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The paleogene synorogenic succession in the northwestern Maracaibo block: Tracking intraplate uplifts and changes in sediment delivery systems

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The integration of sandstone petrography, detrital zircon U-Pb ages, and sedimentological data was carried out for lower Paleogene rocks in four sections of the western Maracaibo Block, allowing for the documentation of a shift from regional to localized fluvial drainage systems associated with intraplate uplifts.

The lower to middle Paleocene units have similar thicknesses, and show a depositional profile varying northward from fluvial-estuarine environments to shallow marine carbonates. Sandstones show high quartz percentages (up to 80%) and detrital zircon age populations are dominantly older than 0.9 Ga (with peaks in 1.55 and 1.8 Ga), with minor populations in the range of 400–600 Ma. In contrast, the upper Paleocene units were deposited in marginal, coal-rich environments, and have strong variations in thickness among the four studied areas. These sandstones show quartz percentages between 40 and 70%, and have a significant increase in metamorphic fragments (approximately 13% of the total framework) as compared to the lower Paleocene sandstones (5–7% of metamorphic lithic fragments). The lower Eocene sandstones, on the other hand, show an increase in k-feldspars and quartz content. The detrital zircon age populations for the upper Paleocene and lower Eocene sandstones in the western sections show a strong decrease in ages from 1.3 to 2.5 Ga and an increase in ages from 55 to 360 Ma; in contrast, age populations older than 0.9 Ga persist in the southern section.

The lower-middle Paleocene rocks suggest a regional, basin-wide drainage system fed by the Cretaceous sedimentary cover exposed in low-amplitude localized uplifts and developed a mixed siliciclastic-carbonatic platform in the shelf areas. On the other hand, the upper Paleocene-lower Eocene synorogenic succession accumulated in several basin compartments separated by more pronounced source areas and recorded the introduction of new ones. These sandstones contain basement rock fragments from marginal uplifts of the Santa Marta Massif and the Central Cordillera, as well as fragments from emerging intraplate ranges, such as the Perijá Range and the Santander massif. Caribbean subduction along the northwestern margin of South America induced tectonic changes inside the Maracaibo Block, modifing sedimentary depocenters from a regional basin (ca. 300 km width) to isolated intermontane basins, which have been separated since the late Paleocene to present.

1. Introduction

The integrated analysis of provenance markers reflects changes in an array of river drainages within a syntectonic sedimentary basin (e.g., Dickinson, 1988; Cibin et al., 2003; Lawton et al., 2003). The uplifting of intraplate ranges, which compartmentalizes former regional sedimentary basins and creates intermontane basins, drives the shift from large- to small-scale drainage networks and induces change in sedimentary environments (Horton, 2005; Sobel and Strecker, 2003; Hilley and Strecker, 2005; Siks and Horton, 2011; Hain et al., 2011; Moreno et al., 2011; Strecker et al., 2011). Large rivers cover extensive areas, and their sediment load carries valuable information about tectonic evolution and the composition of distant sources (Miall, 1996). In tropical areas like the northern Andes, unstable detritus can be lost by chemical weathering in source areas or during temporal storage, with sandstone as a result becoming quartz-rich at distances of more than 100 km away

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(Amorocho et al., 2011; Johnsson et al., 1991); geochemical signatures and detrital zircon populations, however, are left behind (Gibbs, 1967; Xie et al., 2010). In contrast to large river systems, small drainages of intermontane basins are more likely to preserve the composition of surrounding source areas; the conservation of the original sand composition, however, ultimately depends also on climate, rates of tectonic subsidence, and diagenesis (Miall, 1996; Paola, 1988).

Presently, the western Maracaibo block in the northern Andes is segmented by marginal and intraplate uplifts (Fig. 1); we analyzed the lower Paleogene succession of four stratigraphic sections located in different compartments in order to determine when those basins became segmented. The triangle-shaped Maracaibo block is bounded to the west by the Santa Marta-Bucaramanga fault system, to the north by the Oca fault, and to the southeast by the Mérida Andes. Published Late Cretaceous paleogeographic maps indicate that depositional systems from the Magdalena Valley to the Maracaibo block were connected, with a distal source area to the southeast (Guiana shield; Pindell et al., 1998; Villamil, 1999). Orogenic processes during the Cenozoic created intermontane basins like Middle Magdalena and Cesar-Ranchería basins (Fig. 1); however, the time when marginal (Santa Marta massif) and intraplate ranges (Santander-Floresta massifs, Perijá range, Mérida Andes) emerged is still controversial (see Bayona et al., 2008 and Saylor et al., 2011 for discussion). Although Neogene compressional events caused the main uplifts (kilometer-scale) and exposed most of the basements (Kellogg, 1984; Shagam et al., 1984; Parra et al., 2009), it is important to consider previous fault activity and block uplifting. Such activity could have compartmentalized the basins and caused lateral thickness variations, as well as changes in depositional environments and the sediment delivery systems associated with the presence of sedimentary barriers.

In this study, we compare provenance markers and sedimentological data in order to test whether changes in provenance and conditions of deposition are related to sediment supply from a distal source area versus multiple nearby source areas in the western Maracaibo block. New detrital zircon U-Pb ages and petrographic data from two localities in the western Maracaibo Basin (northwestern Maracaibo and Catatumbo) were collected and compared with published data from the Cesar-Ranchería Basin (Bayona et al., 2007, 2011; Ayala-Calvo et al., 2009; Cardona et al., 2011) and the central-east Maracaibo Basin (Xie et al., 2010). Palynological analyses in the four studied areas (Jaramillo, 1999; Jaramillo et al., 2007; Mora et al., 2006) and detrital syndepositional volcanic zircon ages (Bayona et al., 2011; Cardona et al., 2011; this study) constrain the stratigraphic correlation of Paleogene units. Finally, we construct paleogeographicpaleogeographic maps between 65 and 35 Ma to show basin evolution and uplifts in the western Maracaibo block and northern Colombia basins when the Caribbean Plate was advancing around northwestern South America.

2. Geological setting

2.1. Tectonic constraints of the Maracaibo block and associated basins

Sedimentary filling of the Maracaibo block basins began during the Jurassic-Neocomian where the accumulation of red beds, volcaniclastic, and siliciclastic rocks took place in extensional basins (Maze, 1984; Lugo and Mann, 1995). From the Aptian to the Campanian, a regional marine transgression developed an epicontinental sea, and carbonate strata accumulated in the Maracaibo block (Martínez and Hernandez, 1992). By the end of the Cretaceous, marine shales completely covered the Maracaibo block, as well as the Eastern Cordillera, whereas craton-derived quartzose sandstone beds accumulated farther south. Late Cretaceous paleogeographic reconstructions show a regional marine basin bordered to the east and south by the Guiana shield (Etayo-Serna

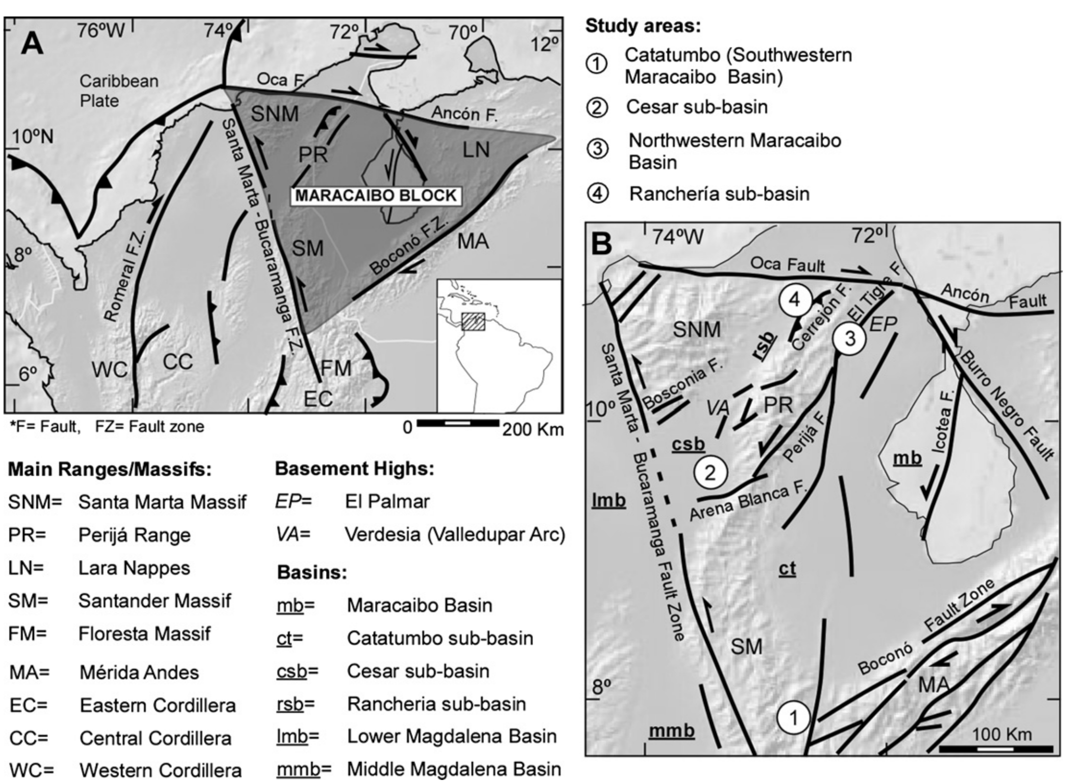

Fig. 1. A: Map of northern Colombia showing main massifs-Ranges and regional faults. B: Detail of western Maracaibo block and location of study areas.

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et al., 1976; Cooper et al., 1995; Lugo and Mann, 1995; Villamil, 1999).

Since the Campanian, the collision of the Great Arc of the Caribbean over northern South America (Burke, 1988; Cardona et al., 2011) caused a diachronous uplift of the Central Cordillera and the Santa Marta Massif, filling adjacent synorogenic basins (Touisaint, 1999; Restrepo et al., 2009; Bayona et al., 2011). The subduction of the Caribbean Plate under the northwestern South American margin began at the Paleocene (ca. 65 Ma), causing granitic intrusions and metamorphism of collisional units in the northwestern corner of the Santa Marta Massif (Cardona et al., 2011). This event was followed by the marginal uplift of the Santa Marta Massif, which increased the tectonic subsidence rates of adjacent basins (Bayona et al., 2011). From the early to middle Eocene, the Lara Nappes accreted to the northern Maracaibo Basin (Mann et al., 2006) and created a foreland basin, where a thick belt (up to 7 km) of Eocene rocks were deposited at the northeastern edge of the present-day Maracaibo Lake (Lugo and Mann, 1995). The Paleocene carbonate platform was exposed in the south and created an unconformity as the forebulge migrated (Escalona and Mann, 2006). In the late Eocene, an isostatic rebound eroded a large amount of Eocene sediments (Escalona and Mann, 2006).

Intense deformational events during the Neogene (Andes Orogeny: Cooper et al., 1995; Villamil, 1999) caused major vertical uplifts, mainly resulting in the Eastern Cordillera, the Santander Massif, the Perijá Range, and the Mérida Andes (Duerto et al., 2006). Fission-track analyses in those areas suggest kilometer-scale erosion from the early Miocene to the Pliocene (Ross et al., 2009; Parra et al., 2009; Mora et al., 2010; Bermúdez et al., 2010, 2011). The extensional faults that were formed during the Mesozoic back-arc phase were also inverted (Duerto et al., 2006). Nevertheless, some pre-Neogene activity was recorded in those ranges. Jurassic rocks at the west of Santander Massif (Ross et al., 2009) and in the western foothills of the Santa Marta Massif (Villagómez et al., 2011a) recorded an early Paleocene phase of deformation. In the northern Perijá Range, normal fault reactivation has been recorded since the late Paleocene (Quijada and Cassani, 1997; Montes et al., 2005; Bayona et al., 2011). Kellogg (1984) proposed that uplift of basement blocks of the northern Perijá Range occurred during the Oligocene based on thermochronological data and kinematic restoration of a balanced cross section, but also recognized that tectonic events had occurred since the early Eocene. On the other hand, a late Eocene uplift of the Perijá Range associated with the clockwise rotation of the Maracaibo has been suggested by Montes et al. (2010). Castillo and Mann (2006) identified some uplifts for the Perijá Range and southwestern Mérida Andes since the Oligocene, and major uplifts in the Late Miocene-Pliocene, forming structures at the southern Maracaibo Basin. Duerto et al. (2006) placed the timing of the main uplift in the Perijá Range in the late Oligocene. Thermochronological studies of basement rocks from the Santander Massif, Eastern Cordillera, and Mérida Andes show evidence of exhumation since the late Eocene in the Floresta Massif, since the Oligocene in the Eastern Cordillera and southwestern Mérida Andes, and major vertical uplifts of all these ranges in the late Miocene-Pliocene (Ross et al., 2009; Parra et al., 2009; Mora et al., 2010; Bermúdez et al., 2010).

Currently, the study areas are separated by ranges and basement highs (Fig. 1). The Perijá Range and the northern portion of the Santander Massif separate the Cesar-Ranchería intermontane Basin (to the west) from the Maracaibo Basin (to the east). In the same way, the Cesar and Ranchería sub-basins are divided at the subsurface level by the basement arc known as the Valledupar Arc. In addition, El Palmar High separates the Manuelote syncline from the northwestern segment of the Maracaibo Basin (Kellogg, 1984). The Catatumbo sub-basin is located at the southwestern margin of the Maracaibo Basin and the foothills of the Santander Massif; our analyzed samples were taken from the foothills area (Fig. 1).

2.2. U-Pb ages and composition of possible source areas

The northeastern Colombian massifs and ranges have units with characteristic U-Pb ages from the mid-Proterozoic to the Paleogene (from 1550 to 50 Ma, Fig. 2) (Cardona et al., 2006; Cardona et al., 2009; Clavijo et al., 1996), whereas the assemblage of ages reported in the Amazonian craton (Guaporé and Guiana shields) include rocks older than 1500 Ma (Tassinari and Macambira, 1999).

In the Santa Marta Massif, Jurassic plutonic and volcaniclastic rocks are the most abundant (Tschanz et al., 1974). Some Mesoproterozoic high-grade metamorphic rocks (granulites, migmatites) associated with the Greenvillian accretional event are found as isolated outcrops in the area as well (Cordani et al., 2005). Permo-Triassic metamorphic and granitic rocks are found in the Sevilla Complex to the northwest of the Santa Marta Massif, which are associated with Pangea formation (Cardona et al., 2010). Remnants of the Caribbean arc outcrop in the northwestern corner of the area (schists and Cretaceous-Paleogene intrusive bodies: Bustamante and Saldarriaga, 2007; Cardona et al., 2011).

Paleozoic metasedimentary-sedimentary rocks are found in the Perijá Range (Forero, 1970), intruded by granites (310–385 Ma for the Lajas Granite: Dasch, 1982). Volcaniclastic and sedimentary Jurassic rocks (140–167 Ma, Dasch, 1982) reach thousands of meters thick, forming a graben depocenter during the extensional phase (González de Juana et al., 1980). These Jurassic rocks are covered by Cretaceous marine rocks (Miller, 1962). In the eastern flank of the Perijá Range (western Maracaibo foothills), a basin-dipping monocline of Paleogene-Neogene rocks is found (Duerto et al., 2006).

The Central Cordillera has an association of rock lithologies and ages similar to the Santa Marta Massif, comprising of Mesoproterozoic high-grade metamorphic rocks (Cordani et al., 2005; García et al., 2009), Jurassic volcaniclastic rocks (Clavijo et al., 2008), and Permo-Triassic two-mica granitoids, ranging from 300 to 211 Ma (Vinasco et al., 2006; McCourt et al., 1984; Ibañez et al., 2008; Rodríguez-Jimenez, 2010). Abundant metamorphic rocks from the Lower Paleozoic (Cajamarca Complex: Maya and González, 1995) and large granitic bodies from the Late Cretaceous (i.e. Antioquian Batholith: Ibañez-Mejía et al., 2007; Ordóñez et al., 2008) are also found in the Central Cordillera. In fact, the Santa Marta Massif and the Central Cordillera were connected until the late Eocene (Villamil, 1999); Gómez et al. (2005) related the separation of the two to strike-slip movements of the Santa Marta-Bucaramanga fault. On the other hand, Montes et al. (2010) proposed that the clockwise rotation of the Santa Marta Massif and the aperture of Lower Magdalena Basin was the main cause of separation of those ranges; the evidence for this hypothesis included observations of Permo-Triassic rocks in the Lower Magdalena Basin basement, Eocene contractional processes in the Ranchería Basin, extensional deformation in the Lower Magdalena Basin, and paleomagnetic data.

The Santander and Floresta Massifs have lower Paleozoic metasedimentary and intrusive granitic rocks (Mojica and Villarroel, 1984), ranging from 522 to 392 Ma (U-Pb ages for Otenga Granite and Pamplona Orthogneiss: Horton et al., 2010a; Banks et al., 1985; Restrepo-Pace, 1995). These zircon ages are related to Paleozoic orogenic and tectonomagmatic events (Shagam, 1975). Cambro-Ordovician age populations are very common in Paleozoic and Jurassic sedimentary rocks (see detrital zircon data in Horton et al., 2010a). Dörr et al. (1995) reported Triassic-Jurassic ages (205–210 Ma) in Paramo Rico granodiorite. Some Jurassic,

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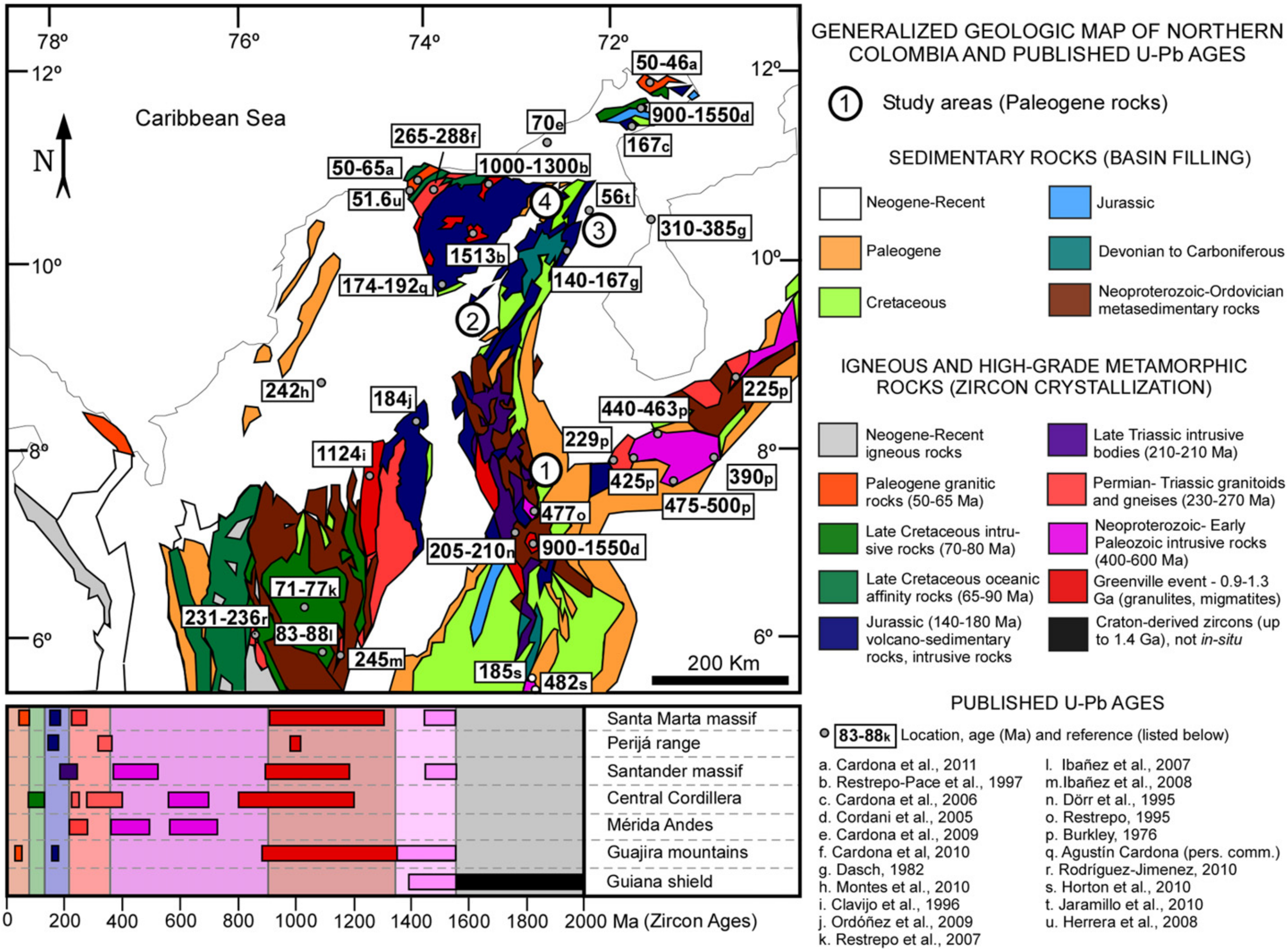

Fig. 2. Generalized geological map of northern Colombia and published U-Pb data over igneous/metamorphic rocks. Geological information was taken from Tschanz et al. (1974), Gómez et al. (2007) and PDVSA-INTEVEP (2007).

syndepositional ages (185 Ma) were also found in Girón formation samples (Horton et al., 2010a).

The Mérida Andes has Neoproterozoic high to medium-grade metamorphic rocks (Iglesias Complex, Bellavista association: PDVSA, 2008) with U-Pb ages from 720 to 585 Ma (Burkley, 1976). Paleozoic sedimentary and metasedimentary rocks, with abundant marine fauna (e.g. graptolites, brachiopods, and bryozoans), were intruded by granitic bodies with crystallization ages between 500 and 425 Ma (González de Juana et al., 1980). Some Triassic intrusive bodies were also found in this area (225–229 Ma; Burkley, 1976).

2.3. The lower Paleogene stratigraphic succession in the study area

In this section, we summarize the lower Paleogene stratigraphy of the study areas (Catatumbo, Cesar, Ranchería, and northwestern Maracaibo, Fig. 1), grouping formal stratigraphic units into four intervals of time. Units have been dated by Palynology (Jaramillo, 1999; Jaramillo et al., 2007; Mora et al., 2006) and syndepositional detrital zircon ages (Bayona et al., 2011; Cardona et al., 2011; this study).

2.3.1. Lower-middle Paleocene units

In the Catatumbo and Cesar sub-basins, the sandy Barco Formation overlies the fine-grained Catatumbo Formation. In contrast, to the north, the coeval units in the Ranchería sub-basin and the northwestern Maracaibo Basin include mixed siliciclastic and carbonate units of the Hato Nuevo-Manantial and Guasare Formations. The Catatumbo Formation consists mainly of fine-grained strata accumulated in estuarine to coastal plain environments (Ayala-Calvo et al., 2009; PDVSA, 2008). The Barco Formation is a sandy unit deposited in a fluvio-estuarine environment, with glauconite and phosphates in the Catatumbo sub-basin (Escalante and Rojas, 1991), as well as upward-fining successions and amalgamated sandy bodies, which are characteristics of meandering and straight rivers (Ayala, 2009). The Hato Nuevo-Manantial and Guasare Formations mainly consist of glauconitic limestone and calcareous glauconitic sandstone beds that accumulated in shallow marine environments. All of these units were deposited in a continuous depositional profile, varying from siliciclastic estuarine-fluvial environments in the south (Catatumbo and Barco Formations) to shallow marine environments in the central-northern Maracaibo Block (Fig. 3).

2.3.2. Upper paleocene units

The contacts between the Barco-Cuervos (Cesar and Catatumbo sub-basins), Manantial-Cerrejón (Ranchería sub-basin), and Guasare-Marcelina Formations (northwestern Maracaibo Basin) are transitional. The four study areas have a common lithological succession that includes mudstone interbedded with lithic-and feldspar-bearing sandstone beds and thick coal seams. These

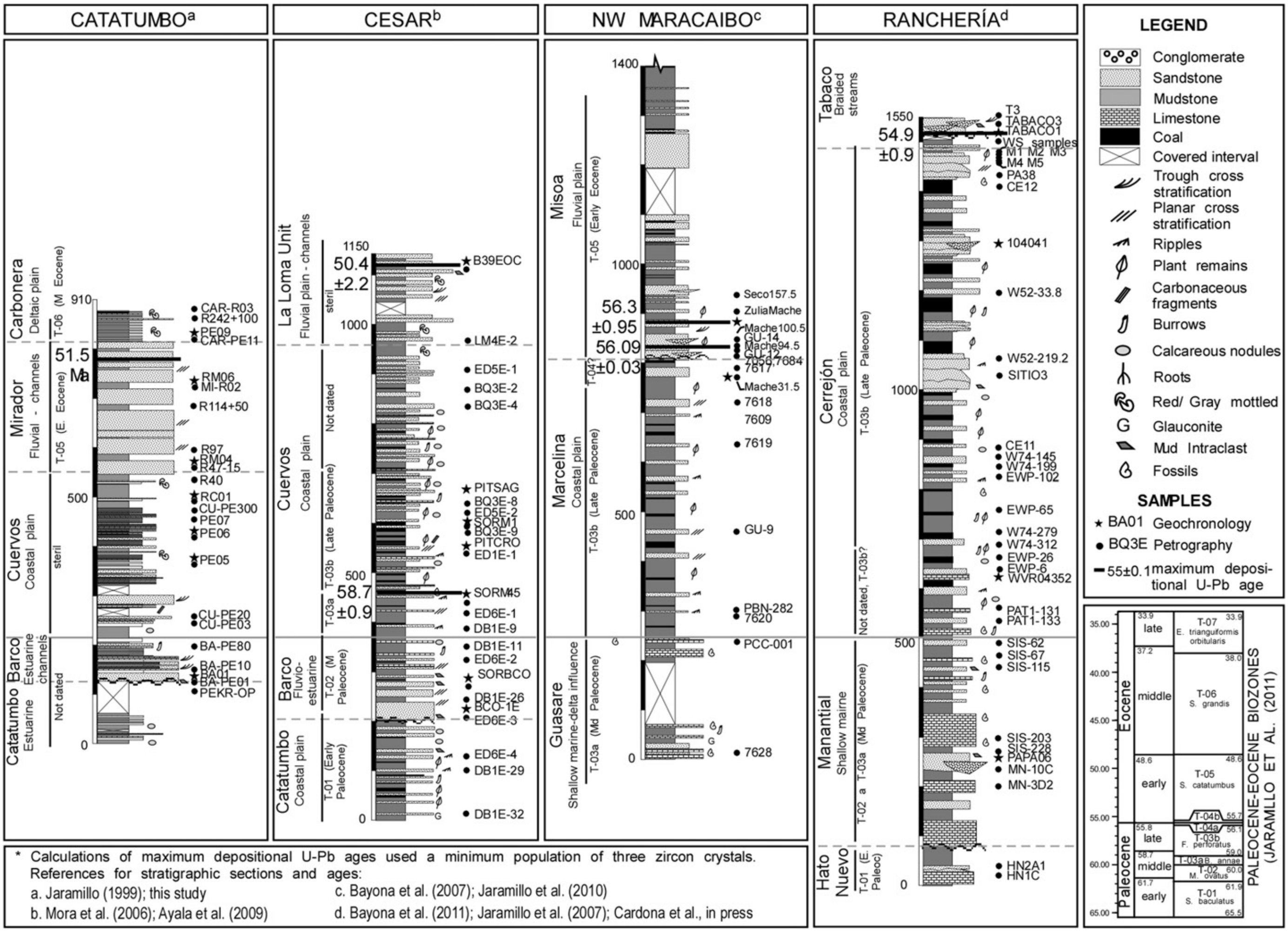

Fig. 3. Stratigraphic sections of Paleogene rocks along the study areas. Datum at base of Cuervos, Cerrejón and Marcelina formations. Note the thickness variations in upper Paleocene rocks.

deposits accumulated on coastal plain-estuarine environments to the west and south (Catatumbo, Cesar, and Ranchería sub-basins: Ayala-Calvo et al., 2009; Bayona et al., 2011) and marginal-deltaic to the east (northwestern Maracaibo Basin: Bayona et al., 2011). The presence of siderite nodules and cements in sandstone beds suggest non-sulfide continental conditions (Tucker, 2001).

The thickness of the upper Paleocene strata is greater than that of the lower-middle Paleocene, and varies abruptly among the four study areas (Fig. 3). Reported thickness for upper Paleocene strata varies from 340 m in the Catatumbo sub-basin (Royero, 2001), to 500 m in the Manuelote Syncline of the northwestern Maracaibo Basin (Bayona et al., 2011), to 700 m in the Cesar sub-basin (Ayala-Calvo et al., 2009), and to 1 km in the Ranchería sub-basin. Upper Paleocene rocks in some areas of the Maracaibo platform were eroded, and the middle Eocene Misoa Formation rests unconformably over the Guasare Formation (Lugo and Mann, 1995). The increase in sedimentation rates and lateral variations in the thickness of upper Paleocene strata have been associated with crustal tilting to the west and high-angle fault activity (Bayona et al., 2011). As suggested by Quijada and Cassani (1997), the El Tigre Fault has been inactive since the early Cretaceous to the mid-Paleocene and was reactivated as a normal fault from the late Paleocene to mid-Eocene. Ayala-Calvo et al. (2009) also suggested the existence of vertical movements of the Perijá Fault during the late Paleocene-Eocene. At the same time, an early subduction of the Caribbean Plate was developing in northwestern Santa Marta Massif, inducing uplifts (Cardona et al., 2011). Vertical movements of high-angle faults would be the distal response of convergence (Bayona et al., 2011).

2.3.3. Lower to middle Eocene units

Lithofacies associations, stratigraphic thickness, and the nature of contact between Eocene units with upper Paleocene strata vary abruptly among the studied areas. Lower Eocene strata include medium-to-coarse grained quartzose sandstones of the Mirador Formation in the Catatumbo sub-basin (160–400 m: Notestein et al., 1944), varicolored mudstones of the La Loma Formation in the Cesar sub-basin (0–700 m: Ayala-Calvo et al., 2009), sandstones and conglomerates of the Tabaco Formation in the Ranchería sub-basin (<100 m: Bayona et al., 2011), and mudstones, coal, sandstones, and conglomerates of the Misoa Formation in the northwestern Maracaibo Basin (1500–4500 m: PDVSA, 2008). Overall, these deposits accumulated in fluvial environments in the southwestern sections (Catatumbo sub-basin), in tidal-influenced fluvio-deltaic environments in the western and central Maracaibo Basin, and in shallow marine conditions to the northeast (Maracaibo Basin: Escalona and Mann, 2006).

The Tabaco Formation in the Ranchería sub-basin rests in angular unconformity over the Cerrejón Formation (Cáceres et al., 1980; Montes et al., 2010), whereas in the northwestern

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Maracaibo Basin, the contact between the Marcelina and the Misoa formations is a disconformity (Bayona et al., 2011). Notestein et al. (1944) reported an unconformity between the Cuervos (late Paleocene) and Mirador (early Eocene) Formations in the Catatumbo sub-basin; however, Royero (2001) and Jaramillo et al. (2010) interpreted this contact as a disconformity with no major loss of time. In the Cesar sub-basin, a paraconformity between the lower Eocene La Loma Formation and Los Cuervos Formation has been suggested by Mora and García (2006), whereas Ayala-Calvo et al. (2009) proposed a transitional contact. Overall, facies dislocations and disconformities characterize the late Paleocene and early Eocene limit in the study area.

2.3.4. Middle to upper Eocene units

In the southwestern Maracaibo Basin, the upper Eocene Carbonera Formation conformably overlies the Mirador Formation, whereas coeval units in the Cesar-Ranchería Basin are absent. The Carbonera Formation is composed of claystones with coal seams and fine sandstones interbedded with fossiliferous limestones (PDVSA, 2008). These deposits accumulated in deltaic plain-swamp environments. In the western Maracaibo Basin, the Carbonera Formation transforms northward into the La Sierra Formation. This unit is comprised of sandstones with a basal conglomerate that accumulated in upper shoreface environments (González de Juana et al., 1980). The la Sierra and Misoa Formations rest unconformably over Cretaceous and Paleozoic rocks in the El Palmar high, a structure to the east of the El Tigre Fault (Kellogg, 1984; Bayona et al., 2011; see location in Fig. 1).

3. Methods

Provenance analyses (petrography, geochronology, paleocurrents, and geochemistry) have proven a direct relationship between basin filling and deformation of nearby ranges, as shown by Bayona et al. (2007, 2008, 2011), Moreno et al. (2011), Horton et al. (2010a, 2010b), Bande et al. (2012), and Cardona et al. (2011) in Colombian basins. In this paper, we integrated sandstone petrography and detrital zircon U-Pb ages, because both analyses are useful for defining source areas, but if used alone, could lead to ambiguous results. As shown by Suttner et al. (1981), intense weathering can modify sandstone mineralogy even if the source area does not change. Likewise, the reworking of older sedimentary units could reproduce the same U-Pb age spectra even if the primary source is not present (Dickinson et al., 2009). Thus, using the provenance results and the above sedimentological interpretations, we can reinforce or dismiss probable interpretations.

For sandstone petrography, 91 thin sections were analyzed (Fig. 3), distributed as follows: (1) nineteen from the Catatumbo sub-basin (southwestern Maracaibo Basin), (2) ten from the northwestern Maracaibo Basin, integrated with four samples from Bayona et al. (2011), (3) four thin sections from the Ranchería sub-basin, integrated with 34 samples from Bayona et al. (2011), and (4) twenty samples from the Cesar sub-basin, from Ayala-Calvo et al. (2009). The previous analyses of Van Andel (1958) were also considered for regional maps and compositional trends, but they were not tabulated for QFL plots since the complete point-counting dataset was not published.

Three hundred framework sand grains (>0.0625 mm) were counted per sample using the Gazzi-Dickinson method (Ingersoll et al., 1984). Most of the samples were fine to medium grained. Several grain types were identified and tabulated in 26 standard categories for comparison between basins (see details in Table 1). Percentages of Quartz-Feldspar-Lithic fragments were recalculated in order to plot the data in QtFL ternary plots (Dickinson, 1985). Total lithic fragments (Lt) were also recalculated to compare the lithic fragment types across the stratigraphic sections and between basins. Ternary plots of *Qc (stable sedimentary fragments), Lsu (unstable sedimentary fragments), and Lm-v (metamorphic and volcanic fragments) were constructed in order to observe the supplies of sedimentary cover, volcanic arc, or basements.

Total petrographic data was compiled in three time intervals: early-middle Paleocene, late Paleocene, and early-middle Eocene. QFL plots and maps showing the petrographic provinces were constructed using such a division.

Samples from seven sandstones in the Catatumbo sub-basin and two in the northwestern Maracaibo Basin were collected, processed, and analyzed by laser ablation, inductively coupled plasma mass spectrometry (LA-ICP-MS). Detrital zircons were separated by standard procedures at the Geology Department of the University of Arizona, using a Wilfley Table (gravity separation), a Frantz separator (magnetic susceptibility separation), heavy liquids (obtaining minerals up to 3.32 g cc^{-1}), and handpicking techniques (to isolate only zircons). Several hundreds of zircons per sample were mounted with epoxy resin and polished to expose the grains. Age determinations were conducted at LaserChron Center (University of Arizona) following the method of Gehrels et al. (2006, 2008). We obtained about 900 U-Pb ages from detrital zircons, as shown in the Data Repository (Table S2). We used 206Pb-238U ages for grains younger than 900 Ma and 207Pb-206Pb ages for grains older than 900 Ma. The data was then plotted in age frequency probability plots (see Results Section). The geochronological information was then integrated with published data from Cardona et al. (2011) in the Ranchería sub-basin and Ayala-Calvo et al. (2009) in the Cesar sub-basin. The U-Pb data of Xie et al. (2010) and Nie et al. (2010) lie out of our study area, but were nevertheless considered to support our interpretations and to track similarly aged populations.

All analyzed data (both the new and published information) were compiled in the three time intervals, as petrographic data. We constructed age histograms that grouped U-Pb ages in six categories, following the criteria presented in Table 2

4. Results

4.1. Catatumbo sub-basin (southwestern Maracaibo Basin)

4.1.1. Sandstone petrography

Paleocene sandstones from the Catatumbo sub-basin (Barco and Cuervos formations) are sublitharenites to litharenites (Fig. 4), with increasing litharenites in the upper Paleocene sandstones. Sedimentary and low-grade metamorphic rock fragments dominate, reaching 27% of the total framework, and include mudstones, chert, and micaceous phyllites (see percentages of all components in Data Repository, Table S1). Here, volcanic lithic fragments are rare, and feldspar fragments (mainly plagioclase) are less than 3% of the framework. The content of polycrystalline quartz increases in the upper Paleocene sandstones (10–12% of total framework, with some samples reaching 24%). We identified chlorite and glauconite as accessory minerals. Most of the grains are fine to medium grained, sub-rounded, and present sutured contacts due to siliceous overgrowths. The matrix is mainly argillaceous (kaolinite), but ferruginous cement is common.

Sandstones from the lower-middle Eocene Mirador Formation are quartzarenites, except for one sample that displayed a sublitharenite composition (Fig. 4). The grain size for these sandstones is coarser than the Paleocene rocks, and have very low porosity values (0–1.5%) because of the siliceous and ferruginous cements. Here, the quartz grains are sub-rounded with sutured contacts, and siliceous overgrowths give crystalline shape to the quartz grains.

Table 1
Parameters for sandstone petrographic counts.

Symbol	Type of framework grain	Calculated parameters
Qm	Monocrystalline quartz	
Qsed	Sedimentary quartz	***QFL plots***
Qpf	Polycrystalline-foliated quartz (elongated crystals)	
Qpd	Polycrystalline-diffuse quartz (equant crystals)	Qt = Qm + Qsed + Qpf + Qpd+Qc
Qc	Chert	F = KF + Pl + Fm + Fu
KF	Potassium feldspar (mainly ortoclase)	L = Ls + Lso + Lmm + Lmg + Lmc + Lv+Lpa + Lu
Pl	Plagioclase	*Lt = L + Qsed + Qpf + Qpd+Qc
Fm	Microcline	(Qt + F + L = 100%)
Fu	Undifferentiated feldspar	(Qm + F + Lt = 100%)
Ls	Sedimentary lithic fragment	
Lso	Oxidized sedimentary lithic fragment	
Lmm	Micaceous metamorphic lithic fragment	***Total lithic fragments plots***
Lmg	Graphite-rich metamorphic lithic fragment	
Lmc	Chlorite-rich metamorphic lithic fragment	*Qc = Qsed + Qc
Lv	Volcanic lithic fragment	Lsu = Ls + Lso
Lpa	Aplitic lithic fragment	Lm-v = Qpf + Lmm + Lmg + Lmc + Lv + Lpa
Lu	Undifferentiated lithic fragment	(*Qc + Lsu+Lm-v = 100%)
Mic	Mica (Muscovite, biotite)	
Chlo	Chlorite	
HM	Heavy minerals (zircon, apatite, epidote, etc.)	***Total calculation (whole rock)***
Opq	Opaque minerals (Oxides-Sulfides)	
Gl	Glauconite	Frmw (total framework grains) =
IntCa	Calcareous intraclasts	Qm + Qsed + Qpf + Qpd + Qc + KF+Pl + Fm + Fu+
IntSil	Siliciclastic intraclast, mud intraclasts	Ls + Lso + Lmm + Lmg + Lmc + Lv+Lpa + Lu+
Fos	Fossil fragments	Mic + Chlo + HM + Opq + Gl + IntCa+IntSil + Fos
Intersticial material (not included in framework counting):		Ints (Intersticial material) = Mtx + OrgMt + CaCm + SilCm + ArCm + FeCm+UnCm
Mtx	Matrix	
OrgMt	Organic matter	Por (porosity) = Por
CaCm	Calcareous cement	
SilCm	Siliceous cement	(Frmw + Ints + Por = 100%)
ArCm	Argillaceous cement	
FeCm	Ferruginous cement	
UnCm	Undifferentiated cement	
Por	Porosity	

Upper Eocene sandstones of the Carbonera Formation show an increment in feldspar fragments, with Plagioclase and potassium feldspar reaching 17% of the total framework in lower samples and 6% in upper samples. However, some of these sandstone beds do not even contain feldspars (Fig. 4). Here, the grain size is fine, and lithic fragments (sedimentary and low-grade metamorphic) increase with respect to the underlying Mirador Formation (up to 14%). Calcareous (dolomite) and ferruginous cements are common in these sandstones.

4.1.2. U-Pb ages of detrital zircons

The distribution of zircon ages (Data repository, Table S2) shows a dominance of Mesoproterozoic populations, with a maximum peak at 1.55 Ga. Other populations are also present, including the ages of 580, 240, and 70 Ma in the lower Paleocene Barco Formation (sample BA01, Fig. 4), as well as the Cretaceous (70–92), Jurassic (169–177 Ma), and Permo-Triassic populations (252–257 Ma) in the upper Paleocene Cuervos and Eocene Mirador Formations (samples PE05, PE06, RC01, RM04, and RM06; Fig. 4). In the upper Eocene Carbonera Formation, Jurassic ages are dominant. A few Paleogene ages (51–64 Ma) were found, however, suggesting that magmatism was present during the Paleogene (samples RC01, PE05, and RM06).

4.1.3. Provenance interpretation for the Catatumbo sub-basin

Most of the sandstone beds in the Catatumbo sub-basin have a quartz content of up to 80% (normalized QFL percent), sub-angular to sub-rounded grains, sedimentary lithic fragments (Ls, Qc), and matrix. Such characteristics indicate more than one depositional cycle. Lower-middle Paleocene sandstone beds mainly have sublitharenites with sedimentary lithic fragments (Qc, Ls), which increase in concentration in the lower interval of the Cuervos Formation (middle-upper Paleocene). In the upper interval of the Cuervos Formation (upper Paleocene), metamorphic lithic and polycrystalline quartz fragments increase, showing more litharenites with respect to the underlying rocks. These variations in the lithic fragment content were also documented by Van Andel (1958) in the Graywacke province of the western Maracaibo Basin (including the Catatumbo sub-basin). According to Van Andel, Paleocene-Eocene sandstones show the reverse order of strata in an orogenic massif, suggesting that the Central Cordillera is a source area for metamorphic lithic fragments. Sedimentary fragments are associated with the reworking of Cretaceous rocks. Dominant populations of Mesoproterozoic ages (peak in 1.55 Ga) in Paleocene rocks show a cratonic origin of zircons. However, lower age peaks younger than 360 Ma can be explained by the input from the Central Cordillera as a secondary source area. Increasing Triassic ages (252–257 Ma) in upper Paleocene units are consistent with the increase in Low-grade metamorphic lithic fragments; thus, the most probable source of Lm is the Paleozoic metamorphic rock in the Central Cordillera. Peaks of 400–600 Ma can be explained by the reworking of lower Cretaceous units (Horton et al., 2010a), because the Cambro-Ordovician basement rocks of the Santander-Floresta Massif and Mérida Andes were not exposed in the Paleocene (Parra et al., 2009; Bermúdez et al., 2010). Cretaceous rocks could also have been introduced by basin edge uplift during the deformation of the Central Cordillera, or could have been eroded from areas far south and transported by a main river; the latter conjecture would explain the widespread distribution of the continental-estuarine units between the Central Cordillera and the

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Table 2
Age population related to probable source areas, as described in the tectonic setting.

Age Group	Possible origin and location of basement with similar ages
40–65 Ma (Paleogene)	These ages are related to Paleogene magmatism related to Caribbean Plate early subduction under the northwestern South American margin. Some intrusive bodies in Santa Marta massif, Guajira area and Central Cordillera are of Paleocene-Eocene age (Herrera et al., 2008; Ordóñez et al., 2008; Cardona et al., 2011); as some plutonic rocks of Central-Eastern Panamá (Montes et al., in press; Villagómez et al., 2011b).
65–130 Ma (Cretaceous)	These ages are related to magmatic pulses in Central Cordillera (i.e. Antioquian Batolith; Restrepo et al., 2007; Ibañez-Mejía et al., 2007) and development of magmatism in the Caribbean Arc (Burke, 1988), including plutonic rocks (Aruba Batholith, Wright et al., 2008); mainly between 70 and 90 Ma. The upper 65 Ma cutoff are marked by the early subduction metamorphism and magmatism along the northwestern margin of South America (Cardona et al., 2011), after ca. 70 Ma collisional event.
130–210 Ma (Jurassic to Neocomian)	These ages are distributed along Andean Ranges (eastern flank of Central Cordillera, Santander Massif, Perijá Range, Santa Marta Massif). They are associated to continental extension, developing Grabens with red beds, volcaniclastic deposits and granitic intrusive bodies (Maze, 1984). The main magmatic events occurred between 140 and 180 Ma.
210–360 Ma (Late Paleozoic-Triassic)	These ages are distributed along Andean Ranges (Central Cordillera, Santander Massif, western flank of Santa Marta Massif, Mérida Andes and basement of Lower Magdalena Valley). They are associated to metamorphic belts along collided margin during Pangea formation (with a peak in 280 Ma) and later granitic plutons during Pangea breakup (Vinasco et al., 2006).
360–900 Ma (Paleozoic-Neoproterozoic)	These ages are associated to old blocks mainly inside eastern Andean Ranges (Eastern Cordillera, Santander Massif, Mérida Andes, Quetame Massif and basement of Llanos Basin), as result of oceanic accreted terrains. An episode of magmatic activity between ca. 520–420 Ma is recorded in plutonic rocks of the Floresta-Santander massifs and in the Mérida Andes (Horton et al., 2010a; Burkley, 1976). Older ages between 530 and 900 Ma could be asociated to rifting phases during Rodinia breakup and formation of Gondwanaland (Li et al., 2008).
900–1300 Ma (Putumayo-Grenville)	During this time, the assembling of Rodinia were characterized by worldwide orogenic events (Li et al., 2008). In NW South America, some remnants are found in the Central Cordillera, Santa Marta, Garzón and Las Minas Massifs, as the Andean foreland basement. The main orogenic events are dated between 990 and 1100 Ma (Putumayo orogen; Ibañez-Mejía et al., 2011), and near to 950 Ma begins metamorphic cooling (Cordani et al., 2005), as the latest an orogenic granites intruded (Tassinari and Macambira, 1999). Ages between 1100 and 1300 Ma could be related to arc-setting magmatism.
1300–1550 Ma (Mesoproterozoic)	Pericratonic belts, associated to accretion events in the SW Amazonian Craton during Mesoproterozoic (Rondonia-San Ignacio geochronological province; Tassinari and Macambira, 1999)
1550–3000 Ma (Paleoproterozoic)	Ages related to the Amazonian Craton (Tassinari and Macambira, 1999). Paleozoic and Mesozoic sedimentary rocks may contain also abundant paleo-mesoproterozoic zircons (Horton et al., 2010a, 2010b; Ayala, 2009), so reworking of previous sedimentary rocks can show abundant rounded zircons with ages up to 1.5 Ga.

Llanos Basin of Colombia (Villamil, 1999). Detrital zircon U-Pb age populations in the Cretaceous rocks of the eastern Cordillera and Perijá Range are generally older than 0.9 Ga, with major peaks in 1.0, 1.5, and 1.8 Ga (Horton et al., 2010a, 2010b; Ayala, 2009). In the Paleocene-Eocene sandstones of the Catatumbo sub-basin, major peaks are commonly found at 1.55 and 1.8 Ga, coherent with a cratonic origin of the zircons. However, the fine-grained strata of the upper Cretaceous indicate that the cratonic sources were a far distance away (Martínez and Hernandez, 1992); the sudden input of quartzose sand-sized material in the Catatumbo sub-basin may be better explained by the reworking of nearby sandy Cretaceous sedimentary cover.

The lower to middle Eocene sandstones (Mirador Formation) are more quartz-rich and coarser-grained than the Paleocene sandstones. No traces of volcanic lithic fragments are found here. There were no significant changes in the detrital age population with respect to the underlying units; thus, we propose that the increase in compositional and textural maturity could be related to the dynamics of the fluvial environment and the dissolution of unstable fragments due to chemical weathering in very slow subsidence basins (100–400 m in more than 15 million years). In humid tropical climates, feldspars and mudstones can leach out during long periods of exposition from source areas, temporal storage, or soil formation (Johnsson et al., 1991). As the rate of tectonic subsidence increased in the late Eocene, as recorded by thick deposition in the Carbonera Formation, the content of Lm and feldspars increased; these sandstones are classified as subarkoses and feldspathic litharenites. The plagioclases are weathered and partially dissolved, suggesting diagenetic alterations. The U-Pb ages of the Carbonera Formation are also different from the previous Paleocene-Eocene populations. A major peak in 190 Ma shows a Jurassic source, with the erosion of Jurassic igneous rocks explaining the feldspar increment. Petrographic counts show few volcanic fragments, thus making granitic intrusive rocks the most probable Jurassic source and not volcaniclastic units.

4.2. Western maracaibo basin

4.2.1. Sandstone petrography

Lower to middle Paleocene sandstone beds of the Guasare Formation have a calcareous content of 10–15% (IntCa, Fos, and CaCm); however, using the siliciclastic fraction, we can classify them as sublitharenites (Fig. 5). The dominant lithic fragments are from sedimentary origin (approximately 5%) and are mainly mudstones; volcanic and metamorphic lithic fragments, on the other hand, are present in smaller amounts. In the upper Paleocene Marcelina Formation, feldspar fragments (plagioclase and k-feldspar) increase significantly (from less than 1% in the Guasare Formation to 13–15% in Marcelina), and monocrystalline quartz decreases (Qm of upper Paleocene sandstones is less than 50%). Thus, the composition includes feldspathic litharenites to lithic arkoses, such that sedimentary and metamorphic lithic fragments are dominant over volcanic ones (usually near to 1%). Calcareous fragments and cement increase in some northern samples (e.g. Paso Diablo mine; Bayona et al., 2007), whereas in other samples, a decrease to 5% is found.

In the Misoa Formation (lower Eocene), the sandstone composition varies from feldspathic litharenites to subarkoses, and only

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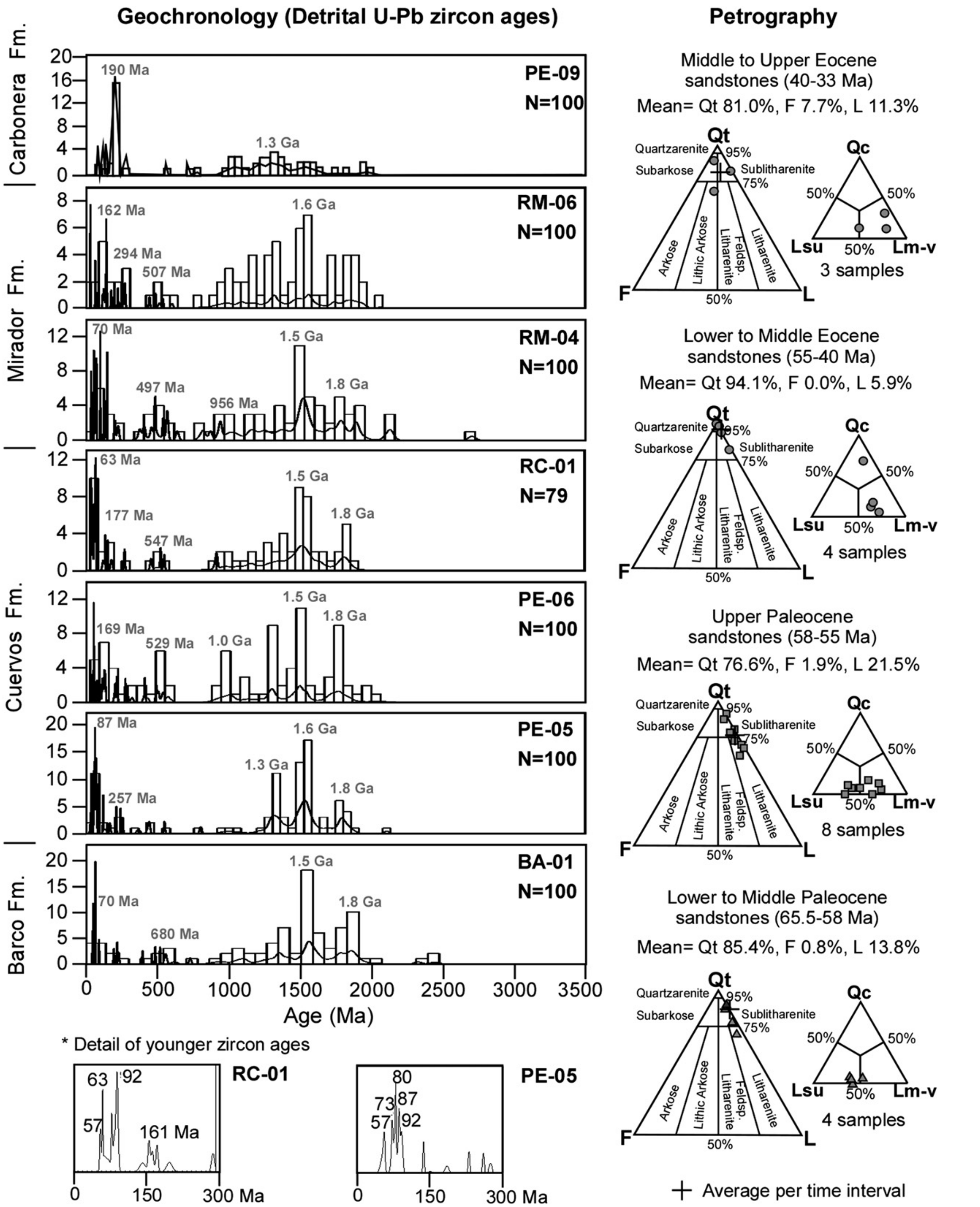

Fig. 4. Provenance data for Paleogene sandstones in the Catatumbo sub-basin. Left: Detrital zircon LAM-ICP-MS U-Pb age frequency distribution plots. Right: Compositional (QFL) and lithic (QcStMt) plots for petrographic samples.

one sample yields a sublitharenite composition. Plagioclase (16%) dominates over potassium feldpsar (8%), and polycrystalline quartz was found in abundance (12–20%). Sedimentary and metamorphic lithic fragments are common, with some basic, volcanic lithic fragments (1–5% of total framework grains). Ferruginous cement and an argillaceous matrix are common. In addition, one felsic volcanic tuff is reported in the lower interval of this unit (Jaramillo et al., 2010).

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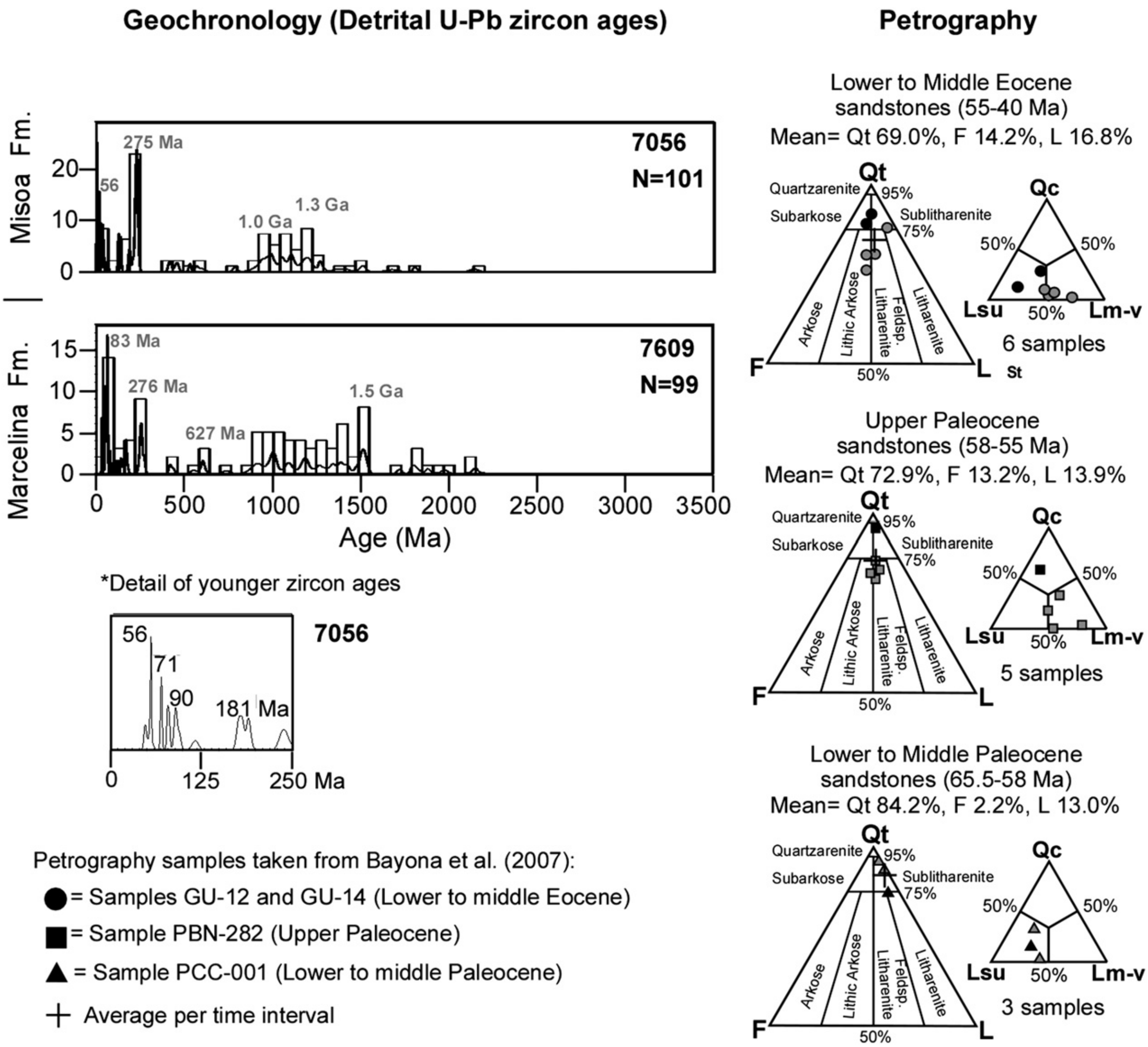

Fig. 5. Provenance data for Paleogene sandstones in the northwestern Maracaibo Basin. Left: Detrital zircon LAM-ICP-MS U-Pb age frequency distribution plots. Right: Compositional (QFL) and lithic (QcStMt) plots for petrographic samples.

4.2.2. U-Pb ages of detrital zircons

Detrital zircon populations for the upper Paleocene Marcelina Formation sandstones and the lower Eocene Misoa Formation sandstones are similar (Fig. 5). The dominant populations include Cretaceous (70–90 Ma), Jurassic (191–194 Ma), Permian (275 Ma), Neoproterozoic (610 Ma), and Mesoproterozoic (1.0–1.52 Ga) ages. However, in the Lower Eocene Misoa Formation, ages in the range of 55–56 Ma were obtained (sample 7056), and a calculation of the maximum depositional age of 56.3 $\pm$ 0.95 Ma (three crystals) was made with the youngest three zircons. In comparison, Jaramillo et al. (2010) reported an age of 56.0 $\pm$ 0.03 (felsic volcanic tuff) in the lower interval of the Misoa Formation.

4.2.3. Provenance interpretation for the western Maracaibo basin

Lower to middle Paleocene sandstones, which are interbedded with shallow marine limestones of the Guasare Formation, are characterized by high concentrations of calcareous components. Micrite fragments present in the Marcelina Formation, together with Lm and feldspar fragments, have been interpreted as the result of sediment mixing from the Santa Marta Massif and the reworking of the Guasare platform (Bayona et al., 2007). Despite the compositional variations between the western Maracaibo and Catatumbo sandstones, we observe a similar upsection increase in compositional immaturity. The presence of Ls fragments in the lower Paleocene sandstones reveals a reworking of the distal sedimentary cover. A probable western source for the upper Paleocene rocks was suggested by Bayona et al. (2007); our detrital zircon data supports this hypothesis (Fig. 5), which shows the presence of Cretaceous and Permian age populations, similar to the ages of the intrusive bodies in the Central Cordillera (Ibañez-Mejía et al., 2007; Restrepo et al., 2007) and the metamorphosed granitoids in the Santa Marta Massif (Cardona et al., 2010).

The Eocene sandstones of the Misoa Formation not only have abundant feldspar and volcanic rock fragments, but they are interbedded with felsic tuffs, indicating near volcanic activity. This local source could explain the compositional variations and the younger ages observed in the detrital zircons. Nevertheless, there is another possible source area that affects the Misoa sandstones;

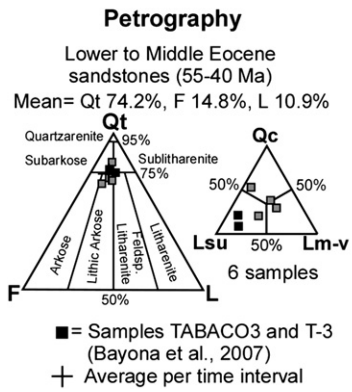

Fig. 6. Compositional (QFL) and lithic (QcStMt) plots for lower Eocene samples of the Ranchería sub-basin (Tabaco formation and fine-grained equivalent unit).

a high Permian peak (275 Ma) suggests the Santa Marta Massif as probable source.

4.3. Ranchería sub-basin

4.3.1. Sandstone petrography

Bayona et al. (2011) reported quartzarenites to sublitharenites in the lower Paleocene sandstones (Hato Nuevo, Manantial formations) and litharenites to feldspathic litharenites in the upper Paleocene sandstones (Cerrejón Formation). An upsection increase of potassium feldspar and metamorphic lithic fragments had also been reported here. The lower Eocene coarse-grained sandstones of the Tabaco Formation and the coeval fine-grained sandstones to the southeast are lithic arkoses to subarkoses (Figs. 6and 7) (Arango, 1996; Jaramillo et al., 1993; López, 2007; Mesa, 2003; Servigeo, 2002), a different petrofacies than the underlying upper Paleocene sandstones. The content of the plagioclase is slightly higher (0–3%) than the potassium feldspar, and microcline is common to all samples (0.3–3.3% of total framework grains). Specifically, the dominant plagioclase is sericitized albite. Although the content of sedimentary lithic fragments and chert is high (8–10% of the total grains framework), volcanic and metamorphic fragments are also abundant and have relatively similar proportions (2–6%, Fig. 8). In fact, the uppermost sample (WS-172.8) has abundant calcareous cement.

4.3.2. U-Pb ages of detrital zircons

The upsection population of detrital zircons changes from a predominance of Mesoproterozoic populations (0.9–1.8 Ga) in the lower Paleocene sandstones, to a dominance of Permo-Triassic, Cretaceous, and Jurassic ages in the upper Paleocene sandstones, and to Cretaceous-Paleogene ages in the lower Eocene sandstones (Fig. 9). A maximum depositional age of 54.9 $\pm$ 0.9 Ma (six crystals) was reported in a sandstone bed in the Tabaco Formation (Cardona et al., 2011).

4.3.3. Provenance interpretation for the Ranchería sub-basin

The lower to middle Paleocene rocks (Hato Nuevo, Manantial formations) are characterized by calcareous components and a quartz-rich composition (Bayona et al., 2007, 2011). The detrital zircon age populations here are very similar to those observed in the Catatumbo and Cesar sub-basins, with a major peak at 1.53 Ga and some populations of 400–600 Ma. Only three zircon crystals are younger than 300 Ma. As discussed previously, cratonic-derived

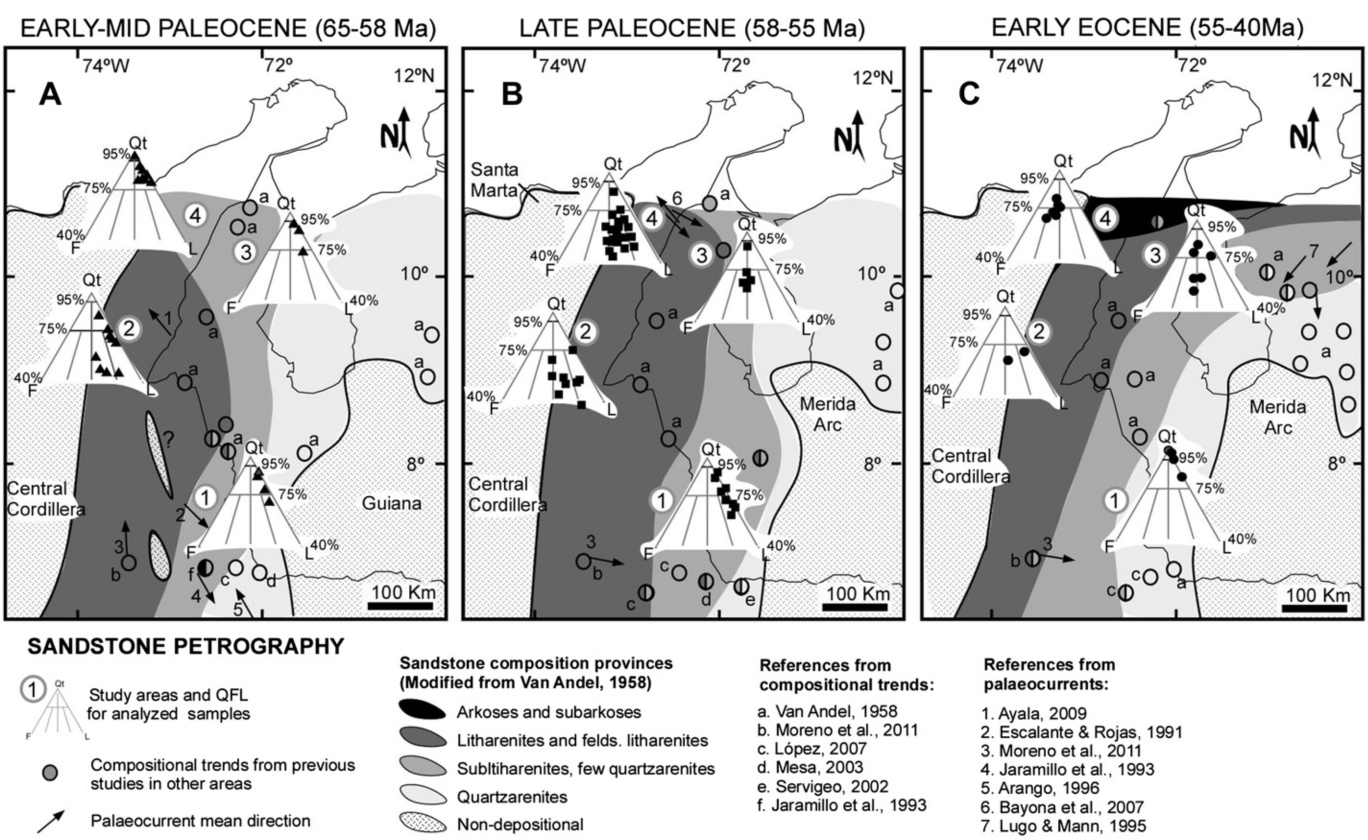

Fig. 7. Sandstone composition for lower Paleocene (A), upper Paleocene (B) and lower Eocene (C) Units of northern Colombia and western Venezuela. Modified from Van Andel (1958). QFL plot for study areas were included.

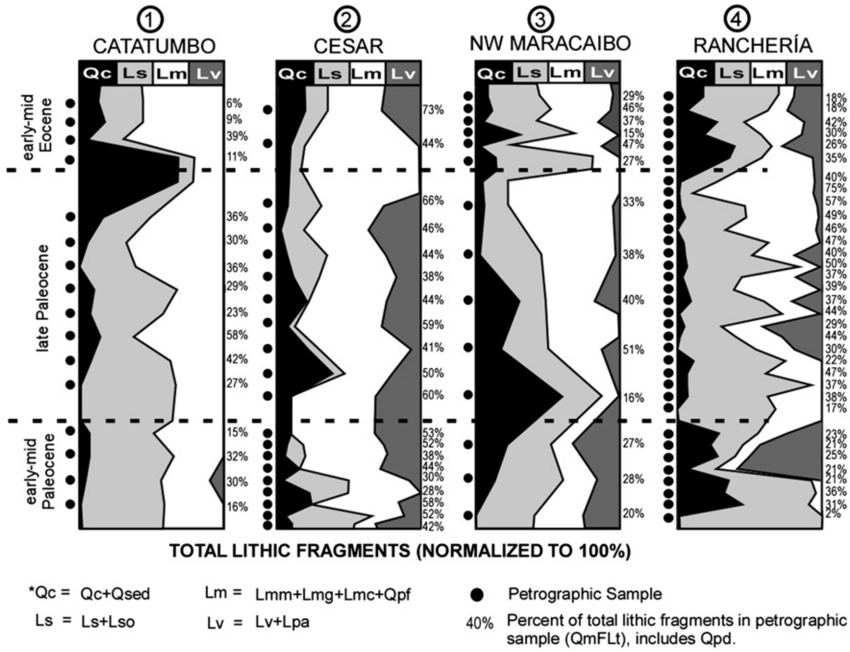

Fig. 8. Lithic fragments variations on sandstones of the four study areas. Data for the Cesar-Ranchería Basin were taken from Bayona et al. (2007) and Ayala-Calvo et al. (2009).

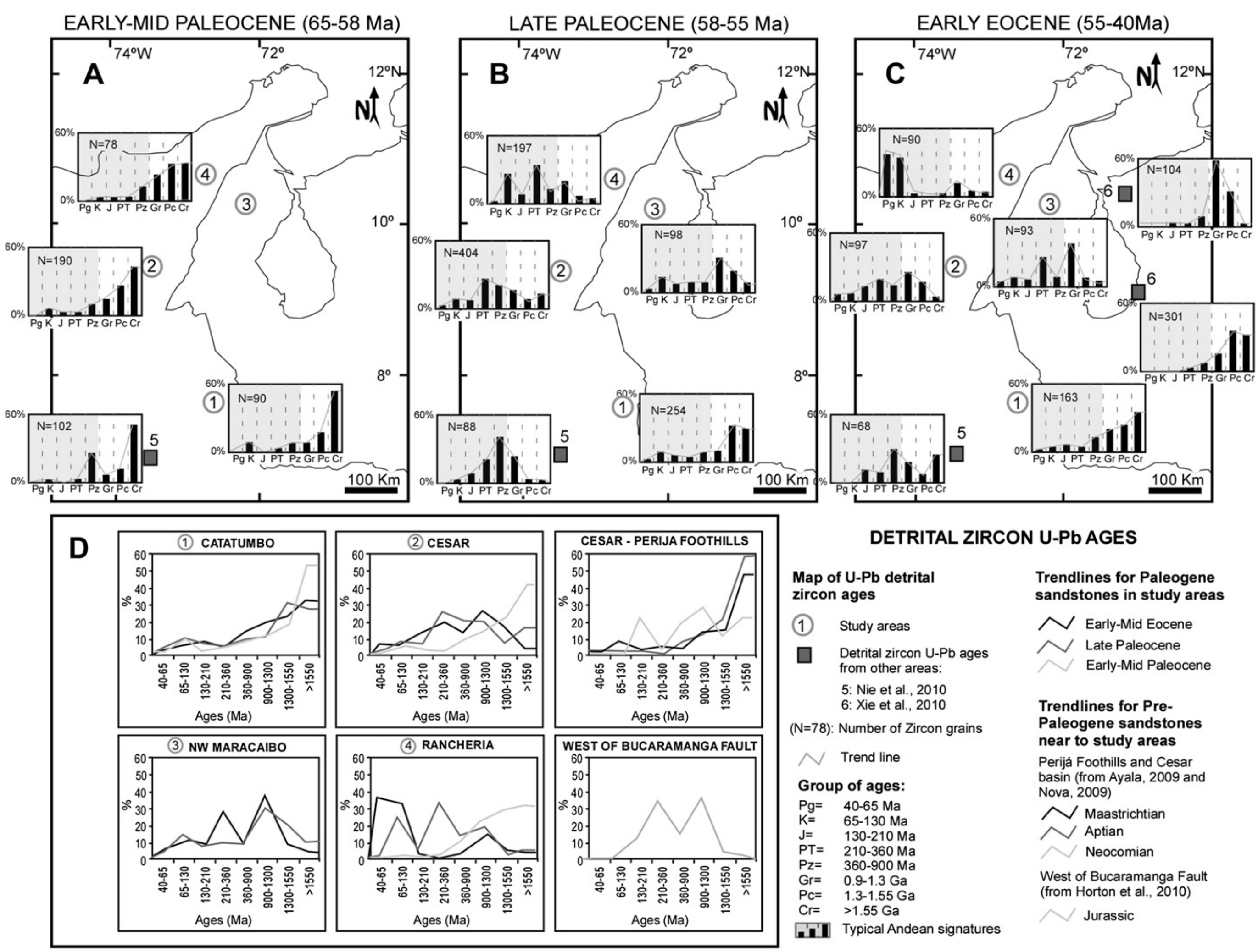

Fig. 9. Detrital zircon LAM-ICP-MS U-Pb age frequency distribution plots for lower Paleocene (A), upper Paleocene (B) and lower Eocene (C) sandstones in the western Maracaibo block for. Note the decreasing of >1.3 Ga ages in upper Paleocene sandstones. D: Detail of trends in U-Pb age frequency distribution plots, compared with pre-Paleogene sandstones.

Cretaceous rocks could possibly supply sediments for this area. Nevertheless, the population between 0.9 and 1.3 Ga is larger than the other areas. This could suggest an emerging massif as a minor source area. The significant changes in sandstone composition and detrital zircon age populations in the upper Paleocene rocks are indeed explained by the introduction of the Santa Marta massif as a source area (Bayona et al., 2007, 2011; Cardona et al., 2011). The uplift of this massif during the Paleocene was a response to the collision and later subduction of the Caribbean plate (Cardona et al., 2011; Villagómez et al., 2011a). Geochronological analyses from Cardona et al. (2011) suggested that the upper Paleocene to lower Eocene rocks of the Ranchería Basin record the progressive erosion of the Santa Marta Massif. Bayona et al. (2011) also interpreted an eastern source area: the reactivated faults disrupting the Guasare platform in the late Paleocene.

4.4. *Cesar sub-basin*

4.4.1. *Sandstone petrography*

The Paleocene to lower Eocene sandstone beds in the Cesar sub-basin are characterized by a high content of low-grade metamorphic lithic fragments (Ayala-Calvo et al., 2009; Ayala, 2009, Fig. 7). The highest content of metamorphic lithic fragments and feldspars (mainly plagioclase) are detected in the upper Paleocene sandstones, whereas the lower Paleocene and lower-middle Eocene sandstones have more sedimentary lithic fragments (Fig. 8).

4.4.2. *U-Pb ages of detrital zircons*

Detrital zircon populations show a clear difference between the lower-middle Paleocene sandstones and the upper Paleocene-lower Eocene sandstones. The former is dominated by Mesoproterozoic ages (1.54 Ga peak, Fig. 9a) with a few zircon ages of 500–600 Ma, whereas the latter is dominated by Permo-Triassic (275–238 Ma) and Cretaceous ages (83–96 Ma), with a few Jurassic ages (160–183 Ma). An age of 58.7 $\pm$ 0.92 Ma (three crystals) was obtained for the upper Paleocene sandstones, and an age of 50.4 $\pm$ 2.2 Ma (three crystals) was obtained for the lower Eocene sandstones.

4.4.3. *Provenance interpretation for Cesar sub-basin*

The lower to middle Paleocene rocks of the Cesar sub-basin are very similar to the studied samples of the Catatumbo sub-basin. The sandstones have similar compositions and detrital zircon age populations, with stable lithic fragments (as Qc) being slightly higher in the Catatumbo sub-basin. The detrital zircon ages have a Mesoproterozoic dominance (ages of 0.9–2.0 Ga, with a major peak in 1.54 Ga), and ages of 500–600 Ma constitute another important population (near 10%). Even a few ages of 80 Ma were found. Such characteristics most likely suggest the same source area for the Cesar and Catatumbo sub-basins in the early-middle Paleocene. The presence of less stable fragments in the Cesar sub-basin may indicate that it was closer to the source area. Ayala-Calvo et al. (2009) interpreted meandering rivers to the northwest (NW) and braided rivers to the southeast (SE) of the Cesar sub-basin, suggesting the Santander Massif as a source area. Recent thermochronological data (Parra et al., 2009; Ross et al., 2009) indicated an early Miocene exhumation for the basement rocks of this massif, but Ross et al. (2009) also suggested that block uplifts and erosion of Mesozoic rocks between 65 and 60 Ma occurred to the west of the Bucaramanga Fault. This local uplift associated with the reactivation of an ancient fault would explain the changes in fluvial dynamics inside the Cesar sub-basin and the local NW–SE paleocurrents of the Barco Formation (Ayala, 2009, Fig. 7).

The sandstone composition and the detrital zircon age populations of the upper Paleocene-lower Eocene rocks in the Cesar and Ranchería sub-basins have similar trends. An increase in subsidence rate in the late Paleocene is observed in both basins. The feldspar content in the Cesar sub-basin is less than that in the Ranchería sub-basin. The detrital zircon age populations also show an increase in age populations between 65 and 300 Ma, suggesting a western source (most likely the Central Cordillera and the Santa Marta Massif). In addition, the 58–50 Ma ages show evidence of volcanic activity during the deposition of the Paleogene units.

5. Discussion

In order to evaluate the variation in the provenance markers, the data was plotted in chronostratigraphic correlations and geographic distributions (Figs. 7–9) for three time intervals: early-mid Paleocene, late Paleocene, and early Eocene. Sandstone composition is shown in QFL plots according to their geographic distribution, allowing for the generation of compositional province maps (Fig. 7). The lithic fragments were also subdivided and plotted in stratigraphic order (Fig. 8), thus allowing for the variations in the stable (Qc, Qsed) and less stable (Lv, Lm, and Ls) fragments to be observed (see Table 1 for codes). The changes in the proportions of Lv, Ls, and Lm among the study areas also provide evidence of the introduction of volcanic or basement sources as well as the reworking of sedimentary units. The U-Pb data was subdivided into age populations as discussed in the Methods Section and summarized in Table 2. In summary, the cratonic signatures have age populations older than 1.3 Ga, the Andean foreland and oldest massif basements have age populations from 1.3 to 0.9 Ga, and other typical Andean signatures have age populations younger than 0.9 Ga. Western sources associated with the Caribbean Plate accretion are from the Cretaceous to the Paleogene. The age groups in Table 2 were then plotted according to geographical distribution in Fig. 9.

With interpreted source areas and emerged massifs from the provenance markers, we constructed paleogeographic maps from the Paleocene to the Eocene (65–35 Ma, Fig. 10). These maps are a modified version of those in Escalona and Mann (2011), which were for northern Colombia and western Venezuela; our maps add more emphasis to the palaeogeographic changes in the western part of the study area.

Sandstone composition and detrital zircon age populations for the lower to middle Paleocene units in all the four studied areas show similarities, despite the fact that these depositional systems vary from siliciclastic to the south and carbonate to the north. The lower-middle Paleocene sandstones show high quartz contents (Qt of up to 75%, Table 3), except for the Cesar sub-basin, where the lower samples are litharenites (Fig. 7a) dominated by Ls fragments (Fig. 8). Paleocurrents indicate mainly northward and northwestward flow directions (except for two localities, Fig. 7a). The detrital zircon ages are similar in all studied areas, with a predominance of paleo-mesoproterozoic age populations (0.9–2.5 Ga in the north and 1.5–2.5 Ga in the south), being less prominent the 0.9–1.5 Ga populations in the southern sections (Fig. 9a). Some minor populations between 400 and 600 Ma are found; on the other hand, Jurassic-Permian ages are almost absent (Fig. 9a). In the Middle Magdalena Valley, there is an important population between 500 and 1000 Ma (Nie et al., 2010), but age populations from 1.5 to 2.5 Ga dominate (Fig. 9a).

The quartzose composition of the lower to middle Paleocene sandstones matches that of multi-cycle sandstones; therefore, the most probable source of sediments is the Cretaceous quartzose sedimentary cover in newly exposed source areas. Some characteristics preclude the provenance of sand-sized quartzose fragments directly from the Guiana shield, such as: (1) the dominance of fine-grained lithologies in the uppermost Cretaceous rocks in the

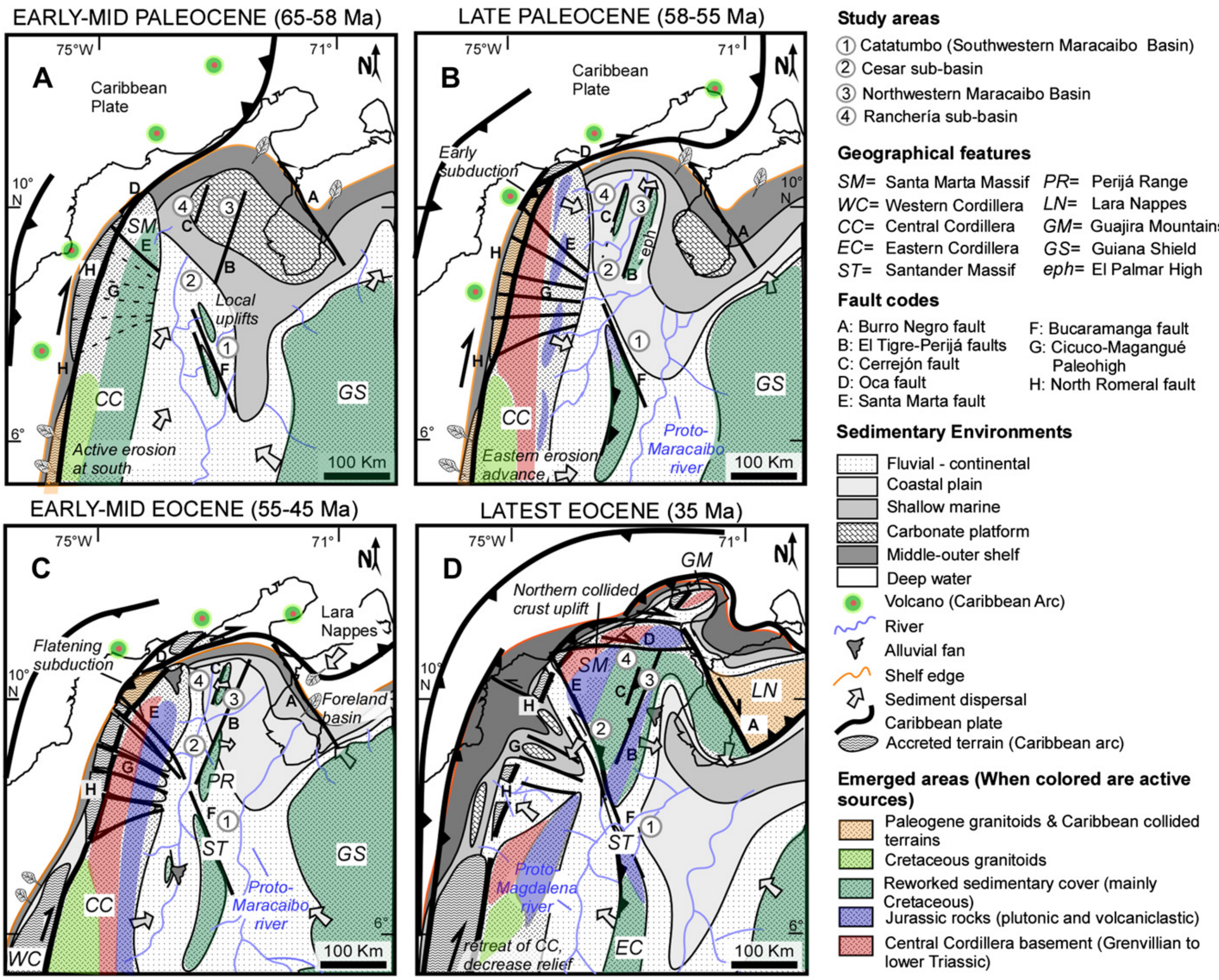

Fig. 10. Depositional model for the western Maracaibo block during Paleogene, and interpreted position of drainages and flux directions. Colored areas are active sources at indicated time interval, as confirmed by provenance markers (Figs. 7–9). The radiating pattern of lower Magdalena Valley faults before late Eocene is taken from Montes et al. (2010).

study area (Martínez and Hernandez, 1992), indicating the retraction of proximal sandstone deposits far away from the Maracaibo block; (2) the high content of sedimentary lithic fragments, suggesting multi-cycle sandstones; and (3) the Neoproterozoic-Ordovician detrital zircon age populations, correlated with intrusive bodies in the Mérida Arc and Santander Massif (Burkley, 1976; Restrepo-Pace, 1995). The detrital zircon age populations of the Cretaceous rocks of the Cesar sub-basin are very similar to those observed in the lower-middle Paleocene rocks of the same area (Fig. 9d), favoring the suggestion of a reworking of Cretaceous

Table 3
Average values for petrographic samples in the four study areas.

Area	Average values for petrography	Lower to middle Paleocene			Upper Paleocene			Lower to middle Eocene		
		Qt	F	L	Qt	F	L	Qt	F	L
Catatumbo	Average	85.4	0.8	13.8	76.6	1.9	21.5	94.1	0	5.9
	Standard deviation	11.3	0.8	10.6	6.5	1.8	5.6	8.4	0	8.4
	No. of samples	*5*			*8*			*4*		
Cesar	Average	68.2	7.6	24.2	58.5	14.4	27.1	69	9.7	21.4
	Standard deviation	12.9	6.7	4.2	12.9	7.9	10	5	10	5
	No. of samples	*7*			*11*			*2*		
NW Maracaibo	Average	84.8	2.2	13	72.9	13.2	13.9	69	14.2	16.8
	Standard deviation	9	2.3	6.8	10.7	6.1	5.1	12.3	8.2	6
	No. of samples	*3*			*5*			*6*		
Ranchería	Average	85.4	2.1	12.5	56.8	16.5	26.7	74.2	14.8	10.9
	Standard deviation	6.5	2.5	5.8	11.7	6.7	10.4	4.9	4.5	1.8
	No. of samples	*8*			*24*			*6*		

rocks. Upper Jurassic-Neocomian rocks tend to have an important population of 0.9–1.3 Ga and some younger ages (e.g. Jurassic, Permian, and Ordovician) because they eroded from the most proximal emerged basements, as shown by the U-Pb age populations in the Girón and Rionegro Formations (Horton et al., 2010a; Nova, 2009). In contrast, middle-upper Cretaceous rocks have ages between 1.5 and 2.8 Ga, usually peaking near 1.5–1.8 Ga (Horton et al., 2010a; Ayala, 2009, Fig. 9d). The erosion of different levels of the Cretaceous rocks could explain the slight variations from the north to the south of the study area.

A rapid uplift in the Central Cordillera occurred ca. 75–70 Ma (Villagómez et al., 2011b), and active denudation of Cretaceous sediments during the Paleocene has been recorded in the southern Middle Magdalena Basin (Gómez et al., 2003). Furthermore, an active supply of the sedimentary cover of the Guiana shield was observed in the Paleocene-Eocene quartzarenites of the Llanos Basin and Llanos foothills (Sweet, 1991; Bayona et al., 2008; Horton et al., 2010b). The paleocurrent directions in northern Colombia (Fig. 7a) suggest that sediments originate from the south of the study areas, allowing for the mixing of western and eastern sources in a regional, basin-wide fluvial system, most likely flowing toward the western Maracaibo area (Fig. 10a). This large-scale river did not bring large amounts of sediments into the shelf areas, because a mixed siliciclastic-carbonatic platform was developed. The increase in lithic content (sedimentary and some metamorphic fragments) in the lower samples of the Cesar sub-basin and some areas of the Catatumbo sub-basin (Van Andel, 1958) could be associated with a few local uplifts. Ross et al. (2009) and Parra et al. (in press) documented the exhumation of Mesozoic rocks to the west of the Bucaramanga fault during the early Paleocene (ca. 60 Ma); the reworking of these Mesozoic units may have supplied lithic fragments to the lower Paleocene rocks and caused local palaeocurrent directions different from the northward trend (Fig. 7a).

By the late Paleocene, relatively coal-rich environments predominated. The upper Paleocene sandstones show significant change with respect to their underlying units, both in composition and detrital zircon age populations, with exception to the Catatumbo sub-basin. Lithic and feldspar content increase sharply in the upper Paleocene and younger units, with Qt contents of 40–70% (Fig. 7b). Regionally, there is a westward decrease in quartz and increase in feldspar content; the average data vary from Qt = 76.6% in the Catatumbo sub-basin, to 56.8% in the Ranchería sub-basin, with $F = 1.9\%$ and 16.5%, respectively (see Table 3). These trends can be associated with the proximity to the main source (Santa Marta Massif-Central Cordillera, as suggested in the Results Section). The Catatumbo sub-basin shows only a slight increase in lithic fragments but not in feldspar content (Figs. 7and 8, Table 3). All basins have similar metamorphic lithic fragments, while the content of sedimentary and volcanic lithic fragments are variable among the basins (Fig. 8). The detrital zircon ages show a significant westward increase in Jurassic and Permo-Triassic populations (Cesar-Ranchería Basin), considerably reducing the ages between 0.9 and 2.5 Ga, and especially ages up to 1.55 Ga (Fig. 9b). The early Paleogene ages (55–65 Ma) represent the maximum age of deposition. In the Catatumbo sub-basin, the detrital zircon age populations remain older among the lower and upper Paleocene sandstones; however, the cratonic ages (>1.55 Ga) decrease and the pericratonic ages (1.3–1.55 Ga) increase, with the appearance of a few Jurassic ages. These slight changes to the increment in the lithic fragments could suggest a nearby supply from Cretaceous rocks.

The variations in sandstone composition, as well as the detrital zircon age populations, suggest the introduction of new source areas, and therefore, a new array of fluvial delivery systems. Lithic, fine-grained sandstones with high concentrations of well-preserved, unstable, angular-shaped grains suggest a proximal supply from a low-sloped source area. An increase in subsidence during the late Paleocene (Bayona et al., 2011) helped to preserve unstable rock fragments despite a tropical humid climate (Wing et al., 2009). Zircon age populations in the range of 65–360 Ma found in upper Paleocene sandstones (Fig. 9b) are present in rocks of the Central Cordillera and Santa Marta Massif (Fig. 2), which were most likely connected until the late Eocene (Villamil, 1999; Montes et al., 2010). This ancient range is located to the west of the sub-basins in this study, and probably acted as a main source area, except for the Catatumbo sub-basin. In the Catatumbo sub-basin, the detrital zircon age population of the upper Paleocene sandstones is similar to that of the lower-middle Paleocene units, with the sandstones having a slightly higher lithic content.

Although deformation of the Central Cordillera has been reported since the Campanian, the northward advancement of plate-margin deformation made the Santa Marta Massif an active source area only until the late Paleocene. In the south of the Middle Magdalena Basin (see location in Fig. 1), the Central Cordillera deformation advanced eastward, forming a regional unconformity between the late Paleocene and early Eocene (Gómez et al., 2003). The uplift of the Santa Marta Massif and the northern Central Cordillera could have been initiated by reverse faulting, followed by an eastward-dip tilting during the late Paleocene-Eocene in response to early subduction, or could have just tilted as a rigid block (Montes et al., 2005; Cardona et al., 2011; Bayona et al., 2011). The first hypothesis explains the 65–58 Ma uplift of the southernmost Santa Marta Massif (Villagómez et al., 2011a), which was most likely associated with the Bosconia fault system (Fig. 1). The contrasting thicknesses among sub-basins can be explained by the reactivation of intraplate high-angle faults inside the Maracaibo Block, causing differential subsidence rates (Bayona et al., 2011), the emergence of local highs (i.e., Palmar High: Quijada and Cassani, 1997) and sedimentary barriers to the depositional system. These intraplate uplifts also explain the mixing of the craton-derived age populations (from the reworking of upper Cretaceous rocks) and younger ones (from the western sources). These reactivated faults would be the distal response of convergence, due to the early subduction of thickened oceanic crust (Cardona et al., 2011).

With an active western source area, the early Paleocene river migrated eastward, draining through the Maracaibo Basin. To the west, a new drainage system fed by many small west-to-east (W–E) rivers took place (Fig. 10b). Local uplifts (west of the Bucaramanga fault) as well as the reworking of Cretaceous units could have supplied unstable sedimentary fragments to the Catatumbo sub-basin. The feldspar content is higher in the Cesar-Ranchería Basin due to its proximity to the main western source area; here, the dominant age populations range from 65 to 360 Ma (Figs. 7b and 9b). At the same time, the Caribbean terrains were closing toward the north-northeast of the Maracaibo Basin, preceding the Eocene synorogenic basin in the Maracaibo area (Lugo and Mann, 1995).

The lower Eocene units are characterized by contrasting detrital zircon age populations (Fig. 9c) and regional changes in sandstone composition with respect to the upper Paleocene rocks. The lower Eocene sandstones show: (1) an increase in potassium feldspar and microcline content (the amount of total feldspar is similar as shown in Table 3 but the proportion between plagioclase and potassium feldspars vary from 2:1 to 1:1 or less); and (2) higher compositional maturity and grain size, except for the northwestern Maracaibo Basin (Fig. 7c), where the content of plagioclase and mafic volcanic fragments increase (Fig. 8 and Appendix S1). The medium to coarse-grained sandstones are generally quartzarenites, whereas the fine-grained sandstones are arkoses-subarkoses and sublitharenites. The detrital zircon age populations are different among the basins, with young age populations in the Ranchería sub-basin and older age populations in the Catatumbo sub-basin. Depositional environments are predominantly fluvial in the Cesar-Ranchería and Catatumbo sub-basins, being more deltaic and shallow marine to the northeast (Maracaibo Basin).

The lower Eocene units record the installation of multiple drainage systems and therefore the beginning of intermontane basins associated with several ranges and massif uplifts within the Maracaibo Block. The increase in potassium feldspars and microclines suggests the introduction of felsic rocks to the source areas. The detrital zircon age populations show a similarity between the Cesar sub-basin and the northwestern Maracaibo Basin (Fig. 9c), suggesting a common source for both areas. These populations are similar to the underlying upper Paleocene rocks, but the Permo-Triassic and Grenvillian age populations increase. Considering that these ages are related to the Central Cordillera-Santa Marta Massif, the western source area is most likely still active, as suggested by Horton et al. (2010b) from the Eocene rocks of the axial Eastern Cordillera. The high-angle faults in the Perijá Range separate the northwestern Maracaibo and Ranchería sub-basins, leaving the latter isolated and dominated by the Santa Marta Massif as a source area (Paleogene granitic bodies in the northwestern corner as suggested by geochronology; Cardona et al., 2011). Angular unconformities over the Paleocene rocks and coarse deposits in the Ranchería Basin (Montes et al., 2010) suggest an active block supplying sediments to the basin. In the Catatumbo sub-basin, our data suggests the same source area for the Paleocene to lower Eocene rocks. Similar detrital zircon ages (older than 1.0 Ga) and petrographic responses were observed in the lower Misoa Formation for the southeastern Maracaibo Basin (Xie et al., 2010; Cardozo, 1996). This suggests a connection between the Catatumbo sub-basin and the southeastern Maracaibo Basin, probably in a large drainage (proto-Maracaibo river, Fig. 10c).

At that time, the early subduction flattened (Cardona et al., 2011) and facilitated the eastern migration of the deformation. At the north end of the Middle Magdalena Valley, a paleo-high was exhumed (La Cira high; Moreno et al., 2011). In our study areas, a basement high (and most likely the beginning of the shortening of the Cerrejón fault) separated the Ranchería sub-basin from the northwestern Maracaibo Basin. Some of the high-angle faults in the Perijá Range likely have vertical movement. To the northeast, the migration of the Caribbean plate has caused a new front of deformation over the Maracaibo Basin. The Eocene history of the Maracaibo Basin is very important because the Misoa Formation is the reservoir for many oil fields in that prolific basin. Several works (e.g. Lugo and Mann, 1995; Mann et al., 2006; Escalona and Mann, 2011) have explained the accretion process of the Caribbean thrust belt (Lara Nappes) and the formation of a foreland basin. The depocenter of this basin was located in the northeast of the Maracaibo Basin, and was fed mainly by a palaeodrainage system from the south (Escalona and Mann, 2006; Xie et al., 2010).

By the end of Eocene, the uplift of the northern part of Colombia caused a retreat of the drainage systems. The Santa Marta-Bucaramanga fault system could have had vertical movements that facilitated the uplift of the southwest corner of the Santa Marta Massif, as suggested by the thermochronological data presented in Villagómez et al. (2011a). We suggest two completely separate drainages (Fig. 10d), with the western one most likely flowing toward the Catatumbo sub-basin because the Lower and Middle Magdalena basins (see location in Fig. 1) were not connected until the mid-Miocene (Gómez et al., 2003). The Carbonera Formation in the Catatumbo sub-basin has a high Jurassic peak with increasing potassium feldspar (Fig. 4), suggesting a supply for the new proximal eastern sources (probably the Santander Massif).

6. Summary and conclusions

The evolution of fluvial drainage systems was recorded in the lower Paleogene sandstones of the western Maracaibo block. Shifts from large to local rivers and the installation of multiple fluvial systems were identified by changes in sandstone composition (introduction of unstable fragments), detrital zircon age populations (new populations associated with local sources), and the isolation of intermontane basins. Different arrays in the drainage systems and basin configurations were observed as the deformation advanced north-northeastward during the motion of the Caribbean around northwestern South America. Marginal uplifts, high-angle fault reactivation, and a foreland basin birth were the products of such interactions from the early Paleocene to the late Eocene.

The lower-middle Paleocene units were deposited in a continuous depositional profile, showing estuarine-fluvial environments in the west and shallow marine environments in the north and east. Sandstone composition (quartz-rich, abundant sedimentary fragments) and detrital zircon ages (dominance of age populations from 0.9 to 2.5 Ga and some to 400–600 Ma) have similar associations in all the study areas, suggesting several depositional cycles. The paleogeographic interpretation for this time period indicates a single basin drained by a large-scale, basin-wide fluvial system, which probably reworked material from Andean sedimentary units in a distal southern area, with minor supplies from the nearby ranges. These local sources could have supplied lithic fragments and changed the regional northward trend of paleocurrents.

The upper Paleocene units accumulated in continental to marginal environments throughout the whole study area, with the development of thick coal seams. Significant variations in sandstone composition (lithic and feldspathic) and detrital zircon ages (dominance of age populations in the range of 65–360 Ma and a drastic decrease in age populations older than 1.3 Ga) were observed with respect to the underlying units, except in the Catatumbo sub-basin where the changes were minor and associated with Cretaceous rock input. A metamorphic input was observed, and quartz content was reduced to 40–70%. In addition, some syndepositional volcanic zircons were found. The variations in the compositional and detrital zircon ages suggest that the Santa Marta Massif and the Central Cordillera are the main source areas, modifying the fluvial configuration. Lithic, fine-grained sandstones with a high content of well-preserved unstable grains were deposited in a high-subsiding basin (Bayona et al., 2011) with proximal, but low-sloped sources. The early subduction of the Caribbean Plate modified the basin configuration, uplifting marginal massifs and generating accommodation space eastward (Bayona et al., 2011). High-angle faults were also reactivated, explaining the contrasting thicknesses among the sub-basins. The depocenter of the large fluvial system migrated to the east, draining through the southern Maracaibo Basin. Small drainages from the west dominated the sedimentary accumulations in most basins of the western Maracaibo Block.

The lower Eocene units were accumulated in continental fluvial environments west-southwest of the Maracaibo Block and fluvial to deltaic environments in the northeast. In the Cesar-Ranchería Basin, few remnants of these rocks are preserved. A regional increase in compositional maturity (except in the northwestern Maracaibo Basin), potassium feldspars, and microclines was also observed. The age populations of detrital zircons had major differences among the basins. Multiple drainage systems were interpreted, associated with massif uplift and the compartmentalization of the regional basin within the Maracaibo Block, even though the western source area was still active. The early subduction angle flattened (Cardona et al., 2011) and facilitated the eastern migration of the deformation, generating local uplifts such as la Cira

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high in the Middle Magdalena Basin (Moreno et al., 2011) and some western areas of the Perijá Range. These local uplifts were sedimentary barriers and supplied sediments to the basins. The Ranchería sub-basin recorded a synorogenic active basin fill fed by the Santa Marta Massif, developing an angular unconformity. In the northeast, the migration of the Caribbean plate caused a new front of deformation over the Maracaibo Basin, accreting the Lara Nappes and creating a foreland basin. The southwestern (Catatumbo) and southeastern Maracaibo Basin would most likely be connected by the same drainage system.

By the end of the Eocene, the uplift of the northern portion of Colombia caused a retreat of the drainage systems. The western flank of the Eastern Cordillera uplifted, isolating the Middle Magdalena Valley from the Llanos Basin. We interpreted two completely separate drainages, with the western drainage most likely flowing toward the Catatumbo area. The Carbonera Formation in the Catatumbo sub-basin has a high Jurassic peak (Fig. 4), suggesting a supply for the new proximal eastern sources (i.e., the Santander Massif).

Although thermochronological and structural data in basement rocks indicate uplifts since the Oligocene for the Perijá Range and Santander Massif (Shagam et al., 1984; Castillo and Mann, 2006; Duerto et al., 2006), erosional unconformities from the early Eocene in the Ranchería and northwestern Maracaibo Basins (Montes et al., 2010; Kellogg, 1984), as well as the provenance data in this study, suggest vertical high-angle fault activity since the late Paleocene-early Eocene. These vertical movements compartmentalized the basin and created local sediment barriers, resulting in contrasting thicknesses and minor sediment input.

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Appendix A. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.jsames.2012.04.005.

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