocks were deeply buried, the original larger taper angle prompted the deformation front to advance westwards, rather than remain stationary to build taper as was suggested by Boyer (1995) based on a modification of the theory of wedge mechanics.

Geological setting

As suggested earlier (Tesón et al., this volume, in press), the Colombian Eastern Cordillera corresponds to a former Mesozoic symmetric graben that has been inverted since the Late Cretaceous in the context of retro-arc foreland basin development associated with subduction orogenesis. As a consequence of this initial configuration, a bivergent orogen has evolved roughly in the same place where former graben depocentres were located (Colletta et al. 1990; Dengo & Covey 1993; Cooper et al. 1995; Mora et al. 2006, 2009, 2010b). The Eastern Cordillera has two marginal foothill belts that reflect the progression of deformation outside the former main rift domain. To the east, the east-vergent eastern foothill belt is located adjacent to the undeformed craton, and to the west, the Magdalena foothill belt bounds the Middle Magdalena intermontane basin, which is located between the Central Cordillera basement uplifts and the inverted graben domain of the Eastern Cordillera (Morales 1958; Gómez et al. 2005a; Mora et al. 2010a; Moreno et al. 2011).

As previously described, both foothills have Cenozoic depocentres in synclines adjacent to the highest structural relief, which in the eastern foothills was associated with the main inversion faults (Parra et al. 2009; Moreno et al., this volume, in press). One of the most studied areas is the Medina basin have been useful in determining the beginning of tectonic loading and uplift of the Farallones inversion anticline, as well as its direct relation to the inversion of the Servitía–Lengüpa Fault. A fundamental question remaining is at what time the same processes occurred on the western flank of the Eastern Cordillera. Furthermore, it is important to test the hypothesis that a simultaneous inversion orogen across opposite margins in a bivergent inversion orogen by reviewing the sedimentary record of the analogue basin of the Nuevo Mundo syncline.

Structural setting

The Nuevo Mundo syncline is a north-plunging structure, c. 60 km long and c. 25 km wide, located at the western foothills of the Eastern Cordillera in NE sector of the Middle Magdalena Valley Basin (MMVB) in Colombia. To the east, the major structural domain of the Santander Massif is separated from the sedimentary domain by the Bucaramanga–Santa Marta strike-slip fault. The region of Mesas and Los Cobardes anticline is located in between the Nuevo Mundo syncline and the Santander Massif (Fig. 1). The Mesas region is a fluvially dissected, 10–20° west-dipping plateau (Julivert 1963, 1970) that is separated from the Cobardes anticline by the inverted Suarez Fault (Fig. 1; Acosta 2002). It makes part of the Jurassic–Cretaceous Tablazo Basin (Etayo-Serna et al. 1969), with up to c. 5 km of alluvial fan and fluvial deposits of the Giron Formation that evolve up-section to shallow marine sequences (Fig. 2). Towards the west, the plateau bends below the Nuevo Mundo syncline. This bend has been called the Chucuri flexure by Julivert (1970) and corresponds with the forelimb of the Los Cobardes anticline (Fig. 1). Carboniferous to Jurassic strata are exposed in the core of the Los Cobardes anticline, which has been interpreted as an inversion anticline (Colletta et al. 1990) associated with the inverted, but not emergent, east-dipping La Salina Fault (Fig. 1).

Methods

A new comprehensive database of sedimentological, petrographic, palaeocurrent and field mapping data for the study area was acquired in this research. These data sets were complemented with
new data on apatite fission track (AFT), and (U–Th)/He thermochronometry in zircon (ZHe) and apatite (AHe). The reconstruction of the thermal history was complemented with vitrinite reflectance data. Finally we used detrital zircon U–Pb geochronology data for provenance analysis.

**Thermochronology**

We employed AFT and ZHe dating in order to investigate the thermal history of rocks during their last cooling event, which we ascribe to thrust-induced exhumation. See Farley (2002) and Tagami & O’Sullivan (2005) for detailed description of the AFT and (U–Th)/He methods, respectively.

Rocks were sampled along a traverse from the Nuevo Mundo syncline to the Santander Massif. AFT analyses were conducted on seven sedimentary and three basement samples by Geotrack Pty Ltd, using the external detector method (Gleadow 1981; Tagami & O’Sullivan 2005). Data acquisition included determination of kinetic parameter chlorine content for each apatite grain in which fission track age or confined track length is measured (Table 1). Vitrinite reflectance ($Ro$) data were acquired in five samples (Table 2) and we used three $Ro$ data and three AFT data from Gómez (2001), and three $Ro$ data and five AFT from Parra et al. (2012).

Zircon (U–Th)/He and apatite (U–Th)/He dating were conducted on four aliquots from five zircon samples of rocks of the stratigraphic units like the Devonian Silgará, the Jura–Triassic Jordan, the Jurassic Pescadero granite, the Lower Cretaceous Tambor and Lower Cretaceous Rosablanca formations from the Mesas region. The same was done for helium in apatite with samples from the same first four units listed before (Table 3). The analyses were performed at the University of Kansas. Thermal modelling of fission track and (U–Th)/He ages, track lengths, kinetic parameter Cl wt% and vitrinite reflectance ($Ro$).
were conducted using the software HeFTy (Donelick et al. 2005; Ketcham 2005a, b) with the kinetic model of apatite annealing of Ketcham et al. (2007).

**Sedimentological analysis**

Detailed stratigraphic sections of Cenozoic units were measured with the Jacob’s staff method in rock outcrops along both limbs of the Nuevo Mundo syncline. A composite stratigraphic section for each limb of the Nuevo Mundo syncline was constructed integrating the detailed sections. Palaeocurrent measurements were completed in 60 sites using the DeCelles method for trough cross stratification (DeCelles et al. 1983). Facies analysis and characterization were performed for the units in the stratigraphic sections (Table 4). The sedimentological description, stratal thickness variation, palaeocurrent measurements, clast counting on conglomerate beds and sandstone petrography were used to identify the lateral and vertical facies distribution, the unroofing path of the Central Cordillera, Los Cobardes–Mesas region and the Santander Massif, and the distribution of loads through time that we link to activity of particular faults.

**Provenance analysis**

A set of 46 thin sections of Cenozoic sandstones was made and 300 points were counted in each section according to the Gazzi–Dickinson method (Dickinson 1985). Conglomerate clast counting was conducted in 19 localities of the La Paz, Mugrosa, Colorado and lower Real formations by...
measuring at least 100 gravel clasts using a 10 cm grid (Table 5).

We report detrital zircon U–Pb ages from 20 Cenozoic samples that were obtained in surface sections and wells in the central and western sectors of the Nuevo Mundo syncline. These ages were combined with 13 published ages from the eastern limb of the syncline (Nie et al. 2010, 2012) in order to provide a regionally meaningful assessment of source area evolution in the western and eastern portions of the Nuevo Mundo syncline (see Supplementary Data). A key element in the use of the detrital U–Pb data is the recognition of a population of zircons, constituted by at least 3% of the analysed grains, with an age <150 Ma, which are unambiguously assigned to a western source in the Central Cordillera (Silva et al., this volume, in press).

Kinematic restoration of a cross section

A balanced cross section through the Nuevo Mundo syncline from the Lisama Oil Field to the Santander Massif was produced. The section was drawn using interpreted seismic lines, wells and available surface geology. An incremental retro-deformation was constructed based on growth stratal relationships seen in seismic lines, thickness changes observed in wells and the thermometric and provenance data presented in this paper. The chronology of the units comes from the direct age assessment in the outcropping unit supported on a detailed pollen-based zonation (Jaramillo et al. 2011; Rodríguez-Forero et al. 2011) and new field mapping.

Previous studies

Relevant studies related to the study area include the results from the Middle Magdalena Valley and the Central Cordillera (Gómez et al. 2005b; Villagómez 2010). In more recent studies, detrital zircon U–Pb ages have been used to determine provenance in sedimentary rocks (Horton et al. 2010; Nie et al. 2012). At least five potential sources of sediment were detected in these studies based on U–Pb ages. The different potential ages for the five main sediment sources are reviewed in this volume (Silva et al., this volume, in press).

Nie et al. (2012) analysed detrital zircon U–Pb ages in rocks of the Nuevo Mundo syncline and found a shift in sediment source area in the Paleocene Lisama Formation from the Guayana Shield to Central Cordillera. The shift was inferred from dominant Mesoproterozoic and older (>1500 Ma) ages in the lower Lisama to the first appearance of a Jurassic–Early Cretaceous age peak in upper Lisama strata. This change was confirmed by a change in dominant northward directed palaeoflow to eastward directed (Moreno et al. 2011).

A shift in composition from litharenites to quartzarenites and a facies change from meandering fluvial to braided fluvial between lower and upper La Paz is interpreted as recording the advance of the orogenic front through uplift of the La Cira–Infantas palaeohigh, at present buried beneath MMV strata (Moreno et al. 2011). The onset of Eastern Cordillera uplift has been suggested to occur during the late Eocene, based on the increase of abundance of Grenville-age zircons in rocks of the upper Esmeraldas Formation (Nie et al. 2012), the recycling of the Eastern Cordillera’s Cretaceous cover and to a change to westward directed palaeoflow of fluvial systems (Caballero et al. 2010).

Eocene to recent exhumation of the eastern Cordillera is further supported by thermochronologic data in the Santander Massif, which suggests exhumation of c. 5 km in a 20 Ma period, c. 35–15 Ma (late Eocene to early Oligocene), plus 3–4 km from 15 Ma to the present (Parra et al. 2012).

Results

Thermochronology

Mesas region and Los Cobardes anticline. Samples of crystalline rocks, from the Devonian Silgará Formation (BU02), Triassic–Jurassic Pescadero Granite (BU01), Triassic–Jurassic Jordán Formation (BU06), Cretaceous Tambor Formation (BU07) and the Cretaceous Rosablanca Formation (BU09; Table 3), have ZHe ages that range between 59.6 ± 7.8 and 49.5 ± 4.0 Ma, which are younger than their estimated stratigraphic ages (v–z in Fig. 1). Vitritine reflectance values of 5.5% were obtained from the Jordan Formation (Table 2), indicating burial heating to c. 311 °C according to the kinetic algorithm of Burnham & Sweeney (1989). This high temperature is above the closure temperature for ZHe (180 °C) and thus reset cooling ages indicate ongoing exhumation in the Mesas region since at least the late Paleocene to early Eocene. Inverse modelling of ZHe, AHe and Ro data from the Jordan and Rosablanca formations shows that cooling could have initiated in the early Paleocene (Fig. 3a, b).

Apatite fission track ages of the Triassic Tiburón and Bocas formations and the Lower Cretaceous Los Santos Formation at each limb of the Los Cobardes anticline yielded cooling ages of 68.9 ± 13.5, 46 ± 6.6 and 71.4 ± 13.8 Ma, respectively (g, f, e in Fig. 1; Table 1). These cooling ages are reset and provide evidence for uplift of the Los Cobardes anticline by the late Paleocene–middle
### Table 1. Apatite fission track data

| Laboratory number | Longitude (°W) | Latitude (°N) | ID map | Unit | Stratigraphic age (Ma) | Number of grains | U238 (ppm) | NS (Rho-S)* | NI (Rho-I)* |
|-------------------|----------------|---------------|--------|------|-----------------------|------------------|------------|-------------|-------------|
| 996-07            | 73.53507       | 7.13858       | a      | Lisama | 60 ± 5               | 20 | 20.8 | 360 (5.953) | 1568 (25.93) |
| 996-16            | 73.39468       | 7.25769       | b      | Real  | 10 ± 5               | 20 | 27.3 | 330 (4.851) | 2315 (34.03) |
| 996-15            | 73.37836       | 7.25568       | c      | Colorado | 19 ± 4             | 20 | 18.0 | 210 (4.100) | 1080 (21.08) |
| 996-9             | 73.41656       | 7.10981       | d      | La Paz | 46 ± 9               | 20 | 29.6 | 318 (7.970) | 1470 (36.84) |
| 996-21            | 73.27587       | 7.14687       | e      | Los Santos | 140 ± 5          | 14 | 30.1 | 255 (11.16) | 859 (37.6)  |
| 996-27            | 73.15973       | 7.21945       | f      | Bocas | 225 ± 25             | 9  | 13.2 | 27 (2.718)  | 358 (16.49) |
| 996-30            | 73.11917       | 7.15191       | g      | Tiburón | 325 ± 25          | 14 | 18.7 | 156 (4.532) | 761 (22.11) |
| 996-39            | 73.05917       | 7.11983       | h      | Intrusivo | >135             | 20 | 23.8 | 85 (1.452)  | 1626 (27.78) |
| 996-37            | 72.98922       | 6.86682       | i      | Silgará | 479 ± 63            | 21 | 32.5 | 91 (2.355)  | 1473 (38.15) |
| 996-31            | 72.98922       | 6.86682       | j      | Silgará | 479 ± 63            | 6  | 19   | 29 (1.92)   | 348 (23.04) |
| 996-36            | 73.16123       | 7.06654       | not shown | Bm/ga | 2                 | 21 | 17   | 104 (1.47)  | 1430 (20.15) |
| 996-20            | 73.16123       | 7.06654       | in map | Bm/ga | 2                 | 20 | 20   | 54 (1.25)   | 1056 (24.39) |
| 996-10            | 73.41244       | 7.10781       | La Paz | 50 ± 1 | 15 | 31 | 327 (9.30) | 1355 (38.52) |
| 996-42            | 73.28973       | 7.19214       | La Luna | 88 ± 4 | 15 | 8  | 21 (0.43)  | 449 (9.19) |
| 996-21            | 73.27587       | 7.14687       | Los Santos | 140 ± 5 | 14 | 30.1 | 255 (11.16) | 859 (37.6) |
| 996-35            | 73.02812       | 7.28308       | Santos | 140 ± 2 | 20 | 33  | 553 (26.08) | 795 (38.75) |
| 996-3            | 73.02874       | 7.30291       | Jordan | 182.5 ± 7.5 | 22 | 9  | 38 (0.94)  | 450 (11.19) |
| 996-34            | 72.99151       | 6.86778       | Intrusivo | 220 ± 20 | 6 | 2  | 1 (0.11)  | 25 (2.63) |
| 996-2            | 73.02706       | 7.30759       | Silgará | 479 ± 63 | 21 | 1  | 3 (0.07)  | 53 (1.21) |
| 996-41            | 73.09911       | 7.12844       | Neis Bm/ga | 680 | 19 | 9  | 41 (0.79)  | 567 (10.93) |
| 996-33            | 72.98776       | 6.86740       | Neis Bm/ga | 680 | 20 | 11 | 31 (0.75)  | 563 (13.21) |

*NS and NI are the number of spontaneous and induced tracks counted to calculate spontaneous (Rho-S) and induced (Rho-I) tracks densities (×10^5 tracks cm^-2).

**ND** is the number of induced tracks counted in the mica external detector for estimating Rho-D.

Pooled (central) age for samples passing (failing) the χ^2 test.

P(χ^2) is the probability (Galbraith 1981; Green 1981). Values >5% are considered to pass it.

ξ is the calibration factor (zeta) based on EDM of fission track age standards represent an age population.

Eocene. Inverse modelling of age and track-length data of the sample of Los Santos Formation shows that the uplift of the Los Cobardes anticline may have initiated as early as Late Cretaceous–early Paleocene (Fig. 3c).

The Upper Cretaceous Umir Formation in the forelimb of the Los Cobardes anticline has Ro values between 0.75 and 0.85% (Table 2, Fig. 1) equivalent to a temperature of c. 130 °C (Burnham & Sweeney 1989), which indicates that the Umir and underlying Cretaceous units attained temperatures sufficiently high to completely erase inherited detrital AFT information and were thus exhumed from a depth below the Partial Annealing Zone (PAZ).

In the Nuevo Mundo syncline, the AFT ages of 63.6 ± 4.1, 49.2 ± 7.2 and 41.2 ± 4.3 Ma, from the Paleocene Lisama, lower–middle Miocene Colorado and upper Miocene Real formations, respectively (a, c, b in Fig. 1), are older than its stratigraphic age. Such a pattern indicates that Cenozoic units were exhumed from within the PAZ and ages are thus mixed.

We interpret the approximate minimum age for the onset of cooling as the reset age nearest to the lower boundary of the exhumed PAZ. A graphic synthesis of AFT age v. elevation, constructed using the data presented in this study and previously published data (Gómez et al. 2005b; Parra et al. 2012), shows what is here interpreted as the base of such exhumed PAZ (Fig. 3d). The base is inferred at c. 60 Ma from Ro values close to 0.7 (c. 120 °C) and AFT ages in sedimentary units older than their stratigraphic ages. This inference indicates that the exhumation of the Mesas region and Los Cobardes anticline started by about 60 Ma.

Santander Massif: Minimum ages for the onset of exhumation are derived from a published age–elevation profile of nine AFT and nine ZHe samples from a single tectonic block over an elevation gradient of c. 1.8 km that is located immediately east of the Bucaramanga fault (Parra et al. 2012). AFT reset ages range from 15.3 ± 1.1 to 28.7 ± 6.4 Ma and ZHe reset ages range from 24.5 ± 2.0 to 32.7 ± 2.6 Ma. Collectively these data allow an onset of exhumation by the late Eocene.

New data from two apatite fission track analyses of the Santander Massif, sampled on plutonic rocks intruding the Bucaramanga Gneiss and...
from the pre-Devonian Silgará Formation (h–j in Fig. 1) yielded AFT ages of 13.5 ± 2.1; 15.7 ± 1.7 and 21.4 ± 4.2 Ma, respectively, which are slightly younger than known ages from these units nearby, but confirms that exhumation of the Santander Massif was already ongoing by the Oligocene.

### Table 2. Vitrinite reflectance data

| ID         | Longitude (°W) | Latitude (°N) | Unit       | Stratigraphic position (m)* | \( R_o \) (%) | \( ±1\sigma \) (%) | Data source                  |
|------------|----------------|---------------|------------|-----------------------------|----------------|---------------------|------------------------------|
| GC996-9    | 73.41656       | 7.10981       | La Paz     | 1750                        | 0.55           | 0.05                | This study                   |
| GC996-10   | 73.41424       | 7.10781       | La Paz     | 1750                        | 0.55           | 0.05                | This study                   |
| 1018-03    | 73.32718       | 7.21711       | Lisama     | 600                         | 0.48           | 0.05                | Parra et al. (2012)          |
| GC996-7    | 73.53507       | 7.13858       | Lisama     | −300                        | 0.48           | 0.05                | This study                   |
| 660-1      | 73.38443       | 7.08595       | Lisama     | −300                        | 0.48           | 0.05                | Gómez (2001)                 |
| 1018-04    | 73.53677       | 7.08469       | Umir       | −800                        | 0.75           | 0.03                | Parra et al. (2012)          |
| 660-37     | 73.34993       | 7.07772       | Umir       | −800                        | 0.85           | 0.05                | Gómez (2001)                 |
| 1018-05    | 73.30650       | 7.14874       | Luna       | −1200                       | 0.75           | 0.03                | Parra et al. (2012)          |
| GC996-42   | 73.28973       | 7.19214       | Luna       | −1200                       | 0.75           | 0.03                | This study                   |
| 660-36     | 73.35006       | 7.04010       | Tablazo    | −300                        | 0.85           | 0.15                | Gómez (2001)                 |
| 08BU01G    | 73.08884       | 6.72978       | Jordán     | −7500                       | 5.59           | 0.39                | This study                   |

*Stratigraphic position of samples from the Eastern Cordillera with respect to a datum, chosen at the bottom of the Lisama Formation.

**Sedimentology**

**Paleocene Lisama Formation.** In the Nuevo Mundo syncline, the Lisama Formation conformably overlie Upper Cretaceous strata of the Umir Formation. The thickness of the Lisama Formation is variable, with c. 950 m in the eastern limb and...
Table 3. ZHe and AHe data

| Unit       | Laboratory no. | Latitude (°N) | Longitude (°W) | ID     | Age (Ma) | ± (Ma) 8% | U (ppm) | Th (ppm) | Sm (ppm) | Ft* |
|------------|----------------|---------------|---------------|--------|----------|-----------|---------|----------|----------|-----|
| Granito    | z08BU01-1      |               | 73.08846      | v      | 45.8     | 3.7       | 82.5    | 79.9     | 4.2      | 0.81|
|            | z08BU01-2      |               |               |        | 48.0     | 3.8       | 128.6   | 242.4    | 7.1      | 0.77|
| Pescadero  | z08BU01-3      |               |               |        | 51.4     | 4.1       | 241.5   | 358.0    | 6.7      | 0.75|
|            | z08BU01-4      |               |               |        | 55.2     | 4.4       | 512.2   | 615.7    | 29.9     | 0.74|
| Silgará    | z08BU02-1      | 73.09362      | 6.70497       | w      | 53.5     | 4.3       | 177.8   | 41.7     | 0.8      | 0.84|
|            | z08BU02-2      |               |               |        | 49.5     | 4.0       | 108.1   | 64.6     | 1.3      | 0.82|
|            | z08BU02-3      |               |               |        | 51.9     | 4.1       | 97.1    | 72.3     | 1.1      | 0.75|
|            | z08BU02-4      |               |               |        | 47.0     | 3.0       | 45.5    | 40.9     | 1.1      | 0.75|
| Jordán     | z08BU06-1      | 73.22101      | 6.70497       | x      | 78.8     | 6.3       | 221.2   | 59.0     | 1.8      | 0.75|
|            | z08BU06-2      |               |               |        | 62.2     | 5.0       | 159.4   | 81.4     | 2.5      | 0.75|
|            | z08BU06-3      |               |               |        | 46.4     | 3.7       | 141.1   | 163.3    | 2.3      | 0.77|
|            | z08BU06-4      |               |               |        | 62.4     | 8.2       | 326.0   | 91.6     | 1.9      | 0.79|
| Tambor     | z08BU07-1      | 73.22723      | 6.64667       | y      | 53.1     | 4.2       | 80.6    | 76.0     | 3.3      | 0.82|
|            | z08BU07-2      |               |               |        | 63.1     | 5.0       | 39.5    | 39.9     | 2.5      | 0.82|
|            | z08BU07-3      |               |               |        | 56.9     | 4.6       | 165.0   | 172.1    | 2.5      | 0.77|
|            | z08BU07-4      |               |               |        | 52.4     | 4.2       | 222.9   | 111.3    | 1.9      | 0.77|
| Rosablanca | z08BU09-1      | 73.24470      | 6.63223       | z      | 47.0     | 3.8       | 212.6   | 193.1    | 2.5      | 0.72|
|            | z08BU09-2      |               |               |        | 54.2     | 6.7       | 278.3   | 38.9     | 1.3      | 0.75|
|            | z08BU09-3      |               |               |        | 47.5     | 3.8       | 311.1   | 175.1    | 1.3      | 0.77|
|            | z08BU09-4      |               |               |        | 44.8     | 3.6       | 74.7    | 81.1     | 1.9      | 0.75|

*Ft, Correction factor owing to loss of alpha particles (depends on grain size) (Ehlers & Farley 2003).
Table 4. Description and interpretation of lithofacies

| Facies association and successions | Sediment environment |
|------------------------------------|----------------------|
| **Lower Real**                     | Mid and distal fan facies. Mid-fan facies towards the eastern limb of the Nuevo Mundo syncline. Braided to distal fan facies towards the western limb. |
| F2 + F6 + F1: pinky to white sandy to gravelly bar and channel deposits with variegated mudstone and claystone floodplain deposits in a fluvial braided, crevasse complex and distal alluvial fan facies with palaeosoils | |
| F2 + F8 + F6 + F1: brown reddish gravelly to sandy bar deposits, channel fill deposits, and palaeosoils of alluvial plain system in a mid to distal–alluvial fan | |
| **Colorado**                      | Upward coarsening mid to distal alluvial fan deposits. Proximal fan facies towards the E limb and distal fan facies towards the western limb of the Nuevo Mundo syncline. |
| F1 + F2 + F6 + F8: brown reddish alluvial sand and gravel channel bar deposits with pedogenized floodplain mudstones and sheetflood sandstones on mid to proximal alluvial fan facies | |
| F2 + F8 + F6 + F1: brown reddish gravelly sand bar deposits, channel fill deposits, red to pink calcrite palaeosoils and variegated mudstones in a braided plain systems of the mid to distal–alluvial fan | |
| **Mugrosa**                       | Upward coarsening fluvial playa lake or alluvial system. Proximal channel to crevasse complex facies towards SE of the eastern limb. Distal floodplain to playa palaeosoil facies towards northwestern limb. |
| F6: brown reddish palaeosoils overprinted on floodplain to playa lake deposits, forming overbank temporary stable soils | |
| F6 + F3: sheet sandstone with floodplain mudstones in a floodplain system and minor splay sandstones from temporary channels | |
| F6 + F4 + F8: floodplain variegated mudstones and minor crevasse splay sandstones in a floodplain system. Development of soils and minor gypsum laminae under arid stable conditions in the floodplain | |
| **Esmeraldas**                    | Lacustrine and tide dominated fluvial towards the eastern limb of the NMS. Fluvial meandering system towards the western limb. |
| F7 + F4 + F5: lacustrine muddy or intertidal deposits. Some fossiliferous sandstone and mudstones with bivalve and gastropod shells (Los Corros Fossil Horizon) | |
| F7 + F3 + F4: coastal plain shale to variegated floodplain mudstone with minor estuarine to fluvial sand deposits | |
| F7 + F3 + F2: floodplain to coastal plain intertidal mudstones with minor channel fluvial meandering sand deposits with estuarine influence | |
| **La Paz**                        | Braided fluvial system with proximal alluvial fan facies towards the SSW of NMS and distal meandering facies towards the NNE (Fig. 5). |
| F7 + F4 – F5: quartzose clean white sandstones. Scarc floodplain deposits, channel sandstones prevail over floodplain. Reworking of sands and stacked channel intervals | |
| F4 – F5 – F7: floodplain variegated mudstone deposits with crevasse channel sandstone. Localized erosion of floodplain | |
| F2 + F3: sandstone channel bars, sand sheets, floodplain mudstones with levels of palaeosoils. Some sandstone with fragments of coal reworked from contemporary swamp deposits | |
| **Lisama**                        | Tide dominated delta. Lower delta plain system with distributary channel and intertidal flat sandy and muddy deposits (Fig. 5). |
| F5 + F2 + F7: prograding deltaic, distributary channel sandstone with mud to sand intertidal flat mudstone and muddy sandstones deposits | |
| F4 + F5 + F7: deltaic, upward coarsening, fine to medium distributary channel sandstones with intertidal mud flat grey mudstones | |
c. 700 m on the western limb of the syncline (Fig. 4). This variation in thickness results from an erosive unconformity between Lisama and the overlying lower Eocene La Paz Formation.

The Lisama Formation is composed of interbedded medium to fine sandstone, dark grey shale, and muddy, very fine sandstone with planar cross stratification, wavy, lenticular and flaser lamination. The petrographic data from the Lisama Formation show an increment of metamorphic and volcanic lithic fragments and plagioclase feldspar along with a decrease in monocristaline quartz from base to top of the unit. In the western limb, petrographic data shows an increase from 4 to 24% igneous–metamorphic fragments, an increase from 12 to 21% in sedimentary lithics and an increase from 2 to 8% in feldspar. In the eastern limb there is an increase from 15 to 35% in igneous–metamorphic, from 7 to 22% in sedimentary and from 7 to 10% in feldspar (Fig. 4; Table 6). The clasts of sedimentary origin are mainly of claystone, siltstone, sandstone, chert and glauconitic sandstones, which together suggest erosion of Cretaceous units, including the La Luna and Tablazo Formations, which include glauconite-bearing and chert horizons. The metamorphic lithics indicate exhumation of basement rocks like those exposed in the Central Cordillera at this time (Villagómez 2010; Fig. 4; Table 6). Palaeocurrent measurements in the Lisama Formation indicate mainly eastward and northward palaeoflow directions and a minor westward direction. Lower Lisama Formation yields northward palaeoflow in the eastern limb and westward palaeoflow in the western limb; upper Lisama Formation yields eastward palaeoflow in both the western and eastern limbs (Figs 4 & 5). The sedimentary properties of this unit have been interpreted as representing deposition in a lower delta plain system with distributary channels and an intertidal flat sandy and muddy depositional system (Moreno et al. 2011).

Detrital zircon U–Pb age data from the western limb of the syncline reveal the first appearance of zircons, 150 Ma, assigned to magmatic arc sources in the Central Cordillera (CC) making up c. 7% of the analysed grains in the lower Paleocene Lisama Formation (Fig. 7; sample LM150509–7). In contrast, the first appearance of such CC-derived zircons in the eastern limb of the Nuevo Mundo syncline occurs in upper Paleocene Lisama Formation (sample U821), which overlies lower Paleocene Lisama sandstones (RS0114011) exhibiting a polymodal distribution of detrital zircon of largely Proterozoic ages (Fig. 7). This age pattern has been also seen in the axial Eastern Cordillera (Saylor et al. 2011) and was used to constrain the minimum age for onset of CC uplift as late Paleocene (Nie et al. 2010, 2012).

We hypothesize that the diachronous first appearance of zircons sourced by the Central

| Formation | Sample no. | Chert | Quartz | Pale arenite and siltstone | Red arenite and siltstone | Limestone | Granite and riolite | Metamorphic | Total |
|-----------|------------|-------|--------|---------------------------|--------------------------|-----------|-------------------|-------------|-------|
| **Eastern limb of Nuevo Mundo syncline** | | | | | | | | | |
| Lw Real | VC174 | 6 | 24 | 11 | 10 | 0 | 41 | 8 | 100 |
| Lw Real | VC173 | 4 | 30 | 14 | 2 | 0 | 48 | 2 | 100 |
| Lw Real | VC164 | 14 | 6 | 7 | 12 | 0 | 43 | 18 | 100 |
| Colorado | VC159 | 3 | 6 | 23 | 10 | 0 | 24 | 34 | 100 |
| Colorado | VC90 | 12 | 14 | 26 | 18 | 0 | 17 | 13 | 100 |
| Colorado | VC140 | 13 | 3 | 31 | 39 | 14 | 0 | 0 | 100 |
| Colorado | VC137 | 11 | 1 | 53 | 16 | 19 | 0 | 0 | 100 |
| Colorado | VC87 | 34 | 13 | 32 | 5 | 16 | 0 | 0 | 100 |
| Mugrosa | VC86 | 28 | 70 | 2 | 0 | 0 | 0 | 0 | 100 |
| Mugrosa | VC136 | 59 | 25 | 8 | 8 | 0 | 0 | 0 | 100 |
| La Paz | VC389 | 22 | 67 | 10 | 1 | 0 | 0 | 0 | 100 |
| La Paz | VC394 | 31 | 59 | 10 | 0 | 0 | 0 | 0 | 100 |
| La Paz | VC404 | 45 | 46 | 9 | 0 | 0 | 0 | 0 | 100 |
| La Paz | VC65 | 39 | 34 | 23 | 4 | 0 | 0 | 0 | 100 |
| La Paz | VC103 | 45 | 36 | 17 | 1 | 0 | 1 | 0 | 100 |
| **Western limb of Nuevo Mundo syncline** | | | | | | | | | |
| Lw Real | VC87 | 40 | 19 | 19 | 0 | 0 | 22 | 0 | 100 |
| Lw Real | VC86 | 34 | 31 | 14 | 0 | 0 | 21 | 0 | 100 |
| Lw Real | VC85 | 47 | 29 | 14 | 0 | 0 | 10 | 0 | 100 |
| Lw Real | VC51 | 19 | 32 | 9 | 9 | 0 | 31 | 0 | 100 |
Cordillera results from competing sources to the east and west of the Nuevo Mundo syncline. Thus, in the early Paleocene, deltaic systems connected to the southern Central Cordillera (Caballero et al. 2013) reached areas as far north as the western limb of the Nuevo Mundo syncline, whereas the uplifting Cobardes anticline (see the structure in Fig. 1 and thermochronological and Fig. 3. Thermochronology data. (a, b) Thermal inverse models based on AHe and ZHe data for samples of the Jurassic Jordan and the Lower Cretaceous Rosablanca formations in the Mesas Region. Thermal solutions support onset of cooling in the early Paleocene to early Eocene. (c) Thermal model based on AFT data for the Lower Cretaceous Los Santos Formation from the Los Cobardes anticline. Time–temperature paths support onset of cooling as early as Late Cretaceous (c. 71 Ma) in the Los Cobardes anticline. (d) Apatite fission track ages and Ro values plotted by their stratigraphic ages for samples from the Los Cobardes anticline and Santander Massif. The base of the PAZ is located where the AFT ages become younger than the stratigraphic ages and the vitrinite Ro value exceeds c. 0.7%. These two changes occur in the upper part of the Unir Formation and suggest that AFT ages of c. 60 Ma value mark the onset of exhumation of the Los Cobardes anticline. (The dark grey lines represent time–temperature paths with a good-fit to the measured apatite-fission track data. Light grey areas correspond to paths with only acceptable fit. Black boxes correspond to constraints in the $t$–$T$ space derived from stratigraphic relationships.)
sedimentological evidence of uplift above) sourced recycled cratonic zircons derived from Cretaceous strata on the eastern limb. In the late Paleocene, deltaic systems prograded eastwards and reached the eastern sector of the Nuevo Mundo Syncline (NMS). We locate the provenance divide between the major western and eastern provenance domains as a NNE axis between catchments draining each major source area domain in the Central and Eastern cordilleras (Figs 6 & 7).

Lower Eocene La Paz Formation. The La Paz Formation unconformably overlies the Lisama Formation. Its thickness is variable, with 1090 m at the eastern limb of the syncline, approximately 1500 m at the southern end, and <90 m in the western limb, making this unit wedge-shaped (Fig. 4). A pebble to cobble conglomerate with a maximum thickness of 24 m of rounded quartz, sub-rounded chert clasts, and a minor proportion of red-bed clasts marks the base of the unit and can be traced around the Nuevo Mundo syncline (Caballero et al. 2010). Above the basal conglomerate, the stratigraphic architecture is mainly stacked channel sandstones and lateral accretion macroforms with clean, medium to coarse conglomeratic, trough cross-stratified sandstone and scarce intercalations of floodplain pedogenized mudstones. Measurements of imbricated conglomerate clasts on the southern basal conglomerate indicate a northward palaeoflow. Palaeocurrent measurements in trough cross-bedded sandstones at all levels yield a bimodal direction of palaeoflow towards NNE or ENE (Figs 4 & 5).

There is a pronounced change in sandstone composition from the litharenites of the upper Paleocene Lisama to the sublitharenites at the base of La Paz and quartzarenites of the upper La Paz, especially at the eastern limb (Tables 5 & 6; Fig. 4). In the western limb, between the Lisama and the La Paz Formations there is a shift from litharenites to lithic arkoses, showing a significant increase in

Fig. 4. Stratigraphic profiles at each limb of the Nuevo Mundo syncline showing lateral and vertical facies distribution, thickness changes, palaeocurrent direction, conventional sandstone and conglomerate composition, and the interpreted erosion window. The dominant growth of the structures either to the east or west of the Nuevo Mundo syncline controlled the thickness of the units. Black points denote U–Pb samples with sample number. In eastern limb samples are from Nie et al. (2012).
| Table 6. Sandstone petrography |
|-----------------------------|
| **Formation** | **Sample** | **Quartz** | **Feldspar** | **Sedimentary plus chert** | **Igneous** | **Metamorphic** | **Total** | **Formation** | **Sample** | **Quartz** | **Feldspar** | **Sedimentary plus chert** | **Igneous** | **Metamorphic** | **Total** |
|----------------|
| **Eastern limb of Nuevo Mundo syncline** |
| Lw Real | SS27 | 65.0 | 26.0 | 9.0 | 0.0 | 0.0 | 100 | La Paz | SS5 | 58.6 | 4.2 | 16.5 | 8.1 | 12.6 | 100 |
| Lw Real | SS26 | 57.0 | 25.0 | 1.0 | 13.0 | 4.0 | 100 | Lisama | SS4 | 38.1 | 5.5 | 21.6 | 15.4 | 19.4 | 100 |
| Lw Real | SS25 | 86.0 | 7.0 | 4.0 | 0.0 | 3.0 | 100 | Lisama | SS3 | 34.0 | 9.7 | 20.4 | 9.2 | 26.7 | 100 |
| Colorado | SS24 | 88.0 | 2.0 | 6.0 | 2.0 | 2.0 | 100 | Lisama | SS2 | 45.9 | 11.8 | 14.6 | 4.8 | 22.9 | 100 |
| Colorado | SS23 | 74.0 | 12.0 | 6.0 | 0.0 | 8.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Colorado | SS22 | 50.0 | 3.0 | 39.0 | 0.0 | 8.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Colorado | SS21 | 67.0 | 3.0 | 22.0 | 0.0 | 8.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Colorado | SS20 | 45.0 | 0.0 | 33.0 | 11.0 | 11.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Colorado | SS19 | 84.0 | 7.0 | 9.0 | 0.0 | 0.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Colorado | SS18 | 85.0 | 0.0 | 15.0 | 0.0 | 0.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Mugrosa | SS17 | 85.0 | 1.0 | 14.0 | 0.0 | 0.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Mugrosa | SS16 | 81.0 | 8.0 | 6.0 | 2.0 | 3.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Esmeraldas | SS15 | 89.5 | 2.4 | 4.8 | 2.7 | 0.6 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Esmeraldas | SS14 | 86.0 | 3.0 | 3.9 | 1.0 | 6.2 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| Esmeraldas | SS13 | 90.1 | 5.3 | 0.7 | 2.0 | 2.0 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS12 | 96.5 | 0.0 | 1.5 | 0.6 | 1.5 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS11 | 87.0 | 0.0 | 6.8 | 1.8 | 4.4 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS10 | 90.0 | 1.0 | 2.7 | 1.7 | 4.6 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS9 | 76.0 | 3.0 | 4.2 | 9.0 | 7.8 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS8 | 89.6 | 0.0 | 5.7 | 4.2 | 0.6 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS7 | 51.1 | 9.7 | 17.9 | 20.4 | 0.9 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
| La Paz | SS6 | 64.7 | 4.1 | 22.6 | 5.3 | 3.3 | 100 | Lisama | SS1 | 70.8 | 7.0 | 7.0 | 3.7 | 11.6 | 100 |
plagioclase feldspar. This conspicuous decrease in lithic content of arenites from late Paleocene to early Eocene indicates an additional source of sediment that suggests a major contribution from a rapidly uplifting sedimentary source to the sediments accumulated in the eastern limb. In contrast, the western limb is inferred to have a source of sediment-shedding igneous grains owing to the increase in plagioclase feldspar.

The lower Eocene fluvial sandstones of the La Paz Formation contain detrital zircons derived from the magmatic arc with an increased abundance of up to 50% in the western limb (Fig. 8) and up to 30% in the upper part of this unit in the eastern limb. The age signal of the La Paz formation in a subsurface sample analysed from the Yarigui well, located in the westernmost reaches of the basin (Fig. 8), shows a small peak at 68 Ma and a major peak at 147–202 Ma, which accounts for c. 80% of the grains analysed. Such a significant signal indicates a small contribution from the magmatic arc and a more local source of volcanioclastic Jurassic rocks of the Norean Group exposed either in the eastern flank of the Central Cordillera or in intra-basin highs (Caballero et al. 2010; Clavijo et al. 2008).

Detrital U–Pb age signatures and a suite of indicative clasts, palaeocurrent directions, changes in composition and the facies distribution together record the establishment of a fluvial network largely fed by the western provenance domain in the Central Cordillera and intra-basin basement highs. In the southern part of the NMS, the facies association allows the interpretation of this unit as mid-alluvial fan facies at the base of the unit and...
fluvial braided to meandering facies in the middle and upper part. To the north, calcrite palaeosols and red pedogenized mudstones are more frequent, indicating stable floodplains in a more distal meandering fluvial plain cut by channels with lateral accretion bodies of sandstone (Caballero et al. 2010; Fig. 6; Table 4). It may be a local contribution of sediment from the Los Cobardes anticline and the Mesas region to the east to the La Paz Formation. We interpret the position of the provenance divide as located just east of the Nuevo Mundo syncline. This provenance divide might have a north to NE direction turning to the east when it leaves the NMS (Figs 6 & 8).

**Middle to upper Eocene Esmeraldas Formation.** The middle to upper Eocene Esmeraldas Formation overlies conformably the La Paz strata and its thickness decreases from 1255 to 570 m between the eastern and western limb of the Nuevo Mundo syncline, respectively (Fig. 4). In the NW sector of the Payoa oil field, the unit is 480 m thick. This unit consists of tabular sandstone layers with trough cross stratification, with good lateral continuity, intercalated with variegated mudstones in the western limb, variegated mudstones and dark-grey, organic matter-rich shales in the eastern limb (Fig. 4). Some levels of the Esmeraldas sandstones are fine-grained and contain abundant organic matter, mud and sedimentary structures like flaser, lenticular and wavy lamination, which could indicate a low-energy environment.

Petrographic data of Esmeraldas show an increase of sedimentary lithics and a decrease in metamorphic and igneous grains towards the top of the section in the eastern limb. In the western limb, there is a decrease in all types of lithics and the feldspar content remains the same as the La

![Fig. 6. Interpretation of facies distribution of Cenozoic units in the Nuevo Mundo syncline. The darker colours indicate higher-energy flow as alluvial fans and the lighter colours indicate low-energy lacustrine to tidal-dominated; grey indicates fluvial. See Table 4 for details.](image-url)
Fig. 7. Detrital zircon U–Pb ages from Paleocene strata in both limbs of the Nuevo Mundo syncline. The first appearance of zircons younger than 150 Ma, denoting a Central Cordillera signature, occurs in the lower Paleocene strata in the western limb and in upper Paleocene in the eastern limb. The early Paleocene provenance divide was located close to the axis of the Nuevo Mundo syncline and migrated eastwards in late Paleocene, indicating a strong influence of the Central Cordillera. The numbers in percent represent the percentage of zircons < 150 Ma in samples having more than 3% abundance.

Fig. 8. Detrital zircon U–Pb ages from lower to middle Eocene strata of the La Paz Formation in the Nuevo Mundo syncline and the western Middle Magdalena Valley Basin. Samples in the western limb of the syncline show peaks < 150 Ma ascribed to the Central Cordillera, whereas in the eastern limb only the upper sample exhibits this signature. The Jurassic peak from the Yarigui sector sample indicates local erosion and deposition from the Jurassic rocks of the Central Cordillera or the basement of the Middle Magdalena Valley Basin.
Paz Formation (Table 6). The decrease in igneous and metamorphic lithics indicates a reduction in the contribution of basement rocks. Palaeocurrent measurements indicate an eastward palaeoflow at the base of the unit, followed by a predominant westward palaeoflow at the middle and upper part of the unit (Fig. 5).

Detrital zircon U–Pb ages in the upper Eocene Esmeraldas Formation shows outstanding increased abundance of up to 65% and up to 31% of CC-derived zircons in the western and eastern limbs of the NMS, respectively, and a new suite of Jurassic–Permian and some Grenvillian ages (Fig. 9). The exception is the Santos111 sample from the northern NMS, which is devoid of zircon detrital ages <150 Ma but has a peak in Jurassic–Permian zircon ages and a large set of Grenvillian and older ages that is indicative of a new source of sediment (Fig. 9).

The reduction of unstable fragments and increase in sedimentary lithics indicates a new source of sedimentary sediment. The changing palaeoflow direction from eastward at the lower part and westward at the upper part indicates a new source located towards the east. The U–Pb age signal that includes a Jurassic–Permian and Grenvillian suite records the beginning of erosion of the Cretaceous and Jurassic rocks which we interpret as belonging to the Santander Massif and Los Cobardes anticline. As we mention above, Late Eocene exhumation of these structures is supported by AFT data. The facies associations, absence of conglomerates, a special suite of sedimentary structures like flaser, wavy, lenticular and the lateral continuity of strata are indicative of a decrease in the environmental energy flow and an increased sediment supply and accommodation that permits the preservation of a variety of structures and organic matter in a lacustrine and/or tidal influenced alluvial valley (Fig. 6) that probably allowed an outwards advance in sediment accumulation and a decrease in the exposure of basement rocks from the Central Cordillera by sedimentary onlap and burial. The depositional boundary advances to the east of the Nuevo Mundo syncline as compared with that of the Early Eocene (Fig. 9).

Oligocene Mugrosa Formation. This unit consists of up to 30 m-thick levels of variegated, mainly red pedogenized mudstone and claystone with interbedded discontinuous, 1–3.5 m thick layers of loose, white, granule coarse sandstone with massive to normal grading and conglomeratic lag at the base, some of them with a white clay matrix. In the eastern limb of the NMS, this unit is 1330 m thick, whereas 14 km west along the

![Fig. 9. Detrital zircon U–Pb ages from upper Eocene strata of the Esmeraldas Formation in the Nuevo Mundo syncline. Central Cordilleran zircons appear in both limbs of the syncline, and are absent in the northern part sample Santos 111. Grenvillian and older peaks, as well as the Permo-Triassic peak in sample Santos111 could indicate provenance from the Santander Massif.](image-url)
western limb, it forms a 672 m thick package of interbedded calcrete and mottled mudstone with embedded isolated sandstone strata and, occasionally, with thin layers of gypsum, which were seen in both limbs and were used as correlation markers (Fig. 4).

In the eastern limb of the NMS, sandstones of the Mugrosa Formation are sublitharenites at the base, which grade upwards to litharenites with a lithic fraction primarily consisting of sedimentary fragments including siltstone, quartzarenites and foraminifera-bearing chert unambiguously related to the La Luna and equivalent units of the Cretaceous strata (Fig. 4; Table 6). In the western limb, the sandstones of Mugrosa Formation are lithic arkoses and comprise the entire unit. Palaeocurrent measurements show westward, southwestwards and northwestward directions (Fig. 5).

Contrasting with the unit below, in the Oligocene Esmeraldas Formation the detrital zircon U–Pb signature of <150 Ma shows an outstanding decrease. Neither the three U–Pb samples from the eastern Nuevo Mundo syncline (VC066, VC067, U08025), nor the two in Caguí area (CAG1-9, CAG1-10), nor the one from the western limb of the syncline (LM150509-4) contain a population of zircons <150 Ma. The peaks seen in these samples represent <3% of grains. Instead, zircon populations in these samples are dominantly of Permo-Triassic, Jurassic and Grenvillian ages (Fig. 10).

We attribute this signature to erosion of the Cretaceous cover and the basement of the Santander Massif in the uplifting Eastern Cordillera. Two sandstones from the Mugrosa Formation in the western limb of the syncline (NM7-LM150509-5, NM8) contain Mesozoic magmatic-arc-derived zircons, although reworking of the previously deposited units is a potential cause for the presence of such population, as is also our interpretation for the CAG1-10 sample in the Caguí Area.

Taken together, these data show a drastic change in the position of the provenance divide and the deposition area in the Oligocene Mugrosa sedimentary record. The provenance divide migrates towards the west of the Nuevo Mundo syncline, resembling today Magdalena River basin axis.

We interpret this change as related to the dominant uplift of the Santander Massif and the Eastern Cordillera to the east. Apparently, the sediment is transported towards a closed basin, the intramontane MMVB, through a playa lake or floodplain environment with channel and crevasse sand deposits along with sheet sands of distal floodplain alluvial fans within a confined alluvial–fluvial valley showing semiarid conditions (Table 4; Figs 4, 6 & 10). There were sporadic lacustrine conditions during the Oligocene in the northern part of the study area (Fig. 10).
environments that allowed deposition of 8 m-thick strata with freshwater molluscs called the Mugrosa Fossil Horizon (Gómez et al. 2005b; Morales 1958).

Lower to middle Miocene Colorado Formation. This unit is composed of very coarse-grained, massive to normal-graded, conglomeratic sandstones, conglomerates and mudstones with abundant thick calcrite palaeosol levels that are distinguished by its conspicuous reddish brown colour ubiquitous in the Nuevo Mundo syncline. The thickness of the Colorado Formation progressively decreases westwards in the Nuevo Mundo syncline from 1400 to 970 m (Fig. 4). In the eastern limb, three coarsening upward cycles of lenticular sandstones, pedogenized mudstones, calcrites and lenticular to tabular clast to matrix-supported conglomerates are present (Fig. 4). In the western limb, normal-graded, granulose sandstones to muddy sandstones and calcrite levels predominate (Fig. 4). Palaeocurrent indicators show westward, southwestward and northwestward palaeoflow directions (Figs 4 & 5).

The sandstone petrography of the Colorado Formation shows litharenites with the highest abundance of sedimentary fragments in the measured section with 39% in sample VC157 and up to 88% of the pebbles in conglomerates in the middle part of the unit (Tables 5 & 6). The lithic fragments include limestone, quartzose sandstones and siltstones. Excellent outcrops of pebble conglomerate contain up to 19% of pale to dark grey phosphatic limestone clasts, like those of the Cretaceous Paja and Rosablanca formations (see the stratigraphic position of those units in Fig. 2). Up to 39% of white and red sandstone and siltstone clasts are also present and are similar to those observed in the Lower Cretaceous Tambor and Jurassic Giron Formations. An increase in granite, rhyolite and metamorphic clasts is observed in the upper part of the unit (Fig. 4).

The lower to middle Miocene Colorado Formation U–Pb detrital zircon signature of samples U08027, LC0803-3, LM150509-6, Cag1-8, Cag1-7 and Cag1-6 shows a contribution of zircons <150 Ma neither in the Nuevo Mundo syncline nor in the Cagüi area. The normalized probability plots (Fig. 11) show Triassic, Permian, Grenvillian, and Proterozoic age populations. Only the sample M09 at the base of unit on the eastern limb of the Nuevo Mundo syncline shows a peak of 5% <150 Ma ages.

The U–Pb signature indicates no important contribution of sediment from the Central Cordillera to this part of the basin. Instead, the provenance is mainly from the Santander Massif and the

Fig. 11. Detrital zircon U–Pb ages from the lower middle Miocene Colorado Formation in the Nuevo Mundo syncline and the Middle Magdalena Valley Basin. Absence of ages <150 Ma supports provenance from the east, through unroofing of the Santander Massif and the Eastern Cordillera.
Eastern Cordillera sedimentary cover and basement as indicated by ubiquitous Triassic, Permian, Grenvillean and Proterozoic age populations and by the direction of palaeocurrents. The petrographic data support this inference as most of the clasts belong to Cretaceous calcareous and sandy units, red beds of the Jurassic and crystalline clast of the basement. We interpret the appearance of magmatic signature in the lower Colorado on the eastern limb as related to recycling of the Palaeogene units in the northern sector of the basin near the Santander Massif. This interpretation means a kilometre-scale uplift of the Santander Massif and Eastern Cordillera to exhume the basement.

The sedimentological data indicate that the depositional system was an alluvial fan with proximal facies in the eastern limb and distal braided fluvial and floodplain facies in the western limb (Fig. 6). The results presented for this unit support an early–middle Miocene migration of the depositional axis and provenance divide towards the west in response to continued uplift and exhumation of the Santander Massif and the Eastern Cordillera (Fig. 11).

Upper Miocene Real Group. This unit overlies the Colorado Formation and only the lower 1100 m of up to 2 km of the Real Group (Ward et al. 1973; Gómez et al. 2005b) was studied. The basal Real is composed of matrix-supported conglomerates that grade to clayey, white sandstones intercalated with minor pedogenized mudstones, and muddy fine sandstones; the sedimentary structures are mainly through cross stratification, plane bed, massive and cut and fill. The upper Miocene Real studied comprises three fining upward cycles. Palaeocurrents consistently show palaeoflow direction towards the west and NW (Figs 4 & 5).

Sandstone petrography data show an upsection increase in plagioclase, igneous volcanic clasts and metamorphic lithics, along with a decrease in sedimentary clasts. Conglomerate petrography shows the same distribution of equivalent clasts with igneous and metamorphic predominating over sedimentary (Tables 5 & 6).

The U–Pb signature of the sample LC0803-5 of the upper Miocene Real Group in the MMVB shows a contribution of c. 47% of detrital zircons <150 Ma, derived from Mesozoic and Cenozoic magmatic sources that reached areas as further east as La Cira area (Fig. 12), mainly from the Central Cordillera. Sample U08028 from the eastern limb of the Nuevo Mundo syncline shows Permian to Triassic age peaks, and sample Cag1-5, from the subsurface in the Cagui, well north of the syncline, has a dominant Proterozoic population (Fig. 12).

We attribute this pattern of crystalline composition enrichment in very coarse-grained facies to exhumation of nearby basement rocks in the Santander Massif east of the Nuevo Mundo syncline, and a decrease in the contribution from the Central Cordillera represented in the sample of the La Cira area (Fig. 12). The U–Pb results confirm the findings of petrography in the NMS area and allowed us to locate the provenance divide axis.

**Fig. 12.** Detrital zircon U–Pb ages from the upper Miocene Real Formation in the Nuevo Mundo syncline and Middle Magdalena Valley Basin. The only signature of Central Cordilleran zircons occurs in the La Cira area (sample LC0803-5), which indicates the position of the provenance divide at this time.
between the western flank of the NMS and the La Cira area, and this axis goes in a north to north-westward direction passing to the west of the Caguí area where the U–Pb signal is from the Santander Massif. The position of the main provenance divide resembles that found at present in the Middle Magdalena Valley (Fig. 12). The sedimentological properties of the basal part of the Real Formation to the Los Cobardes and Mesas regions can be inferred from different lines of evidence. At the top. The proximal alluvial fan facies are located to the NE part of the eastern limb of the NMS, whereas the distal facies are resting towards the western flank and west of the NMS (Fig. 6).

Discussion

Kinematic restoration of a cross section and summary of the evolution of the Nuevo Mundo syncline

We generated an incremental retrodeformation of a cross section using interpreted seismic lines and wells combined with available surface geology, growth stratal relationships evident in seismic lines and thickness changes observed in wells. The kinematic restoration was calibrated using the thermal history of the samples discussed based on AFT, ZHe and AHe data, palaeocurrents and the provenance based on U–Pb ages.

Paleocene. We suggest that the diachronous first appearance of zircons sourced by the Central Cordillera results from competing sources to the east and west of the Nuevo Mundo syncline. In the lower Paleocene, deltaic systems connected to the southern Central Cordillera (Caballero et al. 2013) reached areas as further north as the western limb of the Nuevo Mundo syncline, whereas the uplifting Cobardes anticline sourced recycled cratonic zircons derived from Cretaceous strata to the eastern limb. In the late Paleocene, deltaic systems prograded eastwards and reached the eastern sector of the NMS. We locate the provenance divide between the major western and eastern provenance domains as a NNE axis between catchments draining each major source area domain in the Central and Eastern cordilleras (Figs 6 & 7).

Uplift of the Central Cordillera appears to have occurred during the Late Cretaceous based on AFT data presented in Caballero et al. (2013) and on AFT data from Villagómez (2010). The nearly contemporary, eastward transfer of deformation to the Los Cobardes and Mesas regions can be inferred from different lines of evidence. At the base of the Lisama Formation, petrographic data show an increase in unstable minerals and a sedimentary source containing claystones, chert, glauconite and palaeocurrents towards the NW, which taken together could be interpreted as provenance from the Los Cobardes anticline–Mesas region. In addition to the sedimentary content, igneous and metamorphic clasts increase up-section, which together with palaeoflow components towards the north suggest that sediment sourced from the southern Central Cordillera was transported axially towards north. In the middle part of the Lisama Formation, an increase in crystalline clasts, plagioclase, volcanic lithics and palaeoflow towards the east is interpreted as the Central Cordillera provenance (Figs 4 & 13a). Therefore the Paleocene Lisama Formation was a tectonically controlled deposit in a regressive coastal plain basin. This basin could have been shed of sediment from lateral sources, but an axial component is more probably based on the northward palaeocurrent direction and the facies distribution with distal facies towards the north.

Two important aspects regarding the evolution of this area can be derived from the data and the cross section we present. First, thermochronology results indicate that the onset of exhumation occurred during the Late Cretaceous in the Cobardes anticline, but immediately after maximum palaeotemperatures were reached during the same period (Table 2). To reconcile both of these observations in the cross section, we include an early Paleocene state where almost no exhumation was present and a gentle deformation occurred in the Los Cobardes anticline–Mesas region. Thus, if sedimentation and deformation occurred simultaneously, it is possible to have had enough overburden on units above Late Cretaceous units to be reset for AFT at the western limb of the Cobardes anticline. It is also true that reworking of glauconite should point towards local exposure and recycling of Cretaceous units in the Cobardes anticline during the early Paleocene. However, since the section is a two-dimensional reconstruction, we chose to put more burial during the early Paleocene provided that in adjacent areas along-strike and in the same structure of the Los Cobardes anticline there should be erosion of either Lisama or Upper Cretaceous units. Our interpretation is supported by the lack of evidence for Paleocene deformation in the Santander Massif.

We interpret the change in thickness in the Lisama Formation from 950 to 710 m in the Nuevo Mundo syncline to <300 m in the Lisama oil field as being related to an evident erosional truncation of the Lisama Formation in front of the Nuevo Mundo syncline. This interpretation is further supported by seismic line 1 (Fig. 14b). The truncation resembles an eroded back-limb of a
basement-involved structure associated with a reverse fault or even inversion structures like those found in Parra et al. 2012 (Fig. 15) and in seismic line 2 (Fig. 14b). We therefore suggest that the thinning of the Lisama Formation is associated with a growing structure to the west, as can be seen in previous interpretations in the basin (Fig. 16). Provenance from the adjacent Los Cobardes anticline, east of the Nuevo Mundo syncline, shows that deformation was ongoing during the Paleocene in that area. However, most of the Lisama formation deposited in the early Paleocene there was eroded in the late Paleocene (Fig. 13b). In this context, the location of the provenance divide between western and eastern provenance sources in the Nuevo Mundo syncline is controlled by the growth of two structures: a basement structure west of the Lisama oil field and the growing Los Cobardes anticline to the east. The provenance divide axis (Fig. 7) during the Early Paleocene shows that the western basement structure was dominant, and this was even more remarkable during the late Paleocene.

**Early Eocene.** The base of the La Paz Formation shows less crystalline lithic content than the underlying Lisama Formation, and becomes compositionally more mature towards the top, suggesting the recycling of a sedimentary source. The basal conglomerate indicates recycling of vein quartz,
chert and red sedimentary lithics that indicate a source in the Jurassic red beds of the Girón Formation, and chert-bearing Cretaceous strata sources. The sedimentary facies suggest accumulation in a proximal alluvial setting in the southern part of the syncline and fluvial to the north. This and the palaeocurrent direction towards the north and NE indicate that the most probable source of sediment was located to the south. U–Pb data show an increase in the proportion of Central Cordillera provenance as well as local Jurassic sources. Both observations can be reconciled if a main drainage coming from the south sheds sediments that combine deeper erosional levels in the Central Cordillera with new nearby source areas providing sedimentary lithics from the Eastern Cordillera foothill structures to the south or local highs within the Middle Magdalena Valley Basin. An active Magdalena foothill belt in the western side of the Eastern Cordillera is reinforced by the fact that first the grain size of La Paz is coarser than Lisama, exhumation of the Eastern Cordillera is still allowed in the early Eocene by AFT and He models (see previous sections, Caballero et al. 2013 and Parra et al. 2012) and accumulation rates are faster in the La Paz Formation v. Lisama (since 1 km of sediment was deposited in c. 5 Ma during La Paz deposition and roughly the same amount was deposited in c. 10 Ma during deposition of Lisama).

The thinning of La Paz to the west is an additional conspicuous feature and we interpret that again as related with the growth of the contractional basement structure to the west (Fig. 16). In this scenario, the eastern movement of the provenance divide axis in the Nuevo Mundo syncline is concordant with a more dominant growth of the western basement structure on the basin that shed coarse sediments as a new source area (Figs 8 & 13c). We argue that activity of the Cobardes anticline during the early Eocene was less important than that of the basement structure that prompted the pinchout of La Paz. Furthermore, thermal histories restrict the level of exhumation that could have occurred at that time, as we show in the cross sections.

Late Eocene–Early Oligocene. Petrographic data for the Esmeraldas Formation indicates reduction in crystalline lithic content and recycling of sedimentary rocks because the sandstones are very mature. In the late Eocene, the spatial distribution of the Esmeraldas Formation is wider than the underlying La Paz Formation (e.g. Fig. 16) and the decrease in crystalline lithic content may be due to overburden of basement rocks from the Central Cordillera by sedimentary onlap and burial indicative of tectonic quiescence. The palaeoflow directions and the facies distribution indicate sources located towards the west and east. The recycling of sedimentary rocks, deduced from the increase in the sedimentary lithic fraction, probably reflects erosion of the underlying La Paz, Lisama, and possibly the Umír shales (Fig. 9). Several arguments support the hypothesis that tectonic activity coeval with the lower part of the Esmeraldas Formation was slower than in the previous and following phases.

- Abrupt decrease in unstable lithics v. quartz, and lithofacies that are considerably finer-grained than in La Paz conglomeratic sandstones and conglomerates.
An eastward advance of the sedimentation domain sourced in the Central Cordillera compared with the previous timeframe, as deduced from U–Pb data.

Lower accumulation rates as seen in the 1.2 km of sediments of the Esmeraldas Formation deposited in middle–late Eocene (c. 15 Ma), while a similar amount was deposited in 5 Ma during La Paz Formation deposition.

A westward advance of the pinchout (Fig. 16) of the unit compared with the underlying La Paz Formation. In this case we assume that a rapid east–west thinning of the units during the Palaeogene in the Nuevo Mundo syncline would be probably proportional to tectonic activity in the western basement structures.

The Middle Magdalena Valley basement highs in the west were covered by the Esmeraldas Formation, as observed in seismic lines (Fig. 15). Based on U–Pb data, the provenance axis dividing eastern v. western source areas advanced further to the east compared with the situation during the deposition of La Paz Formation. Therefore the sediments shed from Los Cobardes anticline were presumably less than during previous times (Fig. 9).

Our thermo-chronological data show that the initial exhumation of the Santander Massif started by the Late Eocene, which is the time of accumulation of the Esmeraldas Formation. This interpretation is confirmed by significant Palaeozoic and Grenville detrital zircon U–Pb populations observed in the Santos111 well (Fig. 9). Therefore we suggest a

---

**Fig. 16.** Interpretation of the Nuevo Mundo syncline at depth, showing that thinning of the Lisama Formation is associated to growing structures on the Middle Magdalena Valley Basin, west of the syncline (from Lopez et al. 2001).
scenario where the palaeocurrents and provenance show uplift of areas to the east of the Nuevo Mundo syncline, but the source area was not as close to the basin as it was during the deposition of La Paz and Lisama. Therefore the lithofacies in the Nuevo Mundo syncline were finer grained and with even more influence in the U–Pb age signal from the Central Cordillera compared with the previous times. Thus we suggest that a lateral equivalent, although thinner, of the Esmeraldas Formation covered most of the Cobardes anticline at that time. Based on these assumptions we produced the corresponding step in our kinematic restoration (Fig. 13d).

**Oligocene–Miocene.** Palaeocurrent measurements and facies distribution of the Mugrosa, Colorado and Real formations indicate proximal facies in the eastern part of the basin and distal facies towards the western part, suggesting adominant sediment source located on the eastern area of the basin. The provenance divide axis is radically pushed westwards (Fig. 10) in agreement with a dominant Eastern Cordillera and Santander Massif activity and influx of detritus.

Petrography in the lower part of the Oligocene Mugrosa Formation indicates recycling of chert with foraminifera from the Upper Cretaceous la Luna Formation. The upper part of the unit records increasing provenance from Cretaceous units and these sediments are interpreted as derived either from the Los Cobardes–Mesas region (Figs 4 & 13e) or from the Santander Massif.

Limestone clasts, pale sandstones and siltstones, and red sandstones and siltstones clasts in conglomerates of the lower part of the Colorado Formation, as well as the similar compositional fractions in arenites of the lower part of the Colorado Formation, are interpreted as a record of the exhumation of the limestones and sandstones of the Lower Cretaceous Rosablanca and Tambor and Jurassic red beds of Giron–Jordan units. Those units extensively crop out in the Cobardes anticline, but based on the available AFT models (Fig. 3c) and the A–He ages from those areas, denudation of new units was almost nothing from the early Miocene to the present. Therefore, the previous elastic composition and the igneous and metamorphic lithic content in sandstones and conglomerates on the lower part of the Colorado Formation unambiguously indicate exhumation of the Santander Massif (Figs 4 & 13f). Thus we interpret that most of the observed unroofing sequence corresponds to provenance from the Santander Massif, including the Rosablanca Formation limestones. In the Real Formation, the amount of igneous, sedimentary and metamorphic clasts, facies distribution and palaeocurrent indicates that unroofing of the Santander Massif continued during the deposition of this formation (Fig. 13g).

The Mugrosa and Colorado formations have a maximum thickness of c. 1.4 km each and were deposited in c. 10 and 7 Ma, respectively. These data document local sedimentation rates that are higher than the rates inferred for the deposition of the Esmeraldas Formation. This coincides with a coarsening upwards sequence from the Esmeraldas to the Colorado Formation. All these evidence, together with the westward advance of the domain of sediments sourced by the Eastern Cordillera, as deduced from U–Pb provenance data from the Esmeraldas to Colorado formations (Figs 9, 10 & 11), may indicate a more intense tectonic activity to the east during Colorado and Mugrosa deposition (Oligocene and Miocene) than during the deposition of the Esmeraldas Formation (late Eocene).

The Mugrosa and Colorado Formations thin to the west in the Nuevo Mundo syncline, but the structural cross section and the data from the Lisama oil field wells indicate that this is mostly related to the growth of the Lisama anticline (Fig. 13e, f). The Real Formation was described and sampled in its basal 1100 m, but the thickness of this unit may reach up to 3000 m in the Nuevo Mundo syncline. In addition, the Real Group in its type section at the North side of the Rio Opón is 4054 m thick (Ward et al. 1973) and was deposited in the late Miocene, encompassing c. 6 Ma of accumulation. These data document sedimentation rates even higher than the previous units, corresponding to the final stage of generalized uplift of the Santander Massif. All these elements agree with the advance to the west of the provenance divide deduced for the Real Formation based on U–Pb data.

**Tectonics and sedimentation**

Based on the previous evidence, we hypothesize that the periods of pronounced thinning and wedge-shape geometry of the units coincide with focused tectonic activity in two competing low relief structures: the Los Cobardes anticline and the western basement structures on the Middle Magdalena Valley Basin. The La Paz and Lisama formations are potential examples of deposition in an intermontane piggy-back basin adjacent to these structures with an inlet from the south bringing sediments from the Central Cordillera. In contrast, the deposition of the lower Esmeraldas Formation with a less pronounced westward thinning suggests tectonic quiescence. The Mugrosa and Colorado Formation in the Nuevo Mundo syncline again have wedge-shaped geometry owing to the growth of the Lisama structure at that time (Fig. 13e, f).

In summary, the thinning of the Cenozoic units in this region associated with growing structures
that control provenance and sedimentation patterns is formed in two stages. The first stage is a combination of the growth of basement-involved inversion structures to the west and hinterland tectonic loading to the east in the early Palaeogene. Second, the growth of thin-skinned structures to the west and enhanced dominant load of the Eastern Cordillera in the hinterland occurs in the late Palaeogene–Neogene. The dominant growth of the structures either to the east or west of the Nuevo Mundo syncline controls the position of the local provenance divide deduced from the U–Pb data.

In addition these differential and competing growth of structures on both sides in the Nuevo Mundo syncline throughout the Cenozoic together created a large, original taper with units that rapidly thickened to the east, which whenever the basal, Upper Cretaceous detachment unit of the Umir Formation was deep enough, reduced its basal friction and prompted the advance of a new and thin-skinned thrust sheet in the late Miocene (La Salina Fault). This is in contrast with the Llanos foothills (Delgado et al., 2012), where a larger taper is created by flexural reactivation of normal faults under tectonic loads in the Eastern Cordillera. This component, although not documented in our study area, is schematically shown in our cross sections (Fig. 13). In addition, coinciding with the available models for the eastern foothills (Linares & Rowan 2000; Mora et al. 2006a, 2009, 2010a), we hypothesize from our cross section that the precise place where the La Salina fault ramps up from the basement to reach the upper Umir detachment is controlled by the location of an ancestral, buried normal fault. An additional important tectons and sedimentation relationship is the fact that probably the larger taper angle imposed by different factors acting through the Cenozoic in this area is the reason why the Nuevo Mundo syncline is mostly an advancing west-vergent thrust devoid of east-vergent passive roof duplexes in contrast with the Llanos Foothills (Mora et al. 2010a). The hindward (east in this case) dip of the basement as a control on thrustbelt geometry has been previously proposed by Boyer (1995) and documented in the Llanos Foothills (Boyer 1995; Mora et al. 2010b).

The data we show illustrates that the Nuevo Mundo area is therefore a key location to understand the feedbacks between facies and stratigraphic geometries v. tectonic activity.

Finally it is worth noting that the increasing grain size from the Esmeraldas throughout the Mugrosa to the Colorado Formation (Fig. 4) shows a similar behaviour to that observed in coeval units in the Medina syncline, on the opposite, eastern foothill side of the Eastern Cordillera. In the Medina basin, Parra et al. (2010) identified a coarsening upward cycle of the same age and facies with similar thickness, starting with the sedimentation of the Middle Eocene–upper Mirador Formation under very low accumulation rates. This confirms the extent to which the Oligocene–Miocene tectonism was a regional event with a highly symmetrical distribution on both foothills of the Eastern Cordillera.

This study was funded by theproject ‘Cronología de la deformación en las Cuencas Subandinas’ of ECOPETROL-ICP. The author appreciates the detailed reviews by two anonymous reviewers and Dr M. Nemčok for recommendations that improved the manuscript.

References

ACOSTA, J. E. 2002. Structure, Tectonics and 3D Models of the Western foothills of the Eastern Cordillera and Middle Magdalena Valley, Colombia. Imperial College of Science Technology and Medicine.

BOYER, S. E. 1995. Sedimentary basin taper as a factor controlling the geometry and advance of thrust belts. American Journal of Science, 295, 1220–1254.

BURNHAM, A. K. & Sweeney, J. J. 1989. A chemical kinetic model of vitrinite maturation and reflectance. Geochemica et Cosmochimica Acta, 53, 2649–2657.

CABALLERO, V., PARRA, M. & MORA, A. 2010. Levantamiento de la Cordillera Oriental de Colombia durante el Eoceno tardío–Oligoceno temprano: proveniencia sedimentaria en el Sinclinal de Nuevo Mundo, Cuenca Valle Medio del Magdalena. Boletín de Geología, Universidad Industrial de Santander, 32, 45–77.

CABALLERO, V., PARRA, M., MORA, A., LOPEZ, C., ROJAS, L. E. & QUINTERO, I. 2013. Factors controlling selective abandonment and reactivation in thick skin orogens: a case study in the Magdalena Valley, Colombia. In: Nemčok, M., Mora, A. & Cosgrove, J. W. (eds) Thick-Skin-Dominated Orogenes: from Initial Inversion to Full Accretion. Geological Society, London, Special Publications, 377, First published online March 25, 2013, http://dx.doi.org/10.1144/SP377.4

CIAVU, J., MANTILLA, L. C., PINTO, J., BERNAL, L. & PEREZ, A. 2008. Evolución geológica de la Serranía de San Lucas, Norte del Valle Medio del Magdalena y Noroeste de la Cordillera Oriental. Boletín de Geología, Universidad Industrial de Santander, 30, 45–62.

COLLETTA, B., HEBBARD, F., LETOUZEY, J., WERNER, P. & RUDKIWEicz, J. L. 1990. Tectonic style and crustal structure of the Eastern Cordillera, Colombia from a balanced cross section. In: LETOUZEY, J. (ed.) Petroleum and Tectonics in Mobile Belts. Editions Technip, Paris, 81–100.

COOPER, M. A. & WILLIAMS, C. M. 1989. Inversion Tectonics. Geological Society of London, London, Special Publications, 44.

COOPER, M. A., ADDISON, F. T. ET AL. 1995. Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia. American Association of Petroleum Geologists Bulletin, 79, 1421–1443.
DeCelles, P. G. & Giles, K. A. 1996. Foreland basin systems. *Basin Research*, 8, 105–123.

DeCelles, P. G., Langford, R. P. & Schwartz, R. K. 1983. Two new methods of paleocurrent determination from trough cross-stratification. *Journal of Sedimentary Petrology*, 53, 629–642.

Delgado, A., Mora, A. & Reyes-Harker, A. 2012. Deformation partitioning in the Llanos foreland basin during the Cenozoic and its correlation with mountain building in the hinterland. *Journal of South American Earth Sciences*, 39, 228–244.

Dengo, C. A. & Covey, M. C. 1993. Structure of the Eastern Cordillera of Colombia: implications for trap styles and regional tectonics. *American Association of Petroleum Geologists Bulletin*, 77, 1315–1337.

Dickinson, W. R. 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, B. B. (ed.) *Provenance of Arenites*. Reidel, Dordrecht, 333–361.

Donellick, R. A., O’Sullivan, P. B. & Ketcham, R. A. 2005. Apatite fission-track analysis. In: Reiners, P. W. & Ehlers, T. A. (eds) *Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Reviews in Mineralogy and Geochemistry*. Mineralogical Society of America, Washington, DC, 58, 49–94.

Ehlers, T. A. & Farley, K. A. 2003. Apatite (U-Th)/He thermochronometry: methods and applications to problems in tectonic and surface processes. *Earth and Planetary Science Letters*, 206, 1–14.

Etayo-Serna, F., Renzoni, G. & Barrero, D. 1969. Contornos sucesivos del mar Cretaceo en Colombia. *Primer congreso Colombiano de Geología, Memorias*, 1, 217–252.

Farley, K. A. 2002. (U–Th)/He Dating: Techniques, Calibrations, and Applications: Pasadena, California, Division of Geological and Planetary Sciences. California Institute of Technology, Pasadena, California.

Galbraith, R. F. 1981. On statistical models for fission-tracks counts. *Journal of the International Association for Mathematical Geology*, 13, 471–478, doi: 10.1007/BF01034498

Gleadow, A. J. W. 1981. Fission-track dating methods: what are the real alternatives? *Nuclear Tracks*, 5, 3–14.

Gómez, E. 2001. Tectonic controls on the Late Cretaceous to Cenozoic sedimentary fill of the Middle Magdalena Valley Basin, Eastern Cordillera and Llanos Basin, Colombia. PhD Thesis, Cornell University, USA.

Gómez, E., Jordan, T. E., Allmendinger, R. W., Hegarty, K. & Kelley, S. 2005b. Syntectonic Cenozoic sedimentation in the northern middle Magdalena Valley Basin of Colombia and implications for exhumation of the Northern Andes. *Geological Society of America Bulletin*, 117, 1272–1292.

Gómez, E., Jordan, T. E., Allmendinger, R. W., Hegarty, K. & Kelley, S. 2005b. Syntectonic Cenozoic sedimentation in the northern middle Magdalena Valley Basin of Colombia and implications for exhumation of the Northern Andes. *Geological Society of America Bulletin*, 117, 547–569.

Green, P. F. 1981. A new look at statistics in fission track dating. *Nuclear Tracks*, 5, 77–86, doi:10.1016/0191-278X(81)90029-9

Horton, B. K., Saylor, J. E., Nie, J., Mora, A., Parra, M., Reyes-Harker, A. & Stockli, D. F. 2010. Linking sedimentation in the northern Andes to basement configuration, Mesozoic extension, and Cenozoic shortening: evidence from detrital zircon U–Pb ages, Eastern Cordillera, Colombia. *The Geological Society of America Bulletin*, 92, 1423–1442.

Jaramillo, C., Rueda, M. & Torres, V. 2011. A Palynological Zonation for the Cenozoic of the Llanos and Llanos Foothills of Colombia. *Palynology*, 35, 46–84.

Jordan, T. E. 1981. Thrust loads and foreland basin evolution, Cretaceous, western United States. *American Association of Petroleum Geologists Bulletin*, 65, 2506–2520.

Jordan, T. E., Flemings, P. B. & Beer, J. A. 1988. Dating thrust fault activity by use of foreland-basin strata. In: Klepeish, K. L. & Paola, C. (eds) *New Perspectives in Basin Analysis*. Springer, New York, 307–330.

Julivert, M. 1963. Nuevos datos sobre la dinámica del ámbito del Macizo de Santander durante el Secundario (Cordillera Oriental, Colombia). *Boletín de Geología, Universidad Industrial de Santander*, 12, 45–49.

Julivert, M. 1970. Cover and basement tectonics in the Cordillera Oriental of Colombia, South America, and a comparison with some other folded chains. *Geological Society of America Bulletin*, 81, 3623–3646.

Ketcham, R. A. 2005a. Forward and inverse modeling of low-temperature thermochronometry data. In: Reiners, P. W. & Ehlers, T. A. (eds) *Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Reviews in Mineralogy and Geochemistry*. Mineralogical Society of America, Washington, DC, 58, 275–314.

Ketcham, R. A. 2005b. HeFTy: forward and inverse modeling thermochronometer systems. In: Willet, S. D., Fuller, C. W., Ketcham, R. A., Brandon, M. T., Gleadow, J. W., Kohn, B., Belton, D. X., Dunai, T. J. & Fu, F. Q. (eds) *Computational Tools for Low-Temperature Thermochronometer Interpretation*. Mineralogical Society of America, Chantilly, VA.

Ketcham, R. A., Carter, A., Donellick, R. A., Barberand, J. & Hurford, A. J. 2007. Improved modeling of fission-track annealing in apatite. *American Mineralogist*, 92, 799–810.

Leeder, M. R. & Gawthorpe, R. L. 1987. Sedimentary models for extensional tilt-block/half-graben basins. In: Cowars, M. P., Dewey, J. F. & Hancock, P. L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, 28, 139–152.

LinareS, R. & Rowan, M. G. 2000. Fold-evolution matrices and axial-surface analysis of fault-bend folds: application to the Medina Anticline, Eastern Cordillera, Colombia. *American Association of Petroleum Geologists*, 84, 741–764.

Lopez, C., Fabio, C., Rolón, L., Jaramillo, L. A., Buchelli, F. & Sotelo, C. I. 2001. *Proyecto Evaluación Regional Cuencas Valle Medio del Magdalena – Cordillera Oriental, Colombia, Empresa Colombiana de Petróleos*. Bogotá, Internal Report.

Mora, A. & Parra, M. 2008. The structural style of footwall shortcuts along the eastern foothills of the Colombian Eastern Cordillera: differences with other inversion-related structures. *Revista CTA&F*, 3, 7–21.
Mora, A., Parra, M., Strecker, M. R., Kammer, A., Dematé, C. & Rodriguez, F. 2006. Cenozoic contractional reactivation of Mesozoic extensional structures in the Eastern Cordillera of Colombia. Tectonics, 25, TC2010, doi: 10.1029/2006TC001854.

Mora, A., Gaona, T. et al. 2009. The role of inherited extensional fault segmentation and linkage in contractional orogenesis: a reconstruction of Lower Cretaceous rift basin in the Eastern Cordillera of Colombia. Basin Research, 21, 111–137.

Mora, A., Horton, B. K. et al. 2010a. Migration of Cenozoic deformation in the eastern Cordillera Colombia interpreted from fission track results and structural relationships: implications for petroleum systems. American Association of Petroleum Geologists Bulletin, 94, 1543–1580.

Mora, A., Parra, M., Strecker, M. R., Sobel, E. R., Zeilinger, G., Jaramillo, C., Ferreira Da Silva, S. & Blanco, M. 2010b. The eastern foothills of the Eastern Cordillera of Colombia: An example of multiple factors controlling structural styles and active tectonics. Geological Society of America Bulletin, 122, 1846–1864, doi: 10.1130/B30033.1

Morales, L. G., COLOMBIAN PETROLEUM INDUSTRY 1958. General geology and oil occurrences of the Middle Magdalena Valley, Colombia. In: Weeks, L. G. (ed.) Habitat of Oil: A Symposium. American Association of Petroleum Geologists, Tulsa, OK, 641–695.

Moreno, C. J., Horton, B., Caballero, V., Mora, A., Parra, M. & Sierra, J. 2011. Depositional and provenance record of the Paleogene transition from foreland to hinterland basin evolution during Andean orogenesis, northern Middle Magdalena Valley basin, Colombia. Journal of South American Earth Sciences, 32, 246–263.

Moreno, N., Silva, A. et al. In press. Interaction between thin- and thick-skinned tectonics in the foot-hill areas of an inverted graben. The Middle Magdalena Foothill belt. In: Nemcok, M., Mora, A. & Cosgrove, J. W. (eds) Thick-Skin-Dominated Orogens: from Initial Inversion to Full Accretion. Geological Society, London, Special Publications, http://dx.doi.org/10.1144/SP377.18

Morley, C. K. 1989. Basin inversion in the Osen-Roa thrust sheet, southern Norway. In: Cooper, M. A. & Williams, G. D. (eds) Inversion Tectonics, Geological Society, London, Special Publications, 44, 259–273.

Nie, J., Horton, B. K., Mora, A., Saylor, J. E., Housh, T. B., Rubiano, J. & Naranjo, J. 2010. Tracking exhumation of Andean ranges bounding the Middle Magdalena Valley Basin, Colombia. Geological Society of America Bulletin, 38, 451–454.

Nie, J., Horton, B. K. et al. 2012. Integrated provenance analysis of a convergent retroarc foreland system: U-Pb ages, heavy minerals, Nd isotopes and sandstone compositions of the Middle Magdalena Valley basin, northern Andes, Colombia. Earth Science Reviews, 110, 111–126.

Parra, M., Mora, A., Sobel, E. R., Strecker, M. R. & González, R. 2009. Episodic orogenic-front migration in the northern Andes: constraints from low-temperature thermochronology in the Eastern Cordillera, Colombia. Tectonics, 28, TC4004, doi: 10.1029/2008TC002423.

Parra, M., Mora, A., Jaramillo, C., Torres, V., Zeilinger, G. & Strecker, M. R. 2010. Tectonic controls on Cenozoic foreland basin development in the north-eastern Andes, Colombia. Basin Research, 22, 874–903.

Parra, M., Mora, A., Lopez, C., Rojas, L. E. & Horton, B. K. 2012. Detecting earliest shortening and deformation advance in thrust-belt hinterlands: Example from the Colombian Andes. Geology, 40, 175–178, doi: 10.1130/G32519.1

Rodriguez-Forero, G., Obio-Ikuenobe, F., Jaramillo, C., Rueda, M. & Cadena, E. 2012. Palynology of the Eocene Esmeraldas Formation, Middle Magdalena Valley, Colombia. Palynology, 36 (suppl. 1), 96–111.

Saylor, J. E., Horton, B. K., Nie, J., Corredor, J. A. & Mora, A. 2011. Evaluating foreland basin partitioning in the northern Andes using Cenozoic fill of the Floresta basin, Eastern Cordillera, Colombia. Basin Research, 23, 377–402.

Schlische, R. W. 1991. Half-graben basin filling models: new constraints on continental extensional basin development. Basin Research, 3, 123–141.

Silva, A., Mora, A. et al. In press. Basin compartmentalization and drainage evolution during rift positive inversion: evidence from multiple techniques in the Eastern Cordillera of Colombia. In: Nemcok, M., Mora, A. & Cosgrove, J. W. (eds) Thick-Skin-Dominated Orogens: from Initial Inversion to Full Accretion. Geological Society, London, Special Publications, 377, http://dx.doi.org/10.1144/SP377.15

Tagami, T. & O’Sullivan, P. B. 2005. Fundamentals of fission-track thermochronology. In: Reiners, P. W. & Ehlers, T. A. (eds) Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Reviews in Mineralogy and Geochemistry. Mineralogical Society of America, Washington, DC, 58, 19–47.

Tesón, E., Mora, A. et al. In press. Relationship of Mesozoic graben development, stress, shortening magnitude, and structural style in the Eastern Cordillera of the Colombian Andes. In: Nemcok, M., Mora, A. & Cosgrove, J. W. (eds) Thick-Skin-Dominated Orogens: from Initial Inversion to Full Accretion. Geological Society, London, Special Publications, 377, http://dx.doi.org/10.1144/SP377.10

Villagómez, D. R. 2010. Thermochronology, geochronology and geochemistry of the Western and Central Cordilleras and Sierra Nevada de Santa Marta, Colombia: The tectonic evolution of NW South America. Université de Genève, Geneva.

Ward, D. E., Goldsmith, R., Cruz, J. & Restrepo, A. 1973. Geología de los cuadrángulos H-12 Bucaramanga y H-13 Pamplona, departamentos de Santander y Norte de Santander. Boletín Geológico, Bogotá.

Williams, C. M. & Cooper, M. A. 1989. Geometry and Kinematics of Inversion Tectonics. Geological Society, London, Special Publications, 44, 3–15.

Zoetemeijer, R. 2002. Tectonics and Basin Formation in Convergent Settings, 3rd Sedimentation and Tectonics Intensive. Universiteit Joseph Fourier – Grenoble, Department of tectonics, Faculty of Earth Sciences Vrije Universiteit, Amsterdam.