Quantitative biostratigraphy for the Cuervos Formation (Paleocene) of the Llanos foothills, Colombia: improving palynological resolution for oil exploration

C. A. JARAMILLO[1], F. MUÑOZ[2], M. COGOLLO[2] & F. DE LA PARRA[2]
[1]*Smithsonian Tropical Research Institute, Unit 0948, APO AA 34002-0948, USA*
[2]*Biostratigraphy team, Instituto Colombiano del Petróleo-Ecopetrol, AA 4185, Bucaramanga, Colombia (e-mail: carlos@flmnh.ufl.edu)*

Abstract: Oil exploration in Colombia has traditionally taken place in areas with relatively few structural complexities. However, in the last decade, exploration has moved to regions characterized by complex structural deformation, poor seismic resolution, and many stratigraphic problems, such as in the Llanos foothills. In this region, the major reservoirs occur in mostly continental Paleogene sequences, where palynomorphs are usually the only fossil group found. Thus, palynology has become an important tool in controlling the stratigraphic position of a well during drilling, in testing diverse seismic and structural interpretations, and correlating reservoirs. This study provides a biostratigraphic framework for the Cuervos Formation (Late Paleocene to earliest Eocene) of the Llanos and Llanos foothills, making use of graphic correlation. We used 14 sections with palynological information from outcrops, well cores, and well ditch cuttings. Five informal palynological zones are proposed. Based on the biostratigraphic model produced by this analysis, we reinterpreted a recently drilled well in the Llanos foothills upon which several previous interpretations had been made. A sidetrack of that well was subsequently drilled, validating the proposed model. This is a positive test that the biostratigraphic framework developed for the Cuervos Formation is reliable and can be successfully applied to exploration in the Llanos foothills.

Oil exploration in Colombia has taken place since the 1920s. In 2002, the country produced about 650 000 barrels per day. One of the main targets of Colombian oil exploration has been the Llanos and Llanos foothills basin, located on the eastern side of Colombia (Fig. 1). The stratigraphy of the basin is composed of about 2 km of Upper Cretaceous to Tertiary sediments (Fig. 2). The Carbonera Formation has been generally considered the seal, Mirador, Barco and Guadalupe Formations the reservoirs, and the black shales of the Upper Cretaceous, Gacheta-Luna Formation are the source (Cazier *et al.* 1995; Dzou *et al.* 1999). Most of the Tertiary sediments in the Llanos and Llanos foothills basin are continental with some discrete episodes of marine influence. Toward the Llanos foothills, the complexity of the stratigraphy increases, with large lateral changes in sediment thickness occurring in all units (Fajardo *et al.* 2000).

A cross section of the basin shows that the structural complexity of the basin significantly increases toward the foothills (Linares 1999, Fig. 3). Over the years, the trend of exploration has been moving from east to west (from areas with low structural complexity) to areas with more structural complexities (where larger reservoirs are expected, but the difficulty of finding them increases). Additionally, not only are the structures more complex, the exploration wells are now deeper. There has been a significant trend toward increasing the depth of exploratory wells in the Llanos through the years (Fig. 4). The rough topography of the Llanos foothills and strata dipping at high angles in the foothills have made good seismic resolution difficult to acquire. The level of uncertainty during the drilling phase therefore has increased through the years.

The present resolution of the biostratigraphy being used in Colombia is low compared to the needs of modern exploration in the Llanos foothills (Rubio 1997). For example, only one biostratigraphic zone exists for the Oligocene. Consequently it is not possible to divide the Carbonera C6 to C8 intervals in biostratigraphic terms (Figure 2, C1 to C8 units are subdivisions of the Carbonera Formation, C1 being the youngest). A similar problem occurs with the Carbonera C1 to C5 intervals, all in the lower Miocene, and the Paleocene Barco and Cuervos Formations (Fig. 2). Also, it is not possible to differentiate the lowermost Carbonera C8

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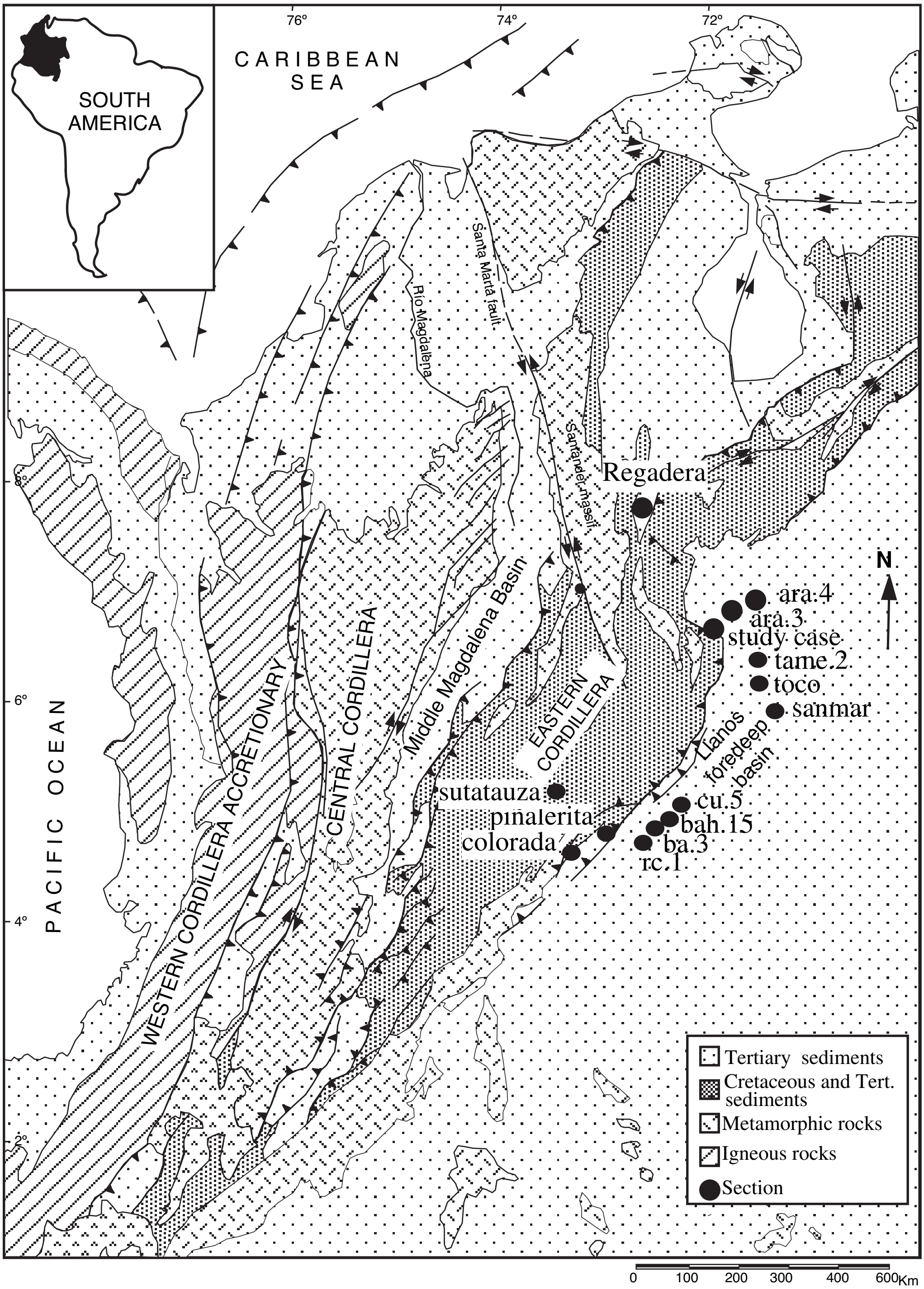


Fig. 1. Geological map of Colombia showing the 14 sections used for the analysis and the case study well (modified from Dengo & Covey 1993).

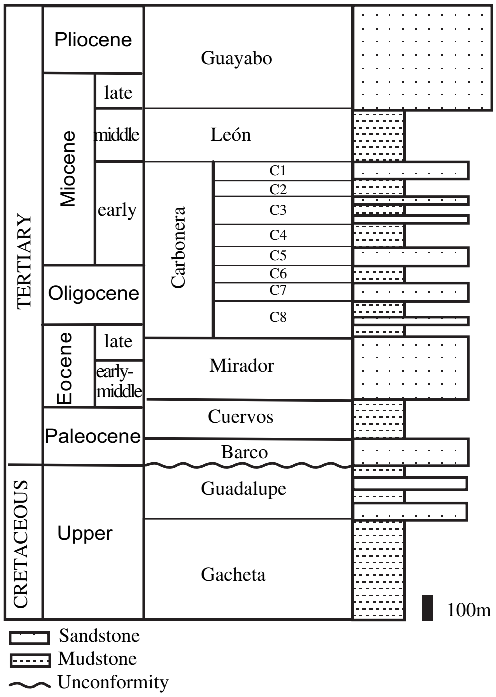


Fig. 2. Generalized stratigraphic column for the Llanos and Llanos foothills basin (after Ecopetrol 1996).

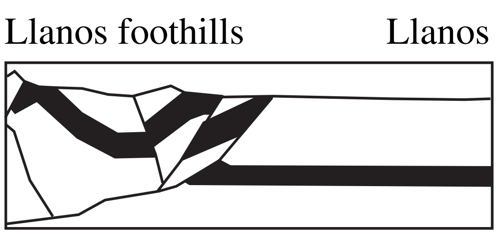


Fig. 3. Schematic structural cross section of the Llanos and Llanos foothills basin (after Linares 1999).

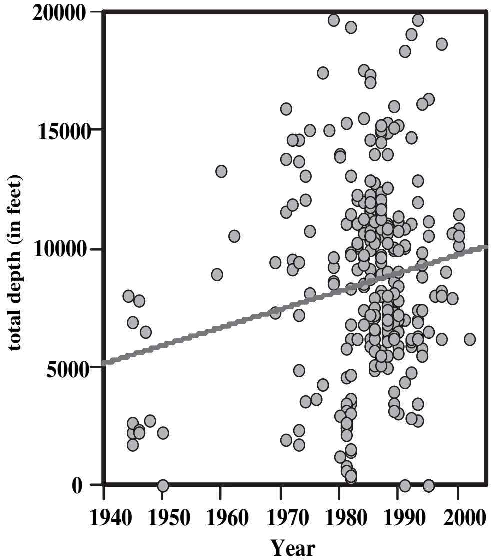


Fig. 4. Bivariate plot of depth of exploratory wells versus drilling year. There is a trend toward increasing the depth of exploratory wells through the years (trend calculated by linear regression, $r = 0.18$, $p < .005$).

versus the top of the Mirador Formation in biostratigraphic terms. This relatively low level of biostratigraphic resolution did not matter for wells drilled during early exploration of the Llanos, as biostratigraphy was mainly used as a rough control during drilling. This scenario has now changed. Exploration has moved into complex areas where more refined biostratigraphy is very important. Thus, biostratigraphy has become an important tool in assessing the stratigraphic position of a well during drilling, in testing diverse seismic, structural and stratigraphic interpretations, and in correlating to understand reservoir continuity.

In this study, a reliable biostratigraphic framework is presented that was developed for the Cuervos and equivalent formations (late Paleocene to earliest Eocene) of the Llanos and Llanos foothills basins based on palynological data and graphic correlation. This framework is then tested to solve a problem that originated during the drilling of an exploratory well in the northern Llanos foothills.

Geological setting

The Cuervos Formation, as it is known by the petroleum industry in the Llanos foothills of Colombia, is a fine-grained, coaly unit located in a stratigraphic position between the two main reservoirs in the region, the Mirador and Barco Formations (Ecopetrol 1996).

The Cuervos Formation was named by Notestein *et al.* (1944) after the Quebrada Los Cuervos in the Catatumbo area. The formation is composed mainly of claystones and shales, with some coal beds in its lower part; the upper part consists of grey and greenish-grey claystones with locally abundant red, yellow, and purple mottling (Notestein *et al.* 1944). Its thickness ranges from 282 to 490 m and increases northwards. The contact with the overlying Mirador Formation is sharp, and locally unconformable (Notestein *et al.* 1944). In the area of La Victoria creek, Germeraad *et al.* (1968) dated the Cuervos Formation as Paleocene (pollen zone of *Retidiporites magdalenensis*). In the Tibú anticline, Gonzalez (1967) dated the Upper Cuervos as Late Paleocene–Early Eocene based on pollen.

The Cuervos lithostratigraphic unit in the Llanos foothills has also been named the 'Arcillas de El Limbo' Formation, defined by Hubach in 1941 (in a Shell internal report, according to Van der Hammen 1958). The type locality is near El Limbo, Cravo Sur River, Colombia. It has been dated as Early Eocene (Cazier *et al.* 1995) or Late Paleocene (Cooper *et al.* 1995) although no biostratigraphic data was published to support the dating.

Methods

The most reliable biostratigraphic tools in the Paleocene of the Llanos and Llanos foothills basin are pollen and spores (Rubio 1997). Fourteen sections with palynological information from outcrops (4), well cores (4), and well ditch cuttings (6) were used for this study (Appendix 1). The outcrop data comes from published information: Piñalerita and Regadera (Jaramillo 2002; Jaramillo & Dilcher 2001), Sutatauza (Sarmiento 1992) and Colorada (Guerrero & Sarmiento 1996). The core and ditch-cuttings data come from internal reports in Ecopetrol databases (Ecopetrol Petroleum Information Bank). All sections are located in the central and northern Llanos foothills and in the Llanos basin near the foothills (Fig. 1, Table 1).

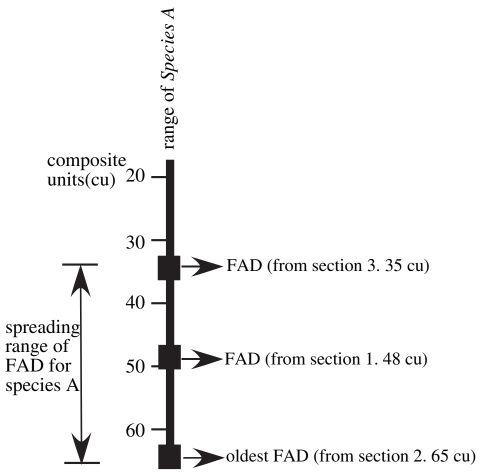
The palynological data were then analyzed using the technique of graphic correlation (Edwards 1984, 1989; Shaw 1964). This technique does not assume *a priori* that any taxon is an index guide or represents a time line. Instead, the technique relies on looking at the whole assemblage to find the true stratigraphic range for each taxon (Edwards 1989), which is done by comparing taxon ranges in different sections and finding lines of correlation.

A detailed taxonomic filtering was done before using the data for the graphic correlation. For example, informal taxa (used by consultants) or some generic assignments were not used in the analysis (e.g. *Psilatricolpites* 'inciertus', *Psilatricolporites* sp.). First occurrence datums (FAD) were not used in wells that only had ditch cutting samples in order to minimize the error introduced by cavings into the wellbore during drilling.

Table 1. *Geographic location of the studied sections*

Section	N	W
ara.3	7.0	–71.8
ara.4	7.0	–71.8
bah.15	5.0	72.7
ba.3	5.0	–72.7
cu.5	5.1	–72.7
guac	4.3	–73.4
rc.1	4.9	–72.7
sanmar	6.0	–71.6
tame.2	6.4	–71.8
toco	6.3	–71.8
Colorada	5.3	–73.5
Piñalerita	4.5	–73.1
Regadera	7.4	–72.4
Sutatauza	5.1	–73.5

A spreading parameter was developed to evaluate the degree of confidence in the position of a datum in the Composite Section. Each datum in the Composite Section represents its oldest FAD or youngest last occurrence datum (LAD) after comparing all sections with the Reference Section. For example, the position of the FAD in the Composite Section of species A is 65 composite units (Fig. 5). This value means that when comparing all the sections with the Composite, the oldest position for this datum is 65 composite units. However, there are other values for this datum that are not included. These values come from other sections that have younger FADs when projected into the Composite Section (Fig. 5). The spreading parameter evaluates this degree of dispersion. A low value of the spreading parameter indicates that the datum has a similar position in the Composite regardless of what section is being analysed, and is therefore a reliable biostratigraphic marker. A high value indicates a wide range for the datum. The spreading parameter for each datum in the Composite Section is calculated using one of the following formulas. For each FAD datum, the spreading parameter = (oldest FAD in composite units – youngest FAD in composite units)/50 (Fig. 5). For each LAD datum = (oldest LAD in composite units – youngest LAD in composite units)/50. The division by the number 50 in the formula is used to standarized the parameter to the exploratory needs in the Llanos foothills. The number 50 represents fifty stratigraphic 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 foothills. The value of standardization could be changed for other basins or exploratory programs.



$$\text{Spreading parameter} = \frac{65-35}{50} = 0.6$$

Fig. 5. Calculation of the spreading parameter for each datum (FAD and LAD) used in the analysis. For each FAD or LAD datum a spreading value was calculated using the formula: (youngest FAD or LAD in composite units – oldest FAD or LAD in composite units)/50.

Only taxa occurring in three or more wells were used to calculate this spreading parameter. Taxa occurring in less than three wells produce artificially low spreading values due to low sample size. They were considered to have an unknown spreading value. High spreading values (>10) indicate that the position of a particular FAD or LAD in the Composite Section is highly variable, within a range of 500 composite units, and therefore not very useful as a biostratigraphic marker. Using them would only introduce noise to the process of correlation.

Taxonomic nomenclature and illustration of the species used in this study can be found in diverse publications (Colmenares & Terán 1993; Doubinger 1973, 1976; Germeraad *et al.* 1968; Gonzalez 1967; Guerrero & Sarmiento 1996; Hopping 1967; Jan du Chêne *et al.* 1978*a*, 1978*b*; Jan du Chêne & Salami 1978; Jansonius & Hills 1976; Jaramillo & Dilcher 2001; Leidelmeyer 1966; Muller *et al.* 1987; Pocknall & Nichols 1996; Regali *et al.* 1974; Rull 1997, 1999; Samant & Phadtare 1997; Sarmiento 1992; Van der Hammen 1954, 1956*a*, *b*, 1957*a*, *b*, 1958; Van der Hammen & Garcia 1966; Van der Hammen & Wymstra 1964; Van Hoeken-Klinkenberg 1964, 1966; Venkatachala *et al.* 1988). Major nomenclatural changes follow those in Jaramillo & Dilcher (2001).

The Composite Section

The Composite Section was built using information from more than 105 000 palynomorph occurrences from 700 palynological samples. The BA3 section was used as the Reference Section because it has the best available information, highest density of samples, the most reliable fossil data set, and is stratigraphically the most complete. Using the technique of graphic correlation, three rounds of correlation were performed. A line of correlation was determined for each section (Table 2). Based on these correlation lines, a Composite Section was built (Table 3, Fig. 6). The Composite also contains the top of the Cuervos and Barco Formations as they were defined in the Reference Section. Fifty taxa with spreading values <10 and twelve with unknown spreading values but with a good potential for biostratigraphy (see Table 3) were plotted in Figure 6.

Biozonation for the Cuervos Formation

The Composite Section (CS) produced here allows dividing the Cuervos Formation into five informal biozones that occur along the Llanos and Llanos foothills (Fig. 6).

Zone Cu-01

Base: FAD of *Bombacacidites annae*. Position in CS: 16114 cu (composite units).

Top: FAD of *Foveotricolpites perforatus*. Position in CS: 16112 cu.

Assemblage: Bombacacidites annae, Ephedripites vanegensis, Foveotriletes margaritae, Gemmamonocolpites gemmatus, Retidiporites magdalenensis, Spinizonocolpites baculatus. Within this zone the last occurrence datum (LAD) of *Palaeocystodinium golzowense* occurs.

Comments: This zone is characterized by high abundances of *Proxapertites operculatus*.

Stratigraphic position: Uppermost Barco Formation to lower Cuervos Formation.

Zone Cu-02

Base: FAD of *Foveotricolpites perforatus*. Position in CS: 16112 cu.

Top: LAD of *Foveotricolpites perforatus*. Position in CS: 15995 cu.

Assemblage: Bombacacidites annae, Retidiporites magdalenensis. Within this zone there

Table 2. *Lines of correlation for each of the sections studied*

Section							
Piñalerita	X	16115	16110	16110	16003	15558	15350
	Y	6485	6296	6301	5698	4999	4392
Regadera	X	15440	15086				
	Y	6398	5601				
Colorada	X	16285	16273	16228	16107		
	Y	2646	2396	1970	1804		
Sutatauza	X	16285	16285				
	Y	6563	3846				
bah.15	X	16165	16164	16115	16109	15875	
	Y	15143	15143	15050	15009	14726	
rc.1	X	16432	16320	16283			
	Y	14822	14682	14677			
cu.5	X	16285	16114	15594	15509	15359	
	Y	17776	17527	17126	17067	16960	
ara.3	X	16285	16285	15786	15545		
	Y	19527	17968	17870	17870		
ara.4	X	16285	16285	15767	15342		
	Y	19231	18566	18010	18010		
guac	X	16269	15434	15099			
	Y	13320	13320	12764			
sanmar	X	16350	16283	15506	15109		
	Y	12068	11387	11387	11227		
tame.2	X	16285	15869	15550	15119		
	Y	14823	14649	14445	14282		
toco	X	16286	15579	15237	15100		
	Y	17732	17339	17166	17145		

X, values from reference section.
Y, values from correlated section.
Each X and Y couplet corresponds to a point along the line of correlation.

are the LADs of *Ephedripites vanegensis, Foveotriletes margaritae, Gemmamonocolpites gemmatus and Spinizonocolpites baculatus*.

Comments: This zone is characterized by acmes of *Proxapertites operculatus*. The top of this zone coincides with the LAD of acmes of *P. operculatus*.

Stratigraphic position: Lower Cuervos Formation.

Zone Cu-03

Base: LAD of *Foveotricolpites perforatus*. Position in CS: 15995 cu.

Top: Base of barren interval. Position in CS: 15892 cu.

Comments: Within this interval occurs the LAD of *Bombacacidites annae* and *Retidiporites magdalenensis*.

Stratigraphic position: Lower part of middle Cuervos Formation.

Zone Cu-04

Base: Base of barren interval. Position in CS: 15892 cu.

Top: FAD of *Tetracolporopollenites maculosus*. Position in CS: 15588 cu.

Assemblage: This is a barren interval with very poor recovery of organic matter and palynomorphs.

Stratigraphic position: Middle to upper Cuervos Formation.

Zone Cu-05

Base: FAD of *Tetracolporopollenites maculosus*. Position in CS: 15588 cu.

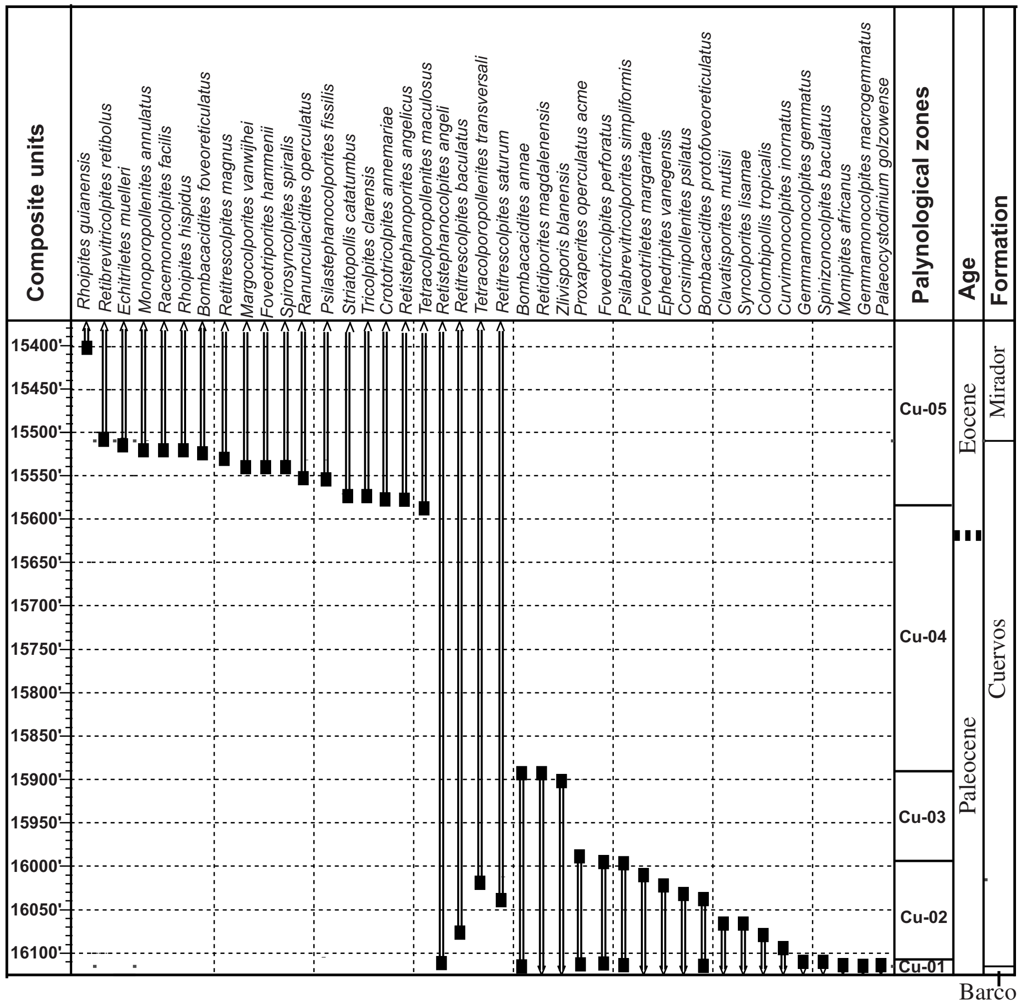


Fig. 6. Biostratigraphic range chart of the key taxa for the Cuervos Formation. Vertical units are composite units that correspond to feet in the Reference Section BA3. Position of the formational boundaries follow those defined in the Reference Section.

Top: FAD of *Rhoipites guianensis*. Position in CS: 15386 cu.

Assemblage: Crototricolpites annemariae, Tricolpites clarensis, Striatopollis catatumbus. Within this zone occurs the FAD of *Striatopollis catatumbus, Echitriletes muelleri, Foveotriporites hammenii, Margocolporites vanwijhei, Monoporopollenites annulatus, Psilastephanocolpites fissilis, Racemonocolpites facilis, Ranunculacidites operculatus, Retibrevitricolpites retibolus, Retitrescolpites magnus, Rhoipites hispidus* and *Spirosyncolpites spiralis*.

Comments: FAD of many species commonly associated to Eocene strata occurs in this zone.

Stratigraphic position: Upper Cuervos to lower Mirador Formation.

Calibration of Composite Section

The calibration of the Composite Section developed here with the geological timescale is still uncertain. There are very few published studies in northern South America that have both palynological information and planktonic foraminifera or nannoplankton that could be used for a first order calibration of the palynological data. The palynological zonation of Germeraad *et al.* (1968) is the only one for northern South America that shows

Table 3. *Composite section for the Cuervos Formation and equivalent units in the Llanos and Llanos foothills*

	Species	Author	Event	CU	S	N
1	*Rhoipites guianensis*	(Van der Hammen & Wymstra 1964) Jaramillo & Dilcher 2001	FAD	15386.1	0.7	9
2	*Cuervos*		top	15510		
3	*Retibrevitricolpites retibolus*	Leidelmeyer 1966	FAD	15512.6	7.0	3
4	*Echitriletes muelleri*	Regali *et al.* 1974	FAD	15516.2	5.6	7
5	*Bombacacidites foveoreticulatus*	Muller *et al.* 1987	FAD	15523.0	12.1	6
6	*Monoporopollenites annulatus*	(Van der Hammen 1954) Jaramillo & Dilcher 2001	FAD	15523.0	3.3	8
7	*Racemonocolpites facilis*	Gonzalez 1967	FAD	15523.0	3.4	3
8	*Rhoipites hispidus*	(Van der Hammen & Wymstra 1964) Jaramillo & Dilcher 2001	FAD	15523.0	7.0	8
9	*Retitrescolpites magnus*	(Gonzalez 1967) Jaramillo & Dilcher 2001	FAD	15530.3	4.1	3
10	*Spirosyncolpites spiralis*	Gonzalez 1967	FAD	15537.6	3.6	10
11	*Foveotriporites hammenii*	Gonzalez 1967	FAD	15537.7	4.5	5
12	*Margocolporites vanwijhei*	Germeraad *et al.* 1968	FAD	15538.0	3.6	6
13	*Ranunculacidites operculatus*	(Van der Hammen & Wymstra 1964) Jaramillo & Dilcher 2001	FAD	15553.8	7.6	8
14	*Psilastephanocolporites fissilis*	Leidelmeyer 1966	FAD	15556.2	5.0	5
15	*Striatopollis catatumbus*	(Gonzalez 1967) Takahashi & Jux 1989	FAD	15574.5	4.3	10
16	*Tricolpites clarensis*	(Gonzalez 1967) Jaramillo & Dilcher 2001	FAD	15574.6	7.5	4
17	*Crototricolpites annemariae*	Leidelmeyer 1966	FAD	15578.4	6.4	3
18	*Retistephanoporites angelicus*	Gonzalez 1967	FAD	15579.1	10.1	9
19	*Tetracolporopollenites maculosus*	(Regali *et al.* 1974) Jaramillo & Dilcher 2001	FAD	15588.3	7.3	5
20	*Bombacacidites annae*	(Van der Hammen 1954) Leidelmeyer 1966	LAD	15892.7	5.0	5
21	*Retidiporites magdalenensis*	Van der Hammen & Garcia 1966	LAD	15892.7	7.8	6
22	*Zlivisporis blanensis*	Pacltova 1961	LAD	15902.1	11.6	4
23	*Proxaperites operculatus acme*	(Van der Hammen 1954) Van der Hammen 1956	LAD	15988.5	2.1	3
24	*Foveotricolpites perforatus*	Van der Hammen & Garcia 1966	LAD	15995.2	2.9	4
25	*Psilabrevitricolporites simpliformis*	Van der Kaars 1983	LAD	15996.2	unknown	1
26	*Foveotriletes margaritae*	(Van der Hammen 1954) Germeraad *et al.* 1968	LAD	16010.2	5.9	6
27	*Tetracolporopollenites transversali*	(Dueñas 1980) Jaramillo & Dilcher 2001	FAD	16020.2	13.4	8
28	*Ephedripites vanegensis*	Van der Hammen & Garcia 1966	LAD	16022.3	5.3	3
29	*Corsinipollenites psilatus*	Jaramillo & Dilcher 2001	LAD	16031.6	unknown	1
30	*Bombacacidites protofoveoreticulatus*	Jaramillo & Dilcher 2001	LAD	16037.8	unknown	1
31	*Retitrescolpites saturum*	(Gonzalez 1967) Jaramillo & Dilcher 2001	FAD	16041.9	17.6	3
32	*Clavatisporites mutisii*	(Van der Hammen 1954) Jaramillo & Dilcher 2001	LAD	16065.8	unknown	2
33	*Syncolporites lisamae*	Van der Hammen 1954	LAD	16065.8	unknown	1
34	*Retitrescolpites baculatus*	Jaramillo & Dilcher 2001	FAD	16079.3	unknown	1
35	*Colombipollis tropicalis*	Sarmiento 1992	LAD	16079.3	unknown	2
36	*Curvimonocolpites inornatus*	Leidelmeyer 1966	LAD	16094.3	unknown	1
37	*Gemmamonocolpites gemmatus*	(Van der Hammen 1954) Van der Hammen & Garcia 1966	LAD	16109.6	3.5	5
38	*Spinizonocolpites baculatus*	Muller 1968	LAD	16110.1	3.5	5

Table 3. (*continued*)

	Species	Author	Event	CU	S	N
39	*Foveotricolpites perforatus*	Van der Hammen & Garcia 1966	FAD	16112.2	0.5	6
40	*Retistephanocolpites angeli*	Leidelmeyer 1966	FAD	16112.7	16.8	4
41	*Psilabrevitricolporites simpliformis*	Van der Kaars 1983	FAD	16113.7	unknown	1
42	*Momipites africanus*	Van Hoeken Klinkenberg 1966	LAD	16113.7	unknown	1
43	*Palaeocystodinium golzowense*	Alberti 1961	LAD	16113.9	2.2	3
44	*Bombacacidites protofoveoreticulatus*	Jaramillo & Dilcher 2001	FAD	16114.3	unknown	1
45	*Momipites africanus*	Van Hoeken Klinkenberg 1966	FAD	16114.3	unknown	1
46	*Gemmamonocolpites macrogemmatus*	Muller *et al*. 1987	LAD	16114.3	2.2	3
47	*Proxaperites operculatus acme*	(Van der Hammen 1954) Van der Hammen 1956	FAD	16115.0	2.1	3
48	*Bombacacidites annae*	(Van der Hammen 1954) Leidelmeyer 1966	FAD	16115.0	0.1	7
49	*Barco*		top	16115		

CU, composite units; FAD, first appearance datum; LAD, Last appearance datum; S, spreading parameter; N, number of wells where datum occurs, Cuervos and Barco Formation tops are also included (as they were defined in reference section).

independent data for a calibration with the geological timescale. These authors used planktonic foraminifera in several sections from South America and western Africa. However, the foraminiferal data presented for the Paleocene of South America were scarce and their stratigraphic and geographic positions were not reported. Without this information, the use of pollen and spores for chronological dating must be carefully considered in the region. The other zonation commonly used in the area is that of Muller *et al.* (1987) which was based on the Germeraad *et al.* (1968) zonation. Muller's scheme subdivided the Paleocene of NW South America into three palynological zones similar to those of Germeraad *et al.* (1968). Comparison of the Germeraad *et al.* (1968) and Muller *et al*. (1987) zonations with the Composite Section allows a preliminary calibration of the Composite Section. We expect to generate data in the coming years to obtain first-order calibrations of the palynological data.

According to the Germeraad *et al.* (1968) and Muller *et al.* (1987) zonations, the Cu-05 zone would correspond to the early Eocene zones of *Retibrevitricolpites triangulatus* (Germeraad *et al.* 1968) or *Rugotricolpites felix* (Muller *et al.* 1987) because of the FAD of *Striatopollis catatumbus*. Neither zonation recognizes the barren interval that is present along the Llanos foothills, zone Cu-04. Facies characteristics of this interval are mottled shales, which seem related to intense oxidation in well drained alluvial soils. This phenomenon is regional and could be linked to the abrupt global heating at the Paleocene–Eocene boundary (Jaramillo 2002). The zone Cu-03 cannot be identified in the Germeraad *et al.* (1968) and Muller *et al.* (1987) zonations. They place the late Paleocene *Foveotricolpites perforatus* zone underneath the Eocene *Retibrevitricolpites triangulatus* (Germeraad *et al.* 1968) or *Rugotricolpites felix* (Muller *et al*. 1987) zones. The zone Cu-03 can be found between these two zones. It has the LAD of *Bombacacidites annae* and *Retidiporites magdalenensis*, two taxa that are restricted to the Paleocene zones of both Germeraad *et al.* (1968) and Muller *et al.* (1987). The zone Cu-02 could correspond to the late Paleocene zone of *Foveotricolpites perforatus* of Germeraad *et al.* (1968) and Muller *et al.* (1987). Lastly, the zone Cu-01 could correspond to the Paleocene *Ctenolophonidites lisamae* zone of Germeraad *et al.* (1968) or *Gemmastephanocolpites gemmatus* of Muller *et al*. (1987) based on the presence of *Bombacacidites annae* and absence of *Foveotricolpites perforatus*. However, *Ctenolophonidites lisamae* and *Gemmastephanocolpites gemmatus,* two key elements of this zone, have not been reported in the studied sections used here.

The base of the Paleocene does not occur within the Composite Section, therefore the Composite Section can be considered as Paleocene in the interval from15 892 to 16 115 composite units, zones Cu-01 to Cu-03 (Fig. 6). A more detailed calibration of the Composite for the Paleocene in the Llanos and Llanos foothills is still uncertain.

Case study

The biostratigraphic framework produced for the Cuervos Formation was used for the interpretation of a well recently drilled in the northern Llanos foothills. During the original drilling, the stratigraphic position of the final depth of the well was difficult to establish. Incompatible biostratigraphic interpretations were produced by four different biostratigraphic consultants, ranging from Paleocene to upper Cretaceous for the deepest 4000 feet of the well. The final interpretation was that the Upper Cretaceous, Guadalupe Formation had been reached and that the strata were dipping almost horizontally (Fig. 7, see previous interpretation). Given the complexity of the problem, Ecopetrol, the state-owned Colombian petroleum company, formed a team that included structural geologists, petrographers, sedimentologists, stratigraphers and biostratigraphers to study the well.

The Composite Section produced in this study was used to re-interpret the well. Four palynological zones for the Cuervos Formation were identified and it was interpreted that the last 4289 feet drilled were in the Cuervos Formation, that the well was moving stratigraphically toward older rocks, and that no faults or repetitions were evident (Fig. 7). The top of the Cuervos Formation was determined to be at 7711 feet and the well ended at 12 000 feet in the zone Cu-02, Lower Cuervos (Fig. 7).

Several other sources of data, such as a Formation Micro-Imaging reinterpretation, petrographic variations and log interpretation, led to a similar conclusion (Meza *et al.* 2002), that the well was drilled in the Cuervos Formation for almost 4000 feet in beds that were steeply dipping (~60 degrees, Fig. 7).

Based on this interpretation, a drilling program was put together in order to reach the Barco Formation by drilling a sidetrack well. The kickoff point was at 10600′ in the original

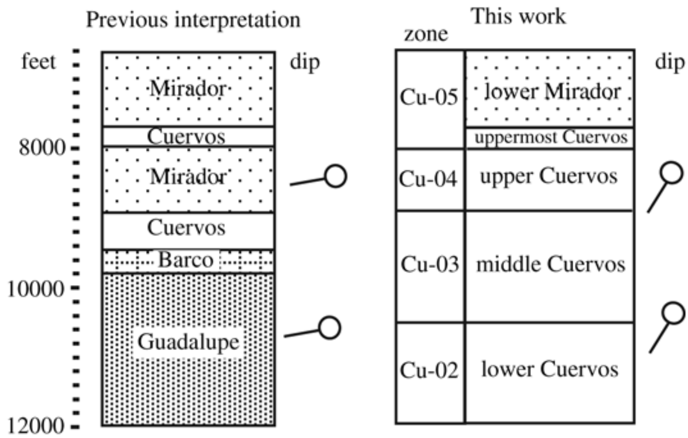


Fig. 7. Biostratigraphic interpretations of the well in the case study. Note that in the previous interpretation the Guadalupe Formation was drilled and strata are almost horizontal. The interpretation presented in this work based on the Composite Section suggests that the Cuervos Formation was drilled for the last 4289 feet and strata are steeply dipping (~60 degrees). Dip measurements coming from interpretation of a Formation Micro-Imaging log .

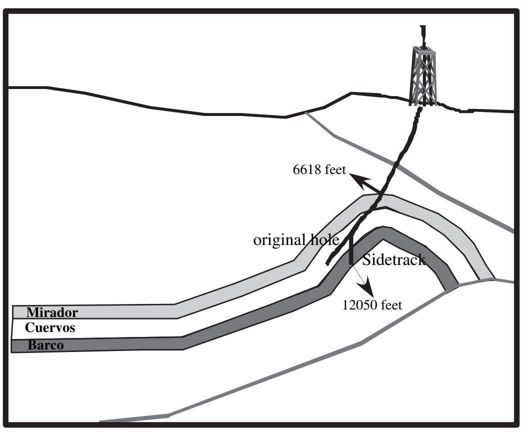


Fig. 8. Schematic geological cross-section of the case study well. The Barco Formation was reached at 11550 feet (measured depth) in the sidetrack and drilled until final depth (12 050 feet). Note that the original hole drilled in the Cuervos Formation is almost parallel to the bedding.

abandoned well (Meza *et al.* 2002). The sidetrack successfully reached the Barco Formation after drilling 1500 feet as the geological model had predicted (Fig. 8). The model was confirmed not only by palynology but also petrographic, petrophysic data, and electric logs. This test confirmed that the biostratigraphic framework developed for the Cuervos Formation works and can be successfully applied to exploration in the Llanos foothills.

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Appendix 1. *FAD and LAD's for the taxa used in the analysis. Tops (in feet) of the Cuervos and Barco Formations are also given.*

	ba.3		Piñalerita		Colorada		rc.1		Sutatuza		tame.2	
Species	FAD	LAD	FAD	LAD	FAD	LAD	FAD	LAD	FAD	LAD	FAD	LAD
Sample type	c	c	o	o	o	o	c	c	o	o	d	d
Aglaoreidia? foveolata			6300	6300								
Bombacacidites annae	16114	16000	6460	5539	1804						14664	14664
Bombacacidites foveoreticulatus	15523	15214	3986				13922	13711				
Bombacacidites protofoveoreticulatus			6460	5893								
Brevitricolpites macroexinatus			4072									
Brevitricolpites microechinatus			5857	5857								
Clavatisporites mutisii			6052	6052					6055	5307		
Colombipollis tropicalis				6129		2068						
Corsinipollenites psilatus				5857								
Crassiectoapertites columbianus	15575	15230					14137.3	13741.3			14285	13565
Cricotriporites guianensis			5001	5001			13724.3	13724.3				
Crototricolpites annemariae	15578	9450					13819	8170				
Crototricolpites protoannemariae			6460	5686								
Curvimonocolpites inornatus				6215								
Echiperiporites akanthos	15538	15516					13763.3	13746.7			14225	11355
Echitriletes muelleri	15516						13804				12705	11355
Ephedripites vanegensis	16057	16022	6300	6129					5403	3949		
Foveotricolpites perforatus	16112	16000	6294	5686	1660							
Foveotriletes margaritae	16730	16010			2412	2373	15087	14604	5622			
Foveotriporites hammenii	15538	15214	4393	4016			13925	13747				
Gemmamonocolpites gemmatus	16248	16242		6300			14671	14633	6101	3949		
Gemmamonocolpites macrogemmatus	16264	16223					14633	14633				
Heterocolpites palaeocenica	16267	16041										
Ischyosporites problematicus			5916	5001								
L. proxapertitoides reticuloides			5001	4016								
Longapertites microfoveolatus			6129	5124								
Longapertites vaneendenburgi	16231	15575			1974.6				5398			
Margocolporites vanwijhei	15526	9450					13925	13925			13785	12905
Momipites africanus			6460	6439								
Monocolpopollenites ovatus			6300									
Monoporopollenites annulatus	15523		4472	4016			13955				13725	
Palaeocystodinium golzowense	16114	16114					14671	14642				
Paleosantalaceaepites distinctus			5916	5857								
Polypodiisporites echinatus			6129	6129								
Polypodiisporites pachyexinatus			5539	5539								
Proxapertites operculatus acme	16114	16092	6300	6215								
Psilabrevitricolporites simpliformis			6439	5686								
Psilastephanocolporites fissilis	15362	15227	4350	4016			14137	13826				
Racemonocolpites facilis	15523	15214	4472				13922	13763				
Ranunculacidites operculatus	15554	9450	4229	4229			13925				14255	12705
Retibrevitricolpites retibolus	15513	15214	4229	4229			13738	13738				
Retidiporites elongatus			5916	5916					5619	4185		
Retidiporites magdalenensis	16267	16000		5686	2458		14671	14577		4185		
Retidiporites poricostatus			6300	6300								
Retistephanocolpites angeli	15579	15259	6406	5539			13829	13734				
Retistephanocolpites williamsi		15588										
Retistephanoporites angelicus	15579	9750	4138				13826	9550			14285	13565
Retitrescolpites baculatus			6129									
Retitrescolpites magnus	15530	15230	4393	4072								
Retitrescolpites peculiaris			6294	5686								
Retitrescolpites saturum	15383	15204	5916	5686			13738	13711				
Retitriporites amplireticulatus			5916	5916								
Rhoipites guianensis	15386	15217	4393				13931				14095	12395
Rhoipites hispidus	15523	15214	4229				13885	13711			14375	12505
Spinizonocolpites baculatus	16267	16233			3189	2373	14671	14633				
Spinizonocolpites breviechinatus			6460	5686								
Spinizonocolpites pachyexinatus			5539	5539								
Spirosyncolpites spiralis	15538	10890	4472				13955	7990			14335	13115
Striatopollis catatumbus	15575	10080	4472				13955				14315	10845
Striatricolporites digitatus			6439	6439								
Syncolporites lisamae			6052	6052					4257			
Tetracolporopollenites maculosus	15588	10720	4275				13829	10928				
Tetracolporopollenites spongiosus			6439	5539								
Tetracolporopollenites transversalis	15579	15214	5792	4153			13955	13747				
Tricolpites clarensis	15575	15214	5001				13783	13763				
Tricolpites protoclarensis				5686								
Verrustephanocolpites rugulatus			5001	4275								
Verrutricolporites reticulatus			4500									
Zlivisporis blanensis	16233	16010	5857	5539					5622	4215		
Cuervos		15510		4995				14087				14420
Barco		16115		6560		1804		14478				

FAD, first appearance datum. LAD, last appearance datum. All datums are in feet, in subsurface mode (even the outcrops). o, outcrop, c, core, d, ditch-cutting.

toco		sanmar		Regadera		bah.15		cu.5		ara.3		ara.4		guac	
FAD d	LAD d	FAD d	LAD d	FAD o	LAD o	FAD c	LAD c	FAD c	LAD c	FAD d	LAD d	FAD d	LAD d	FAD d	LAD d
				5696	5696	15045				17940	17940	18145	18145		
								16809	16809					12765	12765
				6284	6245										
					6458										
17075	13265	11225	10825												
					6230										
								17092	16913						
17307	14545	10675	8835									17945	17945		
16855	13445	9755	8715					16957		16055	15255				
						15039									
						14982				17940	17940	18255	18255		
						15292		18251	17782	18585	18345		18695		
				6235	6084			16945	16809						
							15141								
						15287	15045								
						15145	14957								
						14904									
16505	16445	10535	10535		6458			17087	16942						
					5696										
17185	14545	11225	8835	6284	5604			16960	16863						
						15292	15251								
					6142										
						14869	14863								
16905	16905							17091	17091						
15505	13855	11225	9465					17085	16939	15555	14905				
						15287				17940	17940	18695	18145		
								17098	17098						
17325	16105	11325	11325	5604								17945	17805	13035	12855
								16948	16942						
17185	15305	11325	9285							16055	16055	17905	17805	12765	
17307	14945	11325	10155	6234	6230									13095	13095
							15015						18695		
17307	15795	11325	9465		5604			16960	16809	17515	17515	17695		13155	12645
17325	14345	10015	8415	6235	5856			16960	16809			18005	18005	12975	12975
				6284				16960							
15305	15305	9465	8925	6235	6142			16957	16957	17235	17235				
				6284	6234										
				6284	5604										
								18386	18036						
					6560		14162		17067		17870		18010		13015
	17350						15050		17526						

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