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BIOSTRATIGRAPHY—BREAKING PARADIGMS: DATING THE MIRADOR FORMATION IN THE LLANOS BASIN OF COLOMBIA

CARLOS A. JARAMILLO
Smithsonian Tropical Research Institute, Unit 0946, APO AA 34002, U.S.A.
e-mail: jaramilloc@si.edu
M. RUEDA
ICP, Bucaramanga, Km 7 via Piedecuesta, Colombia
G. BAYONA
Smithsonian Tropical Research Institute, Unit 0946, APO AA 34002, U.S.A.
and Corporación Geológica ARES, Calle 57 24-11 of, 202, Bogotá, Colombia
C. SANTOS AND P. FLOREZ
ICP, Bucaramanga, Km 7 via Piedecuesta, Colombia
AND
F. PARRA
Smithsonian Tropical Research Institute, Unit 0946, APO AA 34002, U.S.A.

ABSTRACT: The two major oil fields in Colombia discovered in the last fifty years are the Caño Limón and Cusiana fields. Caño Limón is located in the eastern region of the unfolded Llanos of Colombia, and Cusiana is located in the leading thrust sheet of the Llanos Foothills. Paleogene strata in both areas were part of a large foreland basin active since the latest Cretaceous. In both cases the main reservoir is a quartz arenite unit, informally called the Mirador formation, that has always been assumed to extend as a continuous Eocene sandstone layer from the Llanos Foothills into the Llanos Basin. However, recent palynological data suggested that this unit is diachronous across the Llanos and Llanos Foothills. Here, we dated 44 sections in the Llanos Basin and Llanos Foothills using a new zonation that is proposed for the region. Biostratigraphic results constrain the age of the Mirador Formation in the Llanos Foothills as early to middle Eocene with no evidence of a biostratigraphic gap with underlying early Eocene strata. In most of the Llanos Basin, including Caño Limón, the quartz arenite unit has an Oligocene age and rests unconformably upon Upper Cretaceous or Paleocene strata. Additionally, there are areas in the Llanos Basin where mudstone, not sandstone, is the dominant facies overlying the unconformity, suggesting that the basal sandstone in the Llanos Basin is not a laterally continuous body of rock. The absence of lower to middle Eocene quartz arenite beds on most of the Llanos Basin can be explained either by bypass or accumulation and subsequent erosion. These results imply a new paleogeography for the time of accumulation of Eocene and Oligocene reservoir units, a different model for basin evolution, and a different fluid-migration history to explain how the Caño Limón and Cusiana oil fields were filled.

INTRODUCTION

The geologic history of the northern Andes foreland Basin is complex due to the interaction of several plates that have produced diverse pulses of deformation at diverse angles starting in the latest Cretaceous (Gómez et al., 2005) and continuing through the Tertiary, with a major deformation pulse during the early Pliocene that uplifted the Eastern Cordillera (Fig. 1; Van der Hammen et al., 1973). The Cenozoic succession involves east-verging thrust faults of the Llanos Foothills (Eastern Foothills of the Eastern Cordillera) and in the adjacent unfolded Llanos Basin consists mostly of fluvial sediments. This succession is characterized by abrupt lateral facies and changes in thickness, syndepositional faulting, local unconformities, and intense dip-slip and oblique-slip faulting. The complexity has also been increased by a nomenclatural chaos in naming formations and by the lack of good outcrop. Under such conditions, biostratigraphy becomes a key element in understanding the Cenozoic geological history of the area.

One key formation in the eastern Andes is the Mirador Formation, composed mostly of channel-fill quartz arenite beds, because it contains the major quantities of hydrocarbon in the region, especially in the Llanos Basin and Llanos Foothills (Fig. 1). These areas have been the main object of hydrocarbon exploration in Colombia during the last thirty years. The stratigraphic nomenclature used by the petroleum industry in the Llanos and Llanos Foothills follows the nomenclature defined for the Catatumbo Basin (Notestein et al., 1944). The Paleogene sequence in the Catatumbo Basin includes, from base to top, the Barco, Cuervos, Mirador, and Carbonera formations. The Carbonera Formation has been subdivided into eight informal members in the Llanos Basin (Bogota-Ruiz, 1988), named C1 to C8, with odd numbers assigned to sandstone beds and even numbers to muddy beds. This informal nomenclature does not have a clear lithostratigraphic description or definition of a type section, nor does it use the common procedures for establishing lithostratigraphic units. This procedure has increased the chaos and disagreement about the definition of these units among the oil companies. In spite of this ambiguity, the Catatumbo nomenclature has been adopted in the Llanos Basin, and it is currently used by oil companies operating in the region.

The Mirador Formation has been reported over the entire Llanos and Llanos Foothills (Bachu et al., 1995; Cooper et al., 1995; Villamil, 1999). The thickness of this unit decreases eastward, from the Llanos Foothills to the Llanos Basin (Cooper et al., 1995; Fajardo et al., 2000) (Fig. 2). It is also called the "basal

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color p 31, 36, 37, 38

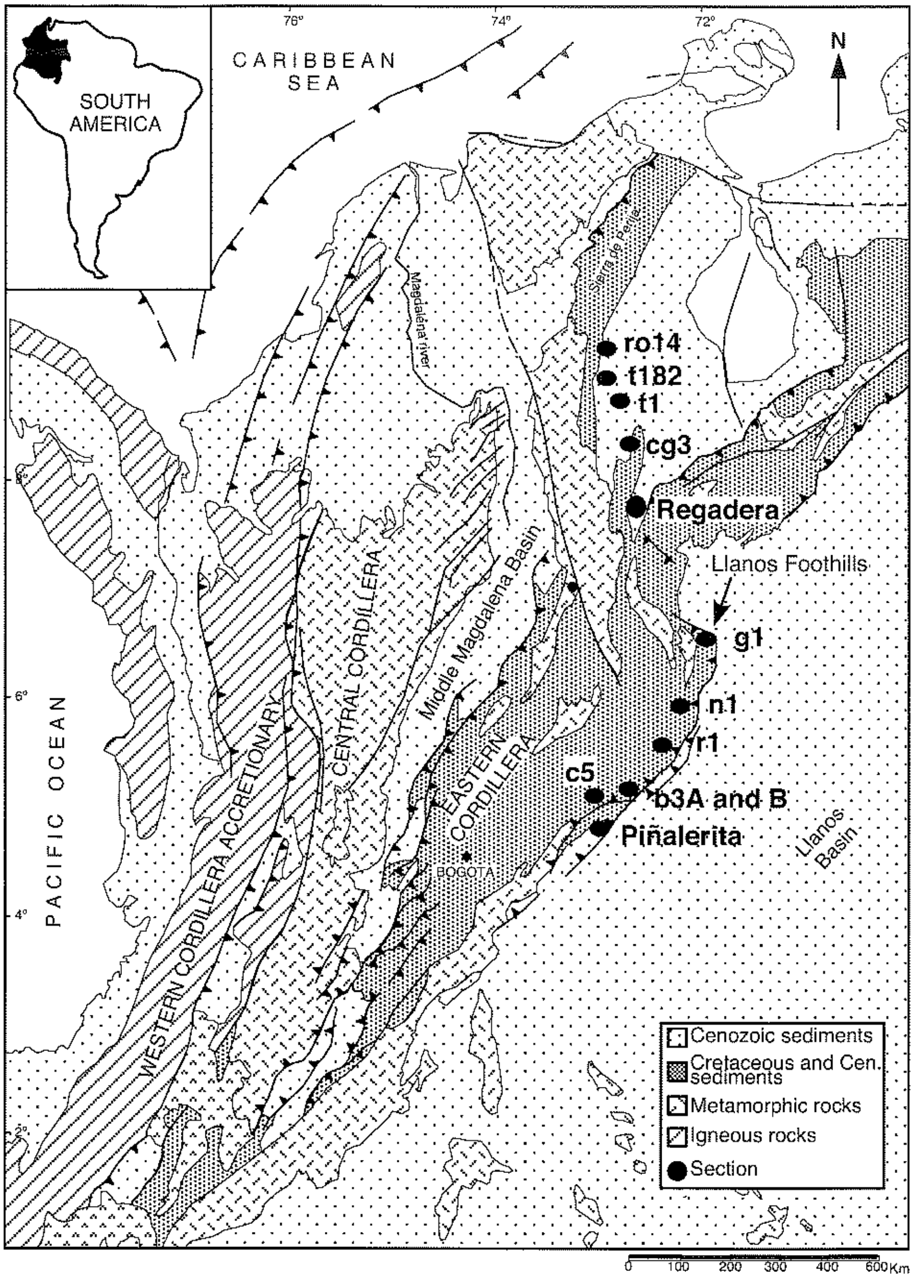

FIG. 1.—Geographic location of the eleven sections used to construct the zonation proposed in this work. Map after Dengo and Covey (1993).

sandstone" because this quartz arenite unit overlies a regional unconformity that separates an Eocene to Holocene sequence from older rocks (Paleocene, Upper Cretaceous, and Paleozoic). The two largest oil fields in Colombia, Caño Limón and Cusiana, have the largest reservoir in a sandstone that has been named the Mirador Formation (Cazier et al., 1995; Cooper et al., 1995; Gabela, 1989). According to the interpretation of some authors, however, the Mirador is absent from the Caño Limón Field (Cleveland and Molina, 1990; Molina, 1991). There are also many small fields scattered over the Llanos, such as the Arauca field, which produces from a "basal sandstone" named Mirador (Instituto Colombiano Petroleo, 2000; Navas, 1985). Biostratigraphic data supporting the understanding of the Mirador Formation are scarce. The only published biostratigraphic information for the Llanos Foothills comes from Jaramillo and Dilcher (2001). Biostratigraphic information from the Paleogene of the Llanos Basin has never been published, except for a well from the Llanos Basin (Germeraad et al., 1968). The Mirador Formation in the Llanos Foothills and the Llanos Basin have been interpreted, regardless of age, as the amalgamation of channel structures filled by fluvial to fluvial-estuarine sand bars (Cooper et al., 1995; Fajardo et al., 2000; Fajardo and Cross, 1996).

We present here a palynological biostratigraphic zonation that was constructed for the late Paleocene to Oligocene of the Llanos and Llanos Foothills. Then, we applied this zonation to the Llanos and Llanos Foothills to date the Mirador Formation, both in the Llanos Foothills and in the Llanos Basin.

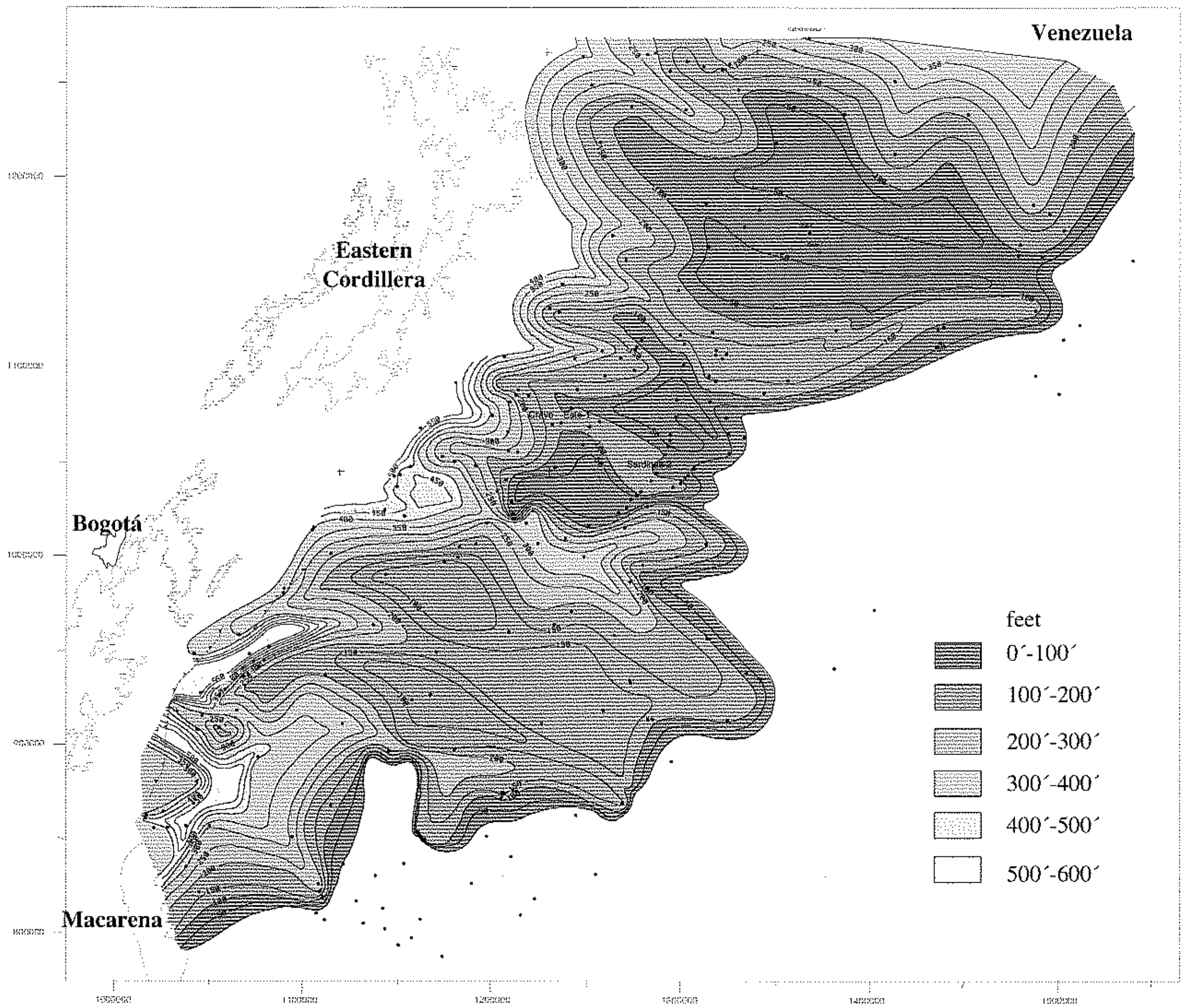

FIG. 2.—Isochore map of the Mirador Formation in the Llanos Basin and Llanos Foothills (after Fajardo et al., 2000).

METHODS

The best biostratigraphic tool in the Paleogene of the Llanos and Llanos Foothills Basin is palynology (Jaramillo and Dilcher, 2001; Rubio, 1997). Eleven sections with palynological information from outcrops (2), well cores (4), and well ditch cuttings (5) were used to produce a biostratigraphic framework for the Mirador Formation and its correlative units (Appendix 1). Sections are located in the Llanos Foothills and Catatumbo Basins (Fig. 1, Table 1).

Palynological data were analyzed using graphic correlation (Edwards, 1984, 1989; Shaw, 1964). This technique does not assume *a priori* that any extinction or origination event represents a timeline. Instead, it assesses the whole assemblage to find the true stratigraphic range for each taxon (Edwards, 1989). First-appearance datums (FAD) were not used in wells that only had ditch cutting samples, in order to minimize the error introduced by caving. The spreading parameter (Jaramillo et al., 2005) was used to evaluate the degree of confidence in the position of a datum in the composite section. Only taxa occurring in two or more wells were used to calculate this spreading parameter. Taxonomic nomenclature and illustration of the

TABLE 1.—Geographic location of the sections used for constructing the zonation proposed here.

Section	N	W	Type of section
Piñalerita	4.5	73.1	outcrop
r1	4.9	72.8	ditch-cutting
b3A and B	5.0	72.8	core
c5	5.1	72.7	core
n1	5.6	72.3	ditch-cutting
g1	7.0	71.8	core/outcrop/ditch
Regadera	7.4	72.4	outcrop
cg3	8.2	72.7	ditch-cutting
t182	8.5	72.7	ditch-cutting
t1	8.6	72.7	core
ro14	9.1	72.9	ditch-cutting

TABLE 2.—Composite section for the Llanos Basin and Llanos Foothills, interval Eocene–Oligocene. Ninety-two events with spreading values < 70 were included in the zonation. c.u. = composite units, SP = spreading parameter (as defined by Jaramillo et al., 2005), event FAD = first-appearance datum, event LAD = last-appearance datum. M.g,M.f,J.s ACME = combined acmes of *Magnastriatites grandiosus, Mauritiidites franciscoi, Jeanduforia seamrogiformis,* and *Verrucatosporites usmensis.*

Taxon	c.u.	SP	event	Zone
Cicatricosisporites dorogensis	3240.0	0	LAD	T-11
Psilaperiporites minimus	3477.8	59	LAD	
Psilaperiporites robustus	4271.8	14	LAD	
M.g,M.f,J.s ACME	4300.0	0	LAD	T-10
Psilatricolporites costatus	4910.0	12	FAD	
Retistephanoporites crassiannulatus	4615.5	13	FAD	
Ctenolophonidites cruciatus	4730.0	38	LAD	
M.g,M.f,J.s ACME	5060.0	0	FAD	T-09
Retitricolporites "planopolaris"	5060.0	15	FAD	
Verrutricolporites rotundiporus	5336.0	21	FAD	
Scabratricolporites planetensis	5543.0	22	FAD	
Retitrescolpites magnus	5362.3	44	LAD	
M. f. pachyexinatus (long spines)	5481.0	44	LAD	
Clavatricolpites densiclavatus	5391.0	69	LAD	
Nothofagidites huertasii	5600.0	8	LAD	T-08
Crassiectoapertites columbianus	5780.0	0	FAD	
Magnastriatites grandiosus	5795.7	1	FAD	
Magnaperiporites spinosus	5750.0	5	FAD	
Retitricolporites "esponjosus"	5978.6	8	FAD	
Psilatricolporites pachydermatus	5807.1	19	FAD	
Foveotriporites hammenii	5822.0	30	LAD	
Bombacacidites soleaformis	5630.0	32	LAD	
Psilastephanocolpites verrucosus	5612.8	34	LAD	
Retistephanocolporites festivus	5900.0	37	LAD	
Bombacacidites foveoreticulatus	5630.0	41	LAD	
Retibrevitricolporites grandis	5780.0	61	LAD	
E. trianguliformis var. orbicularis	5990.0	0	LAD	T-07
Concavissimisporites fossulatus	6038.0	2	FAD	
Verrucatosporites usmensis	6200.0	5	FAD	
Retistephanoporites angelicus	6400.8	8	FAD	
Echiperiporites akanthos	6038.0	15	FAD	
Verrutricolporites reticulatus	5990.0	0	LAD	
Multiporopollenites pauciporatus	6026.0	2	LAD	
Venezuelites? distinctus	5990.0	5	LAD	
Bombacacidites fossureticulatus	5990.0	9	LAD	
Echitetracolpites? tenuiexinatus	5990.0	11	LAD	
Poloretitricolpites absolutus	6400.8	11	LAD	
Pseudostephanocolpites perfectus	6350.0	21	LAD	
Corsinipollenites undulatus	6071.3	22	LAD	
Luminidites colombianensis	6274.3	28	LAD	

species used in this study can be found in diverse publications (Colmenares and Terán, 1990, 1993; Doubinger, 1973, 1976; Germeraad et al., 1968; Gonzalez, 1967; Guerrero and Sarmiento, 1996; Hopping, 1967; Jan du Chêne et al., 1978a; Jan du Chêne et al., 1978b; Jan du Chêne and Salami, 1978; Jansonius and Hills, 1976; Jaramillo, 2002; Jaramillo and Dilcher, 2001; Leidelmeyer, 1966; Muller et al., 1987; Pardo-Casas et al., 2003; Pocknall and Nichols, 1996; Regali et al., 1974; Rull, 1997a, 1997b, 1998a, 1998b, 1999; Sarmiento, 1992; Van der Hammen, 1954, 1956, 1957a, 1957b, 1958; Van der Hammen and García, 1966; Van Hoeken-Klinkenberg, 1964, 1966; Venkatachala et al., 1988; Venkatachala and Kar, 1969). Nomenclatural changes proposed by Jaramillo and Dilcher (2001) have been followed in this paper.

TABLE 2 (continued).

Taxon	c.u.	SP	event	Zone
Spinizonocolpites grandis	6441.2	4	LAD	
Jandufouria seamrogiformis	7243.9	12	FAD	
Retibrevitricolpites triangulatus	7243.9	12	FAD	
Corsinipollenites undulatus	7330.0	13	FAD	
Echitetracolpites? tenuiexinatus	6700.0	14	FAD	
Verrutricolporites reticulatus	7403.0	15	FAD	
Ranunculacidites operculatus	6616.4	17	FAD	
Pseudostephanocolpites perfectus	7443.6	17	FAD	
Retitrescolpites? irregularis	7550.9	18	FAD	
Foveotricolporites rugulatus	6700.5	20	FAD	
Brevitricolpites macroexinatus	7403.0	24	FAD	
Bombacacidites soleaformis	7228.6	25	FAD	
Rhoipites guianensis	7384.9	27	FAD	
Perisyncolporites pokornyi	7384.9	28	FAD	
Retisyncolporites angularis	7384.9	28	FAD	T-06
Lanagiopollis crassa	7384.9	28	FAD	
Perfotricolpites digitatus	7512.4	28	FAD	
Ctenolophonidites cruciatus	6652.2	38	FAD	
Rugotricolporites felix	6652.2	2	LAD	
Ischyosporites problematicus	7383.5	12	LAD	
Longapertites proxapertitoides	6848.4	13	LAD	
Cricotriporites guianensis	6628.6	15	LAD	
Gemmastephanoporites breviculus	6686.8	15	LAD	
Apiculatasporites? cingulatus	6441.2	18	LAD	
Bombacacidites simplireticulatus	6652.2	20	LAD	
Cricotriporites minutiporus	6601.1	42	LAD	
Retistephanocolpites angeli	6686.8	46	LAD	
Monocolpopollenites ovatus	6700.5	53	LAD	
Syncolporites marginatus	7330.0	55	LAD	
Cicatricosisporites dorogensis	7631.3	19	FAD	
Crototricolpites annemariae	7835.1	1	FAD	
Polypodiisporites sp.	7835.1	4	FAD	
Echimonocolpites densus	7761.2	5	FAD	
Longapertites proxapertitoides	7828.1	5	FAD	
Cricotriporites guianensis	7660.0	6	FAD	
Cricotriporites macroporus	7660.0	17	FAD	
Bombacacidites simplireticulatus	7657.0	20	FAD	
Racemonocolpites facilis	7734.6	20	FAD	
Foveotriporites hammenii	7761.2	21	FAD	
Retitrescolpites magnus	7747.9	24	FAD	
Cyclusphaera scabrata	7660.0	25	FAD	T-05
Striatopollis catatumbus	7660.0	25	FAD	
Spirosyncolpites spiralis	7761.2	25	FAD	
Retistephanoporites minutiporus	7836.3	26	FAD	
Bombacacidites brevis	7761.2	28	FAD	
Monoporopollenites annulatus	7734.6	34	FAD	
Bombacacidites foveoreticulatus	7734.6	35	FAD	
Rhoipites hispidus	7761.2	43	FAD	
Margocolporites vanwijhei	7770.3	58	FAD	
Psilastephanocolporites fissilis	7779.2	60	FAD	
Tetracolporopollenites maculosus	7852.9	28	FAD	

The resulting zonation was applied to 44 wells and outcrop sections located in the Llanos and Llanos Foothills. Ditch cutting and cores were used to date the "basal sandstone" or Mirador Formation. Shale breaks were used to choose the sampling depth when working with ditch cutting samples. Samples were also taken below the base and above the top of the "basal sandstone".

THE ZONATION

A composite section was built using information from more than 105,000 palynomorph occurrences from 500 palynological samples. The g1 section was used as the reference section because it is stratigraphically the most complete: it has the largest thickness and the most samples, and it shows no evidence of major facies discontinuities (Table 1). Using the technique of graphic correlation, we performed three rounds of correlation. A line of correlation was determined for each section (Appendix 2). Based on these correlation lines, a composite section was built (Table 2). Ninety-two events with spreading values < 70 were included in the zonation (Table 2). A spreading value of 70 represents 70 feet in the reference section. This number was chosen based on the level of precision in giving a top that is expected by drilling engineers in the Llanos foothills. These events were divided into six groups to produce a zonation. FAD corresponds to First Appearance Datum, and LAD to Last Appearance Datum.

Jaramillo et al. (2005) proposed a zonation for the upper Paleocene Cuervos Formation that consists of five zones (Cu01 to Cu05). The zonation presented here is a continuation of that zonation.

Zone T 05 *Tetracolporopollenites maculosus*
(modified from Jaramillo et al., 2005, Zone Cu 05)

Base: FAD of *Tetracolporopollenites maculosus*
Top: FAD of *Cicatricosisporites dorogensis*
Age: Early Eocene
Events: FAD within this zone include *Crototricolpites annemariae, Polypodiisporites* sp., *Echimonocolpites densus, Longapertites proxapertitoides, Cricotriporites guianensis, Cricotriporites macroporus, Bombacacidites simplireticulatus, Racemonocolpites facilis, Foveotriporites hammenii, Retitrescolpites magnus, Cyclusphaera scabrata, Striatopollis catatumbus, Spirosyncolpites spiralis, Retistephanoporites minutiporus, Bombacacidites brevis, Monoporopollenites annulatus, Bombacacidites foveoreticulatus, Rhoipites hispidus, Margocolporites vanwijhei, Psilastephanocolporites fissilis.*
Comments: FADs of many species commonly associated with Eocene strata occur in this zone.

Zone T 06 *Spinizonocolpites grandis*

Base: FAD of *C. dorogensis*
Top: LAD of *Spinizonocolpites grandis*
Age: Middle Eocene
Events: FAD of *Jandufouria seamrogiformis, Retibrevitricolpites triangulatus, Corsinipollenites undulatus, Echitetracolpites? tenuiexinatus, Verrutricolporites reticulatus, Ranunculacidites operculatus, Pseudostephanocolpites perfectus, Retitrescolpites? irregularis, Foveotricolporites rugulatus, Brevitricolpites macroexinatus, Bombacacidites soleaformis, Rhoipites guianensis, Perisyncolporites pokornyi, Retisyncolporites angularis, Lanagiopollis crassa, Perfotricolpites digitatus, Ctenolophonidites cruciatus.* LAD of *Rugotricolporites felix, Ischyosporites problematicus, Longapertites proxapertitoides, Cricotriporites guianensis, Gemmastephanoporites breviculus, Apiculatasporites? cingulatus, Bombacacidites simplireticulatus, Cricotriporites minutiporus, Retistephanocolpites angeli, Monocolpopollenites ovatus, Syncolporites marginatus.*

Zone T 07 *Echitriporites trianguliformis orbicularis*

Base: LAD of *Spinizonocolpites grandis*
Top: LAD of *Echitriporites trianguliformis orbicularis*
Age: Late Eocene
Events: FAD of *Concavissimisporites fossulatus, Verrucatosporites usmensis, Retistephanoporites angelicus, Echiperiporites akanthos.* LAD of *Verrutricolporites reticulatus, Multiporopollenites pauciporatus, Venezuelites? distinctus, Bombacacidites fossureticulatus, Echitetracolpites? tenuiexinatus, Poloretitricolpites absolutus, Pseudostephanocolpites perfectus, Corsinipollenites undulatus,* and *Luminidites colombianensis.*

Zone T 08 *Nothofagidites huertasii*

Base: LAD of *Echitriporites trianguliformis orbicularis*
Top: LAD of *Nothofagidites huertasii*
Age: Early Oligocene
Events: FAD of *Crassiectoapertites columbianus, Magnastriatites grandiosus, Magnaperiporites spinosus, Retitricolporites* "esponjosus", and *Psilatricolporites pachydermatus.* LAD of *Foveotriporites hammenii, Bombacacidites soleaformis, Psilastephanocolpites verrucosus, Retistephanocolporites festivus, Bombacacidites foveoreticulatus, Retibrevitricolporites grandis.*

Zone T 09 *Retitrescolpites magnus*

Base: LAD of *Nothofagidites huertasii*
Top: FAD of combined acmes of *Jandufouria seamrogiformis, Magnastriatites grandiosus, Mauritiidites franciscoi minutus* and *V. usmensis.*
Age: Early to Middle Oligocene
Events: FAD of *Retitricolporites* "planopolaris", *Scabratricolporites planetensis,* and *Verrutricolporites rotundiporus.* LAD of *Retitrescolpites magnus, Mauritiidites franciscoi pachyexinatus,* and *Clavatricolpites densiclavatus.*
Comments: Some acmes of *C. dorogensis* are common within this zone

Zone T 10 Combined acme

Base: FAD of combined acmes of *Jandufouria seamrogiformis, Magnastriatites grandiosus, Mauritiidites franciscoi minutus* and *V. usmensis.*
Top: LAD of combined acmes of *Jandufouria seamrogiformis, Magnastriatites grandiosus, Mauritiidites franciscoi minutus* and *V. usmensis.*
Age: Middle Oligocene
Events: FAD of *Psilatricolporites costatus* and *Retistephanoporites crassiannulatus.* LAD of *Ctenolophonidites cruciatus.*
Comments: Some acmes of *Horniella* sp. 3, *C. dorogensis,* and *Psilatriletes* 20–50 um are common within this zone.

Zone T 11 *Jandufouria*

Base: LAD of combined acmes of *Jandufouria seamrogiformis, Magnastriatites grandiosus, Mauritiidites franciscoi minutus* and *V. usmensis.*
Top: LAD of *Cicatricosisporites dorogensis*
Age: Late Oligocene
Events: LAD of *Psilaperiporites minimus* and *Psilaperiporites robustus.*

Comments: Acmes of *J. seamrogiformis* and *P. pokornyi* are common within this zone.

DATING THE MIRADOR FORMATION

Llanos Foothills

The proposed zonation was used to date seven sections along the Llanos Foothills (Table 3). The biostratigraphic position of the Mirador Formation is similar in all of them (Fig. 3). The Mirador accumulated during zones T 05 and T 06, supporting an Early to Middle Eocene age for these deposits. Accumulation of Carbonera unit C8 occured during zones T 07 to T 09, and Carbonera C7 accumulated during zone T 10. There is no unconformity at the contact between the Cuervos and Mirador formations. Both the top of Cuervos and the base of the Mirador formations accumulated during zone T 05.

Llanos Basin

The proposed zonation was used to date 37 sections in the Llanos Basin (Table 3, Fig. 3). There are marked differences with

TABLE 3.—Palynological dating of the Mirador Formation and underlying sediments in 40 sections from the Llanos Basin and Llanos Foothills. Zones T 05 to T 11 follow the zonation proposed in this paper. Zone Cu 03 after Jaramillo et al. (2005). Wells are located in Figures 4 and 5.

section code	Palynological zones above unconformity	Palynological zones below unconformity	Location	Latitude	Longitude
1	T-06	Upper Cretaceous	Llanos	3.77	73.73
2	T-06	Upper Cretaceous	Llanos	3.97	73.5
3	T-06	Upper Cretaceous	Llanos	4.07	73.38
4	T-06	Upper Cretaceous	Llanos	3.37	73.85
5	T-06	Upper Cretaceous	Llanos	3.43	73.93
6	T-08	Cu-03	Llanos	5.02	72.35
7	T-08	Cu-03	Llanos	6.95	71.85
8	T-08	Cu-03	Llanos	4.95	72.6
9	T-09	Cu-03	Llanos	6.95	71.83
10	T-09	Upper Cretaceous	Llanos	6.93	71.13
11	T-09	Cu-03	Llanos	6.57	71.75
12	T-09	Upper Cretaceous	Llanos	6.27	71.8
13	T-09	Upper Cretaceous	Llanos	4.9	72.25
14	T-09	Cu-03	Llanos	5.05	72.45
15	T-09	Cu-03	Llanos	6.98	71.68
16	T-09	Cu-03	Llanos	6.97	71.83
17	T-09	Upper Cretaceous	Llanos	6.72	71.35
18	T-09	Upper Cretaceous	Llanos	6.73	71.6
19	T-09	Upper Cretaceous	Llanos	6.88	71.07
20	T-9 to T-10	Upper Cretaceous	Llanos	4.8	72.08
21	T-9 to T-10	Cu-03	Llanos	5.03	72.35
22	T-9 to T-10	Cu-03	Llanos	5.07	72.5
23	T-9 to T-10	Upper Cretaceous	Llanos	5.02	71.97
24	T-9 to T-10	undetermined	Llanos	5.23	71.95
25	T-9 to T-10	Upper Cretaceous	Llanos	5.37	71.97
26	T-9 to T-10	Upper Cretaceous	Llanos	5.1	72.2
27	T-9 to T-10	Upper Cretaceous	Llanos	5.15	72.27
28	T-9 to T-10	Cu-03	Llanos	4.97	72.2
29	T-10	Upper Cretaceous	Llanos	6.9	71.42
30	T-10	Upper Cretaceous	Llanos	6.95	71.33
31	T-10	Upper Cretaceous	Llanos	6.93	71.85
32	T-10	Upper Cretaceous	Llanos	6.97	71.1
33	T-10	Upper Cretaceous	Llanos	6.98	71.52
34	T-10	Cu-03	Llanos	5.57	72.23
35	T-10	Cu-03	Llanos	5.38	72.15
36	T-10	undetermined	Llanos	5.38	71.87
37	T-10	Upper Cretaceous	Llanos	5.12	71.83
38	T-05	T-05	Llanos foothills	4.98	72.73
39	T-05	T-05	Llanos foothills	5.1	72.65
40	T-05	T-05	Llanos foothills	7.03	72.17
41	T-05	T-05	Llanos foothills	4.68	73.15
42	T-05	T-05	Llanos foothills	5.62	72.3
43	T-05	T-05	Llanos foothills	5.43	72.45
44	T-05	T-05	Llanos foothills	4.9	73.02

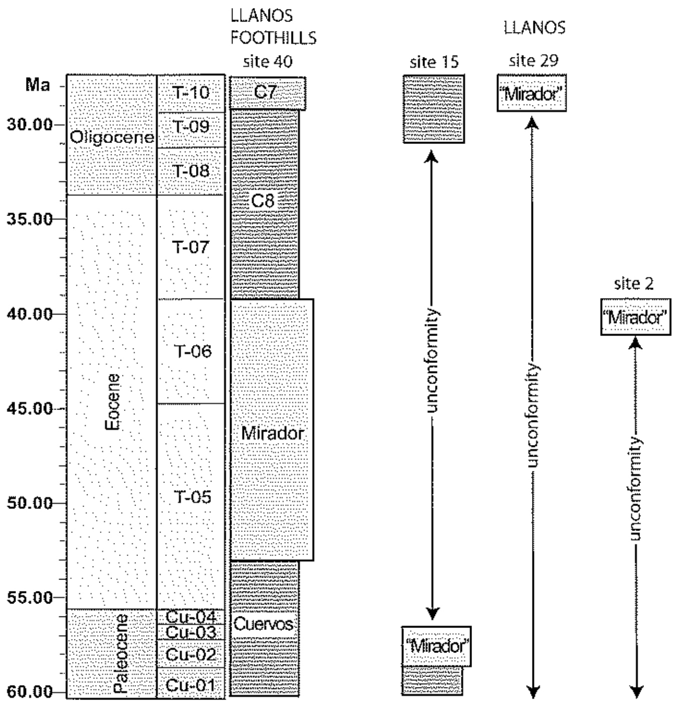

FIG. 3.—Dating several sections in the Llanos Basin and Llanos Foothills using the zonation proposed in this study. Paleocene zones after Jaramillo et al. (2005).

the Llanos Foothills. There is a large unconformity at the lower contact of the Mirador Formation. The sediments just below the unconformity are dated as either Late Cretaceous or late Paleocene (zone Cu 03 of Jaramillo et al., 2005, Table 3, Fig. 4). The Mirador Formation (sediments just above the unconformity) dates as either T 06, T 08, T 09, or T 10 (Table 3, Fig. 5). In sites 7, 9, 15, 16, and 34 (Table 3, Fig. 5), sandy sediments that were named Mirador are correlative with the upper Paleocene Cuervos Formation (zone Cu 03 of Jaramillo et al., 2005). In these five sites the sediments above the unconformity are fine-grained strata of Oligocene age (zones T 09 or T 10), whereas the sediments below the unconformity are sandstones of late Paleocene age (e.g., site 15, Fig. 3). The lack of detailed biostratigraphic data helped to create the confusion of the sandy sediments with the Mirador Formation.

The age of the strata below the unconformity indicates a variable missing section (or lacuna) in the Llanos Basin. The lacuna of the unconformity increases eastward (Figs. 3–5). Strata below the unconformity are late Paleocene near the Foothills (zone Cu 03) and Late Cretaceous in the eastern Llanos Basin (Fig. 4). In contrast, there is no unconformity between the Mirador and underlying Cuervos Formation along strike of the Llanos Foothills (Figs. 3, 4).

The spatial distribution of the age of the sediments above the unconformity (Fig. 5) shows that sedimentation is progressively onlapping the unconformity west to east, and also south to north until a midpoint in the Llanos, and then north to south to the northern part of that point. More section is missing in northern Llanos than in west-central Llanos. Clearly, the uppermost Cuervos, Mirador, and lower Carbonera C8 formations of the Llanos Foothills are not correlative with most of the rocks in the Llanos Basin (Fig. 3). Furthermore, the Mirador Formation in the Llanos Basin is generally a basal sandy unit above the unconformity that is highly variable in age, having accumulated at several times from the middle Eocene (e.g., site 2, zone T 06, Fig. 3) to the middle Oligocene (e.g., sites 29-37, zone T 10, Fig. 3). Biostratigraphic studies in Apure (Guafita and Victoria oil fields), southwestern Venezuela, also record the absence of Eocene assemblages usually occurring during the time of accumulation of the Mirador Formation in northwestern Venezuela (Monroy and van Erve, 1988), confirming the pattern shown here.

THE MIRADOR FORMATION AS A LITHOSTRATIGRAPHIC UNIT

The Mirador is a term imported from the Catatumbo Basin, where a holostratotype was defined. A hypostratotype has not been defined for the Mirador in the Llanos Basin and Llanos Foothills in order to extend the use of the term outside of the Catatumbo Basin. However, common practice among petroleum geologists in the region is to use the Mirador cropping out in the Llanos Foothills as the "hypostratotype section" for the Mirador Formation (Fig. 3).

A formation is a lithostratigraphic unit that is defined on the basis of its lithologic properties or a combination of lithologic properties and stratigraphic relationships, not by its inferred age (Murphy and Salvador, 1999). Should we then still use the Mirador Formation in the Llanos? The highly variable age, from Middle Eocene to Middle Oligocene, of the basal sandstones overlying the unconformity in the Llanos Basin would not matter. They could still be considered a part of the same formation, inasmuch as age is not a criterion defining a formation (Salvador, 1994). The Mirador Formation, then, would be a highly diachronous formation.

The Mirador Formation in the Llanos also would be highly compartmentalized, not a single sandstone layer, because facies above the unconformity in the Llanos Basin are not always sandstones (e.g., site 15, Fig. 3). Wells 34, 12, 9, 16, 15, 33, 29, and 30 have a mudstone facies above the unconformity (Fig. 5), suggesting that the Mirador Formation or "Basal Sands" across the Llanos Basin is not a single and continuous lithological unit. Those basal sandstones and mudstones are onlapping on the unconformity, as shown in seismic images in the southern Llanos Basin (Bayona et al., 2006a; Bayona et al., 2006b), as is the case in many foreland basins (Leckie et al., 2004). The connectivity of the Mirador in the Llanos Foothills and the noncontinuous Mirador basal sandstones in the Llanos Basin is still very difficult to assess. Published cross sections assume a connection (e.g., Cooper et al., 1995), but intense deformation of the leading front of the thrust belt and more than 6 km of synorogenic strata overlying Eocene strata in the footwall preclude a good seismic image of the western Llanos Basin.

TECTONIC IMPLICATIONS

Regional tectonic models of the Eastern Cordillera, Llanos Foothills, and Llanos Basin (Cooper et al., 1995; Villamil, 1999; Gómez et al., 2005) suggest the development of a foreland basin since the latest Cretaceous for the northern Andes. The interpretation of a foreland basin is mostly supported by the eastward thinning of Tertiary synorogenic beds. Even though the role of the Eastern Cordillera in the geometry of the Paleogene foredeep is still a subject of controversy, the interpretation of a foreland setting is supported by the presence of several unconformities in the Llanos Basin. The eastward increase of the time interval encompassed by the lacuna of these unconformities (compare Figures 4 and 5) can be explained by the migration of a subaerial

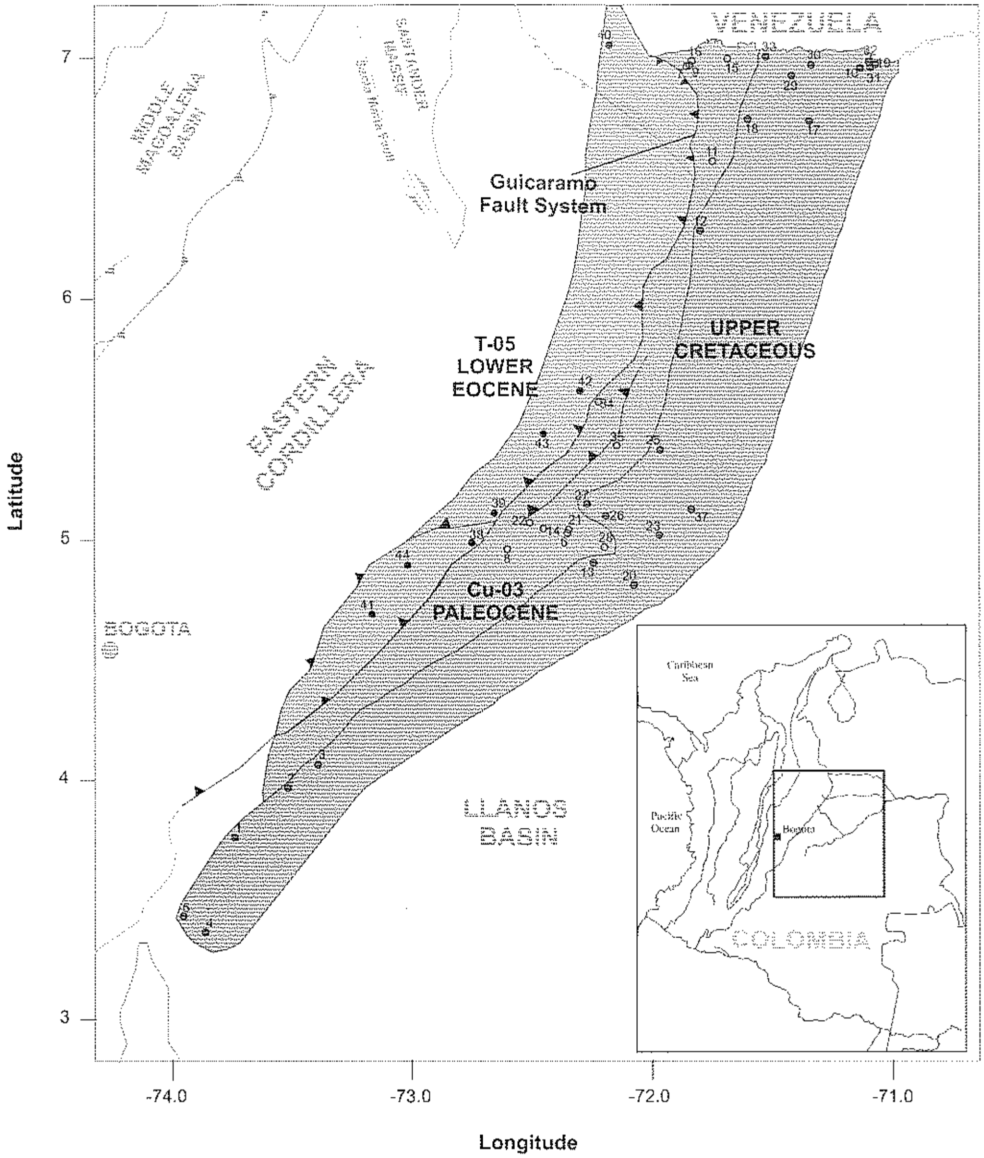

FIG. 4.—Spatial distribution of the age of the sediments below the unconformity of the "basal sandstone" or Mirador Formation in the Llanos Basin and Llanos Foothills. Zones after Figure 3.

forebulge, as modeled by Crampton and Allen (1995); the forebulge was later buried during the Oligocene.

Our results indicate that the "basal sandstone" or Mirador Formation of the Llanos Foothills and Llanos Basin is very diachronous (Figs. 3, 5) and not continuous across the Llanos Basin (sites 7, 9, 15, 16, and 34 in the Llanos Basin have fine-grained sediments above the unconformity; see Figure 5 and Table 3). Therefore, the position of the foredeep/forebulge depozones during the upper Eocene–Oligocene is more complex than assumed by a simple "static" foreland setting, and probably structures in the Llanos Basin locally reactivated by flexural deformation (extensively discussed in Bayona et al., 2007, and Bayona et al., 2008) contributed to the compartmentalization of the foredeep–forebulge transition and the diachronous onset of Paleogene deposition.

The filling geometry of the foreland basin and associated unconformities are important for understanding several processes in a basin. For example, previous models of flow of formation waters have considered a continuous basal sandstone layer bounded at the base by a regional unconformity (Villegas et al., 1994). Here we have shown that this case for the Llanos Basin is not as simple as has been assumed before.

Three events of deposition are proposed to explain the record of the Eocene Mirador Formation in the Llanos Foothills and basal sandstone units of Paleocene and Oligocene age in the Llanos Basin (Bayona et al., 2006a). The first event, of Late Paleocene age, corresponds, from east to west, to an unconformity in most of the Llanos Basin: deposition of quartz arenites in the western Llanos Basin and fine-grained deposition of the Cuervos Formation in the Llanos Foothills; the thickness of Upper Paleocene beds increases westward. The former deposits record low-subsidence deposition adjacent to the subaerial forebulge, whereas the latter deposits record higher rates of subsidence in a foredeep depozone. The second event of Eocene age, records the deposition of the

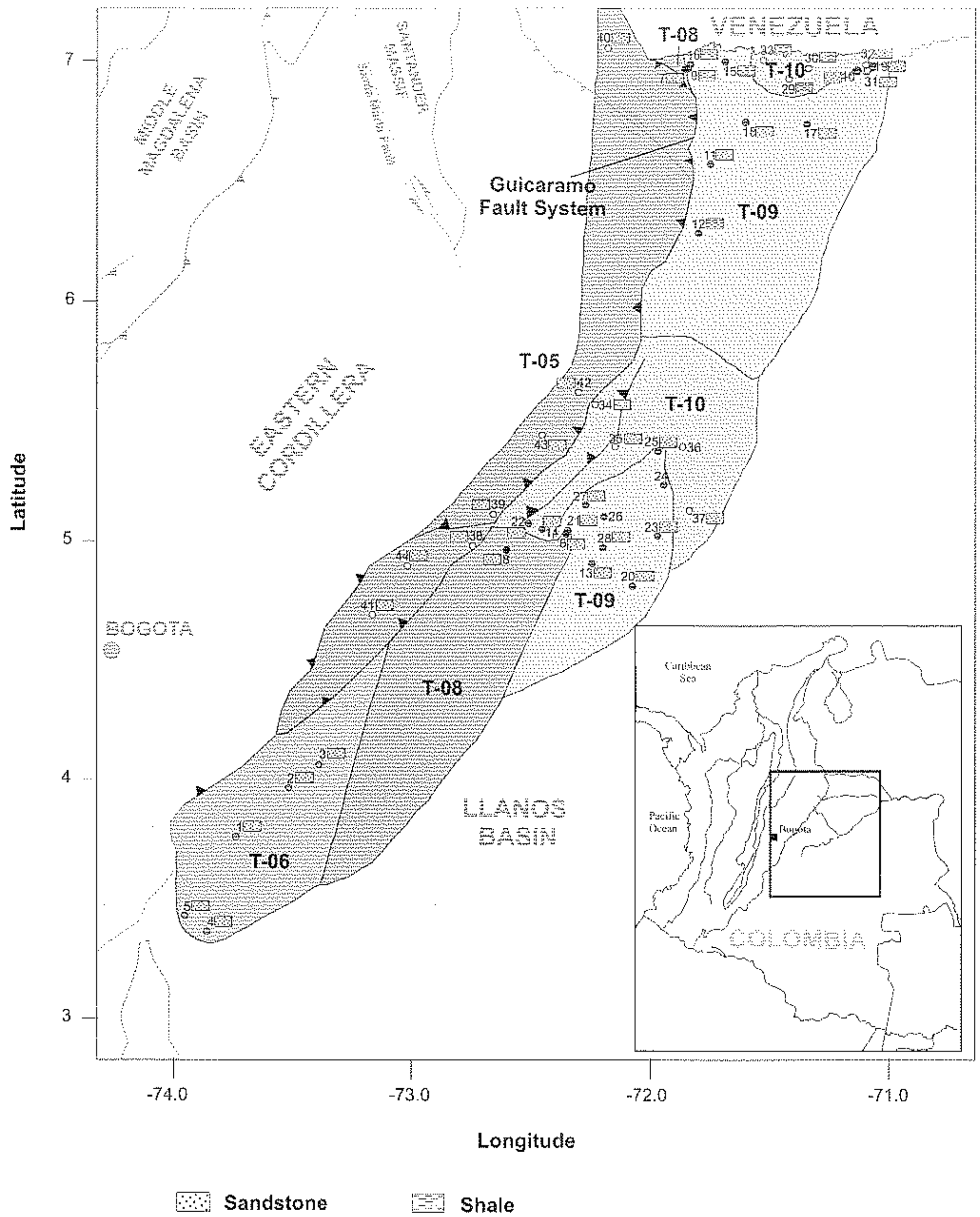

FIG. 5.—Spatial distribution of the age of the sediments above the unconformity of the "basal sandstone" or Mirador Formation in the Llanos Basin and Llanos Foothills. Zones after Figure 3

Mirador Formation in the Llanos Foothills. Deposition of quartz arenite channel beds indicates that the area of low subsidence shifted westward from the Llanos Basin to the Llanos Foothills. The absence of Eocene and Paleocene strata in the Llanos Basin may be explained either by subaerial exposure/bypass of sediments or thin deposition and later erosion. The third event is represented by the eastward onlapping of the basal sandstone unit on the Llanos Basin during the latest Eocene and Oligocene times, and thick fine-grained deposition of the Carbonera Formation in the Llanos Foothills. The eastward migration of foredeep/forebulge depozones from the Llanos Foothills to the Llanos Basin was not uniform because earlier deposition took place in the northern and southern segments of the Llanos Basin (Fig. 5). An explanation of these irregularities needs to be investigated with the integration of the kinematics of structures in the Eastern Cordillera, the Merida Andes, the Macarena massif, and intraplate uplifts in the Llanos Basin.

CONCLUSIONS

Dating of 44 sections in the Llanos Basin and Llanos Foothills indicates that the sandstones named the Mirador Formation or "basal sandstones" in the Llanos Basin are much younger than the Mirador Formation in the Llanos Foothills. While the base of the Mirador Formation is lower Eocene in the Llanos Foothills (zone T 05) and overlies lower Eocene strata, the Mirador Formation in the Llanos Basin ranges from middle Eocene to late Oligocene (zones T 06, T 08, T 09, and T 10) and overlies Paleocene and upper Cretaceous strata. The upper Cuervos, Mirador, and lowermost Carbonera formations in the Llanos Foothills do not have an equivalent in most of the Llanos Basin. Even though most of the basal sandstones in the Llanos are correlative with several levels of the lower Carbonera Formation in the Llanos Foothills, there are other "basal sandstones" that yielded a Late Paleocene age and are correlative with the Cuervos Formation. Therefore, stratigraphic correlations in active tectonic basins must not use the stratigraphic position of a unit, even overlying a regional unconformity, as a solid criterion for correlation.

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Electronic Appendix

APPENDIX 1.—FAD and LAD datums for each section used in the graphic correlation analysis. All values are given in feet.

APPENDIX 2.—Graphic Correlation equations. Values are given in feet. All equations are linear models that compare a section against the reference section (reference section is g1) producing a Line of Correlation (LOC). This LOC is divided into several segments. The end points of each segment of the LOC are given in pairs. Whereas the number to the left corresponds to a depth in the reference section, the number to the right corresponds to a depth in the chosen section. The values of the intercept (b) and the slope (m) are given for each segment of the LOC.