

## LACUSTRINE SYSTEMS IN THE EARLY MIOCENE OF NORTHERN SOUTH AMERICA—EVIDENCE FROM THE UPPER MAGDALENA VALLEY, COLOMBIA

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**ABSTRACT:** Extensive areas covered by semi-permanent water bodies were common during the Miocene in the Neotropics. These floods are noteworthy because of their possible role in promoting the high biological diversity observed today in the Amazonia. In particular, a relatively good understanding of the floods has been achieved for the Llanos basin of Colombia and western Amazonia. In these two basins the evidence suggests episodes of marine incursions and development of lacustrine systems at different times during the Miocene. Other intra-montane basins in Colombia, like the Middle and Upper Magdalena basins, also show clear evidence that water bodies covered them during that time. However, the chronostratigraphy and paleoecology of these deposits are still unclear. In this study, we use the palynological record of the Middle and Upper Magdalena valleys to establish the age of the deposits of the Barzalosa Formation, a unit that preserves a detailed record of a lacustrine system deposited during the late early Miocene in the Upper Magdalena Valley. The results indicate that the Barzalosa Formation is correlative with the lacustrine deposits of the La Cira fossiliferous horizon in the Middle Magdalena Valley. This indicates that extensive lacustrine systems covered the intramontane basins of the northern Andes during the early Miocene. Paleocologically, the Barzalosa Formation is the result of the evolution of a lacustrine system in three phases, which show marked differences in the proportion of algae, palynological composition and sedimentary depositional sequence. Climate and tectonic processes were the most probable mechanisms controlling the evolution of the Barzalosa system.

### INTRODUCTION

The Neogene saw important regional paleogeographic changes in the Neotropics (Rodazz et al. 2010; Reyes-Harker et al. 2015). These included the final phases of uplift of the Andes Cordillera (Horton et al. 2010; Mora et al. 2010; Hoorn et al. 2018 and references therein), the onset of the Amazon River (Gorini et al. 2013; Hoorn et al. 2017) and the occurrence of several marine-lacustrine incursions (Hoorn 1993; Webb 1995; Wesselingh 2006; Boonstra et al. 2015; Jaramillo et al. 2017). They produced environmental and ecological changes that are believed to have modulated the mega-diversity of the Amazon basin (Hoorn et al. 2010). Miocene incursions have received particular attention because of their relationship with the origin of the Amazon basin. In particular, it is believed that marine incursions of the Miocene played an important role as drivers of biodiversity dynamics in the Amazon by favoring biogeographical isolation and promoting allopatric speciation (Webb 1995; Rasanen et al. 1995; Lovejoy et al. 1998; Hoorn et al. 2010 and references therein).

Based on palynology and sedimentology, Jaramillo et al. (2017) inferred the occurrence of two distinct marine intervals in two drill cores from the Llanos basin of Colombia (called Saltarin) and the Amazon/Solimoes basin of Brazil (called 105-AM) (Fig. 1). They used the proportion of marine palynomorphs (the sum of foraminifera and dinoflagellates, and acritarchs) in relation to the total count of palynomorphs (the sum of pollen and spores) as indicator of marine influence. According to Jaramillo et al. (2017) the first marine incursion occurred during the early Miocene (EMI) (from 18.1 to 17.2 Ma in the Llanos basin and from 18.0 to 17.8 Ma in the Amazon/Solimoes basin) and the second occurred during the middle

Miocene (MMI) (from 16.1 to 12.4 Ma in the Llanos basin and from 14.1 to 13.7 Ma in the Amazon/Solimoes basin) (Fig. 1). Based on the evidence from the two cores and the seismic interpretation of the area (by regionally tracing the seismic reflectors of the marine horizons) Jaramillo et al. (2017) proposed that shallow marine waters covered the western Amazon region at least twice during the Miocene. These two marine incursions were short events rather than fully marine conditions lasting for several million years.

On the other hand, Hoorn et al. (2010) proposed the occurrence of a mega-wetland system in the Neotropics during the Miocene based on evidence from palynology, sedimentology, and paleontology. Hoorn et al. (2010) subdivided the history of this system into three phases (Fig. 1). The first, denominated “Precursor phase”, corresponds to a fluvial-lacustrine period (between 24 and 16 Ma) in which lacustrine conditions alternated with episodes of Andean and cratonic fluvial drainage as well as marine influence. The second, called the “Pebas phase”, corresponds to a mega-wetland system between ~16 and 11.3 Ma in which the lacustrine conditions expanded to their maximum extension. The third, called the “Acre phase”, occurred between ~11.3 Ma to 7 Ma and is the incipient transcontinental Amazon River system (Hoorn et al. 2010). During its maximum extent the Pebas system covered an area of more than  $1.5 \times 10^6$  km<sup>2</sup> comprising much of the present western Amazonian lowlands (Hoorn et al. 2010) (Fig. 1).

Although most of the studies of the Neogene floods have focused on the Llanos and Amazon basins (Jaramillo et al. 2017 and references therein), the sedimentological and paleontological evidence suggest that these episodes were not restricted to western Amazonia. There is evidence of

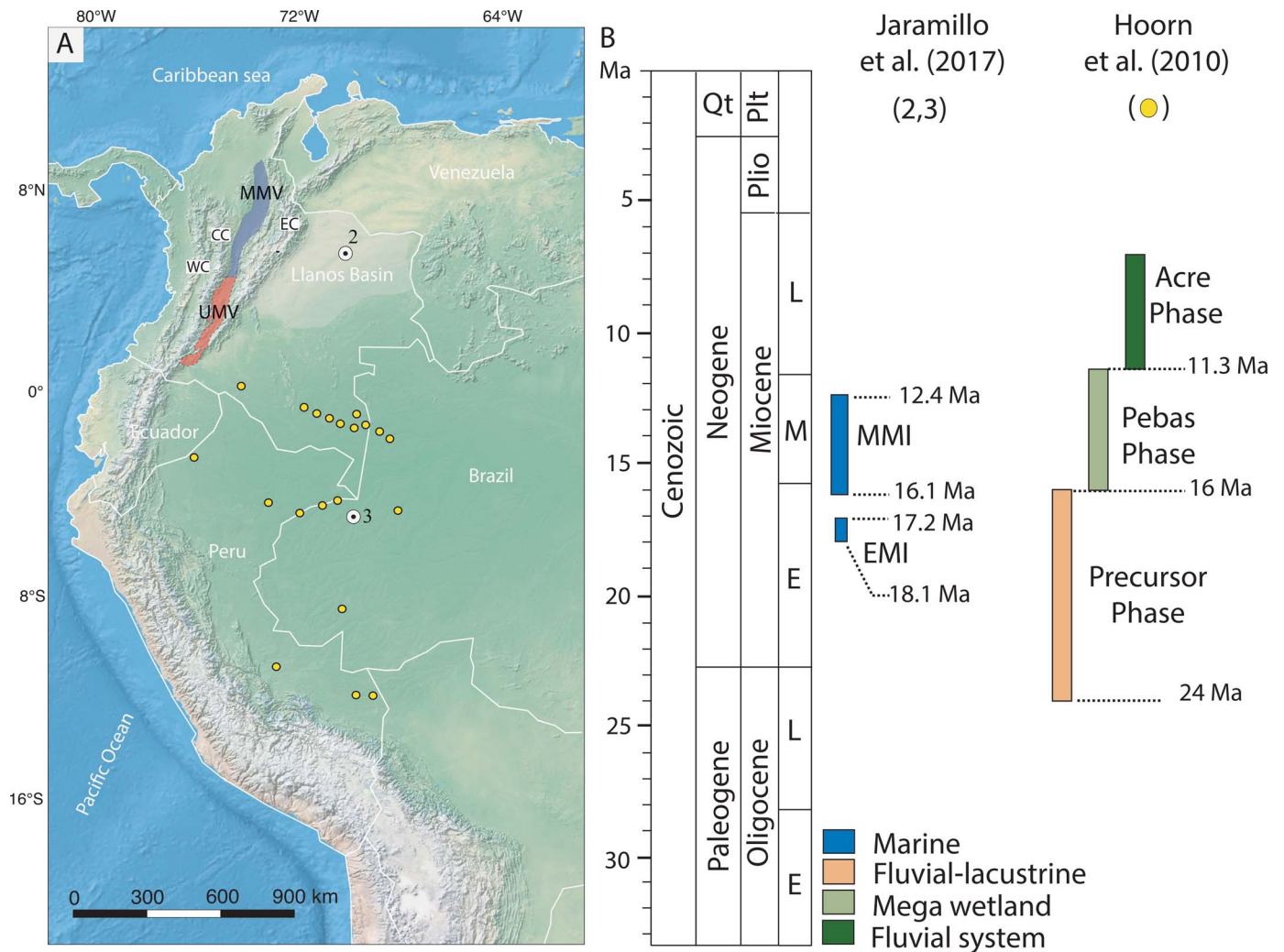


FIG. 1.—Location and chronostratigraphy of the sections studied and discussed in the text. **A**) Map of northern South America showing the location of the sections and areas discussed in the text. **B**) Chronostratigraphy of the flooding events proposed by Hoorn et al. (2010) and Jaramillo et al. (2017). Yellow circles indicate sections used by Hoorn et al. (2010) in the interpretation of the Pebas System. Numbers two and three indicate sections used by Jaramillo et al. (2017) in the interpretation of the EMI and MMI events (2= Salтарin Core, 3= 105AM core). Abbreviations: UMV = Upper Magdalena Valley; MMV = Middle Magdalena Valley; WC = Western Cordillera; CC = Central Cordillera; EC = Eastern Cordillera.

marine-lacustrine influence in sediments from the sub-Andean basins of northern South America during the Miocene. The middle Magdalena valley (MMV) and upper Magdalena valley (UMV) are two sedimentary hinterland basins located between the Central and Eastern cordilleras of the Andes in Colombia (Fig. 2). Both basins show substantial evidences of flooding during the Miocene (Pilsbry and Olsson 1935; Guerrero 1997a). However, neither the relationship between the floods in the two basins nor their correspondence with flooding episodes in the Amazon and Llanos basins (Hoorn et al. 2010; Jaramillo et al. 2017) has been clearly established.

In this work, we compare the palynological records of the UMV and MMV with the aim to establish the relationship between the floods that occurred in these two basins and their correspondence with the deposits of the Llanos and Amazon basins. Specifically, we focus our analysis on deposits of the Barzalosa Formation in the UMV. We establish the age of the unit and based on its palynological content make inferences about its environment of deposition.

#### GEOLOGICAL SETTING

In this work we use the terms flood and flooding to make reference to episodes in which landscapes were covered by water in specific intervals of time. The process that caused these episodes may correspond to marine incursions or the establishment of lacustrine systems. Palynologically, marine conditions could be interpreted by the presence of dinoflagellates and microforaminifera while lacustrine conditions are generally inferred by the presence of algae like *Pediastrum* and *Botryococcus*.

#### Floods in the Upper Magdalena Valley (UMV)

At least two regional flooding events have been recognized in the Barzalosa Formation (Oligocene–Miocene? (De Porta 1974)) and Honda Group (middle to late Miocene (Guerrero 1997a)) of the UMV. The evidence from the Honda Group has been largely described in the literature (van der Wiel et al. 1992a, 1992b; Kay et al. 1997 and chapters therein) whereas evidence from the Barzalosa Formation is scarce and mainly corresponds to unpublished internal reports of oil companies.

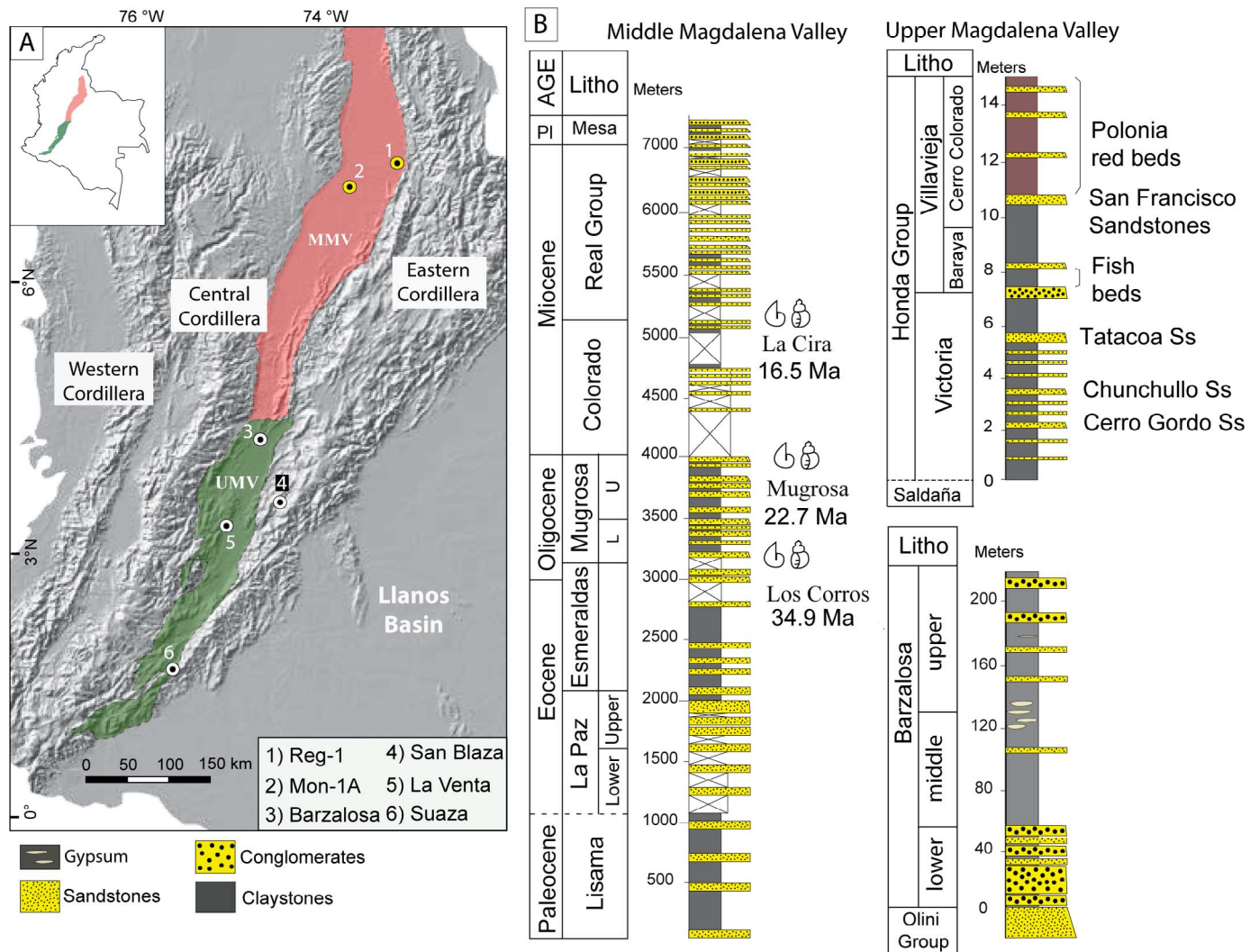


FIG. 2.—Location and general stratigraphy of the sections discussed in the text. **A**) Map of Colombia showing the Middle and Upper Magdalena Valleys (MMV and UMV) and wells and sections discussed in the text. **B**) Composite stratigraphic columns of the MMV and UMV. The main lithological characteristics of the MMV were adapted from Gomez et al. (2005). The stratigraphic position and ages of the three fossiliferous horizons (Los Corros, Mugrosa, and La Cira) were estimated from the lines of correlations of the wells Reg-1 and Mon-1A. The main lithological characteristics of the UMV were adapted from an internal report of Ecopetrol and STRI (2011). The information from for the Barzalosa Formation and Honda Group correspond to the localities Barzalosa and La Venta, respectively. The San Blaza and Suaza correspond to small outcrops of the Barzalosa Formation with shell fragments.

### The Barzalosa Formation

The Barzalosa Formation was originally described by Scheibe (1934) and redefined by Caceres and Etayo-Serna (1969). In its type area, the unit can be informally subdivided into three segments (De Porta 1974; Ecopetrol-STRI 2011) (Fig. 2). The lower segment comprises thick layers of conglomerates intercalated with siltstones and fine-grained sandstones. The middle segment comprised thick layers of siltstones and claystones intercalated with medium thickness layers of fine to medium-grained sandstones. Gypsum veins are also common in the middle segment, oriented perpendicular to the claystone and siltstone bedding plains. The upper segment comprises thick layers of oligomictic conglomerates intercalated with claystones and siltstones. The stratigraphic thicknesses in the type area are 56 m, 126 m, and 45 m for the lower, middle, and upper segments, respectively.

Although no fossils are found in the type area, two isolated outcrops of the Barzalosa Formation located in the Suaza Creek (1.82°N, -75.83°W; 45 m thick) and San Blaza Creek (3.40°N, -74.75°W; 1.5m thick) (Fig. 2) each

present one layer 1.3 m thick containing abundant remains of gastropods and bivalves, ranging in size between 0.5 and 1.0 cm (Ecopetrol-STRI 2011). Unfortunately the limited exposure of these two outcrops, does not allow a determination of the exact stratigraphic position of the fossil horizons with respect to the informal subdivision of the formation.

Unpublished palynological reports from wells drilled in the UMV basin suggest a late Oligocene–early Miocene age for the Barzalosa Formation. However the age of the unit has not yet been clearly established. These reports also indicate the occurrence of important abundances of freshwater algae, specifically *Botryococcus* and *Pediastrum* in specific intervals of the Barzalosa Formation, which suggest lacustrine influence during the deposition of the unit.

### Floods in the Middle Magdalena Valley (MMV)

Three rich fossiliferous deposits have been described in the MMV (Pilsbry and Olsen 1935). These fossil deposits known as “Los Corros”,

“Mugrosa”, and “La Cira” are stratigraphically located at the top of the Esmeraldas, Mugrosa, and Colorado Formations respectively (Fig. 2). The fauna reported by Pilsbry and Olsson (1935) consists of fresh-water mollusks with a few slightly brackish-water elements for the Los Corros and La Cira fossiliferous horizons, whereas the Mugrosa fauna is composed exclusively by fresh-water mollusks. Pilsbry and Olsson (1935) explain that the three horizons must differ widely in age, although the molluscan association does not allow precise age estimates. They suggested a late upper Eocene age for the Los Corros horizon because of faunal similarity shared with the Saman Formation in northern Peru, the late Jacksonian of Southern United States of America, and the Ludian of Europe. Nuttal (1990) reviewed the palynological zones related with the three fossil horizons, previously calibrated in time with planktonic foraminifera, to suggest an Oligocene age for the Los Corros horizon. A palynological study by Rodriguez et al. (2012) in the Nuevo Mundo Syncline area of the MMV corroborated the late Eocene age proposed by Pilsbry and Olsson (1935) for the Los Corros horizon.

Pilsbry and Olsson (1935) tentatively assigned a middle Oligocene age to the Mugrosa horizon, based on the presence of the freshwater snails genus *Hemisinus*, which is also found in Oligocene sequences of Antigua and Cuba. Finally, based on its stratigraphic position, Pilsbry and Olsson (1935) suggested an upper Oligocene or lower Miocene age for the La Cira fossiliferous horizon while Nuttal (1990) proposed a middle Miocene age. Wesselingh et al. (2001) and Wesselingh (2006) suggest that the malacofauna of the La Cira was the precursor of the Pebas fauna and estimated an early Miocene age. Palynological age determinations place the La Cira horizon in the late Oligocene (Van der Hammen 1957), and early to middle Miocene (Ramirez 1988; Olaya 1997).

## METHODS

### *Chronostratigraphy*

To establish a temporal equivalence among the floods in the MVV and UMV, and in particular to establish the age of deposition of the Barzalosa Formation, the palynological records of the two basins were compared. First, for the MMV a standard reference section (SRS) was constructed by using information from the wells Mon-1A and Reg-1 (Fig. 2). These two wells were used in the zonation proposed by Jaramillo et al. (2011) and are therefore calibrated with the geological time scale. Because the SRS is based on projected events, measurements are expressed in terms of composite units rather than feet or meters. In this sense, composite units represent a measure of time that is scaled to strata in the SRS (Hood 1988).

Three additional biostratigraphic events were added to facilitate the construction of the SRS. These events have been recognized regionally and are commonly used for intra-basin correlations. They correspond to the “Los Corros”, the “Mugrosa”, and the “La Cira” horizons described above (Pilsbry and Olsson 1935) and located at the tops of the Esmeraldas, Mugrosa, and Colorado formations respectively (Fig. 2). In ditch cutting samples, recovery of shell fragments is used by well loggers to locate the three horizons and to establish regional correlations. In the SRS, the three horizons were interpreted as follows. The La Cira fossiliferous horizon was positioned between 6490 and 9091 composite units due to the presence of shell fragments and elevated abundance of algae reported in Mon-1A between of 2133.6 and 2398.7 m. According with the lines of correlation and calibration proposed by Jaramillo et al. (2011) the La Cira Horizon was therefore deposited between 17.7 and 16.1 Ma (Fig. 2). The Mugrosa fossiliferous horizon was positioned at 14393 composite units because of the presence of shell fragments at 972.3m in Reg-1. According with the lines of correlation and calibration of Reg-1 proposed by Jaramillo et al. (2011), the Mugrosa horizon was deposited approximately at 22.7 Ma. (Fig. 2). The Los Corros fossiliferous horizon was positioned at 16164 composite units in the SRS based on the presence of shell fragments at

2209.8m in Reg-1. The age of the Los Corros Horizon can be approximated to late Eocene (34.9 Ma) based on the line of correlation and calibration of R-1 proposed by Jaramillo et al. (2011) and the palynological analysis by Rodriguez et al. (2012) (Fig. 2).

The palynological content of 128 samples from five wells located in the UMV (Hig-1= 16 samples; Gc1= 29 samples; Gb1= 59 samples; Nd1= 13 samples; Ym1= 11 samples) (Fig. 4) and distributed throughout the Barzalosa and Honda Formations were compared with the MMV standard reference section (SRS) using a probabilistic approach. The probabilistic approach uses maximum likelihood to estimate the age of an individual sample or group of samples (Punyasena et al. 2012). This technique uses the relative abundance of microfossils (in this case palynomorphs) to correlate the known stratigraphic ranges of taxa based on the changing abundance through time and to weigh relative influence in an isolated sample. The first step is to produce a baseline model that represents the changes in abundance over time, and to which a single sample or set of samples can be compared. This baseline model represents the entire *a priori* knowledge of all known taxa and their abundance data for all time slices. Changes in abundance in the model can be described in absolute measures of time (e.g., millions of years), as relative measures of time (e.g., older or younger) or as any significant measure of change through time or another gradient of interest (e.g., stratigraphic position). The taxon abundances of the model provide the comparative data against which all single-sample estimates are matched. Once the individual samples are compared with the model, the final result is a likelihood distribution describing the position of the sample in the gradient as a range of probabilities. A downloadable version of the software used to complete the analysis is available in the personal webpage of one of the authors (<http://publish.illinois.edu/punyasena/>).

The baseline model of the current study is based on the MMV standard reference section (SRS). This model represents the best current knowledge of the changing abundance of palynomorphs species in the MMV for the time when the flooding events occurred. The gradient of the baseline model uses the age of each sample estimated from the graphic correlation project in Jaramillo et al. (2011). The comparison of each sample from the UMV with our baseline model produces a probabilistic estimate of its age. Because each sample is compared against the same baseline model, this approach reduces the subjectivity involved in the age estimation.

The samples from the UMV as well as the samples associated with the three fossiliferous horizons in the standard reference section are characterized by high abundances of *Pediastrum* and *Botryococcus*. Two samples or intervals could exhibit a high probability of correlation simply because the abundance of the algae and not because they have similar palynological associations. To further explore this possibility, the maximum likelihood estimates were calculated both including and excluding the abundances of *Pediastrum* and *Botryococcus* from the standard reference section and from the samples of the UMV. Because the results were almost identical, only the results discarding the algae are presented. Only samples with counts higher than 20 palynomorphs were used in the maximum likelihood analysis.

### *Paleoecology*

The palynomorphs recovered in the samples from the UMV were classified into one of two categories. The first category algae include *Botryococcus* and *Pediastrum*. The second category, continental palynomorphs include pollen and spores (Online Supplemental File 1). Indicator of marine conditions, were not used in this study because neither foraminifera nor dinoflagellates were found in any of the samples. Because Gb-1 have the most complete record of the Barzalosa Formation, more than 731.5 m thick and 94 palynological samples, the paleoecology and environments of deposition of this well were analyzed in detail. In

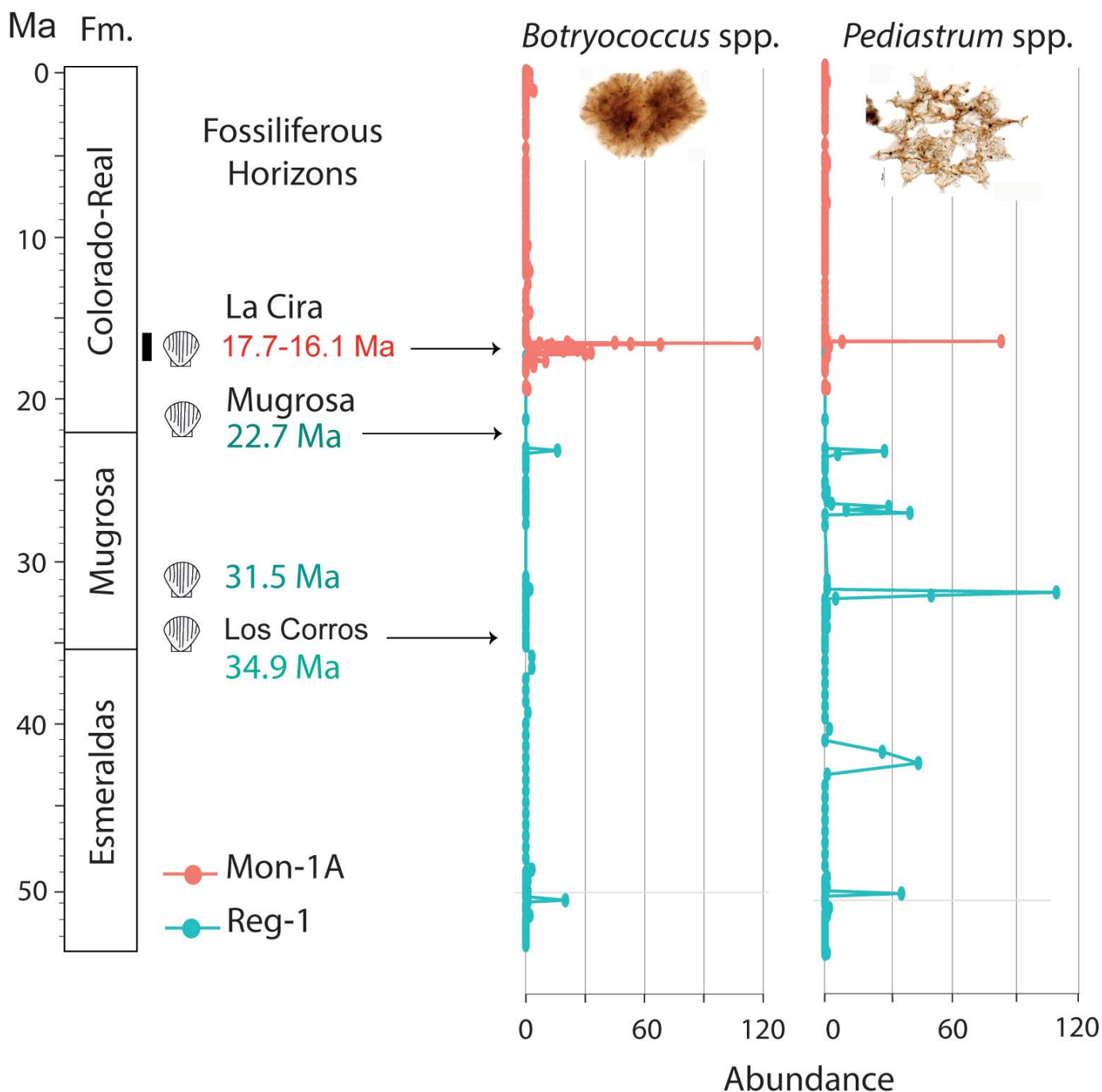


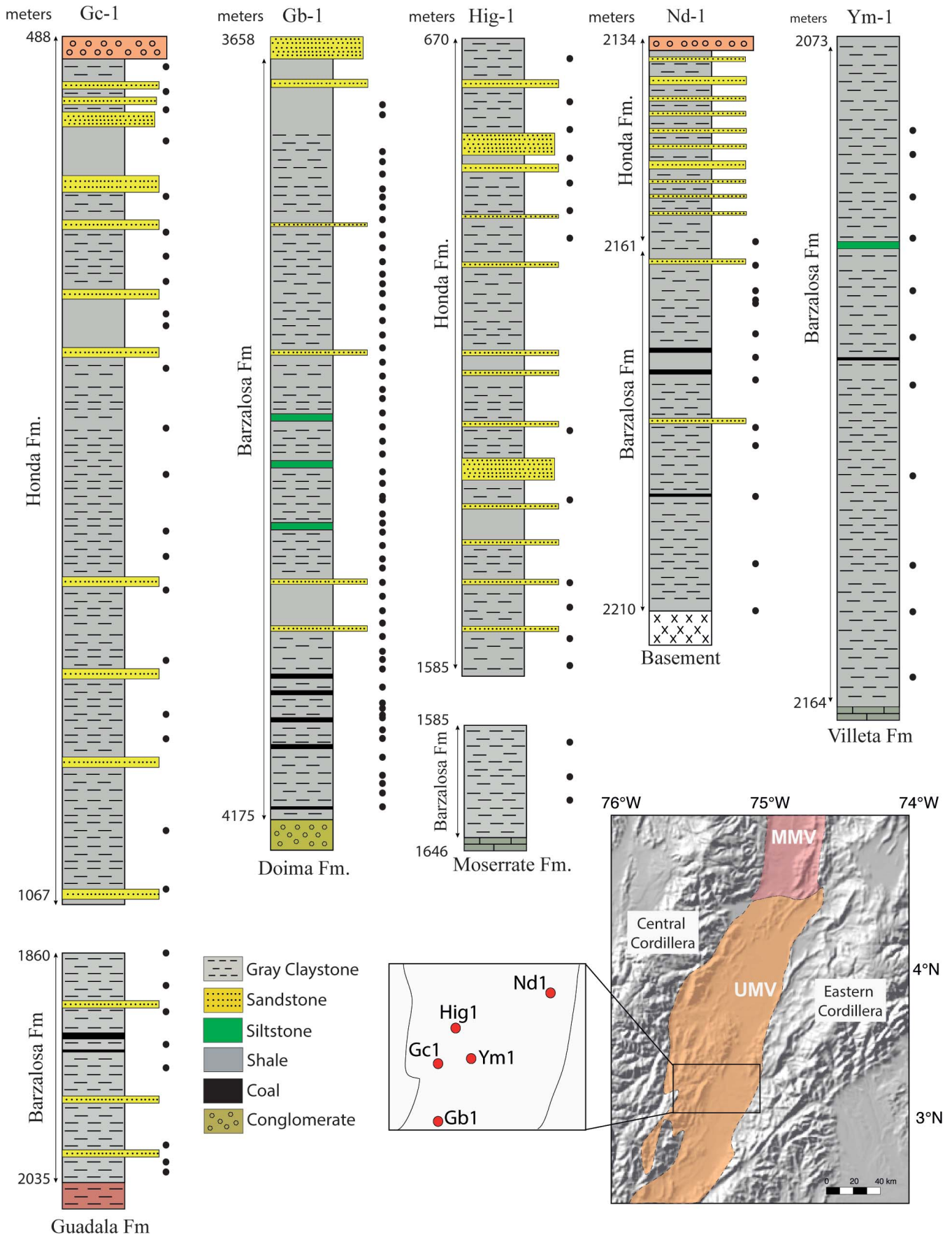
Fig. 3.—Standard Reference Section (SRS) for the Middle Magdalena Valley using the wells Mon-1A and Reg-1 shows the stratigraphic position and age interpretation of the shell fragments recovered during the drilling of the two wells.

comparison, the other wells are only between 37 and 300 m thick and have only a few palynological samples (Fig. 4).

**Algae.**—This category includes all the individuals belonging to species of the genus *Botryococcus* and *Pediastrum*, and its presence is used as evidence of freshwater influence.

*Pediastrum* is a genus of the family Hydrodictyceae (class Chlorophyceae, order Sphaeropleales) that along with three other genera (*Euastropsis*, *Hydrodictyon*, and *Sorastrum*) belongs to the coccal green

algae with a polynuclear life cycle (Leliaert et al. 2012). The genus *Pediastrum* has a worldwide distribution and comprises 24 living species. Some of them are cosmopolitan while others are restricted to cold, temperate or warm regions. In the fossil record, 15 species and numerous varieties from the total of 24 extant species have been described (Komarek and Jankovska 2001). Although *Pediastrum* is not an integral part of routine palynological analysis, the species of the genus are ecologically distinct and has served for ecological identification in both Quaternary (Whiteside 1965; Sarmaja-Korjonen et al. 2006; Weckstrom et al. 2010;



Whitney and Mayle 2012) and pre-Quaternary studies (Nielsen and Sorensen 1992; Jankovska and Komarek 2000; Tell and Zamaloa 2004; Tahoun et al. 2017). Extant members of the genus *Pediastrum* are all freshwater species. The rare occurrence of the genus in marine settings has been explained as caused by freshwaters influxes (Brenner and Foster 1994; Matthiessen et al. 2000). The geographical distribution of species of *Pediastrum* is mainly determined by two factors: global distribution responds to temperature, whereas regional distribution is better explained by water quality (Tell 2004). In the northern mid latitudes, changes in the abundance of *Pediastrum* have been interpreted to reflect changes in trophic state and erosion in the catchment (Van Geel 2002) while variation in tropical and subtropical regions are thought to reflect changes in temperature (Rull et al. 2008), lake levels (Gosling et al. 2008) and increase or decrease of the macrophyte cover in lakes (Caballero et al. 1999; Lamb et al. 1999). Changes in communities of *Pediastrum* have shown a relationship with nutrient availability (Bradshaw et al. 2005), pH and dissolved organic carbon (Weckstrom et al. 2010), water quality (Jankovska and Pokorny 2002), water level (Whitney and Mayle 2012), and presence of littoral vegetation (Danielsen 2010). In the present study, the occurrence of *Pediastrum* was recognized mainly to the genus level. The reason is that most of the samples used in this study come from oil industry activities where the main objective was biostratigraphy rather than detailed taxonomic identification. In this study, the abundance of *Pediastrum* was used as an indicator of freshwater depositional conditions (lakes and ponds).

*Botryococcus* (Kutzing 1849) (Botryococcaceae, Trebouxiiales, Trebouxiophyceae, Chlorophyta) is a green colonial microalga widespread in freshwater and brackish lakes, reservoirs, ponds, or even ephemeral lakes situated in continental, tropical, alpine and temperate zones (Aaronson et al. 1983). *Botryococcus* occurs as colonies of various sizes with individual cells ranging in size from 5 to 15µm and colonies from 10 to 100µm (Guy-Ohlson 1992). The taxonomy of the genus is still unclear. Komarek and Marvan (1992) defined 13 species based on morphological characters from light microscopy observations in fixed natural samples. However, diagnostic characters such as color, cell size, and colony form had the potential to change within a clonal strain when placed under different culture conditions (Plain et al. 1993). For this reason the taxonomic system proposed by Komarek and Marvan (1992) has not been widely used, and a single species, *Botryococcus braunii*, is currently used in most studies (Kawachi et al. 2012). Colonies of *Botryococcus* occur throughout the entire Phanerozoic and they became very widespread especially during the Mesozoic and Cenozoic (Aaronson et al. 1983). *Botryococcus* has little biostratigraphical importance, but can be used, by analogy with the modern microalga, to interpret palaeoecological and climatic conditions and for paleoenvironmental reconstructions (Guy-Ohlson 1992). Modern *Botryococcus* is worldwide distributed and although it is prevalent in tropical regions, it also tolerates cooling events (Herrmann 2010). It is found in fresh and brackish water lakes and seawater near river estuaries where is a very important contributor of organic content (kerogen) (Metzger and Largeau 2005). It is rarely found in lakes deeper than 100 m, as it is an autotrophic alga that requires sufficient sunlight and clear water (Li-Ming et al. 2010). *Botryococcus* prefers calm waters with few underwater plants and low sedimentary/nutrient input from the outside thus it favors oligotrophic to mesotrophic waters but also tolerates eutrophic conditions (Herrmann 2010). In normal lacustrine conditions, *Botryococcus* can bloom and may form floating mats of several centimeters thick spreading over an area of several hundred square meters (De Decker 1988). Earlier records indicate that *Botryococcus* colonies flourished in both fresh and brackish water in lake facies of organic rich black mudstone and fine

siliceous mudstones, but rarely in near-shore and shallow-water lake facies (Prasad and Sarkar 2000; Ji et al. 2010). In the present study, the presence and abundance of *Botryococcus* is used as indicator of lacustrine conditions.

**Continental Palynomorphs.**—This category includes abundances of formal and informal species of pollen and spores.

Once all the species were classified, an index of lacustrine influence (LI) was calculated for those samples with counts higher than 50 palynomorphs.  $LI = L/T$ , where L is the abundance of algae (*Pediastrum* and *Botryococcus*) and T is the total count of the sample. The contribution of *Pediastrum* and *Botryococcus* to LI was also calculated.

#### Indicator Species Analysis

The continental palynological association (pollen and spores) of the Barzalosa Formation was determined using an indicator species analysis using the R package *indicspecies* (De Caceres and Legendre 2009). This analysis estimates the relationship between the species occurrence or abundance values from a set of sites or samples and the classification of the same site or samples into groups (De Caceres and Legendre 2009). For this purpose, only the well Gb-1 was used because it represents the section with the most complete palynological record of the Barzalosa Formation. Only the abundance of terrestrial palynomorphs in samples with counts higher than 50 were used in the analysis. The groups correspond to the three intervals interpreted based on the proportion of algae.

#### Environments of Deposition

To further explore the depositional sequence of the Barzalosa Formation, the lithology from well Gb-1 was extracted from the well log. The lithological sequence includes five lithologies (shale, sandstones, gray claystones, coal, and siltstones) reported between 3666.2 and 4282.9 m (Online Supplemental File 2).

To establish the depositional sequence, a transition matrix method based on Markov chain was used (TM). TM is a method for quantitative stratigraphy, which supposes that the succession of facies in a set of stratigraphic logs can be considered as a Markov process (Davis 2002). A Markov process is a succession of states or events in which the occurrence of a given state depends on the previous one (Powers and Easterling 1982). In the case of Gb-1 the states or events represent the changes in lithology. The TM starts with a state transition matrix, which consist of a two-way table that record the number of transitions between every couple of states. Sequences are then defined based on the statistically significant transitions (Ndiaye et al. 2014). Three methods have been proposed to separate significant from random transitions. In the Walker method (Walker 1979), the sequence is obtained by comparing the observed probability of transition between states with randomly occurring transitions. The Harper method (Harper 1984) transitions probabilities greater than random are tested for statistical significance. For each transition between two states, the probability of having at least the observed number of successions in N trials is computed. This corresponds to the binomial probability. Considering the null hypothesis that a transition occurs at random, it can be rejected if the binomial probability is greater or equal to the chosen level of significance (Ndiaye et al. 2014). In the Turk method (Turk 1979) the transition matrix is separated into noise and signal matrices. Several iterations are often necessary to isolate these two matrices, which are produced iteratively based on *a priori* or posterior hypothesis based on residual analysis (Ndiaye et al. 2014). The final sequence is computed

FIG. 4.—Lithology of the Barzalosa Formation and Honda Group in five wells drilled in the Upper Magdalena Valley. The lithological information was extracted from wells logs. Black dots indicate stratigraphic positions of samples used in the study. Abbreviations: MMV= Middle Magdalena Valley; UMV= Upper Magdalena Valley.

using the difference between the observed and the random matrix. The significant transitions of the Barzalosa Formation were obtained using the Walker method at the 99% confidence level. The results are shown as lithology relationship diagrams (LRD) in which two given lithologies are linked with an arrow showing the probability, greater than random, to pass from one lithology to another. When transitions are simultaneously from A to B and from B to A, we say that A-B transition is cyclical. When transitions only go from A to B, the transition is referred as simple.

The TM analysis was executed in the software Strati-Signal (Ndiaye 2007).

## RESULTS

### Chronostratigraphy

The SRS for the MMV results from the integration of data from wells Mon-1A and Reg-1 (Fig. 3). The SRS comprises a total of 288 samples, from which 185 correspond to Mon-1A and 103 to Reg-1. Four different stratigraphic levels characterized by abundant fragments of mollusks were recognized during the drilling of Mon-1A and Reg-1. These levels were interpreted to be the “Los Corros” and the “Mugrosa” fossil horizons in Reg-1, while the La Cira fossiliferous horizon was recognized in Mon-1A (Fig. 3). Another stratigraphic level with mollusks was recognized, between the Los Corros and Mugrosa fossil horizons, in the well Reg-1 (~31.5 Ma) (Fig. 3). The fragments in this level could be the result of contamination by borehole caving or may be part of the Mugrosa or the Los Corros horizon. The ages of the horizons were estimated using the palynological zonation of Jaramillo et al. (2011) (Fig. 3). The palynological analysis of the SRS shows that the Los Corros and Mugrosa horizons are associated with the presence of algae, whereas the La Cira horizon contains elevated abundances of *Pediastrum* and *Botryococcus*. *Pediastrum* is also abundant in some samples that apparently are not related to the fossil horizons (Fig. 3). These abundances could be explained as the product of isolated local lakes in fluvial systems (e.g., oxbow lakes in meandering systems) or as result of contamination by caving.

A total of 127 samples distributed in five wells (Hig-1 = 16 samples; Gc-1 = 29 samples; Gb-1 = 58 samples; Nd-1 = 13 samples; Ym-1 = 11 samples) (Fig. 4) from the Upper Magdalena Valley (UMV) were compared with the SRS of the MMV. The samples are distributed through the Barzalosa and Honda Formations. The Barzalosa Formation is represented by 92 samples distributed in the five wells while the Honda Formation is represented by 35 samples distributed in two wells (Gc-1, Hig-1) (Fig. 4). According to the well logs, the Barzalosa Formation unconformably overlies the Guaduala and Doima formations (Paleocene and Oligocene in age) in Gc-1 and Gb-1, respectively; the Monserrate and Villeta formations (Cretaceous in age) in Hig-1 and Ym-1, respectively; and the basement in Nd-1 (Fig. 4). The Honda Formation overlies the Barzalosa Formation in the five wells (Fig. 4) (not shown for Gb-1 and Ym-1).

Palynologically the samples from the UMV show very good recovery of palynomorphs, with conspicuous abundances of *Botryococcus* and *Pediastrum* accompanied by a diverse association of pollen and spores. Interestingly, neither foraminifera nor dinoflagellates were found in any of the samples.

According to the maximum likelihood results (Fig. 5) the samples related with the Barzalosa Formation show high probability of correlation with the interval in the standard reference section (SRS) related to the La Cira fossiliferous horizon. This is especially evident in wells in which only samples from the Barzalosa Formation were analyzed. In Gb-1, the well with the most complete sampling coverage, the samples are concentrated around 16.5 Ma with the highest probabilities stratigraphically located at the lower part of the interval (Fig. 5). A histogram of the mean probabilities by palynological biozone corroborate that most of the samples

in Gb-1 are related to the biozone T-13 (Jaramillo et al. 2011) and to a lesser extent to the biozone T-12 (Fig. 5).

In spite of their low probability values, the samples from the upper interval are also concentrated around 16.5 Ma (Fig. 5). In wells Nd-1 and Ym-1 the samples from the Barzalosa Formation show high probabilities of correlation with the interval of the SRS interpreted as deposited between 16 and 17.5 Ma. This interval corresponds to the La Cira fossiliferous horizon. The probability values in the samples from these two wells are higher than those in Gb-1 (Fig. 5). In Hig-1, two samples from the Barzalosa Formation show high probabilities of correlation with the interval at 16.5 Ma while the sample 1597.1 m, also from the Barzalosa Formation, shows higher probability of correlation with ages younger than 12 Ma (Fig. 5). Finally, the samples related to the Barzalosa Formation in Gc-1 show high probability of correlation with the interval between 16.5 Ma and 17.5 Ma (Fig. 5).

The samples from the Honda Formation in well Hig-1 show in general low probability values. Some of the samples correlate with the interval associated to the La Cira fossiliferous Horizon while others seem to correlate with ages younger than 1 Ma (Fig. 5). In Gc-1, the samples from the Honda Formation also show low probability values that correlate with the interval between 16.5 and 17.5 Ma. However, the sample at 816.8m shows a high probability of correlation with younger ages (~12 Ma) (Fig. 5).

### Paleoecology

In terms of the lacustrine-related palynomorphs the five wells from the UMV exhibit relatively elevated LI values (Fig. 6). The Honda Formation in wells Gc-1 and Hig-1 show high abundances of *Botryococcus*. In Hig-1 high abundances are restricted to the upper segment while in Gc-1 the high abundances are distributed through the entire interval. The Barzalosa Formation also shows elevated proportion of algae in the five wells (Fig. 6).

By using the proportions of *Botryococcus* and *Pediastrum* it is possible to visually separate three intervals in Gb-1 (Fig. 7). The three intervals are also evident when the samples are grouped by the proportion of the two algae using a constrained hierarchical clustering (Juggins 2017). The samples between 4175.7 and 4114.8 m (interval 1) show relatively low SI values. *Pediastrum* dominate the association, although low proportions of *Botryococcus* are observed in some samples (Fig. 7). The samples between 4114.8 and 3886.2 m (interval 2) show generally elevated SI values and, in contrast to the interval 1, the association is dominated almost exclusively by *Botryococcus* with sporadic occurrences of *Pediastrum* (Fig. 7). The LI in samples between 3886.2 and 3703.3 m (interval 3) show an increasing trend from base to top, with a decline toward the end of the interval (Fig. 7). *Botryococcus* and *Pediastrum* contribute to the lacustrine component during this interval (Fig. 7).

A general characterization of the organic matter in GB-1 show the consistent presence of structured phytoclasts (cuticles and vegetal tissues) and woody material throughout the entire section with minor proportion of amorphous organic matter and degraded phytoclasts that indicate the occurrence of lacustrine environments. An increase in amorphous material and degraded phytoclasts is observed between 3840.4 and 3779.5 m, which coincide with elevated abundances of *Pediastrum* spp. in interval 2.

### Indicator Species Analysis

A total of 72 species distributed in 50 samples were used in the analysis (eight samples from interval 1; 27 samples from interval 2; 15 samples from interval 3). The indicator species for interval 1 are *Rhoipites guianensis*, *Echitriporites* sp., *Malvacipolloides maristellae*, and *Malvacidites* sp. The last two species are very abundant during this interval although they are also present in the intervals 2 and 3 (Fig. 7). Intervals 2 and 3 share the indicator species *Psilatrilites* < 25 µm and *Retitricolpites simplex* var. *minor*. The



Middle Magdalena Valley  
Standard Reference Section

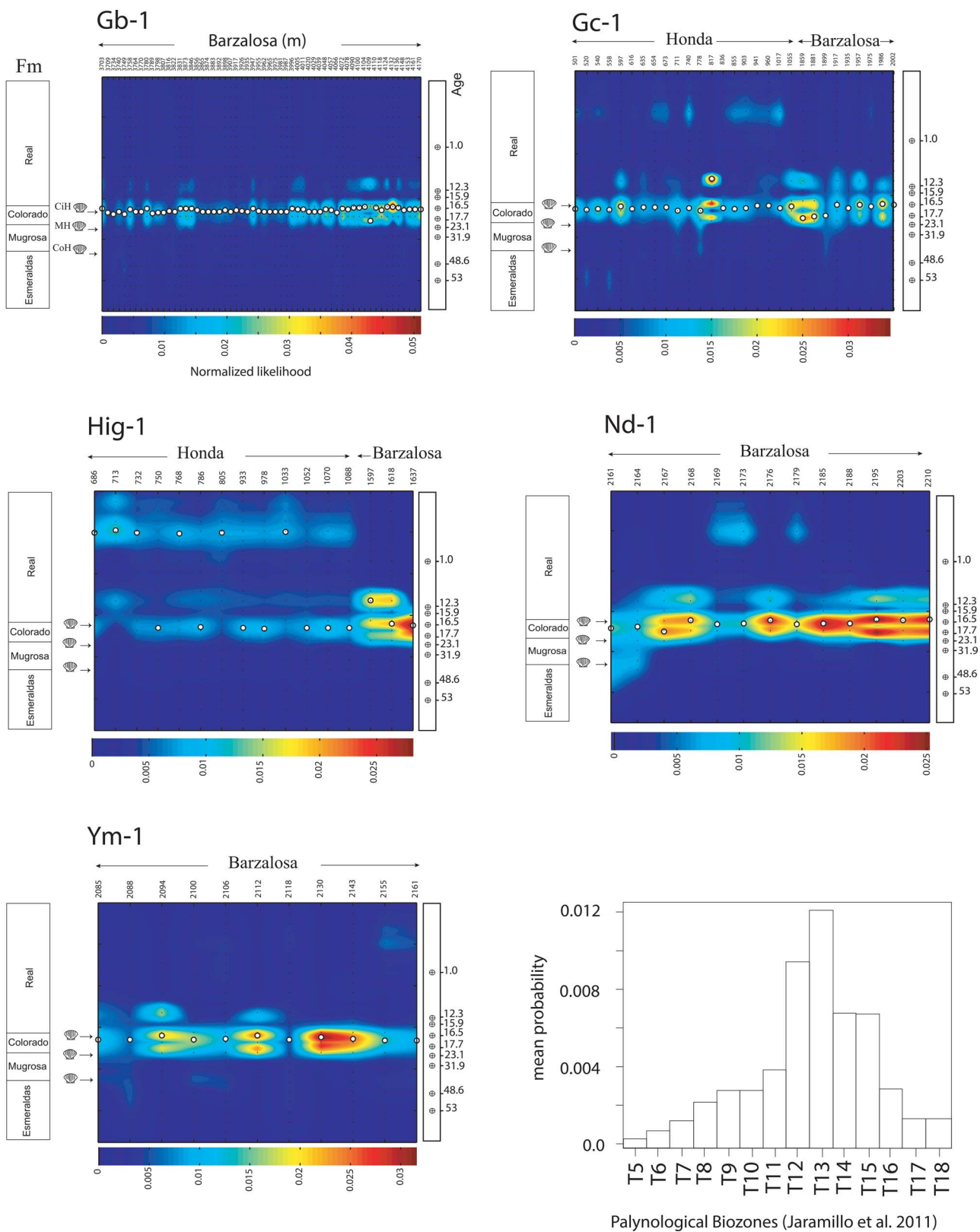


FIG. 5.—Age estimates for 198 samples distributed in five wells drilled in the Upper Magdalena Valley. Normalized likelihoods values are represented by color, with higher and lower likelihood values represented by red and blue, respectively. Maximum likelihood estimates are denoted by with circles. Lower right panel is a histogram of the mean probability by biozone for the samples of the Barzalosa Formation in Gb-1.

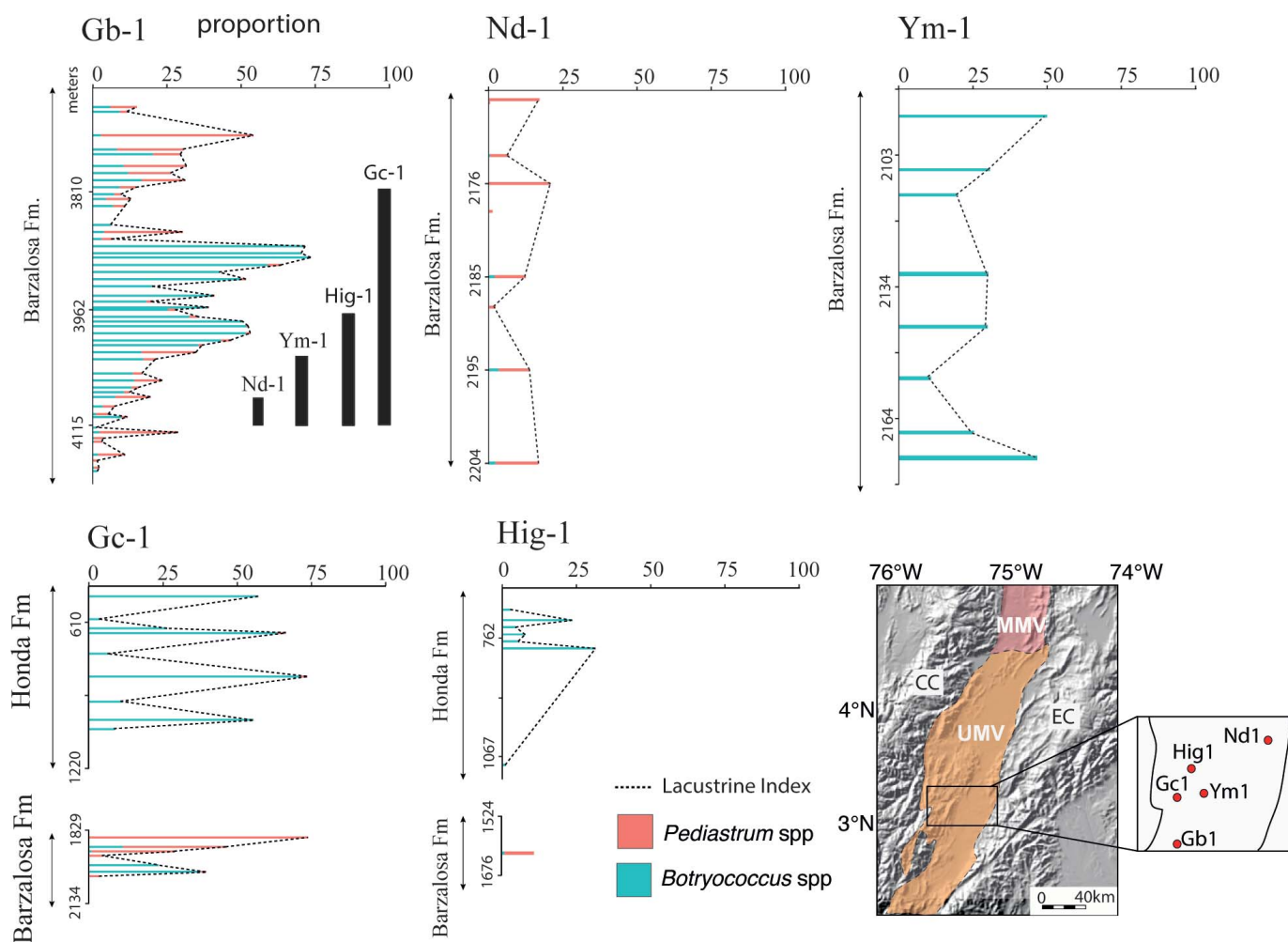


FIG. 6.—Proportions of *Botryococcus* and *Pediastrum* with respect to the total count of terrestrial palynomorphs (pollen and spores) in segments of the Barzalosa Formation and Honda Group in wells drilled in the Upper Magdalena Valley. To highlight the differences in scale, Nd-1, Ym-1, Gc-1, and Hig-1 are shown at the same scale in the panel of Gb-1.

abundance of these two species is very low in comparison with the indicator species of the interval 1, but they are stratigraphically restricted to intervals 2 and 3 (Fig. 7). The algae *Azolla* is an indicator species of interval 3, although its abundance is very low (<10 individuals) and is also reported in one sample from interval 2 (Fig. 7). Other abundant terrestrial palynomorphs distributed throughout the three intervals are *Laevigatosporites tibuensis*, *Magnastriatites grandiosus*, *Mauritidites francisci* var. *minutus*, *Psilamonocolpites medius*, *Psilatrilletes* 25–50, *Retitricolpites simplex*, and *Verrucatosporites usmensis* (Fig. 7).

#### Environments of Deposition

A transition matrix method based on Markov chain (TM) was used to analyze the depositional sequence of the three intervals of the Barzalosa Formation in Gb-1 (Fig. 7). Interval 1, between 4357.1 and 4108.7 m, which includes the base of the formation, was not investigated regarding palynology and therefore is not shown in Figure 7. Intervals 2 and 3 were interpreted between 4108.7 and 3886.2 m and 3886.2 and 3675.8 m respectively (Fig. 7).

The computed chi-square from the intervals 1 and 3 exceed the critical value suggesting that the data are not random. The data from interval 2 do not exceed the critical value suggesting therefore randomness (interval 1: critical  $X^2$  at 95% confidence level: 11.07, computed  $X^2$ : 19.0; interval 2:

critical  $X^2$  at 95% confidence level: 11.07, computed  $X^2$ : 1.6; interval 3: critical  $X^2$  at 95% confidence level: 3.8, computed  $X^2$ : 4.7).

The probability and random and Walker matrices are presented in the Table 1, while the results are shown as lithology relationships diagrams (LRD) (Fig. 7). For interval 1, the LRD shows two cyclical transitions (shale-coal and gray claystone-sandstone) and one simple transition (shale-clay) (Fig. 7). The transitions with the highest probability of occurrence are sandstone to gray claystones and coal to shale. The sandstone and coal are not shown in the stratigraphic column (Fig. 7) because they occur below the interval with palynological analysis, which was not included in the figure. The stratigraphic distribution of these two lithologies is presented in Online Supplemental File 2. In terms of thickness and number of layers, the dominant lithology in interval 1 is gray claystone (Table 2).

The LRD for interval 2 show two cyclical transitions (shale-coal, shale-sandstone) and one simple transition (silt-shale) (Fig. 7). These transitions are random according to a chi-square test. The transitions with the highest probability of occurrence are coal to shale, silt to shale and sandstone to shale. In terms of thickness and number of layers, the dominant lithology in this interval is shale (Table 2).

The LRD for interval 3 show a single transition sequence (shale-clay-sandstone-shale) (Fig. 7). The transition with the highest probability of occurrence is shale to clay followed by sandstone to shale and clay to

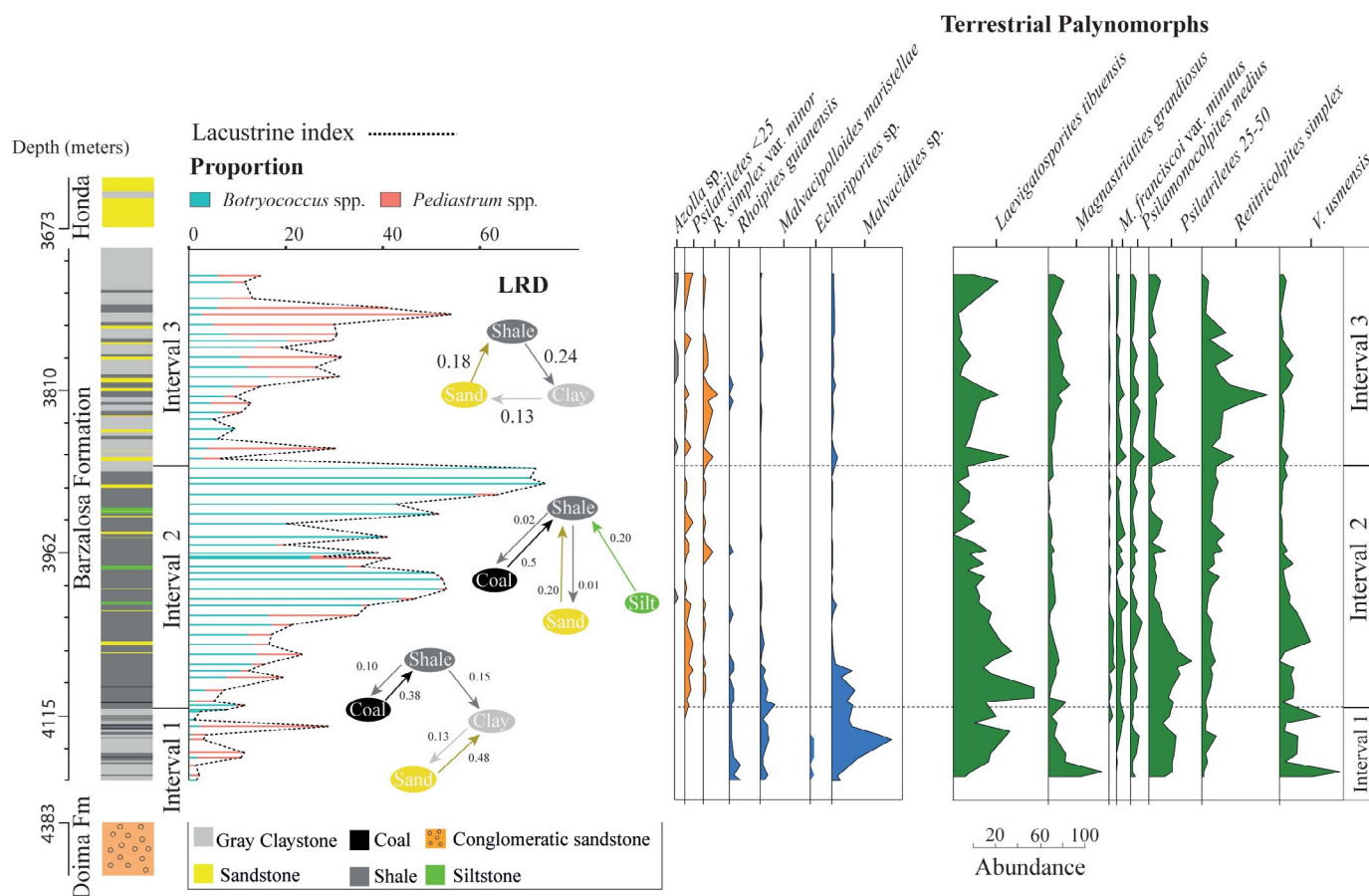


FIG. 7.—Subdivision of the Barzalosa Formation in Gb-1 based on the proportion of algae (*Botryococcus* and *Pediastrum*), lithology and palynological composition. The sandstone and coal intervals in the Interval 1 are not shown in the stratigraphic column because they are far below the interval with palynological analysis, which was not included in the figure. The stratigraphic distribution of these two lithologies is presented in the Online Supplemental Fil 2. LDR=Lithology Relationship Diagram. Colors in the abundance palynomorphs diagram groups species by intervals. Color blue correspond to species that are abundant in the interval 1; color green show species that are abundant in the three intervals; and color orange show species that are abundant in interval 3.

sandstone. In terms of thickness and number of layers, the dominant lithology in this interval is gray claystone (Table 2).

## DISCUSSION

The age of the Barzalosa Formation has been inferred from its stratigraphic position (De Porta 1974). The results presented in this study show that the Barzalosa Formation and the La Cira fossiliferous horizon share a similar palynological composition. The elevated abundances of the algae *Pediastrum* and *Botryococcus* indicate the occurrence of lacustrine systems in the Middle and Upper Magdalena valleys during the deposition of these units.

### Chronostratigraphy

The La Cira fossiliferous horizon was interpreted from a composite section in which not only this horizon but also the Mugrosa and the los Corros fossiliferous horizons were identified by the occurrence of shell fragments. The approach of including the three fossiliferous horizons in the analysis opened the opportunity to compare the Barzalosa Formation with other possible correlative deposits. In the composite section and specifically in Mon-1A, the La Cira fossiliferous horizon was interpreted based on the abundance of algae and shell fragments between 2133.6 and 2380.4 m. According to Jaramillo's zonation (Jaramillo et al. 2011) this

interval was deposited between 17.5 and 16.5 Ma (palynological zone T-13 *E. maristellae*). The results of the maximum likelihood analysis show a high probability of correlation between the samples of the Barzalosa Formation and the La Cira fossiliferous horizon (Figure 5). The Barzalosa Formation would therefore have been deposited between 17.5 and 16.5 Ma.

The composite section does not show the three intervals interpreted for the Barzalosa Formation in Gb-1. The elevated abundances of *Botryococcus* and sporadic occurrences of *Pediastrum* in the composite section open the possibility that the middle interval (interval 2) in Gb-1 is correlative with the La Cira fossiliferous horizon while the intervals 1 and 3 have no counterpart in the composite section. The histogram of ages in Gb-1 (right panel, Fig. 5) supports this interpretation and suggests that the Barzalosa Formation possibly covers a longer time interval.

In terms of biostratigraphy, the palynological zone T13-*E. maristellae* is delimited at the base and top by the first appearance datum (FAD) of *Malvacipoloides maristellae* and *Grimsdalea magnaclavata*, respectively. Biostratigraphic key taxa with FADs within this zone include *Bombacacidites baculatus* and *Echitricolporites spinosus*, while *Rugotricolporites intensus*, *Retistephanoporites minutiporus*, *Cyclusphaera scabrata*, and *Echinatisporites brevispinosus* show their last appearance datum (LAD) during this interval (Jaramillo et al. 2011). Of those taxa mentioned above, only *M. maristellae* and *E. spinosus* were reported in the wells from the Upper Magdalena Valley used in this study. The intermittence in presence

TABLE 1.—Probability, Random and Walker matrices for the intervals of the Barzalosa Formation in Gb-1.

Interval 3 (3886.2–3675 meters)												
Litho	Probability matrix			Random matrix			Walker matrix					
	C_gray	Shale	Sandstone	C_gray	Shale	Sandstone	C_gray	Shale	Sandstone			
C_gray	0	0.41	0.58	0	0.55	0.45	0	-0.13	0.13			
Shale	0.81	0	0.18	0.57	0	0.42	0.24	0	-0.24			
Sandstone	0.33	0.66	0	0.52	0.47	0	-0.18	0.18	0			
Interval 2 (4108.7–3886.2 meters)												
Litho	Probability matrix				Random matrix				Walker matrix			
	Shale	Coal	Sandstone	Siltstone	Shale	Coal	Sandstone	Siltstone	Shale	Coal	Sandstone	Siltstone
Shale	0	0.15	0.61	0.23	0	0.13	0.6	0.26	0	0.02	0.01	-0.03
Coal	1	0	0	0	0.5	0	0.34	0.15	0.5	0	-0.34	-0.15
Sandstone	0.88	0	0	0.11	0.68	0.10	0	0.21	0.20	-0.10	0	-0.09
Siltstone	0.75	0	0.25	0	0.54	0.08	0.37	0	0.20	-0.08	-0.12	0
Interval 1 (4357.1–4108.7 meters)												
Litho	Probability matrix				Random matrix				Walker matrix			
	C_gray	Shale	Coal	Sandstone	C_gray	Shale	Coal	Sandstone	C_gray	Shale	Coal	Sandstone
C_gray	0	0.35	0.17	0.47	0	0.41	0.25	0.33	0	-0.63	-0.073	0.13
Shale	0.7	0	0.3	0	0.54	0	0.19	0.25	0.15	0	0.10	-0.25
Coal	0.33	0.66	0	0	0.48	0.28	0	0.22	-0.15	0.38	0	-0.22
Sandstone	1	0	0	0	0.51	0.30	0.18	0	0.48	-0.30	-0.18	0

of these species highlights the difficulty to correlate stratigraphic units based exclusively in the occurrence of biostratigraphic marker species. As shown, this difficulty can be overcome by using quantitative methods like the maximum likelihood approach that use the relative abundance of the

species. Finally, the Barzalosa Formation stratigraphically overlies the Honda Formation. According to Guerrero (1997b), the Honda Formation was deposited between 13.5 and 11.5 Ma. This supports our interpretation of the age of the Barzalosa Formation.

TABLE 2.—Summary of the lithology of the three intervals of the Barzalosa Formation in Gb-1.

Interval 3 (3886.2–3675 meters)				
Lithology	Number of layers	Total thickness (m)	Mean thickness (m)	Standard deviation (m)
Gray claystone	13	142.3	10.9	9.1
Sandstone	9	23.5	2.6	1.2
Shale	11	44.5	4	1.5
Total number	33	210.3		
Interval 2 (4108.7–3886.2 meters)				
Lithology	Number of layers	Total thickness (m)	Mean thickness (m)	Standard deviation (m)
Shale	14	196	13.7	9.4
Sandstone	9	13.4	1.4	1.15
Siltstone	4	12.1	3	2.1
Coal	2	0.9	0.45	0.6
Total number	29	222.5		
Interval 1 (4357.1–4108.7 meters)				
Lithology	Number of layers	Total thickness	Mean thickness (m)	Standard deviation (m)
Gray claystone	18	357.5	19.8	35
Coal	6	2.1	0.3	0.12
Sandstone	8	6.4	0.79	0.94
Shale	10	19.5	1.9	1
Total number	42	385.5		

### Paleoecology and Environments of Deposition

Of the five wells analyzed in this study, Gb-1 shows the most complete record of the Barzalosa Formation. The palynological analysis, and specifically the proportions of *Botryococcus* and *Pediastrum*, allows division of this unit into three intervals (Fig. 7). The basal interval is characterized by relatively low SI values with *Pediastrum* dominating association. The middle interval shows an increasing trend in SI that in contrast with the basal interval is almost entirely dominated by *Botryococcus*. The upper interval shows a decline and posterior increase in SI with *Pediastrum* and *Botryococcus* alternating in the dominance of the association (Fig. 7).

The change in the relative abundance between the *Botryococcus* and *Pediastrum* is a consequence of the ecological and climatic conditions of the lacustrine systems (Tyson 1995; Medeanic 2006). Changes in the trophic state of a lake from oligotrophic to eutrophic usually results in a decrease in the *Botryococcus*: *Pediastrum* ratio (BP ratio) (Pollinger 1986). Salinity also seems to be a significant factor, with *Botryococcus* being euryhaline and *Pediastrum* stenohaline (Tyson 1995). Interestingly, the three intervals defined based on the proportion of algae (Fig. 7) also show marked differences in their depositional sequences, which were explored using a Markov chain approach. Although the three intervals show similar lithologies, their thickness, number of layers and distribution vary (Table 2). More important, the lithology relationship diagram indicates that the three intervals are characterized by different and specific lithological transitions (Fig. 7). It is noteworthy that the few studies (Scheibe 1934; Caceres and Etayo-Serna 1969; De Porta 1974; Acosta et al. 2002) have also divided the Barzalosa Formation, based on lithology, into three units or intervals (Fig. 2). A lower segment of thick layers of conglomerates intercalated with siltstones and fine-grained sandstones. A middle segment of monotonous thick layers of siltstones and claystones showing gypsum veins intercalated with sporadic layers of fine to medium-grained sandstones. An upper segment that corresponds to thick layers of oligomictic conglomerates intercalated with claystones and siltstones with sporadic gypsum veins. Unfortunately, the lithological information that can be extracted from a well log is restricted almost exclusively to the general type of lithology, which prevents an accurate sedimentological interpretation. However, the lithology of Gb-1 shows in general a good concordance with the lithology of the three intervals described in the literature. The absence of gypsum veins in the middle and upper intervals of Gb-1 could be explained by differences in the environment of deposition or more plausible by the difficulty of identifying minerals in ditch cutting samples.

Based on the palynological and sedimentological information from Gb-1 we suggest that the deposits of the Barzalosa Formation are the result of the evolution of a lacustrine system. It is well established that due to changes in climate and/or tectonic subsidence, non-marine basins commonly evolve from one lake type to another (Lambiasi 1990). In fact, most basin fills contain a predictable evolution between lacustrine facies associations (Neal et al. 1997). For example the Green River Formation in Wyoming (USA) records a complete gradational cycle of lake basin types from overfilled, balanced fill, and underfilled, then back through balanced fill and overfilled (Carroll and Bohacs 1999). Detailed sedimentological analyses in sections distributed along the UMV basin are necessary to establish the evolution of the Barzalosa system.

To summarize, with the information from the present study it is possible to interpret the three intervals of the Barzalosa Formation as follows. The basal interval (interval 1) is characterized by a low BP ratio that suggests moderate lacustrine influence and high nutrient content. During this interval, and the lowest part of the interval 2, *Malvacipoloides maristellae* and *Malvacipoloides* sp. reached their maximum abundances (Fig. 7). *Malvacipoloides maristellae* is a key taxon to identify to the palynological zone T-13 (16.1–17.7 Ma) (Jaramillo et al. 2011), that is the zone

associated to the deposition of the Barzalosa Formation and the La Cira fossiliferous horizon. Interestingly, this species is also very abundant in the basal interval of the Mariñame section (Salamanca et al. 2016), which is an outcrop located in the Caquetá River (Colombia) deposited between 17.7 and 16.1 Ma. Similar to Gb-1, *M. maristellae* in Mariñame section is accompanied by low abundances of *Botryococcus* and a total absence of marine palynomorphs. Mariñame was deposited in floodplain environments in wet conditions (Salamanca et al. 2016). A similar environment of deposition is interpreted for the interval 1 in Gb-1.

The middle interval in Gb-1 (interval 2) shows a continuous increasing trend of LI (Fig. 7). The dominance of *Botryococcus* suggests a decrease of both the biological activity and the amount of nutrients. During this interval, the fine lithologies (shale, siltstone) predominate and sandstones represent only 6% of the total thickness (Table 2). The low proportion of sandstones suggests the absence of fluvial systems capable of delivering sediments into the lake, which would explain the low nutrient content suggested by the BP ratio. The information from outcrops indicates the occurrence of gypsum veins in the middle interval of the Barzalosa Formation (Caceres and Etayo-Serna 1969; De Porta 1974). Elevated abundances of *Botryococcus* accompanied by gypsum have been associated with periodic deposition of gypsiferous or other shallow water evaporitic facies (Nagappa 1957). This could correspond to the environment of deposition of the middle member of the Barzalosa Formation. The increasing trend in LI (Fig. 7) during this interval is indicative of geographic expansion of the lacustrine system. This expansion moved the shoreline, increasing the abundance of *Botryococcus* and decreasing the proportion of terrestrial palynomorphs. The decrease in terrestrial palynomorphs is either the result of a low contribution of the plants that previously were closer to the lacustrine system or the dilution of the terrestrial material by the increase of *Botryococcus*. The decrease in the amount of nutrients is explained by the retrogradation of the discharge zones due to the expansion of the lacustrine system.

Finally, the upper interval (interval 3) shows fluctuations of the BP ratio with *Botryococcus* and *Pediastrum* alternating in dominance (Fig. 7). The lithological relationship diagram indicates a cyclic sedimentary sequence that involves the transition from shale to clay, from clay to sandstone, and from sandstone to shale (Fig. 7). The thickness of these lithologies (Table 2) suggests either variability in the duration of the cycles or changes in the sedimentation rates or a combination of both. Unfortunately, with the available information it is not possible to discard any of them. However, the cyclic sedimentation suggests variability in the sediment discharge and therefore intermittency in the amount of nutrients that reached the lacustrine system. Climatic fluctuations cannot be discarded either, which could be the factor controlling sedimentation. During this interval the lacustrine system contracted again resembling the conditions of the interval 1.

It is now well established that the interaction between rates of sediment-water supply and accommodation space controls lakes occurrences, distribution of their strata and the character of their organic and inorganic components (Bohacs et al. 2000). Sediment and water supply are controlled by climate while accommodation is a tectonic process. In this sense, it is possible that a combination of climate and tectonics were the mechanisms controlling the expansion and contraction of the lacustrine system of the Barzalosa Formation. The contribution of each component is still unclear.

### Paleogeography

Hoorn et al. (2010) proposed a mega wetland system, including some episodes of marine incursions during the Miocene in the Neotropics (Fig. 1). These marine incursions were also documented by Jaramillo et al. (2017) for the Llanos basin of Colombia and the Solimoes basin of Brazil. The exclusive occurrence of lacustrine-related algae found in the present study indicates that lacustrine to swamp environments prevailed in the

middle and upper Magdalena valleys. This resembles the “Pebas phase” of the Pebas system in which the mega wetland expanded reaching its maximum extension (Hoorn et al. 2010). The absence of marine palynomorphs (dinoflagellates and foraminifera) indicates that the marine incursions did not reach the UMV.

In terms of paleogeography, the single foreland basin that encompassed the middle and the upper Magdalena valleys, the Eastern Cordillera and the Llanos basin was disrupted at least since the late Eocene to earliest Oligocene prior to the onset of the major late Neogene exhumation pulses of the Andes (Nie et al. 2010; Moreno et al. 2011; Ochoa et al. 2012). During Miocene times, the Eastern Cordillera already separated the middle Magdalena valley from the Llanos basin (Parra et al. 2009; Caballero et al. 2010). The timing of isolation of the UMV from the Llanos basin is less clear. Using sedimentological information and apatite fission tracks, Guerrero (1997b) estimated that the initial phase of uplift of the Eastern Cordillera at the latitude of the UMV occurred approximately at 12.9 Ma. Other studies however have suggested a positive relief for the Eastern Cordillera at least since approximately 22 Ma (Horton et al. 2010; Mora et al. 2010; Farris et al. 2011; Moreno et al. 2011). The correlation and paleoenvironmental similarities between the Barzalosa Formation and Pebas phase of the Pebas System suggest that the UMV and western Amazonia regions were geographically connected 16.5 Ma ago. This implies that 16.5 Ma ago the Eastern range of the Andes Cordillera at the latitude of the UMV still did not form enough relief to separate the two basins. This scenario implies that lacustrine conditions were dominant in western Amazonia. However, Jaramillo et al. (2017) demonstrated the occurrence of two marine incursions (EMI and MMI) in western Amazonia during this time. This opens the possibility that if marine waters covered both the Llanos basin and Amazonia, the Eastern Cordillera was probably acting as a physiographic barrier between the Llanos-Amazonas basin and the UMV. This separation would explain the environmental differences between the regions. More information about the paleoecology of western Amazonas and the uplift of the Eastern Cordillera is necessary to fully understand the Miocene paleogeography of the Neotropics.

### CONCLUSIONS

The intramontane basin of the Upper Magdalena Basin in Colombia preserves a complete record of a lacustrine system deposited during the early Miocene in northern South America. By comparing the palynological record of the Upper and Middle Magdalena basins we determine that the Barzalosa Formation is correlative with the La Cira fossiliferous horizon. According with the palynological zonation proposed by Jaramillo et al. (2011) the La Cira fossiliferous horizon corresponds to the zone T13-*E. maristellae*, which ranges in age between 17.7 and 16.5 Ma. Accordingly, the Barzalosa Formation was deposited during this interval. The exact time of deposition is difficult to estimate based exclusively on palynology. Complementary dating methods are necessary to narrow the age of the Barzalosa Formation.

The Barzalosa Formation provides an excellent opportunity to assess and complement our knowledge about the paleogeography of the Neotropics during the Miocene. The entire Barzalosa Formation is characterized by the elevated abundances of *Pediastrum* and/or *Botryococcus* and absence of marine microfossils like dinoflagellates or foraminifera. The abundances of algae were evidenced in several wells from the Upper Magdalena Valley. The well Gb-1 allowed separating the Barzalosa Formation into three intervals based on the relative proportions of *Botryococcus* and *Pediastrum*. The three intervals are in good agreement with the sedimentology. According to the modern ecological preferences of *Pediastrum* and *Botryococcus*, the three phases interpreted in Gb-1 exhibit marked differences in nutrient availability, which could be the result of differences in the contributions of fluvial inputs and/or climatic changes. The lacustrine index suggests the expansion and contraction of the lacustrine system,

which produced changes in the contribution of terrestrial palynomorphs and the input of nutrients to the system.

The exclusively occurrence of algae in the Upper and Middle Magdalena suggests the occurrence of extensive lacustrine systems in these two intramontane basins during the early Miocene. If marine waters occupied the Llanos basin and western Amazonia during this time it is possible that the Eastern Cordillera was already acting as orographic barrier separating the two areas. If lacustrine conditions were dominant in western Amazonia, it is possible that the Eastern Cordillera was not forming enough relief and western Amazonia and the Upper Magdalena Valley were connected and the Barzalosa Formation is the continuation of the Pebas system toward the west. Further studies are necessary to fully understand the paleogeographic configuration of the Neotropics during the Miocene.

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### SUPPLEMENTAL MATERIAL

Data are available from the PALAIOS Data Archive: <https://www.sepm.org/supplemental-materials>.

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