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Palynostratigraphy of the Umir Formation, Middle Magdalena Valley Basin (MMVB) Colombia

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ABSTRACT

The Late Cretaceous Umir Formation in Middle Magdalena Valley Basin (MMVB) was recently acknowledged as a new target. However, there is little known about the regional distribution of the Umir Formation since it is affected by structural complexity and a major regional unconformity. To improve biosteering of the Umir Formation and reduce exploratory risks, a detailed biostratigraphic analysis of the Umir Formation in the MMVB is presented. Eighty samples from four cores drilled in the Central Eastern MMVB were analyzed for palynological content. These cores represent 976.6 meters of the Middle to Upper Umir Formation.

The sediment yielded a good recovery of pollen, spores and dinoflagellate cysts of Maastrichtian age, typical of Northern South America. The assemblage is dominated by species such as *Echimonocolpites protofranciscoi*, *Proteacidites dehaani*, *Buttinia andreevi*, *Spinizonocolpites baculatus*, *Proxapertites* spp., *Colombipollis tropicalis*, *Arecipites regio*, *Echitriporites trianguliformis*, *Echitriporites suescae*, *Psilatriletes* spp., *Scabratriletes granularis* and *Gabonisporis vigorouxii*. Dinoflagellate cyst assemblages include abundances of *Andalusiella* and *Palaeocystodinium* genera and skolochorate cysts dominated by *Achomosphaera - Spiniferites* complex. *Manumiella seelandica*, a dinoflagellate cyst that is a latest Maastrichtian global marker is recorded for the first time in the MMVB.

Three informal zones (A, B and C) are proposed. Zone A covers the Middle Umir, and Zones B and C characterize the Upper Umir member. Alternating spikes of peridinoid (*Andalusiella* and *Palaeocystodinium* genera) and skolochorate cysts, and abundances of *Echimonocolpites protofranciscoi* and *Proxapertites* genus characterize layers close and within the Upper Umir sandstones, showing potential to assist correlations and to evaluate lateral continuity of this new reservoir.

Based on the palynological assemblages, it is suggested that the Middle Umir Formation was deposited in a lagoonal environment with coastal swamps and estuarine conditions that evolved into a semi-restricted bay with river influx for the Upper Umir formation.
Palynological record of the Umir Formation reflects both the drastic replacement of the gymnosperms by the angiosperms and the Late Cretaceous provincialism of peridinacean dinocysts.
1. INTRODUCTION

The Middle Magdalena Valley Basin (MMVB) in Central Colombia is one of the most productive oil basins in the country. Thus far, oil exploration has been mainly focused on Eocene - Oligocene clastic reservoirs (Figure 1). In the MMVB petroleum system, the Upper Cretaceous formations have been traditionally considered to form the seal of the stratigraphic traps with Lower Cretaceous reservoirs (Prince et al., 2011). The Upper Cretaceous formations also serve as seals in west-verging thrusts that overlap Cenozoic reservoirs. In Paleogene and Neogene plays (areas in which hydrocarbon accumulations or prospects of a given type occur), the Upper Cretaceous formations are considered the economic basement (Prince et al., 2011); i.e. the rock layers below which economic hydrocarbon reservoirs are not expected to be found.

In this mature basin, ongoing oil exploration focuses on complex structural areas such as the Western foothills of the Eastern Cordillera (Villamil, 2003) and Cretaceous sequences (Córdoba et al., 2000; Prince et al., 2011). The Late Cretaceous Umir

Figure 1. A) Location of Middle Magdalena Valley Basin (MMVB). Red areas correspond to exploratory blocks where the Umir Formation is targeted. In Santa Lucía and San Luis fields, the Umir Upper sandstones are oil producers.
formation has become a new target since it has produced oil in Santa Lucia and San Luis oil fields (Ortiz and Flórez, 1997, see Figure 2).

**Figure 2.** Generalized stratigraphic column in MMVB (from Ecopetrol, 2009). See Figure 1 for location.

Interest in this target has also peaked since Prince et al. (2011) defined a new Aptian-Maastrichtian petroleum system containing the Umir Upper sandstones as a reservoir. Despite the recent increased interest of oil companies in this formation, the main problem for exploration lies within the high structural complexity of the unexplored western foothills of the Eastern Cordillera and the presence of the Middle Magdalena Valley Unconformity. As a result, there is little known
on this new reservoir and its regional distribution, so exploratory risks are high. This is despite the fact that a large number of palynological studies have been published for the Late Cretaceous in Colombia (e.g. Germeraard et al., 1968; Sole de Porta, 1972; Muller et al., 1987; Sarmiento, 1992; Yepes, 2001; Pocknall, 2001; Jaramillo and Rueda, 2004). But in reality, just a few projects have focused on the Middle Magdalena Valley Basin (e.g. Van der Hammen, 1954; Van der Hammen, 1957; Germeraard et al., 1968; Sole de Porta, 1971). The scarcity of publications on the palynostratigraphy of the Umir formation is most likely due to the earlier lack of interest in the Umir Formation from the oil industry, as these companies (e.g., Ecopetrol, SHELL, BP) lead and funded most of the geological research that has been done in the basin.

Hence, this research project specifically aims to build the biostratigraphic framework for the Late Cretaceous Umir Formation in the MMVB to enhance geological distribution models and reduce exploratory risks. Palynology is the best micropaleontological proxy for the Umir Formation since depositional conditions allowed for preservation of abundant terrestrial (pollen and spores) and marine (dinoflagellate cysts and acritarchs) palynomorphs. Additionally, as discussed above, palynology has been a successful tool (Figure 3) in solving problems associated with oil exploration in Colombian basins for the past 40 years (Germeraard et al., 1968; Sole de Porta, 1972; Mullet et al., 1987; Jaramillo and Rueda, 2004; Jaramillo et al., 2006; Torres et al., 2008; Contreras et al. 2010; Jaramillo et al. 2011).

The major biostratigraphic events defined via this study will be used to develop regional correlations and will serve as a key tool for on-site, real-time biostratigraphic control of future MMVB exploratory wells.

1.1 Campanian-Maastrichtian Palynological Zonations in Colombia and Western Venezuela

Maastrichtian palynological studies in Colombia and Western Venezuela have led to the development of four zonal schemes defined by Van der Hammen (1954; 1957), Germeraard et al. (1968), Muller et al. (1987) and Sarmiento (1992). Figure 3 provides the location of each study sections while Table 1 summarizes the four zonations.
Van der Hammen (1954; 1957) studied the Guaduas Formation (Sutatauza area, Eastern Cordillera) and the Umir Formation (Middle Magdalena Valley basin) in Colombia and proposed 3 zones and 8 subzones for the Maastrichtian (Table 1, Figure 3). The zones were defined considering changes in the abundance of three main groups: the *Psilatriletes* group, including all the *Psilatriletes* spores; the *Monocolpites medius* group, composed mostly of *Monocolpites minutus*, *Monocolpites huertasii* and *Monocolpites medius*; and the angiosperms group, that include four genera; *Tricolpites*, *Triporites*, *Tricolporites* and *Stephanocolpites*. According to Van der Hammen (1954), the zonal changes reflect climatic or evolutionary events. For instance, the increase of
arboreal pollen up section is interpreted as being related to the radiation of angiosperms (Van der Hammen, 1954) in late Cretaceous. The zonation was calibrated using Maastrichtian foraminifera and ammonites from both the lowest zone (Maastrichtian A1 zone, Middle Magdalena Basin) and the uppermost zone (Maastrichtian C zone, Catatumbo basin) (Van der Hammen, 1957). Campanian associations were not recognized.

This pioneer work is no longer considered valid since the palynological systematic nomenclature has changed considerably in the last fifty years, and morphotypes described by Van der Hammen (1954; 1957) have been revised and associated to other genera. For instance, the species *Monocolpites humbertoides* initially described as a monocolpate pollen was amended as a zonosulcate grain belonging to *Proxapertites* genus (Sarmiento, 1992). Additionally, with the increase of palynological knowledge, the stratigraphic range of some taxa has changed, and palynomorphs previously considered exclusively Maastrichtian have been found in younger sediments.

<table>
<thead>
<tr>
<th>AGE</th>
<th>TROPICAL ZONE</th>
<th>NORTHERN SOUTH AMERICA</th>
<th>COLOMBIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paleocene</td>
<td>Retiporiteis magadenensis</td>
<td>Zone 16 <em>Foveotricolpites perforatus</em></td>
<td></td>
</tr>
<tr>
<td>Danian</td>
<td></td>
<td>Zone 15 <em>Gemmastephanocolpites gemmatus</em></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Zone 14 <em>Spicianocolpites baculatus</em></td>
<td></td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Proteaidites dehaani</td>
<td>Zone 13 <em>Proteacidites dehaani</em></td>
<td></td>
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<td></td>
<td></td>
<td>Zone 12 <em>Crassitrilocpores subprolatus</em></td>
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<tr>
<td></td>
<td></td>
<td>Zone 11 <em>Auriculidites reticulatis</em></td>
<td></td>
</tr>
<tr>
<td>Maastrichtian</td>
<td></td>
<td>Zone 1 <em>Butinia andreevi</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zone 1 <em>Syncolpores laumae</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zone 1 <em>Zonotricolpites variabilis</em></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Comparison of four existing Late Cretaceous palynological zonations for Northern South America (modified from Pocknall et al., 2001).
Germeraard et al. (1968) analyzed data from Africa, Northern South America and Borneo and proposed the first palynological zonation for Tertiary sediments in tropical areas. Although this classic zonal scheme was focused mainly on the Cenozoic, Germeraard et al. (1968) defined the zone *Proteacidites dehaani* for the Maastrichtian. The zone was characterized by the co-occurrence of *Proteacidites dehaani* and *Jugoperiporites gutjahri* plus high abundances of *Foveotriletes margaritae*. The base of this zone was not established, but the top, marked by the last occurrence of *Proteacidites dehaani*, was clearly identified inside the Orocue Formation in Western Venezuela. In Colombia, this zone was recognized in the Colon Mito-Juan Formations (Catatumbo Basin, Northern Colombia) and in the Umir formation (Middle Magdalena Valley Basin). The Zone *Proteacidites dehaani* was calibrated using foraminifera assemblages and ammonites recovered from its lower section (Germeraard et al., 1968).

Muller et al. (1987) analyzed palynological data from Colombia, Venezuela, Trinidad, Guyana, Surinam and Brazil and proposed a zonation for the Late Cretaceous - Cenozoic in Northern South America. The chart contains six superzones for the Cretaceous, including the super zone VI for the Campanian - Maastrichtian interval (Table 1). The zonation was calibrated using the same criteria employed by Germeraard et al. (1968). Super zone VI was divided by Muller et al. (1987) into three zones: the Zone 11 *Auriculidites reticularis*, the Zone 12 *Crassitricolporites subprolatus*, and the Zone 13 *Proteacidites dehaani* (Table 1). Zone 11 (*Auriculidites reticularis*), covering the Campanian–lowermost Maastrichtian, was characterized as a taxon-range zone. Its base was defined by the last occurrence of *Droseridites senonicus* plus the first occurrences of *Auriculiidites reticularis* and *Buttinia andreevi*, and its top by the last occurrence of *Auriculiidites reticularis*. The zone was based on data from a well located in the Faja Petrolífera del Orinoco in Venezuela and has an equivalent in Brazil (Muller et al., 1987). Zone 12 (*Crassitricolporites subprolatus*) covers part of the Maastrichtian (Table 1) and is based on data published by Regali et al. (1974) for the Campos Basin, Brazil. Its base corresponds to the last occurrence of *Auriculiidites reticularis* and its top to the first occurrence of *Proteacidites dehaani*. Biostratigraphic events occurring within this zone include the first occurrences of
Crassitricolporites subprolatus, Aquillapollenites, Scollardia, Retidiporites magdalenensis, Proxapertites group and Ilexpollenites; and last occurrences of Crassitricolporites subprolatus, Crassitricolporites brasiliensis, Ariadnaesporites complex and Zlivisporis blanensis in the top of the zone. Zone 13 (Proteacidites dehaani) was defined by the first occurrences of Proteacidites dehaani at its base and Spinizonocolpites baculatus at its top. Biostratigraphic events occurring in this zone are the first appearance data of Foveotritetes margaritae, Stephanocolpites costatus, Proxapertites operculatus group, Spinizonocolpites group, Ulmoideipites genus, Spinizonocolpites intrarugulatus sp. nov and Gemmamonocolpites macrogemmatus; and last occurrences of Buttinia andreevi, Proteacidites dehaani, Crassitricolporites brasiliensis, Aquilapollenites and Scollardia. This zone corresponds to the late Maastrichtian and its top marks the important Cretaceous-Tertiary boundary. The reference section for Zone 13 is located in Western Venezuela inside the Guasare formation, and it was recognized in Colombia, in the Catatumbo basin inside the Colón and Mito-Juan formations (Muller et al., 1987).

Muller’s zonation provided a good palynostratigraphic framework for Northern South America. Nevertheless, its use for the Late Cretaceous of the Middle Magdalena Valley Basin is restricted as the zonation was mostly based on data from Brazil and Venezuela. Only one of the three zones proposed for the Campanian – Maastrichtian interval, the Zone 13 Proteacidites dehaani includes data from Colombia and was recognized in the Catatumbo basin. Furthermore, some of the taxa used in the zonation have not been recorded in Middle Magdalena Valley Basin, and the stratigraphic range of others has changed or is longer in this basin most likely as a result of environmental differences.

A palynological zonation based exclusively on data from Colombia was published by Sarmiento (1992). He analyzed a stratigraphic section of the Guaduas Formation in the Eastern Cordillera and proposed a zonation for the Maastrichtian - Paleocene interval for Central Colombia (Table 1, Figure 3). In his research, Sarmiento (1992) identified 79 palynomorphs including 9 new genus, 33 new species and 6 new combinations. This work constitute the basis of the systematic nomenclature used in subsequent palynological studies on the Maastrichtian - Paleocene of
Colombia. His zonation includes two zones: Zone I (Buttinia andreevi) for the Maastrichtian;  
and Zone II (Foveotriletes margaritae) for the Paleocene (Table 1). Zone I (Buttinia andreevi) 
was characterized by high abundance of Psilatriletes guaduensis, Psilamonocolpites medius and 
Psilatricolporites rubini (Sarmiento, 1992; 1994). Taxa restricted to this zone are Echimonocolpites 
echiverrucatus, Spinizonocolpites echinatus, Retimonocolpites claris, Crusafontites grandiosus, 
Clavatriletes mutisii, Inaperturopollenites cursi, Psilamonocolpites ciscudaed and Retitricolpites 
Belskii. Occurrences of Annutriporites iversenii, Proxapertites humbertoides, Retidiaporites 
magdalenensis, Buttinia andreevi, Bacumorphomonocolpites tausae, Ephedripites multicostatus, 
Stephanocolpites guaduensis, Echimonocolpites protofranciscoi and Retitricolpites josephinae are 
also frequent. At the top of the zone, Buttinia andreevi disappeared but is recorded again at the 
top of Zone IIA (Sarmiento, 1992). Zone I (Buttinia andreevi) is correlated to the Maastrichtian 
zone A of Van der Hammen, (1954; 1957), the Proteacidites dehaani zone of Germeraad et al., 
(1968) and the Zone 13 of Muller et al. (1987) (Table 1). Zone II (Foveotriletes margaritae) 
includes two subzones: Subzone IIA Zonotricolpites variabilis and Subzone IIb Syncolporites 
lisamae (Table 1). Sarmiento (1992) suggested that the boundary between Zones I and II 
corresponds to the Cretaceous – Tertiary boundary, but an abrupt palynological change expected 
to evidence the K/T boundary was not recognized. This said, the first appearances of 38 species 
occur immediately below or within Subzone IIA. A few first appearances were found below the 
boundary (i.e. Proxapertites psilatus, Gemmamonocolpites dispersus, Syndemicolpites typicus, 
Foveotriletes margaritae, Longapertites vaneendenburgi and Racemonocolpites racematus); others 
at the boundary (i.e. Longapertites perforatus, Psilabrevitricolporites annulatus, Mauritiidites 
franciscoi, Zonotricolpites variabilis); and some above the boundary (i.e. Echimonocolpites coni, 
Retitricolporites exinamplius, Proxapertites verrucatus and Proxapertites operculatus). The base 
of the Subzone IIB (Syncolporites lisamae) is marked by the last occurrences of Duplotriporites 
ariani, Bacumorphomonocolpites tausae, Ephedripites multicostatus, Araucariacites australis and 
Zlivisporis blanensis; and the first occurrences of Syncolporites lisamae, Spinizonocolpites tausae 
and Psilatritiletes martinensis. Occurrences of Foveotriletes margaritae, Divissisporties enormis,
*Echitriporites trianguliformis* and *Gemmamonicolpites dispersus* were also recorded inside Subzone IIB. Sarmiento (1992) correlated zone II (*Foveotriletes margaritae*) to the Maastrichtian Zones B and C of Van der Hammen (1954; 1957), and to the Danian zones *Foveotriletes margaritae* of Germeraad et al. (1968) and the Zone 14 *Spinizonocolpites baculatus* of Muller et al. (1987) (Table 1).

Although the systematic palynology published by Sarmiento (1992) is a reference for any Maastrichtian – Paleocene palynological studies in Colombia, the pollen zones and ages published are controversial. Zone I *Buttinia andreevi* was correlated to Zone *Proteacidites dehaani* of Germeraad et al. (1968) and Muller et al. (1987) despite the fact that *Proteacidites dehaani*, the key marker defining this zone, was not recorded in the Guaduas section. Sarmiento (1992) clarified that the correlation was done considering the stratigraphic position and not pollen assemblages. Other inconsistencies in Sarmiento’s work relates to zone II *Foveotriletes margaritae*, dated as Danian and correlated to zones *Foveotriletes margaritae* of Germeraad et al. (1968) and Muller et al. (1987). Muller et al. (1987) defined the base of the zone by the first occurrence of *Spinizonocolpites baculatus*, and the top by the first occurrence of *Gemmastephanocolpites gemmatus*. In the Guaduas section, *Spinizonocolpites baculatus* has a wider stratigraphic range and *Gemmastephanocolpites gemmatus* was not recovered. The acme (high abundance) of *Proxapertites operculatus*, a diagnostic event recognized regionally in the lower Paleocene of Colombia was not mentioned either by Sarmiento (1992). Rather he identified occurrences of *Araucariacites australis, Tetradiites umirensis, Colombipollis tropicalis, Ulmoideipites krempii, Periretisyncolpites giganteus, Buttinia andreevi, Bacumorphomonocolpites tausae* and *Duplotriporites ariani* both in the zone I (Maastrichtian) and zone II (Danian). In fact, the top of the subzone IIA (still Danian) was defined by the last occurrence of *Buttinia andreevi, Bacumorphomonocolpites tausae, Duplotriporites ariani* and *Araucariacites australis*. Later studies showed that most of these taxa occur in the Late Maastrichtian, and became extinct in the K/T boundary (De la Parra, 2009).
1.2 Other Maastrichtian Palynological Studies of Colombia and Western Venezuela.

Other biostratigraphic studies of the Maastrichtian of Colombia and Venezuela described palynological assemblages and new morphotypes (Sole de Porta, 1971; 1972) and provided a detailed analysis of the K/T boundary palynological changes in the region (Yepes, 2001; Pocknall, 2001; De la Parra 2009) (Figure 3).

Sole de Porta (1971) described palynological assemblages from the Maastrichtian - Paleocene Guaduas Formation (Eastern Cordillera) identifying four new genus (Baculamonocolpites, Bacumorphomonocolpites, Crusafontites, and Foveomorphomonocolpites), two new species (Bacumorphomonocolpites tausae and Crusafontites grandiosus) and new sub-species for Leiotriletes guaduensis, Baculamonocolpites espinosus and Foveomorphomonocolpites humbertoides.

Sole de Porta (1972) analyzed the Cimarrona Formation (Zaragoza and Primavera members) in the Southern Middle Magdalena Valley Basin. Two palynological assemblages including occurrences of Proteacidites dehaani, Buttinia andreevi, Foveotriletes margaritae, Cyatheacidites vanderhammeni, Leiotriletes guaduensis, Muerrigerisporis americanus, Schizeaoisporites cicatricos, Baculamonocolpites minimus, Bacumorphomonocolpites tausae, Annutriporites iversenii, Annutriporites annulatus, Echimonocolpites minutispinosus, Foveomorphomonocolpites humbertoides, Retidiporites magdalenensis, Magnatriporites umirensis, Plicapollis bellus and Monoporisporites grandis, among others, were identified. The assemblages, dated both as Maastrichtian, were calibrated using micropaleontological analysis conducted by De Porta (1966), and were correlated to the Proteacidites dehaani zone of Germeraad et al. (1968).

Yepes (2001) analyzed the Río Molino section in Northern Colombia (in the Cesar Rancheria Basin) and the Río Loro section in Western Venezuela, where the Colon and Mitojuan formations are exposed (Figure 1). Using dinoflagellates cyst assemblages, he identified biostratigraphic events that provide a mean to differentiate Upper Campanian from Lower and Upper Maastrichtian, and provide the basis to place the K/T boundary. To establish the Upper Campanian - Lower Maastrichtian boundary, Yepes (2001) used the highest occurrences of
Xenascus ceratioides, Odontochitina operculata, Trichodinium castanae, Hystrichodinium sp. and Palaeohystrichophora infusorioides; and the lowest occurrences of Areoligera senonensis, Cerodinium diebelii, Trithyrodinium evittii, Yolkingygmium lanceolatum, Phelodinium tricuspe, Cordospaheridium fibrosum, Andalusia spp., Seleganium sp. Palaeocystodinium spp. and Palaeocystodinium australinum. The upper Maastrichtian was characterized using the occurrences of Dispharogena carposphaeropsis, Glaphyrocysta perforate, Manumiella seelandica and Thalassiphora patula. Yepes (2001) recognized the K/T boundary using the lowest occurrences of Damassidinium californicum and Senoniasphaera inornata that are restricted to the Danian (Early Paleocene). Even though, Maastrichtian biostratigraphic studies based on dinoflagellates cysts are scarce in Northern South America, Yepes (2001) found key dinoflagellate events that correlate to known biomarkers of global significance. The events he described were calibrated with calcareous nannofossils and planktonic foraminifera events reported by Martinez (1989) and Martinez and Hernández (1992) for the Río Molino section.

Poknall et al. (2001), using graphic correlation in the Río Loro Section (Western Venezuela), calibrated the terrestrial palynological record of the Maastrichtian – Paleocene interval with dinoflagellate cysts assemblages from the Amoco’s corporate global database. As a result, these authors differentiated assemblages for the Lower and Upper Maastrichtian and for the Danian. The Lower Maastrichtian was characterized by abundances of Cyathidites australis and Mauritia crassibaculatus; minor frequencies of Spinizonocolpites baculatus, Echitriporites trianguliformis, Proxapertites spp., Areccipites spp., and Foveotriletes margaritae; and the first appearances of Colombipollis tropicalis and Kleithosphaeridium truncatum. The dinoflagellate assemblage was dominated by occurrences of Palaeocystodinium golzowense and Andalusia spp. Pocknall et al. (2001) recognized abundances of Palaeocystodinium golzowense, Glaphyrocysta perforatum and Andalusia polymorpha in Middle Maastrichtian assemblages. Low frequencies of Cyathidites australis, Foveotriletes margaritae and Proxapertites spp., and the last occurrence of Dinogymnium pustulicostatum were also recorded. The latest Maastrichtian was defined by occurrences of Glaphyrocysta perforatum and Dinogymnium pustule, and abundance of Areccipites spp, Cyathidites
australis, Foveotriletes margaritae, Mauritia crassibaculatus, Proteacidites spp., Proxapertites spp., Spinizonocolpites baculatus and Spinizonocolpites echinatus. Finally, occurrences of Damassidinium californicum, Fibrocysta bipolaris, Kenleyia lophophora, Turbiosphera filose, Carpatella cornuta and Caslidinium fragile defined the Early Danian.

As Sarmiento (1992), Pocknall et al. (2001) recorded occurrences of Proteacidites dehaani, Crusafontites grandiosus, Periretisyncolpites giganteus and Araucariacites australis in the Paleocene. Buttinia andreevi, one of the key Maastrichtian taxa, was not recorded.

De la Parra (2009) analyzed the K/T boundary in a stratigraphic section in Cesar-Rancheria basin (Northern Colombia) by using several statistical techniques to estimate extinction percentages and changes in diversity related to the boundary (Figure 1). He calculated an extinction percentage of 48-70% and showed that the high diversity Cretaceous palynoflora was replaced by a low diversity Paleocene assemblage. Some of the species that became extinct at the boundary include Echimonocolpites protofranciscoi, Buttinia andreevi and Protecidites dehaani, restricting their range to the Late Cretaceous (De la Parra, 2009).

In summary, several studies and zonal schemes have proposed biostratigraphic events for the late Cretaceous in Colombia and Western Venezuela (Van der Hammen, 1954; Van der Hammen, 1957; Germeraard et al., 1968; Sole de Porta, 1971; Sole de Porta, 1972; Muller et al., 1987; Sarmiento, 1992; Yepes, 2001; Pocknall, 2001; De la Parra, 2009) however, only a few have been conducted on the Umir Formation in Middle Magdalena Valley Basin (Germeraard et al., 1968; Van der Hammen, 1954; Van der Hammen, 1957; Sole de Porta, 1972). Applying these zonations in Middle Magdalena Valley Basin is constrained by inconsistencies in systematic nomenclature, differences in the stratigraphic range of some taxa in the basin, and the absence of some of the events due to facies changes. Hence, analyze the palynological content of the Umir Formation in order to develop a palynostratigraphic framework for the Late Cretaceous in the Middle Magdalena Valley Basin is long overdue and is the specific focus on this thesis. The zonation developed will provide a detailed biostratigraphic framework that will be correlated throughout the basin and contextualized using the regional palynological frame.
2. OBJECTIVE

The aim of this project is to conduct a detailed palynological analysis of one composite section encompassing the Umir formation in Middle Magdalena Valley Basin to develop a biostratigraphic framework for the Late Cretaceous Umir Formation. Major biostratigraphic events will be used to develop regional correlations, and serve as a key tool for on-site, real-time biostratigraphic control of exploratory wells.
3. GEOLOGICAL SETTING

The Middle Magdalena Valley Basin (MMVB) is an intermontane basin located between the Central and Eastern Cordilleras in Central Colombia (Figure 4). From the Triassic to the Middle Miocene, the MMVB used to be part of a larger regional basin made off the Eastern Cordillera and the Llanos basin (Cooper et al., 1995; Villamil, 1999; Gómez et al., 2005). The development of the Central Cordillera (to the west), the Eastern Cordillera (to the East) and the tectonic evolution of the Northwestern Margin of South America had a major impact on the MMVB formation (Cooper et al. 1995; Gomez et al., 2003; Rolón, 2004; Gomez et al., 2005). The tectonic development of this basin can be summarized in four main events: 1) Triassic – Aptian rifting; 2) Early Cretaceous – Campanian thermal subsidence; 3) Late Cretaceous - Early Eocene uplift of the Central Cordillera; and 4) Middle Miocene – Recent uplift of the Eastern Cordillera (Cooper et al. 1995; Villamil, 1999; Gómez et al. 2005; Rolón 2004).

The Triassic to Earliest Cretaceous rifting phase was related to the separation of North and South America (Cooper et al., 1995). The synrift megasequence is represented by 3000 to 5000 meters of Jurassic red beds and volcaniclastic strata in the Eastern Cordillera and MMVB (Gómez et al., 2003). By Early Cretaceous, the initial Jurassic continental environments were replaced by sequences indicative of paralic (deposits laid down on the landward side of a coast) and shallow marine conditions (Cooper et al., 1995).

During the Early Cretaceous to Campanian, the MMVB underwent thermal subsidence associated with a back-arc setting. As a consequence, a marine transgression flooded the Colombian Cretaceous basin depositing a sequence of shales, mudstones and chert beds (Cooper et al., 1995). The rise of sea level coupled with anoxic conditions and upwelling led to the deposition of a series of organic-rich mudstones, cherts and phosphates that constitute the most prolific source rock in Northern South America (Cooper et al. 1995; Gómez et al. 2005).

Later in the Early Maastrichtian, the diachronous accretion of the Western Cordillera caused the initial uplifting of the Central Cordillera and the beginning of the inversion of Triassic - Jurassic extensional faults (Gomez et al. 2005). Shortening continued until the Early Eocene.
and produced an abrupt change in the depositional environments in the Middle Magdalena Valley Basin, the Eastern Cordillera, and the Llanos Basin (Cooper et al., 1995; Gómez et al., 2003; Gómez et al., 2005). Conditions were predominantly marine during most of the Cretaceous, then became transitional for the Latest Cretaceous – Paleocene and fluvial in the Early Eocene. These coarsening upward sequences consist of shallow marine, coastal plain, estuarine, coal-rich alluvial plain and alluvial fan deposits (Cooper et al., 1995; Gómez et al., 2003). Since the initial uplift of the Central Cordillera during the Late Cretaceous, the deformation associated with the uplift migrated eastward until the Early Eocene. The propagation of the deformation combined with the ending of the Central Cordillera uplift in the Early Eocene resulted in a key stratigraphic feature: the Middle Magdalena Valley unconformity (MMVU) (Gómez et al., 2003; Gomez et al., 2005).

The MMVU separates Mesozoic and Paleocene units from the Middle Eocene and Neogene formations (Gómez et al., 2003; Gomez et al., 2005). This regional unconformity dips eastward to the Eastern Cordillera and is continuous to the west in the Central Cordillera. The stratigraphic hiatus associated with the MMVU decreases toward the east. Preserved thicknesses of both the Mesozoic/Paleocene sequence and the onlapping Middle Eocene/Neogene sequence increase eastward, to the western foothills of the Eastern Cordillera (Gómez et al., 2003; Gomez et al., 2005) (Figure 4). The thickness of these sequences decreases northward to the Cachira Arch (Gómez et al., 2003; Gomez et al., 2005), while the time gap associated with the unconformity decreases toward the east. This trend is recorded regionally throughout the MMVB (Figure 4) (Gómez et al., 2003; Gomez et al., 2005).

The major deformation of the Eastern Cordillera and Llanos Foothills started in the Middle Miocene and continued until the Pliocene. It resulted from the collision of the Panamá - Baudó arc with the northwestern margin of South America (Dengo and Covey, 1993; Cooper et al., 1995; Gómez et al., 2003; Gómez et al., 2005). This intense tectonic pulse reactivated and finalized the tectonic inversion of the Jurassic extensional faults and created new compressional structures, including thrust fans and triangle zones in the Llanos foothills (Cooper et al., 1995; Rolón, 2004). As a consequence the Eastern Cordillera was uplifted and eroded (Cooper et al., 1995; Gómez et
al., 2003; Gómez et al., 2005) and the Llanos Basin and Middle Magdalena Valley Basin became isolated (Cooper et al., 1995). At this stage, the MMVB acquired its current configuration.

Figure 4 Simplified paleogeographic map of Colombia and Western Venezuela during the Maastrichtian (Adopted and modified from Villamil, 1999). The dot-lined arrow indicates the location of the depocenter in the basin during the Campanian. Notice how the depocenter migrated from a western location (in Eastern Central Cordillera) to a central location in the Maastrichtian (Villamil, 1999).
3.1. Tectonic and Stratigraphic Framework for the Maastrichtian in Middle Magdalena Valley Basin

As mentioned above, the initial uplift of the Central Cordillera during the Early Maastrichtian by accretion of the Western Cordillera produced a dramatic change in the depositional environments of the Middle Magdalena Valley Basin, Eastern cordillera and Llanos Basin (Cooper et al. 1995; Villamil, 1999; Gómez et al., 2003; Gómez et al., 2005). Predominantly marine conditions were replaced by coastal plain and deltaic environments. Campanian-Maastrichtian rocks in the MMVB recorded the northward withdrawal of the sea in North Western South America. This regression continued into the late Maastrichtian and Early Paleocene (Villamil, 1999; Gómez et al. 2003). The major mechanisms controlling the sedimentation in this large basin during these periods were the eastward migration of the center of deposition and the decrease of accommodation space (Villamil, 1999).

During the Campanian, the depocenter axis of the basin was located along the Eastern foothills of the Central Cordillera and the westernmost area of the MMVB. Epicontinental seas covered eastern Colombia and western Venezuela and distal facies were deposited in the north and west (Villamil, 1999). After the initial Early Maastrichtian uplift of the Central Cordillera, the position of the depocenter switched to a new location along the western foothills of the Eastern Cordillera (Villamil, 1999). Hence, a new Maastrichtian marine seaway with a NE-SW orientation was created. Facies deposited in Middle Magdalena Valley basin were very close to the depocenter and consisted mostly of shales, mudstones and claystones forming the Umir Formation (Villamil, 1999). The Buscavidas shale in Southern MMVB and Colon Mito-Juan formations in the Catatumbo Basin represent similar facies and are correlated with the Umir. In eastern and westernmost areas, discontinuous coarse clastic sediments were deposited, including the Cimarrona formation in southeastern MMVB (Villamil, 1999).

3.2. Lithostratigraphy and Depositional Environment of the Umir Formation

The Umir formation was originally described by Morales (1958) as a series of dark, bluish-
gray and black thin bedded shales for the lower section; and dark gray thin-bedded shales with several coal beds and intercalations of fine-grained sandstones and siltstones in the upper section. In the type locality, its thickness corresponds to approximately 1000 m. The contact of the Umir formation with the underlying La Luna formation is slightly unconformable; and it is conformable with the overlying Lisamae Formation (Morales, 1958).

A detailed study by Ecocarbón (1996) conducted in the San Luis area, in the Los Andes Syncline (central MMVB), differentiated three intra-Umir members (Figure 5). The lower member is characterized by a series of blue-grayish to black mudstones with thin bedding, alternated with nodular ferruginous siltstones and carbonate with micaceous laminations. Coal beds were not recognized in this member. The boundary with the middle member was defined on the first occurrence of coal beds. This overlying middle member consists of black to gray shales alternating with ferruginous siltstones and coal beds with thicknesses ranging from a few centimeters to 3 meters. The limit between the middle and upper members corresponds to a 12 meter-thick sandstone. The Upper member is composed of light gray to black carbonate mudstones and black to gray mudstones alternating with siltstones and shales and include up to 31 coal beds in the lower part and coal beds up to 0.6 meters in thickness in the middle part. Fine to middle grained sandstones were also identified. The total thickness of the Umir Formation in this region is estimated to be approximately 1400 meters.

![Figure 5](image-url)
Ortiz and Flórez (1997) conducted a sequence stratigraphic analysis of the Umir formation using cores collected by Ecocarbón (1996). Two distinct facies were defined: the lake-fill facies consisting of shales, coal beds, and laminated mudstones and siltstones; and the channel - crevasse splay facies made of intraformational conglomerates, crossed-stratified sandstones, laminated sandstones and siltstones. Four low frequency cycles were identified. The lake-fill facies predominates in the basal three cycles; and in the uppermost cycle, the channel - crevasse splay facies is dominant. The vertical distribution of the facies marks a decrease of accumulation space within the Umir (Ortiz and Flórez, 1997). Based on this model, Ortiz and Flórez (1997) interpreted the depositional environment for the Umir Formation either as a bay with paralic conditions or a semi-restricted lagoonal area, with channel influence in the area close to coastline.

In its original description, to the Umir formation was assigned a Campanian – Maastrichtian age (Morales, 1958; Julivert, 1968). Petters (1955), using foraminiferal assemblages from Western Venezuela recognized, from base to top, the zones Siphogenerinoides cretacea, Siphogenerinoides bramlettei and Ammobaculites colombianus. The report of the Campanian ammonite Stantonoceras associated with the Siphogenerinoides cretacea zone, in the Southern Upper Middle Magdalena Valley, supported the Campanian age for the base of the Umir (Morales, 1958). Maastrichtian ammonites within the Siphogenerinoides bramlettei and Ammobaculites colombianus zones confirmed the Maastrichtian age for the rest of the formation (Petters, 1955).

Nevertheless, Tchegliakova (1995; 1996) revaluated the Campanian age assigned to the Lower Umir. Tchegliakova (1995) studied a section located in the northwestern Middle Magdalena Valley, where the contact with the underlying La Luna Formation is exposed. She recorded occurrences of Ammobaculites colombianus and Rugoglobigerina macrocephala, restricting the age of the formation to the Middle to Upper Maastrichtian. Also, Tchegliakova (1996) analyzed the Umir and Cimarrona formations in the Honda-Guaduas area, in Southern Middle Magdalena Valley basin. Foraminiferal assemblages of Middle to Late Maastrichtian planktonic zones Gansserina gansseri and Abathomphalus mayaroensis were recognized. The Campanian was not recognized in this section either (Tchegliakova, 1996).
4. MATERIALS AND METHODS

Eighty samples were collected from a Middle to Upper Umir Formation composite section. This composite section consists of four cores drilled by Ecocarbón (1996) during a coal exploration campaign on the western side of the Los Andes syncline, in the Central Eastern MMVB (Figure 6). The correlation between cores and their stratigraphic position were established using a stratigraphic framework based on the recognition of coal beds and sandstone levels identified in previous surface studies (Ecocarbón, 1996; Ortiz and Florez, 1997).

Figure 6. Location of the cores PPI-3, PPM-5, PPM-2, and PPM-1 in San Luis Area, Los Andes syncline, Central-Eastern MMVB.
Figure 7. Composite stratigraphic section of the Middle/Upper Umir Formation in the Los Andes syncline, Central-Eastern MMVB, Colombia (modified from Ortiz and Florez, 1998).
The stratigraphic position and the intervals covered for each core are shown in figure 7. The Middle Umir Formation was recovered from Cores PPI-3 (6.3804N; 73,4052W) and PPM-5 (6.3926N; 73.401W) (Figure 7). These cores were drilled to 261 meters and to 261.60 meters, respectively. Cores PPM-1 (6.4135N; 73.3947W) and PPM-2 (6,4045N; 73.391W) covered the Upper-middle to Uppermost Umir Formation, and were drilled to 166 and 288 meters, respectively (Figure 7). The composite section corresponds to approximately 900 meters of stratigraphic thickness.

The samples were prepared for palynological content in the Biostratigraphy Laboratory of the Colombian Petroleum Institute (ICP). The procedure followed the technique described by Traverse (1988), and involved the initial digestion of 20 grams of sample in hydrochloric (HCl) and hydrofluoric (HF) acids for dissolving carbonates and silicates, respectively. Heavy liquid separation was performed using zinc bromide (ZnCl₂) to remove residual minerals. A controlled oxidation was performed on the half portion of the residue in order to disaggregate palynomorphs from organic debris and clays. The residues were sieved using a 10 µm nylon screen. Two slides, one oxidized and one non-oxidized were analyzed per sample.

Palynological analyses were conducted using a BX41 Olympus light microscope at the Center for Excellence in Palynology (CENEX) at Louisiana State University (LSU). A minimum of 300 grains of spores, pollen, acritarchs and dinoflagellate cysts were tabulated per slide when possible. Following this step, the rest of the slide was scanned without tabulation in order to scan potentially rare species. The slides were scanned using a 20x objective and detailed examination and description of palynomorphs was done under a 60x oil immersion objective.

Species identification was made using formal descriptions and illustrations from specialized literature (Van der Hammen, 1954; Van der Hammen, 1957; Van der Hammen and García de Mutis, 1966; Germeraad et al., 1968; Sole de Porta, 1971; Sole de Porta, 1972; Muller et al., 1987; Sarmiento, 1992; Jaramillo and Dilcher, 2001; Yepes, 2002; Jaramillo and Rueda, 2004; Jaramillo et al., 2007; Jaramillo et al., 2010; Slimani et al., 2010) and the “Morphological Electronic
Database of Cretaceous-Tertiary and Extant pollen and spores from Northern South America” by Jaramillo et al. (2011). Taxonomic revision was done using the reference palynotheca curated at the Smithsonian Tropical Research Institute (STRI) in Panama, and in the Colombian Petroleum Institute (ICP) in Colombia, where holotypes and paratypes of pollen, spores and dinoflagellates cysts from Northern South America are available.

Distribution and range charts were generated using Stratabugs biostratigraphic data management software.
5. RESULTS

A total of 201 morphotypes were identified and 17,410 palynomorphs were counted. The morphotypes include 156 species of pollen and spores, 39 species of dinoflagellate cysts, 3 species of acritarchs, and 3 species of unknown algae. Although palynomorph assemblages consist of spores, pollen, dinoglagellates cysts, acritarchs, foram linings and other algae, 95% of the recovered palynomorphs belong to pollen and spore groups, while only 5% includes dinoflagellates cysts, acritarchs, foram lining and algae. Fungal spores and abundant organic matter were recovered in all the samples. The recovery was variable but good in general: 80% of the samples, equivalent to 64 slides, were palynologically productive and only 20% of them (16 slides) had a total counting of palynomorphs below 100 grains. Those samples with low recovery were removed from quantitative analysis.

Figure 8. Relative abundance of significant palynomorph groups in the composite section for Middle – Upper Umir Formation.
Percentages of significant palynomorphs groups are presented in figure 8. Distribution charts for each core are given in Appendixes A to D. Generalized quantitative distribution and range charts for the Umir Formation is included in Appendixes E to F. The palynomorphs taxa recovered are listed in Appendix G and illustrated in Plates 1–7.

5.1. Palynology of Core PPI-3

Good recovery of palynomorphs and organic matter were found in this section, with the exception of the interval between 244 and 196 m, at the base of the core, where the total counting of palynomorphs in slides 196 m, 208.10 m, 232 m and 244 m was below 100 grains (see Appendix A for details and Figure 9 for summary). Fern spores, including mainly psilate-trilete spores, are the dominant component in palynological assemblages with a relative abundance ranging from 50% to 80% of the assemblage recovered, followed by *Echimonocolpites protofranciscoi* (10% to 30%), *Spinizonocolpites* group (5% to 12%) and Angiosperm pollen (3% to 10%). Palm pollen represented by monocolpate grains comprise from 1 to 6% of the assemblages, while dinoflagellates cysts range from 2 to 6% (Figure 9).

The interval between 244 m and 196 m, with low recovery, is characterized by low relative abundances of *Psilatriletes* group and *Echimonocolpites protofranciscoi* along with
occurrences of *Araucariacites australis, Gabonisporis vigorouxii, Muerrigerisporis “ardilenses”, Neoraistrickia “constrictus”* and *Crusafontites grandiosus* (Appendix A). Angiosperm pollen reaches 10% of the assemblage and includes occurrences of *Echitriporites trianguliformis, Proxapertites humbertoides, Psilatricolpites josephinae, Retitricolpites josephinae* and *Ulmoideipites krempii.*

Good recovery was obtained between 184 m and 128 m. This interval is characterized by high abundances of *Psilatriletes* group, moderate abundances of *Echimonocolpites protofranciscoi* and low relative abundances of *Echitriletes “protomulleri”, Gabonisporis vigorouxii* and *Retitricolpites josephinae.* Beutinia andreevi, Verrutritles virueloides, Zlivisporis blanensis, Gemmamonocolpites dispersus, Echitritiletes “acanthotritiletoides” and Ulmoideipites krempii are also found within this zone. A spike in spores of *Laevigatosporites granulatus* identified at 161.1 m constitutes one of the most important biostratigraphic event in this interval (Appendix A).

From 108 m to 9.10 m, high relative abundance of the *Psilatriletes* group and *Echimonocolpites protofranciscoi* dominate the assemblages. Abundances of *Spinizonocolpites baculatus* and *Spinizonocolpites “brevicolpatus”* increase between 121.80 and 99.70 m. Low relative abundance in *Scabratriletes “granularis”* and *Diporoconia cf. Diporoconia iskaszentgyoeryi* occur between 108 and 99.70 m. *Arecipites regio, Buttinia andreevi, Crusafontites grandiosus, Echimonocolpites “pachyexinatus”, Echitriporites trianguliformis, Stephanocolpites costatus* and *Ulmoideipites krempii* are continuously present in the assemblage from 56 m upwards. Sparse occurrences of *Annutriporites iversenii, Bacumorphomonocolpites tausae, Foveotriletes margaritae* and *Monocolpites grandispiniger* are also recorded (Appendix A).

The highest abundance in dinoflagellate cysts recovered for core PPI-3 is registered at 48 m. This event include species such as *Spiniferites sp., Andalusiella polymorpha, Cerodinium sp., Lingulodinium sp. and Senegalinium sp.* Other dinoflagellate cysts recorded in this core include *Cordosphaeridium sp., Exochosphaeridium sp., Palaeocystodinium sp.* and *Florentinia aff. mantellii.* Overall, dinoflagellate cysts exhibit a good preservation.
5.2. Palynology of Core PPM-5

Good recovery of palynomorphs was obtained between 280 and 100.3 m except for the interval between 88 and 32 m, where the recovery was poor. Within this zone, only the slide at 68.80 m had a total counting higher than 100 grains (see Appendix B for details and Figure 10 for summary). Palynological assemblages are dominated by the *Psilatriletes* group and *Echimonocolpites protofranciscoi*. Relative abundances of these two morphotypes show opposite tendencies: the percentage of *Psilatriletes* group increases from 50%, at the base of the core, to 90% at the top, while the percentage of *Echimonocolpites protofranciscoi* varies from 35% at the base to 5% at the top (Figure 10). Angiosperm pollen also exhibit the same tendency, with decreased abundances upward, from 12% to 5.

![Figure 10. Relative abundances of predominant palynomorph groups in Core PPM-5.](image)

In addition to high relative abundances of *Psilatriletes* group and *E. protofranciscoi*, moderate relative abundances of *Spinizonocolites baculatus* and *Araucariacites australis*, and low relative abundances of *Proteacidites dehaani* and *Verutriletes virueloides* characterize palynological assemblages between 280 and 172.05 m. Moderate relative abundances of *Psilatricolpites hammenii* were registered between 280 and 230.50, and a spike of *Diporoconia cf. Diporoconia iskaszentgyoerygi* was recorded at 243 m. Occurrences of *Bacumorphomonocolpites tausae*,
Buttinia andreevi, Echitriletes “protomulleri”, Gabonisporis vigorouxi, Periretisyncolpites giganteus and Retitricolpites josephinae are also observed (Appendix B).

The interval between 160 and 100.30 m is marked by an increase in relative abundances of the Psilatriletes group and a decrease of Echimonocolpites protofranciscoi. Also decrease abundances of Spinizonocolpites group and Diporoconia cf. Diporoconia iskaszentgyoergy are noted. First occurrences of Arecipites regio, Clavasporites mutisii, Cingulatisporis verrucatus, Echimonocolpites “pachyexinatus”, Gemmamonocolpites dispersus, Horniella lunarensis, Periretisyncolpites magnosagenatus, Proxapertites verrucatus and Retidiporites botulus are recorded in this interval.

As stated above, only one layer (at 68.8 m) yielded a rich assemblage within the poor-recovery interval (88 and 32 m). Predominant species recovered include specimens of the Psilatriletes group along with occurrences of Arecipites sp., Araucariacites australis, Buttinia andreevi, E. protofranciscoi, Retitricolpites josephinae, Spinizonocolpites baculatus and Ulmoideipites krempii (Appendix B).

The recovery of dinoflagellate cysts was poor to fair and their distribution scattered. The assemblage includes occurrences of Andalusiella sp., Andalusiella gabonensis, Cerodinium diebelii, Dinogymnium acuminatum, Dinogymnium sp., Exochosphaeridium sp., Fibrocysta sp., Glaphyrocysta sp., Senegalinum microspinosum and Spiniferites sp.

5.3. Palynology of Core PPM-2

Good recovery of palynomorphs was obtained in the intervals 273 to 97.4 m and 41 to 30 m, while the interval between 87 to 49.80 m yielded only a poor assemblage (see Appendix C for details and Figure 11 for summary). High relative abundances of Psilatriletes group and Echimonocolpites protofranciscoi again dominate the palynological assemblages. Two spikes of E. protofranciscoi relative abundances occurred at 206.30 m (54%) and 109.90 m (64 %) (Figure 11). Below the lower spike, between 273 and 212.40 m, high relative abundances of Scabratriletes granularis and Spinizonocolpites baculatus, and moderate relative abundances of Araucariacites
australis, Echitriporites suescae, Proxapertites humbertoides, Proxapertites operculatus and Proxapertites verrucatus characterize the interval. Occurrences of Bacumorphomonocolpites taurusae, Buttinia andreevi, Diporoconia cf. Diporoconia iskaszentgyoerygi and Syndemicolpites typicus are also registered (Appendix C).

Within the interval between 206.30 m and 109.90 m (the two spikes of E. protofranciscoi), the assemblage is dominated by high relative abundances of the Psilatriletes group and Scabratrilete granularis and moderate relative abundances of Psilatricolpites hammenii, Scabratrilete granularis and Spinizonocolpites baculatus.

Poor recovery of palynomorphs was obtained between 87 and 49.80 m. Between 41 and 30 m, the Psilatriletes group and E. protofranciscoi dominate the assemblage. Moderate relative abundances of the Proxapertites group (P. humbertoides, P. operculatus, P. psilatus, P. sulcatus, P. verrucatus) including a spike in Proxapertites operculatus at 41 m characterize this interval. Moderate relative abundances of Echitriporites trianguliformis and occurrences of Areopicites regio, Colombipollis tropicalis, Monocolpites grandispiniger, Proteacidites dehaani and Stephanocolpites costatus are also present. In addition to the Psilatriletes group, ferns spores are also represented by moderate to low abundances of Foveotriletes margaritae, Gabonisporis vigorouxi, Murrigerisporis ardelensis and Scabratrilete granularis (Appendix C).

The distribution of dinoflagellate cysts was sparse and their preservation was decent. A
spike of dinocysts was identified at 146.30 m with relative abundances making up to 20% of the assemblage. The association consists of *Achomosphaera ramulifera*, *Achomosphaera* sp., *Cerodinium* sp., *Spiniferites* sp., *Hystrichodinium* sp. and *Phelodinium* sp. Between 273 to 158 m, fair to poor recovery of dinoflagellate cysts was registered. The assemblage is characterized by occurrences of *Achomosphaera* sp., *Andalusiella rhomboides*, *Andalusiella* sp., *Areoligera senonensis*, *Cerodinium speciosum*, *Cordosphaeridium* sp., *Dinogymnium* sp., *Florentinia mantelli*, *Hystrichokolpoma* sp., *Senegalinium* sp. and *Spiniferites* sp.

Occurrences of *Andalusiella gabonensis*, *Andalusiella* sp., *Cerodinium speciosum*, *Cerodinium* sp., *Exochosphaeridium* sp., *Fibrocysta* sp., *Palaeocystodinium golzowense*, *Palaeocystodinium* sp., and *Senegalinium* sp. characterized the assemblage between 97.4 and 30 m. Worth noted is the first occurrence of *Manumiella seelandica*, a late Maastrichtian global marker, at 74.70 m (Appendix C).

### 5.4. Palynology of Core PPM-1

In general, good recovery of palynomorphs was obtained at this core, except at 160 and 72.25 m, where the recovery was poor. As in the previous cores, high relative abundances of the *Psilatriletes* group and *Echimonocolpites protofranciscoi* dominate palynological assemblages. This said, the percentages of these two morphotypes are lower at the top of the core, and angiosperm pollen and dinoflagellate cysts constitute a much important component (Figure 11). The relative abundance of the *Spinizonocolpites* group also drops to a maximum of 5%.

Between 152 and 85 m, the *Psilatriletes* group and *E. protofranciscoi* are associated with moderate to low abundances of *Araucariacites australis*, *Echitriporites suescae*, *Psilatricolpites hammeni*, *Retitricolpites josephinae* and *Scabbratriletes granularis*. Low relative abundances of *Arecipites regio*, *Foveotriletes margaritae*, *Gemmamonocolpites dispersus*, *Longapertites proxapertitoides* var. *proxapertitoides*, *Syndemicoliptes typicus* and *Tetradites umirensis* are also tabulated (see Appendix D for details and Figure 12 for summary).

Between 152 and 124 m, dinoflagellate cysts represent 10% of the association (Figure 10).
Dinocysts assemblages consist of *Spiniferites* sp. and *Achomosphaera* sp. accompanied by low numbers of *Andalusiella gabonensis*, *Andalusiella – Palaeocystodinium* Complex, *Cerodinum* sp. and *Florentinia mantellii*.

As mentioned above, the percentages of *Psilatriletes* group and *E. protofranciscoi* decreased between 60 and 23.54 m, and are being replaced by angiosperm pollen and dinoflagellate cyst. Moderate frequencies of *Proxapertites* group, mostly *P. humbertoides* and *Proxapertites operculatus* are also registered. Low numbers of *Proxapertites verrucatus*, *Proxapertites psilatus*, *Proxapertites sulcatus*, *Colombipollis tropicales*, *Echitriporites suescae*, *Retitricolpites josephinae*, *Psilatricolpites hammenii*, *Stephanocolpites costatus* and *Ulmoideipites krempii* are recorded too. In addition to the *Psilatriletes* group, fern spores are represented by moderate relative abundances of *Scabratriletes granularis* and *Foveotriletes margaritae* (Appendix D).

Dinoflagellate cysts comprised 20 – 35% of the association in this interval. The sample taken at 60 m yielded moderate relative abundances of *Achomosphaera* sp. and *Andalusiella* sp. and some *Spiniferites* sp., *Cordosphaeridium* sp., *Hystrichosphaeridium* sp., *Areoligera senonensis*, *Palaeocystodinium* sp., *Andalusiella polymorpha*, *Andalusiella gabonensis* and *Cerodinum* sp. The assemblage in the sample taken at 51.93 m consists mainly of Gonyaulacacean cysts. *Achomosphaera* sp. and *Spiniferites* sp. dominate the association and occurrences of *Cordosphaeridium* sp., *Achomosphaera ramulifera*, *Fibrocysta* sp., *Hystrichokolpoma bulbosum*,

![Figure 12. Relative abundances of predominant palynomorph groups in Core PPM-1.](image-url)
*Hystrichosphaeridium* sp., *Lingulodinium* sp. and *Oligosphaeridium* sp. were also registered (Appendix D). This interval is not only richer in marine palynomorph, it is also much more diverse in dinoflagellate species recovered.

The slide taken at 42 m mostly yielded peridinoid cysts such as specimens from the genera *Andalusiella* and *Palaeocystodinium*. A moderate relative abundance of *Andalusiella* sp. and *Andalusiella polymorpha* along with occurrences of *Andalusiella gabonensis*, *Andalusiella mauthei*, *Andalusiella rhomoboides*, *Palaeocystodinium australinum* and *Cerodinium* sp. were also noted. Specimens of *Fibrocysta* sp. were also recognized at this level. Again worth noted are the occurrences of *Manumiella seelandica* and *Alysogiminum euclaense* that are also found at this level (Appendix D).
6. DISCUSSION

6.1. Biostratigraphy

Three informal biostratigraphic zones (A to C) are proposed based on the analysis of qualitative and quantitative biostratigraphic events observed in cores PPI-3, PPM-5, PPM-2 and PPM-1 (Figure 13). The zones were defined mostly by using changes in palynological assemblages and abundances, along with a few last or first occurrence data (Appendixes E and F). As is sometimes the case with biostratigraphic events, it is important to keep in mind that events might be influenced by environmental and facies changes and these events are thus sometimes regional in scope and hence cannot be strictly considered as global biostratigraphic events. Since the Umir Formation recorded a dramatic change in depositional environments from predominantly marine conditions, in the Campanian, to transitional conditions in the Maastrichtian, the occurrence of some taxa might have been controlled by changes in facies.

When possible, the zones have been correlated with previous palynological zonations (Van der Hammen, 1954; Van der Hammen, 1957; Germeraard et al., 1968; Sole de Porta, 1971; Sole de Porta, 1972; Muller et al., 1987, Sarmiento, 1992) and age determinations have been based on biostratigraphic events previously reported for Late Cretaceous sections in Northern South America and Africa (Germeraard et al., 1968; Muller et al., 1987; Sarmiento, 1992; Yepes, 2001; Pocknall, 2001; Jaramillo and Rueda, 2004; De la Parra, 2009; Slimani et al., 2010), or in global range charts (e.g., Williams and Bujak, 1985; Williams et al., 1993).

Quantitative distribution and range charts for the composite section are presented in Appendices E and F, respectively. The zonation developed through this study and the most important biostratigraphic events are summarized in figure 13. The three zones are described below, from base to top.

6.1.1 Palynological Zone A

Definition: The top of the zone is defined by the last occurrence of Ariadnasporites sp. and the first occurrence of Dinogymnium sp. Its base corresponds to the base of the section.
Figure 13. Zonation and key biostratigraphic events of the Umir formation, San Luis area, Middle Magdalena Valley Basin (MMVB).
Characteristics: This zone is dominated by an assemblage of fern spores including high relative abundances of the *Psilatriletes* group, along with moderate abundances of *Scabratriletes granularis*, *Echitriletes “protomulleri”* and *Gabonisporis vigorouxii*, and low abundances of *Verrutriletes virueloides* and *Verrutriletes “magnovirueloides”*. A spike in *Laevigatosporites granulatus* was recognized in the lower part of the zone.

High to moderate abundances of *Echimonocolpites protofranciscoi* and moderate relative abundances of the *Spinizonocolpites* group characterize the middle of this section. Occurrences of *Araucariacites australis*, *Buttinia andreevi*, *Echitriporites trianguliformis*, *Retitricolpites josephinae* and *Ulmoideipites krempii* are common and continuous. Occurrence of dinoflagellate cysts is sparse but *Spiniferites* sp., *Exochosphaeridium* sp. and *Senegalinium* sp. were recorded in the lower and middle section.

Stratigraphic position: This zone includes the lower section of the Middle Umir formation recorded in Core PPI-3 and the first samples of Core PPM-5.

### 6.1.2 Palynological Zone B

Definition: The base of this zone is marked by the first occurrence of *Dinogymnium* sp. and the top of this zone is defined by the first occurrence of *Achomosphaera* sp.

Characteristics: The last occurrences of *Tricolpites “marginobaculatus”* and *Echistephanocolpites “minutiechinatus”* and the first occurrence of *Psilamonocolpites operculatus* are recorded close to the base of the zone. Also, the last appearance of *Retistephanocolpites “jandufouriodes”* and the full range of *Echitriletes “intercolensis”* and *Psiladiporites “operculatus”* are restricted to this interval.

In addition to these events, the palynological assemblage is dominated by the *Psilatriletes* group and *Echimonocolpites protofranciscoi*. Moderate relative abundances of *Scabratriletes granularis*, *Psilatricolpites hammeni* and *Proteacidites dehaani* occurred in the lower part of the Zone B. A spike in *Diporoconia* cf. *Diporoconia iskaszentgyoeryi* was recorded above the base of the zone.
As in Zone A, occurrence of dinocysts is sparse, but first occurrences of *Fibrocysta* sp., *Cerodinium speciosum*, *Andalusiella gabonensis* and *Andalusiella* sp. are identified within this zone.

Stratigraphic position: This zone covered the Upper section of the Middle Umir formation and its top coincides with the boundary between Middle and Upper Umir established by Ecocarbón (1996). This zone was recognized in Core PPM-5 and the base of Core PPM-2.

### 6.1.3 Palynological Zone C

**Definition**: The base of this zone is defined by the first occurrence of *Achomosphaera* sp., and the top is not defined as it coincides with the top of the studied section.

**Characteristics**: This zone is characterized at its top by an increase in the occurrence of dinoflagellate cysts. The first occurrences of *Areoligera senonensis*, *Florentia mantellii*, *Hystrichodinium* sp. and *Andaluseilla rhomboides* are recorded at the base of this zone. In the upper section, the first occurrences of *Andalusiella gabonensis*, *Andalusiella mauthei*, *Alysogymnium euclaense*, *Manumiella seelandica*, *Hystrichokolpoma bulbosum* and *Palaeocystodinium golzowense* are also registered. In addition, three spikes in gonyaulacacean and peridinoids cysts are recognized. From base to top, these events were identified as follows: in the lower section, a spike in *Spiniferites* sp., *Achomosphaera* sp., and undifferentiated gonyaulacacean dinocysts is identified; in the upper section, in the top of the Upper Umir sandstones, a spike in *Spiniferites* sp. and *Achomosphaera* sp. along with low abundances in *Andalusiella* sp. and *Hystrichokolpoma bulbosum*, *Achomosphaera ramulifera*, *Hystrichosphaeridium* sp., *Cordosphaeridium* sp. are recognized; and finally, above the Upper Umir sandstones, a spike in peridinoid cysts including several species of the genera *Andalusiella* and *Palaeocystodinium* was recorded. The occurrence of *Manumiella seelandica* at the top of the section is important as a late Maastrichtian stratigraphic marker. Occurrences of *Fibrocysta* sp. along the Upper Umir Sandstones are also frequent.

In addition to dinoflagellate cyst events, an increase in the numbers of *Proxapertites* was also identified. *Proxapertites operculatus* shows a spike in relative abundance in the middle section.
of the Upper sandstones, and moderate frequencies of Proxapertites humbertoides were recognized above the sandstones. Moderate frequencies of Arecipites regio and Echitriporites trianguliformis were also identified in this interval. At the base of the section high frequencies of Scabratriletes granularis, Psilatricolpites hammenii and Spinizonocolpites baculatus are significant. Also, the stratigraphic range of Syncolporites lisamae and Psilabrevitricopites simpliformis is restricted to this zone.

Stratigraphic position: This zone covered the Upper Umir formation and its Upper section includes the Upper Umir sandstones. This zone was recognized in Cores PPM-1 and PPM-2.

6.2 Age Assessment and Comparison with Previous Studies

6.2.1 Pollen and Spores Assemblages

Several species considered as important key taxa in previous palynological biostratigraphic studies of the Late Cretaceous of Northern South America were recorded in Middle – Upper Umir Formation in the San Luis area (MMVB). The key taxa include: Echimonocolpites protofranciscoi, Proteacidites dehaani, Buttinia Andreevi, Foveotriletes margaritae, Spinizonocolpites baculatus, Stephanocolpites costatus, Colombipollis tropicalis, Proxapertites operculatus, Proxapertites humbertoides, Duplotriporites ariani and Araucariacites australis. Other taxa previously restricted to the Paleocene, including Proxapertites psilatus, Syncolporites lisamae, Longapertites vaneendenburgi, Psilabrevitricolpites annulatus and Zonotricolpites variabilis (Samiento, 1992) were also registered in the Umir Formation. Proteacidites dehaani was recovered throughout the entire studied section showing low numbers but a continuous record. Germeraard et al. (1968) used this taxa and its co-occurrence with high abundances in Foveotriletes margaritae to characterize the Maastrichtian in tropical areas. In the Umir formation in MMVB, occurrences of F. margaritae associated with P. dehaani are also believed to mark the same stratigraphic level. According to Germeraard et al. (1968), the last occurrence of P. dehaani marks the K/T boundary. Hence the co-occurrence of these two species is used to restrict the age of the interval analyzed to the Late Maastrichtian.
Muller et al. (1987) also used the range of *P. dehaani* to define Zone 13 *Proteacidites dehaani*, a Late Maastrichtian zone defined for Colombia and Northwestern Venezuela. According to Muller’s zonation, this zone is also marked by the first appearance of *Foveotriletes margaritae, Stephanocolpites costatus, Spinizonocolpites* spp. and *Ulmoideipites* spp. The last occurrence of *Buttinia andreevi, Proteacidites dehaani* and *Aquillapollenites* sp. at the top of the zone indicate the Cretaceous − Tertiary boundary (Muller et al. 1987). In the Umir formation (MMVB), all these taxa (except for *Aquillapollenites* sp. that exhibits a sparse recovery) are present throughout the studied interval. When comparing the results from this study to Muller’s events, a Late Maastrichtian age is also confirmed for the Umir in MMVB.

Moderate frequencies of *Spinizonocolpites baculatus* were recorded throughout the Umir Formation in the San Luis area. The first occurrence of *Spinizonocolpites baculatus* is mostly known as a marker for the base of the Paleocene, restricted to the early Cenozoic (Muller et al., 1987). The results of this study are in disagreement with this general view, but they concur with the report of minor frequencies of *Spinizonocolpites baculatus* as early as the Lower Maastrichtian of Western Venezuela (Pocknall et al. 2001).

High to moderate frequencies of *Echimonocolpites protofranciscoi* and a continuous record of *Buttinia andreevi* were identified throughout the Umir Formation in the San Luis area, with spikes in abundance of *E. protofranciscoi* in Zones B and C (Upper Umir). In the Eastern Cordillera, Sarmiento (1992) recognized both *Echimonocolpites protofranciscoi* and *Buttinia andreevi* as abundant in the Maastrichtian (Zone I *Buttinia andreevi*) with occasional occurrences in Zone II *Foveotriletes margaritae* dated as Paleocene (Sarmiento, 1992). However, as it will be explained below, Paleocene zones IIA and IIB of Sarmiento (1992) actually correspond to the Maastrichtian. In the Cesar-Rancheria basin (Northern Colombia) *Echimonocolpites protofranciscoi, Buttinia andreevi* and *Protecidites dehaani* became extinct at the K/T boundary, restricting these species to the Cretaceous (De la Parra, 2009).

The palynological assemblages in the Umir Formation are very similar to those recorded by Sarmiento (1992) in the Guaduas Formation (Eastern Cordillera, Colombia). The Maastrichtian
Zone I *Buttinia andreevi* (Sarmiento, 1992) was defined by the high abundance of *Psilatriletes guaduensis* and *Psilamonocolpites medius* and occurrences of *Buttinia andreevi, Echimonocolpites protofranciscoi, Proxapertites humbertoides, Bacumorphomonocolpites tausae, Annutriporites iversenii, Retidiporites magdalenensis, Stephanocolpites guaduensis*, and *Retitricolpites josephinae* (Sarmiento, 1992). Taxa restricted to this zone include *Retimonocolpites claris, Crusafontites grandiosus*, and *Clavatriletes mutisii* (Sarmiento, 1992). In the Umir Formation in MMVB, the palynological assemblages are dominated by the *Psilatriletes* group, *Crusafontites grandiosus, Clavatriletes mutisii, Annutriporites iversenii, Proxapertites humbertoides* and *Bacumorphomonocolpites tausae*. As is the case for *B. andreevi, E. protofranciscoi* and *P. dehaani*, the stratigraphic range of these taxa in the San Luis section (MMVB) is wide and corresponds to the entire interval analyzed. The only difference in the assemblages is the presence of *P. dehaani* in the Umir Formation that was not recognized as a taxon present in Zone I *Buttinia andreevi* of Sarmiento (1992).

Sarmiento (1992) proposed the Zone II *Foveotriletes margaritae* (including subzones IIA and IIb) for the Upper Guaduas Formation (Eastern Cordillera) and assigned a relative age of Danian to this interval. The Subzone IIA was characterized by the first occurrence of several species including *Foveotriletes margaritae, Longapertites vaneendenburgi, Proxapertites operculatus, Proxapertites verrucatus, Proxapertites psilatus, Gemmamonocolpites dispersus, Syndemicolpites typicus, Psilabrevitricolporites annulatus* and *Zonotricolpites variabilis*. The top was established using the last occurrences of *Duplotriporites ariani, Bacumorphomonocolpites tausae, Araucariacites australis* and *Zlivisporis blanensis*. In the Umir formation in MMVB, *F. margaritae, L. vaneendenburgi, P. operculatus, P. verrucatus, P. psilatus, G. dispersus, S. typicus* and *P. annulatus* were recorded co-occurring with *B. andreevi, E. protofranciscoi* and *P. dehaani* that are restricted to the Maastrichtian, and with *Crusafontites grandiosus* and *Clavatriletes mutisii* that according to Sarmiento (1992) are restricted to his Maastrichtian Zone I. Then, the first occurrences used by Sarmiento (1992) for defining the Paleocene Subzone IIA should be reconsidered as being of Late Maastrichtian age.
The definition and age of subzone IIB *Syncolporites lisamae* (Sarmiento, 1992) is controversial too. Sarmiento (1992) used the first occurrence of *Syncolporites lisamae* for determining the base of the zone and reported occurrences of *Foveotriletes margaritae*, *Echitriporites trianguliformis* and *Gemmamonocolpites dispersus*. In the Umir Formation in MMVB, the first occurrence and the stratigraphic range of *Syncolporites lisamae* was recorded only in Zone C of the Upper Umir Formation. At this interval, the assemblage includes occurrences of *F. margaritae*, *E. trianguliformis* and *G. dispersus* (as in Sarmiento’s zone) but also *B. andreevi*, *E. protofranciscoi* and *P. dehaani*, which are all key Maastrichtian markers (Germeraard et al., 1968; Muller et al., 1987; De la Parra, 2009) and *Crusafontites grandiosus* and *Clavatriletes mutisii* that according to Sarmiento (1992) are restricted to the Maastrichtian too. Hence, Sarmiento’s subzone IIB *Syncolporites lisamae* should also be re-evaluated and assigned a Late Maastrichtian age.

### 6.2.2 Dinoflagellate Cysts Assemblages

Several dinoflagellate cysts recorded in the studied section have a first global occurrence in the Latest Campanian or close to the Campanian-Maastrichtian boundary. Genus *Andalusiella*, *Palaeocystodinium* and *Senegalinium* have their first appearances in the Uppermost Campanian (Williams et al., 1993), the Upper Campanian (Willliams and Bujack, 1985) and the Latest Campanian (Williams et al., 1993), respectively. In the Umir Formation, the first occurrence of *Senegalinium* sp. was recorded in core PPI-3 at 244 m, corresponding to the base of the studied section. *Palaeocystodinium* sp. was registered by the first time in core PPI-3 at 184 m (Zone A, lower section of the Middle Umir Formation), and the lowest occurrence of the genus *Andalusiella* (first appearance of A. polymorpha) was recorded in core PPI-3 at 48 m. On this basis, an age no older than Latest Campanian is assigned for the Middle member of the Formation. However, in the Rio Loro section in Western Venezuela, Pocknall et al. (2001) using graphic correlation established that the first occurrence of *Andalusiella polymorpha* in Northern South America is restricted to the Late Maastrichtian. Other taxa of global significance for the Latest Campanian recognized in the Umir Formation are the FADs of *Cerodinium diebelii* (Lentin and Williams, 1980; Williams and
Bujak, 1985) found in core PPM-5 at 137 m and of *Areoligera senonensis* (Williams et al., 1993) found in core PPM-2 at 224.1 m. These species are recorded through the Maastrichtian up to the K/T boundary.

The first occurrence of *Manumiella seelandica* in core PPM-2 at 74.7 m and low numbers of the same taxa registered in core PPM-1 at 26 m restrict the age of the upper section of the Umir Formation to the Latest Maastrichtian. The first occurrence of *Manumiella seelandica* is a global event that has been used for identifying the Latest Maastrichtian in several areas (Slimani et al, 2010). In sections located in Northern Colombia and Western Venezuela, Yepes (2001) found *M. seelandica* associated to *Disphaerogena carpsophaeropsis* and *Glaphyrocysta perforata* just below the Maastrichtian – Danian boundary. Spike abundances of this species below the K/T boundary has been also reported in Georgia (Firth, 1987), in the Mediterranean regions (Habib and Saeedi, 2007), in Ghana (Oboh-Ikuenobe et al., 1998) and in Morocco (Slimani et al., 2010).

The first occurrences of *Cerodinium speciosum* and *Hystrichokolpoma bulbosum*, recorded in core PPM-5 at 172.05 m (middle section Zone B) m and in core PPM-1 32.7 (Top Zone C) also support a Late Maastrichtian age for the Middle and Upper Umir Formations. These two events were recognized by Slimani et al. (2010) in the Late Maastrichtian of Morocco and have been recognized in the Northern Hemispheres in sections calibrated using bellemnite zones and planktonic foraminifer *Globotruncanana gansseri* zone (Aurisano, 1989; Slimani et al., 2010).

To summarize, dinoflagellate cyst assemblages in the Umir Formation restrict the Middle member to the Late Maastrichtian and the Upper Member to the Latest Maastrichtian. These results are in agreement with the age proposed by Tchegliakova (1995) using foraminiferal assemblages of the planktonic zones *Gansserina gansseri* and *Abathomphalus mayaroensis* for the northwestern Middle Magdalena Valley Basin.

Table 2 presents the ages assigned to zones A, B and C and their probable correlation with previous studies.
6.3 Paleoenvironmental Interpretation

Pollen, spores and dinoflagellate cysts recovered from the Middle – Upper Umir Formation were grouped in five categories in order to conduct a palaeoenvironmental interpretation. The five categories defined using the known taxonomic affinity of some taxa and morphological features, include spores, palms, *Spinizonocolpites*, marine palynomorphs and “other angiosperms” groups. The relative abundance of each group in each sample was expressed in percentages, and changes in these values were used to determine the most probable depositional environment for the formation (figure 14). The species and genera included in each group are shown in table 3.

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Table 2. Comparison between the informal zones proposed for the Late Maastrichtian in the Urmi Formation and previous Late Cretaceous zonation developed for Northern South America (Modified from Poknall et al., 2001).
The spore group is the most abundant component of the palynological assemblages in Umir Formation. Its relative abundance ranges from 60%-90% in the Middle Umir formation to 30%-70% in the Upper member, where three spikes in the lower - middle section reach the 90% (Figure 14). This group includes fern spores, with Psilatriletes group as the most abundant, accompanied by Foveotriletes margaritae, Scabratriletes "granularis", Gabonisporis vigorouxii and species from genera Echitriletes and Verrutiretes, among others (Table 3).

The abundance and dominance of Psilatriletes group in the Maastrichtian in Colombia has been also recorded in the Guaduas Formation (Eastern Cordillera), where their occurrence was interpreted as indicative of coastal swamps (Sarmiento, 1992; 1994). Fern spores have been also

Table 3. Significant palynomorph groups used in the paleoenvironmental interpretation. Species represented by a single specimen (singletons) were removed from the analysis.
considered as an abundant component in coastal pollen assemblages where erosion and transport are dominant, because they are transported by rivers from coastal swamps and inland forests (Rull, 2000; 2002).

Palms group is the second most abundant component of the palynological assemblages in the Umir Formation. Its abundance is variable along the studied section: ranging from 10% to 40% in the lower section of the Middle Umir Formation; from 10% to 20% in the upper section of the Middle member; and reaching 40% - 60% in some spikes located in the Upper member of the formation (Figure 14). The dominant species in this group is *Echimonocolpites protofranciscoi*,

Figure 14. Paleoenvironmental interpretation of the Umir Formation (Central Eastern MMVB) based on the relative abundance (expressed in percentages) of significant palynomorph groups.

Palms group is the second most abundant component of the palynological assemblages in the Umir Formation. Its abundance is variable along the studied section: ranging from 10% to 40% in the lower section of the Middle Umir Formation; from 10% to 20% in the upper section of the Middle member; and reaching 40% - 60% in some spikes located in the Upper member of the formation (Figure 14). The dominant species in this group is *Echimonocolpites protofranciscoi*,

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but psilate monocolpate grains from genera *Areccipites, Monocolpites, Monocolpopollenites, Psilamonocolpites, Cycadopites* are also included; along with monocolpate grains from genera such as *Echimonocolpites, Gemmamonocolpites, Longapertites, Retimonocolpites* and *Rugomonocolpites* (Table 3). *Diporoconia cf. Diporoconia iszkaszentgyoergyi* was also included in this group as it is considered as a palm pollen (Frederiksen et al. 1985).

Palm pollen was recognized as abundant in previous studies in the Umir Formation (Van der Hammen, 1954; 1957); and in the Guaduas Formation (Eastern Cordillera), where its occurrence was associated mainly with tidal swamps and alluvial plains (Sarmiento, 1992; 1994). According to Rull (2000; 2002), palms are an important component in coastal environments due to their ability to colonize bar sands and prograding sand deposits.

*Spinizonocolpites* group represents the homonymous genus and includes three different species, the most common being *Spinizonocolpites baculatus* (Table 3). Although its relative abundance was low, ranging from 2% to 10%, the group was frequent and its record was continuous through the studied section (Figure 14). *Spinizonocolpites* genus has been taxonomically related to current mangrove palm *Nypa* (Germeraard et al., 1968; Rull, 1998), the only palm present in mangrove ecosystems that nowadays is restricted to estuarine areas and coastlines of Southern Asia (Germeraard et al., 1968; Rull, 1998). Considered as representative of mangrove pollen, *Spinizonocolpites* genus evidences estuarine conditions with a high sea level and wetter conditions (Rull, 2000; 2002).

Marine palynomorphs group consists of dinoflagellate cysts, acritarchs and foram linings (Table 3). Its distribution along the Umir Formation was very similar to the record of *Spinizonocolpites* genus, and was frequent and continuous through the section. The relative abundance of this group was low in the Middle Umir Formation ranging between 2%-6% with a spike equivalent to 10% in the lower section (Figure 14). The Upper Umir formation recorded an increase in the relative abundance of dinoflagellate cysts, changing from 10% in the lower section, and reaching 30% to 40% of the assemblages in the top of the section, where the Upper Umir sandstones are located (Figure 14).
Two different categories of dinoflagellate cysts were distinguished in the upper interval of the Upper Umir formation: the peridinoid group consisting of *Andalusiella, Palaeocystodinium, Senegalinium, Cerodinium, Lejeunecysta* and *Manumiella* genera; and the *Spiniferites - Achomosphaera* group, that includes morphotypes from these two genera. Although these categories were defined using morphological criteria, they probably reflect distinctive ecological conditions (Yepes, 2001).

Peridinoid cysts are considered to be produced essentially by heterotrophic dinoflagellates (Harland, 1988; Schioler et al., 1997; Yepes, 2001). These cysts occur in large numbers in Cenozoic assemblages where diatoms are also abundant (Powell et al., 1990). Hence, they have been used as indicators of high paleoproductivity related either to upwelling currents (Powell, 1990; Brinkuis, 1994; Eshet et al., 1994) or to river mouths (Brinkhuis, 1984) and river runoff (Yepes, 2001).

In the Maastrichtian of Northern Colombia and Western Venezuela, Yepes (2001) recognized a marked dominance of peridinoid cysts in the Colón Formation, where this group constituted approximately 80-100% of the dinocyst assemblages in some intervals. Because of the lack of sedimentological evidence for upwelling currents, Yepes (2001) suggested a high continental nutrient supply and closeness to a deltaic system to explain their abundance.

In the Umir Formation, peridinoid cysts constitute 30%-40% of the palynological assemblages (Figure 14), but they are the dominant component of the dinocyst associations in the uppermost section. The difference with respect to the values recorded by Yepes (2001) may be explained by the geographic position of the MMVB in constrast to Yepes’ sections, and the Maastrichtian paleogeography proposed by Villamil (1999) for Colombia and Western Venezuela. According to Villamil (1999), a marine seaway oriented in a NE-SW direction covered the Middle Magdalena Valley Basin and the western foothills of the Eastern Cordillera, in the South, and the Catatumbo and the Maracaibo Basins in the North during the Maastrichtian. The most distal facies were deposited in the north and west, where the sections studied by Yepes (2001) (Río Molino and Río Loro sections) are located. Because MMVB is located in the south, closer to continental areas, a lower marine influence is expected to be highlighted in the palynological record of MMVB.
As in Northern Colombia and Western Venezuela, the abundance of peridinoid cysts in the Umir Formation seems to be related with intense river influx and high nutrient supply derived from the continent. In MMVB, there is no evidence of upwelling systems either, but there is evidence of intense tectonic activity provided by the upward-coarsening lithology of the Umir Formation, and recorded in the intra-formational conglomerates and the cross-stratified sandstones located in the Upper Umir member. The Maastrichtian tectonism in the basin is associated with the accretion of the Western Cordillera in the Early Maastrichtian that caused the initial uplifting of the Central Cordillera (Gomez et al. 2005). This event also triggered an abrupt change in the depositional environments where conditions predominantly marine became transitional for the Latest Cretaceous – Paleocene (Cooper et al., 1995; Villamil, 1999; Gómez et al., 2003; Gómez et al., 2005). The effects of this event also include the withdrawal of the sea in a northward direction (Villamil, 1999) and the decrease in the accommodation space (Cooper et al., 1995; Ortiz and Flórez, 1997; Villamil, 1999; Gómez et al., 2003; Gómez et al., 2005).

The second abundant group of dinoflagellate cysts recorded in the Umir Formation is the Spiniferites - Achomosphaera complex that includes species of Spiniferites and Achomosphaera genera. Although the abundance of this group increases in the Upper member of the Umir formation, using these genera to infer environmental conditions is complex since both of them could occur either in offshore or transitional environments. Besides, the taxonomic identification of the taxa belonging to this group was usually possible only to the genus level and that prevent using them for environmental interpretations. In this study, it is considered that their occurrence evidence marine influence and brackish conditions during the deposition of the Umir Formation.

The last category interpreted is the “other angiosperms” group that includes tricolpate, trirporate, tricolporate, stephanocolpate, stephanocolporate and pantoporate grains produced in coastal forests (Sarmiento, 1992), open forests and inland (Rull, 1997; 2002) (Table 3). The relative abundance of this group is continuous and constant in the Middle Umir Formation, ranging from 2% to 10% (Figure 14). In the Upper member, the abundance of this component increases up to 20% of the assemblages. The increment in the abundance of this group may be associated with the
intense fluvial transport of sediments evidenced by the Upper Umir sandstones and the abundance of peridinacean cysts. Since the morphotypes included in this group are related to open forests and the inland, their occurrence and increase could be linked to an increase in fluvial transportation. According to Rull (1997) pollen derived from inland vegetation and mountain communities is abundant in coastal sediments when the sea level is low and erosion and transport are present.

Finally, considering the relative abundance of each category, their distribution along the Umir Formation and their environmental implications; and also, considering sedimentological interpretations by Ortiz and Flórez (1997), it is proposed that the formations were deposited within a lagoonal environment, with coastal swamps and estuarine conditions for the Middle Umir Formation. The environment for the Upper Umir member probably corresponds to a semi-restricted bay with strong river influx in the zone close to the coastline (Figure 14).

6.4 Palynological Record of the Umir Formation and the Global Setting

During the Cretaceous period occurred one major evolutionary event: gymnosperms (including conifers and cycadeoids) that were the dominant component of the vegetation during the earliest part of the Mesozoic, were rapidly replaced by angiosperms (Figure 15). During this event named the “Cretaceous Terrestrial Revolution” (Lloyd et al., 2008), all gymnosperm groups experienced decline, but podocarpoid and araucarioid conifers were more dramatically affected (Peralta and Falcon, 2012) (Figure 15). The decline of these two conifer groups correlates with a notable increase in the occurrence of angiosperms that changed from 32% in the Campanian to 78% in the Maastrichtian (Peralta and Falcon, 2012) (Figure 16a).

In the Umir Formation, angiosperms are by far the dominant component of the pollen assemblages and gymnosperms are only a minor constituent. Angiosperms, represented by 106 species, constitute 80%-90% of the pollen assemblages in the Middle Member (assigned to the Late Maastrichtian), and 90%-100% of the associations in the Upper Umir Formation (assigned to the Latest Maastrichtian) (Figure 16b). Gymnosperms, represented only by three species, are dominated by *Araucariacites australis* (a pollen grain derived from a gymnosperm belonging to
the Araucarioid group), and they showed a continuous but decreasing record along the formation. In the Middle Umir, gymnosperms constitute up to 18% of the pollen grains, decreasing upward. In the Upper Umir Formation, they represent 10% of the associations at the base, and only 1%-2% at the top (Figure 16b).

Figure 16 shows a comparison between the changes in percentage of abundance for gymnosperms and angiosperms estimated by Peralta and Falcon (2012) and the changes in percentage of abundance for gymnosperms and angiosperms in the Late Maastrichtian Umir Formation, Central-Eastern Middle Magdalena Valley Basin (Figures 16a and 16b, respectively). Although Peralta and Falcon (2012) calculated the changes in percentage using global data from a fossil wood database, and in this study the changes were estimated using pollen assemblages from one site in the Neotropics, there is a strong correspondence in the proportion of gymnosperms and angiosperms during the Maastrichtian: in both graphs, gymnosperm abundance correspond to 10%-15% approximately, and angiosperm abundance are above the 80% (Figures 16a and 16b).

The dominance of *Araucariacites australis* (pollen grain produced by an araucarioid conifer) in the gymnosperm group of the Umir Formation and its decline could be explained if we consider the general distribution of araucarioids during the Cretaceous and their co-occurrence with the initial angiosperms. Araucarioids and podocarpoids were the most abundant gymnosperms constituting 40.1% of all the associations (Peralta and Falcon, 2012). They were globally distributed from 80°N to 80°S, but they were specially concentrated in tropical and paratropical belts while they had low records in temperate zones (Peralta and Falcon, 2012)(Figure 15). In their initial stage, angiosperms occurred mainly in humid tropical and subtropical areas that used to be dominated by araucarioids (Peralta and Falcon, 2012). Since the appearance and rise of the angiosperms is considered the main cause of the decline of the gymnosperms, it makes sense that araucarioids were the group of gymnosperms most affected by the radiation of the flowering plants as is recorded in the Late Maastrichtian Umir Formation, deposited in the tropical areas of Northern Western South America.
Figure 15 Paleogeographic distribution of Cretaceous conifers and angiosperms based on a fossil wood database (from Peralta and Falcon, 2012).

6.4.1 Dinoflagellate Cyst Assemblages from Umir Formation and Late Cretaceous Provincialism

Dinoflagellate cyst assemblages identified in the Umir Formation in Central Eastern Middle Magdalena Valley Basin reflect the Campanian - Maastrichtian provincialism of peridinacean cysts as recognized by Lentin and Williams (1980).

Based on the latitudinal distribution of peridinacean cysts, Lentin and Williams (1980)
defined three distinctive suites or provinces: the Malloy suite (tropical to subtropical province), the Williams suite (temperate province) and the McIntyre suite (boreal province). The Malloy suite was characterized by the co-occurrence of genera *Andalusiella, Cerodinium, Lejeunecysta*
and *Senegalinium* using data from Spain, Senegal, Brazil and Venezuela. The distribution of this assemblage restricted the Malloy suite to tropical to subtropical paleolatitudes. The Williams suite was defined using the occurrence of species of *Alterbidinium*, *Chantagiella* (the smaller taxa), *Isabelidinium*, *Spinidinium* and *Trithyrodinium*. This assemblage, restricted to temperate areas, was recognized in the Scotian Shelf-Grand banks, offshore eastern USA, southern England and France. Finally, the McIntyre suite, characterized by species of *Chantagiella* (the larger taxa) and *Laciniadinium*, was recorded in sections in Arctic Canada, the Mackenzie delta, Saskatchewan, Alberta, South Dakota and Wyoming. The McIntyre suite represents boreal assemblages reflecting cool temperate conditions (Lentin and Williams, 1980). Although this provincialism was initially recorded in the Campanian, several studies in the Maastrichtian recognized the same distribution of peridinacean cyst (Firth, 1987; Oboh-Ikuenobe et al., 1998; Yepes, 2001; Slimani et al, 2011).

In the Umir Formation, peridinacean cyst assemblages are characterized by the dominance of *Andalusiella* and *Palaeocystodinium* genera accompanied by common occurrences of *Senegalinium*, *Cerodinium* and *Lejeunecysta* genera. This association places the Umir formation dinocyst assemblages into the tropical to subtropical Malloy suite described by Lentin and Williams (1980), evidencing presence of tropical warm waters during the Late Maastrichtian in MMVB.

In Northern Colombia (Río Molino section) and Western Venezuela (Río Loro section), similar dinocyst assemblages belonging to the Malloy Suite were reported in the Maastrichtian Colón and Mito-Juan Formations by Yepes (2001).
7. CONCLUSIONS

Pollen and spore assemblages identified in the Middle-Upper Umir formation, in Central Eastern MMVB, provided a Late Maastrichtian age for the formation. Global dinoflagellate cyst events, including the occurrence of *Manumiella seelandica* at the top of the section, restrict the upper member to the Latest Maastrichtian, in a time interval that is directly preceding the K/T boundary.

Comparison with previous studies showed similarities with the regional biostratigraphic framework (Germeraad et al., 1968; Muller et al., 1987), but also highlighted some differences with local studies conducted in the Eastern Cordillera (Sarmiento, 1992). Specifically, biostratigraphic events used to define pollen zones assigned to the Danian in the Eastern Cordillera were recorded in the Late Maastrichtian in MMVB. Hence, a revision of the zonation proposed by Sarmiento (1992) is necessary.

Three informal zones (A-C) are proposed using last and first occurrence data and relative abundance. These zones provide a detailed biostratigraphic control for the entire formation. Zone A is marked by the predominance of fern spores and covers the Middle Umir Formation. Zones B and C are marked by higher abundances in dinoflagellate cysts and an increase in angiosperms abundance, and cover the Upper member.

Important biostratigraphic events including spikes of peridinoid cysts (*Andalusiella* and *Palaecosytodinium* genera), skolochorate cysts (mainly *Achomosphaera–Spiniferites* complex) and pollen from *Echimonocolpites protofranciscoi* and *Proxapertites* genus were identified at the top of Zone C in the Upper Umir sandstones. These events, which characterize layers below, within and above the sandstones, are recognized for the first time in the Umir Formation and in the MMVB. They have a high potential to assist intrabasinal correlations when evaluating lateral continuity of this new petroleum target.

Considering the relative abundance of pollen, spores and dinoflagellate cysts, their distribution along the formation and their environmental implications, the Middle Umir formation is believed to have been deposited within a lagoonal environment with coastal swamps and
estuarine conditions; while a semi-restricted bay with strong river influx in the zone close to the coastline must have existed during the deposition of the Upper member.

In the Umir Formation, angiosperms are represented by 106 species and they are by far the dominant component of the pollen assemblages, making up to 80% - 99% of the associations. Gymnosperms, represented only by 3 species and dominated by *Araucariacites australis*, are a minor component and show a decline in their abundance, from 18% at the base of the section to only 1%-2% at the top. The dominant and increasing abundance of the angiosperm pollen, and the decreasing and subordinate role of the gymnosperms, reflect the global replacement of the gymnosperms by the angiosperms.

Peridinacean dinocyst assemblages identified in the Umir Formation in MMVB reflect the Campanian - Maastrichtian provincialism of peridinacean cysts recognized worldwide. The association characterized by the dominance of *Andalusiella* and *Palaeocystodinium* genera accompanied by common occurrences of *Senegalinium*, *Cerodinium* and *Lejeunecysta* genera locates Umir Formation assemblages into the tropical to subtropical Malloy suite proposed by Lentin and Williams (1980).
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APPENDIX A
QUANTITATIVE DISTRIBUTION OF PALYNOMORPHS IN CORE PPI-3 (MIDDLE UMIR FORMATION) EXPRESSED IN ABSOLUTE ABUNDANCES
APPENDIX A. Quantitative distribution of palynomorphs in Core PPI-3 (Middle Umir Formation) expressed in absolute abundances
APPENDIX B
QUANTITATIVE DISTRIBUTION OF PALYNOMORPHS IN CORE PPM-5 (MIDDLE UMIR FORMATION) EXPRESSED IN ABSOLUTE ABUNDANCES
APPENDIX B. Quantitative distribution of palynomorphs in Core PPM-5 (Middle Umur Formation) expressed in absolute abundances

**Interval (cm)**: 0m - 300m

**Scale**: 1:2000

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### Absolute Abundance

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**Figure Description**: Graph showing the quantitative distribution of palynomorphs in Core PPM-5, with intervals ranging from 0m to 300m. The absolute abundance is indicated for each sample interval, demonstrating the distribution pattern across the core's length.
APPENDIX C
QUANTITATIVE DISTRIBUTION OF PALYNOMORPHS IN CORE PPM-2 (MIDDLE - UPPER UMIR FORMATION) EXPRESSED IN ABSOLUTE ABUNDANCES
APPENDIX C. Quantitative distribution of palynomorphs in Core PPM-2 (Middle - Upper Umir Formation) expressed in absolute abundances

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**Spores And Pollen**

- **Dolomite Cycle**
- **Total**
APPENDIX D
QUANTITATIVE DISTRIBUTION OF PALYNOMORPHS IN CORE PPM-1 (UPPER UMIR FORMATION) EXPRESSED IN ABSOLUTE ABUNDANCES
APPENDIX D. Quantitative distribution of palynomorphs in Core PPM-1 (Upper Umir Formation) expressed in absolute abundances

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Diagram showing the quantitative distribution of palynomorphs in Core PPM-1 (Upper Umir Formation) with absolute abundances.
APPENDIX E
RANGE CHART OF PALYNOMORPHS IN THE UMIR FORMATION, SAN LUIS AREA,
MIDDLE MAGDALENA VALLE BASIN (MMVB)
APPENDIX E. Range Chart of palynomorphs in the Umir Formation, San Luis Area, Middle Magdalena Valle Basin (MMVB)

Depth | Samples | Zone | Spores And Pollen | Developmental Cycle | Age | MA | Fa | Fa* | Samples | Depth

Zone A

Zone B

Zone C

Depth

Samples

Range Chart of palynomorphs in the Umir Formation, San Luis Area, Middle Magdalena Valle Basin (MMVB)
APPENDIX F
QUANTITATIVE DISTRIBUTION OF PALYNOMORPHS IN THE UMIR FORMATION,
SAN LUIS AREA, MIDDLE MAGDALENA VALLE BASIN (MMVB)
APPENDIX F. Quantitative distribution of palynomorphs in the Umir Formation, San Luis Area, Middle Magdalena Valley Basin (MMVB)

Text Keys

APPENDIX F. in the Umir Formation, San Luis Area, Middle Magdalena Valley Basin (MMVB)

Quantitative distribution of palynomorphs
APPENDIX G
ILLUSTRATIONS OF SELECTED TAXA IDENTIFIED IN THE UMIR FORMATION.
PLATE 1

1 Laevigatosporites granulatus. Sample PPM-1 85.8 m, EF F25
2 Striamonoletes sp. Sample PPI-244 m EF W42
3 Psilatrilites group Sample PPM-5 280 m EF M23
4 Psilatrilites group Sample PPM-5 280 m EF G25
5 Kuylisporites waterbolkii Sample PPM-2 146.3 m EF N23
6 Polypodiisporites sp. Sample PPM-1 160 m EF W53
7 Ariadnaesporites sp. Sample PPM-5 280 m EF W26
8 Chomotrilites minor Sample PPM-5 216 EF O16
9, 10. Echitriletes sp. Sample PPM-1 143 EF J16
11, 12 Rugulatisporis sp. Sample PPM-5 125,5 m EF G30
13, 14 Clavatrilites mutisii Sample PPI-3 140 m EF R20
15, 16 Fovetriletes margaritae Sample PPM-1 26 EF H56
17 Gabonisporis vigorouxii PPI-3 161,1 m EF H25
1,2 *Hamulatisporis caperatus*. Sample PPM-1 124 m, EF V31
3,4 *Polypodiaceoisporites sp*. Sample PPM-2 m EF N51
5,6 *Verrutriletes “macrogemmatus”*, Sample PPI-3 128 m EF F46
7,8 *Cingulatisporis verrucatus* Sample PPM-5 160 m EF K99
9 *Echitriletes intercolensis* Sample PPM-5 126.5 m EF D12
10, 11 *Echitriletes intercolensis* Sample PPM-5 172.05 m EF Q52
12,13 *Muerrigerisporis “ardilensis”* Sample PPI-3 184 m EF N11
14, 15 *Neoraistrickia “constrictus”* Sample PPI-3 220 m EF R47
16. *Cicaticrosisporites* sp. Sample PPI-1 220 m EF M19
17 *Echitriletes “acanthotriletoides”* Sample PPI-3 161,1 m EF Q11
18 *Scabratriletes granularis* Sample PPM-2 170.4 m EF Q24
19 *Zlivisporis blanensis* Sample PPM-1 51.93 EF O56
20 *Magnopsilatriletes “magnovirueloides”* PPI-3 244 m EF H19
21 *Verrutriletes virueloides* PPI-3 84 m EF M25
PLATE 3

1,2 *Araucariacites australis*. Sample PPI-3 220 m, EF H21
3,4 *Retipollenites “afropollensis”*. Sample PPI-3 244 m EF Y52
5 *Arecipites regio*, Sample PPM-1 133.2 m EF U41
6 *Arecipites regio*, Sample PPM;5 100.3 m EF U9
7,8 *Cycadopites sp.* Sample PPM-5 253 m EF R45
9 *Callialasporites dampieri*. Sample PPI-3 161.7 m EF W47
10 *Monocolpophollene sp.* Sample PPM-5 100.3 m EF L45
11 *Monocolpophollene sp.* Sample PPM-5 100.3 m EF P9
12 *Retimonocolpites retifossulatus* Sample PPI-3 100.3 m EF R18
13 *Retimonocolpites retifossulatus* Sample PPI-3 125.5 m EF H12
14 *Rugemonocolpites “perfectus”* Sample PPI-3 184 m EF U8
15 *Baculamonocolpites* sp. Sample PPM-5 253 m EF E39
16 *Foveomonocolpites “heterofoveolatus”* sp. Sample PPM-1 160 m EF E49
17 *Bacumorphomonocolpites taurusae* Sample PPI-3 161,1 m EF M25
18 *Bacumorphomonocolpites taurusae* Sample PPI-3 161,1 m EF P23
PLATE 4

1 *Echimonocolpites protofranciscoi*. Sample PPI-3 161.1 m, EF N35
2, 3 *Echimonocolpites pachyexinatus*. Sample PPM-1 23.54 m, EF V59
4, 5 *Gemmamonocolpites dispersus*. Sample PPM-1 92.05 m EF U57
6 *Longapertites vanendeerburgi*. Sample PPM-1 60 m EF T55
7 *Lonagapertites* sp. Sample PPM-1 51.93 m EF N10
8 *Longapertites proxapertitoides var. proxapertitoides*. Sample PPI-1 244 m EF G10
9 *Longapertites proxapertitoides var. proxapertitoides*. Sample PPM-1 133.2 m EF E42
10 *Proxapertites verrucatus*. Sample PPM-1 92.05 m EF J30
11 *Proxapertites verrucatus*. Sample PPM-1 92.05 m EF W24
12 *Monocolpites grandispiniger*. Sample PPM-2 224.1 m EF U27
13 *Proxapertites verrucatus*. Sample PPM-2 158 m EF Q12
14 *Proxapertites “diminutus”*. Sample PPM-2 41 m EF M16
15 *Proxapertites operculatus*. Sample PPM-2 41 m EF R20
16 *Proxapertites humbertoides*. Sample PPM-1 51.93 m EF V20
PLATE 5

1, 4 *Spizözonocolpites baculatus*. Sample PPM-5 230.5 m, EF M11
2, 3 *Spizözonocolpites intrarugulatus*. Sample PPM-1 115.25 m, EF W53
5 *Spizözonocolpites “clavatus”*. Sample PPM-1 115.25 m EF H51
6 *Spizözonocolpites “clavatus”*. Sample PPM-5 88 m EF S14
7 *Spizözonocolpites “clavatus”*. Sample PPM-5 276.5 m EF J26
8, 9 *Spizözonocolpites “brevibaculatus”*. Sample PPM-5 267.6 m EF J21
10, 11 *Retidiporites magdalenensis*. Sample PPM-5 253 m EF W8
12, 13 *Retidiporites botulus*. Sample PPM-5 112 m EF H57
14, 15 *Psilamonocolpites operculatus*. Sample PPM-5 243 m EF P49
PLATE 6

1, 2 *Aquilapollenites magnus*. Sample PPM-5 172.05 m, EF S51
2, 3 *Aquilapollenites* sp. Sample PPM-1 92.05 m, EF C42
5 *Foveotricolpites hammeni*. Sample PPM-1 104.5 m EF R7
6 *Foveotricolpites hammeni*. Sample PPM-5 230.5 m EF P22
7, 8 *Psilabrevitricolpites marginatus*. Sample PPM-5 216 m EF U46
9 *Annutriporites iversenii*. Sample PPM-2 146.3 m EF G8
10 *Annutriporites iversenii*. Sample PPM-1 92.05 m EF H17
11 *Syndemicolpites typicus*. Sample PPM-1 42 m EF U25
12 *Syndemicolpites typicus*. Sample PPM-2 230.15 m EF U12
13 *Psilabrevitricolporites annulatus*. Sample PPM-5 253 m EF N39
14, 15 *Scabrastephanocolpites guaduensis*. Sample PPM-5 100.3 m EF W46
16 *Retibrevitricolpites brevicolpatus*. Sample PPI-3 140 m EF U39
17 *Retibrevitricolpites brevicolpatus*. Sample PPM-5 100.3 m EF Q49
18 *Echitriporites trianguliformis*. Sample PPM-5 253 m EF F55
19 *Echitriporites sue scae*. Sample PPM-1 92.05 m EF N23
20 *Echitriporites sue scae*. Sample PPM-1 143 m EF S24
PLATE 7

1 *Proteacidites dehaani*. Sample PPM-1 104.5 m, EF W10
2 *Proteacidites dehaani*. Sample PPM-5 184.5 m, EF Q22
3, 4 *Horniella lunarensis*. Sample PPM-1 51.93 m, EF T58
5, 6 *Retritriporites “crassoreticulatus”*. Sample PPI-3 38.3 m EF E41
7 *Retiritricolpites josephinae*. Sample PPM-1 51.93 m EF M16
8 *Retiritricolpites josephinae*. Sample PPI-3 140 m EF R10
9 *Retiritricolpites josephinae*. Sample PPI-3 232 m EF F15
10, 11 *Retiritricolpites “operculoesponjosus”*. Sample PPI-3 161.1 m EF R11
12 *Psilatricticolporites “scabratus”*. Sample PPM-5 88 m EF O50
13 *Zonotrichicolpites variabilis*. Sample PPM-2 41 m EF T16
14, 15, 16 *Syncolporites lisamae*. Sample PPM-1 60 m EF G17
17, 18, 19 *Syncolporites lisamae*. Sample PPM-1 85.8 m EF P46
20 *Syncolporites marginatus*. Sample PPM-1 60 m EF M31
21, 22 *Colombipollis tropicalis*. Sample PPM-1 42 m EF X10
PLATE 8

1 *Crusafontites grandiosus*. Sample PPI-3 224 m, EF T22

2, 3 *Retistephanocolpites minimus*. Sample PPI-3 140 m, EF S6

4 *Retistephanocolpites “jandufourioides”*. Sample PPM-5 68.8 m, EF O43

5 *Retistephanocolpites “jandufourioides”*. Sample PPM-5 267.6 m EF 239

6 *Stephanocolpites costatus*. Sample PPM-1 42 m EF U25

7 *Stephanocolpites costatus*. Sample PPM-2 41 m EF S54

8 *Echistephanocolpites “minutiechinatus”*. Sample PPM-5 253 m EF S42

9 *Echistephanocolpites “minutiechinatus”*. Sample PPM-5 253 m EF U48

10 *Buttinia andreevi*. Sample PPI-232 140 m, EF Q52

11 *Buttinia andreevi*. Sample PPM-2 224.1 m, EF O54

12, 13 *Periretisyncolpites giganteus*. Sample PPM-2 224.1 m EF K39

14 *Periretisyncolpites baculatus*. Sample PPM-5 160 m EF N29

15 *Periretisyncolpites magnosagenatus*. Sample PPM-2 244.1 m EF K45

*Periretisyncolpites giganteus*. Sample PPM-2 224.1 m EF K39
PLATE 9

1 *Andalusiella gabonensis*. Sample PPM-5 172.05 m, EF O46
2 *Andalusiella polymorpha*. Sample PPM-1 42 m, EF O26
3 *Andalusiella polymorpha*. Sample PPM-1 42 m, EF V17
4 *Andalusiella romboides*. Sample PPM-1 42 m, EF V14
5 *Andalusiella* sp. Sample PPM-1 42 m, EF Q28
6 *Andalusiella mauthei*. Sample PPM-1 42 m, EF U11
7 *Andalusiella mauthei*. Sample PPM-1 42 m, EF U52
8 *Andalusiella mauthei*. Sample PPM-1 42 m, EF U52 Phase Contrast
9 *Andalusiella polymorpha*. Sample PPM-1 42 m, EF K27
PLATE 10

1 *Andalusieilla* sp. Sample PPM-1 42 m, EF X15

2 *Andalusieilla* sp. Sample PPM-1 42 m, EF X15 Phase Contrast

3 *Andalusieilla mauthei*. Sample PPM-1 42 m, EF U14

4 *Palaeocystodinium australinum*. Sample PPM-1 42 m, EF S12

5 *Palaeocystodinium australinum*. Sample PPM-1 42 m, EF S12 Phase Contrast

6 *Palaeocystodinium golzowense*. Sample PPM-1 160 m, EF F11

7 *Andalusieilla rhomboides*. Sample PPM-2 224.1 m, EF H10/2

8 *Cerodinium diebelii*. Sample PPM-5 137 m, EF P27

9 *Cerodinium diebelii*. Sample PPM-5 137 m, EF P27
PLATE 11

1 *Manumiella seelandica*. Sample PPM-1 42 m, EF U53
2 *Manumiella seelandica*. Sample PPM-1 42 m, EF U53 Phase Contrast
3 *Fibrocysta* sp. Sample PPM-1 143 m, EF Q50
4 *Alysogimnium euclaense*. Sample PPM-1 42 m, EF K23
5 *Dinogynium* sp. Sample PPM-5 253 m, EF H11
6 *Cerodinium speciosum*. Sample PPM-2 97.4 m, EF G13
7 *Senegalinium* sp. Sample PPI-3 244 m, EF U42
8 *Dinogynium heterocostatum*. Sample PPM-2 134 m, EF G38
9 *Dinogynium acuminatum*. Sample PPM-5 280 m, EF K12
PLATE 12

1 Achomosphaera sp. Sample PPM-1 51.93 m, EF K22
2 Achomosphaera sp. Sample PPM-1 124 m, EF U27
3 Achomosphaera ramulifera. Sample PPM-2 224.1 m, EF W22
4 Hystrichokolpoma sp. Sample PPM-1 51.93 m, EF Q19
5 Cordosphaeridium sp. Sample PPM-1 60 m, EF Q60
6 Hystrichokolpoma bulbosum. Sample PPM-1 51.93 m, EF P16
7 Hystrichokolpoma bulbosum. Sample PPM-1 51.93 m, EF P16
8 Dinogymnium heterocostatum. Sample PPM-2 134 m, EF G38
9 Foram lining. Sample PPI-3 184 m, EF G20
PLATE 13

1 *Areoligera senonensis*. Sample PPM-2 224.1 m, EF Q19

2 *Areoligera senonensis*. Sample PPM-2 224.1 m, EF Q19 Phase Contrast

3 *Florentinia mantelli*. Sample PPM-2 224.1 m, EF Y21

4 *Florentinia mantelli*. Sample PPM-2 224.1 m, EF Y21

5 *Florentinia* sp. Sample PPM-1 196 m, EF U43

6 *Hystrichodinium* sp. Sample PPM-1 85.8 m, EF X26

7 *Hystrichokolpoma* sp. Sample PPM-1 42 m, EF Q16

8 *Exochosphaeridium* sp. Sample PPI-3 184 m, EF I38
Carlos Santos was born in Bucaramanga, Colombia. He received a Bachelor of Science degree in Geology from the Universidad Industrial de Santander in May, 2005. Following graduation, he worked as a junior palynologist during 2005-2010 in the Colombian Petroleum Institute. In 2010 he was accepted for graduate studies at the Department of Geology and Geophysics at Louisiana State University, where he was held a graduate teaching assistantship for the period August 2010 to December 2011 and a educational curatorial assistantship from the LSU Museum of Natural during January –May 2012.

Upon completion of his MS program in spring 2012, Carlos will be working in the Colombian Petroleum Institute.