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Review article

Paleopalynology in Colombia: A review

Paleopalinología en Colombia: una revisión

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Abstract

Palynology is an important tool for establishing age and interpreting paleoenvironments in both continental and marine deposits. This paper provides a summarized overview of the palynological information published for deposits in Colombia ranging from the Paleozoic to the Miocene-Pliocene. We found 111 publications in indexed journals contain palynological data from 511 sections or wells. Palynology of the Paleozoic in Colombia has been mainly studied in the Eastern Llanos; the Triassic-Jurassic is virtually unknown; there are studies on the Cretaceous in the Eastern Cordillera, the Upper Magdalena Valley, and Catatumbo; the Paleogene has been studied in sedimentary rocks of the Llanos foothills, the Eastern Cordillera, the Middle Magdalena Valley, Catatumbo, and in some isolated spots in La Guajira and the Caribbean while the Neogene has been studied in the Amazon, the Eastern Cordillera, and the Llanos foothills. Recent publications for the Caribbean and Pacific regions and a palynological zonation for the Llanos and its basins have been successfully used in other basins in the country. In recent years, the interest of the Colombian government in exploring new areas for hydrocarbon exploration in the Caribbean facilitated a partnership between the National Hydrocarbons Agency and the University of Caldas to conduct palynological studies in deposits ranging from the Late Cretaceous to the Quaternary. Here we present a summary of the main advances in Caribbean palynology.

Keywords: Palynology; Colombia; Colombian Caribbean; Paleozoic; Mesozoic; Cenozoic.

Resumen

La palinología es una herramienta importante para establecer la edad e interpretar los paleoambientes en depósitos tanto continentales como marinos. En esta revisión se presenta de manera resumida la información palinológica publicada sobre depósitos en Colombia que van desde el Paleozoico hasta el Mioceno-Plioceno. Encontramos 111 publicaciones en revistas indexadas que contienen datos palinológicos de 511 secciones o pozos. La palinología del Paleozoico en Colombia se ha estudiado principalmente en los Llanos Orientales; el Triásico-Jurásico es prácticamente desconocido; del Cretácico hay estudios en la cordillera Oriental, el Valle Superior del Magdalena y el Catatumbo; del Paleógeno, en rocas sedimentarias del Piedemonte Llanero, la cordillera Oriental, el Valle Medio del Magdalena y el Catatumbo; además, hay algunos trabajos puntuales en La Guajira y el Caribe, en tanto que el Neógeno cuenta con estudios en el Amazonas, la cordillera Oriental, y el Piedemonte Llanero. Se destaca el incremento de publicaciones recientes sobre el Caribe y el Pacífico. Actualmente está publicada una zonación palinológica de los Llanos Orientales y el piedemonte que se ha empleado con éxito en otras cuencas del país. En los últimos años, el interés del Estado colombiano por conocer nuevas áreas de exploración de hidrocarburos en el Caribe permitió una alianza entre la Agencia Nacional de Hidrocarburos y la Universidad de Caldas, en cuyo marco se han desarrollado estudios palinológicos en depósitos que van desde el Cretácico tardío al Cuaternario, algunos publicados recientemente. El resumen de los principales avances de la palinología en el Caribe colombiano se presenta en esta revisión.

Palabras clave: Palinología; Colombia; Caribe colombiano; Paleozoico; Mesozoico; Cenozoico.

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Introduction

Since the 1940s, paleopalynology, i.e., the study of non-soluble organic matter extracted from sedimentary rocks by chemical methods, has rapidly developed around the world given its biostratigraphic and paleoenvironmental potential, especially in the hydrocarbon industry. Many researchers have contributed to the development of the discipline, among them **Hyde & Williams** (1944), **Faegri & Iversen** (1989), **Traverse** (1988, 2007), **Tyson** (1995), and **Jansonius & McGregor** (1996).

In Colombia, the development of this discipline dates back to the 1950s when the initial geological mapping and stratigraphic work was led by government institutions such as the *Servicio Geológico Nacional* (now *Servicio Geológico Colombiano*). Later, oil and gas companies joined these efforts by investing capital, and, therefore, the advancement of paleopalynology in the country has been closely linked to this industry's interests. As a result, palynological studies in areas with low interest in hydrocarbon exploration have been scarce or absent. However, at least 40 Colombian palynologists, either from the industry or academy, have contributed to the country's paleopalynological knowledge and evolution, although much of the data generated for the industry has not been published because of confidentiality policies (**Pardo *et al.***, 2022). To date, there are no paleopalynological studies compiled in the country enabling a general overview of their development and the identification of knowledge gaps that need to be filled. Such a compilation would facilitate the selection of new study areas and the evaluation of existing publications.

In this context, the present study has two main goals: to review and organize the publications on Colombian paleopalynology using as a framework the geological time and the Colombian sedimentary basins, and to summarize the palynological advances in the Caribbean area including the Sinú-San Jacinto and the Cesar-Ranchería Basins.

Method

We collected and reviewed the scientific articles published about Colombian paleo-palynology spanning from the 1950s to the present (**Figures 1-2, table 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3370). The literature was organized in strati-graphic order from the oldest to the most recent age following the Paleozoic (lower-upper), Mesozoic (Triassic-Jurassic and Cretaceous), and Cenozoic (Paleogene and Neogene) eras (**Figures 3-6**, **table 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3370). We also include a series of 11 plates with micrographs of palynomorphs from the Creta-ceous to the Neogene (**Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3372) and maps showing the locations of published palynological studies. Using the map of the Colombian sedimentary basins (**Barrero *et al.***, 2007), we grouped the basins into sedimentary regions as follows: 1) Pacific and Caribbean (including Guajira, Cesar-Ranchería, Lower Magdalena Valley, Sinú-San Jacinto, and Chocó and Tumaco basins); 2) Western Cordillera; 3) Cauca Valley (including Amagá and Cauca-Patía basins); 4) Central Cordillera; 5) Magdalena Valley (Middle and Upper); 6) Eastern Cordillera (including the Catatumbo basin); 7) Eastern Llanos (including Llanos foothills), and 8) Amazon (including Caguán-Putumayo and Amazon basins) (**Figures 1 a, b and 2**).

Results

The beginnings

In Colombia, the first palynological studies were led by Thomas van der Hammen, who studied sedimentary deposits in the Eastern Cordillera and the Magdalena and Cauca valleys between the 1950s and 1960s. His publications include the basic principles of palynological nomenclature (**van der Hammen**, 1954a), treatises on pollen and spore systematics with the description of morphotypes (**van der Hammen**, 1956a; 1956b; **van der Hammen & García-de Mutis**, 1966), and the recognition of upper Cretaceous and Tertiary palynofloras of Colombia (**van der Hammen**, 1954b; 1957a; 1961). His work laid the foundation for palynological studies in northern South America. However, some of his ideas and part of the proposed nomenclature are not in use or have been updated.

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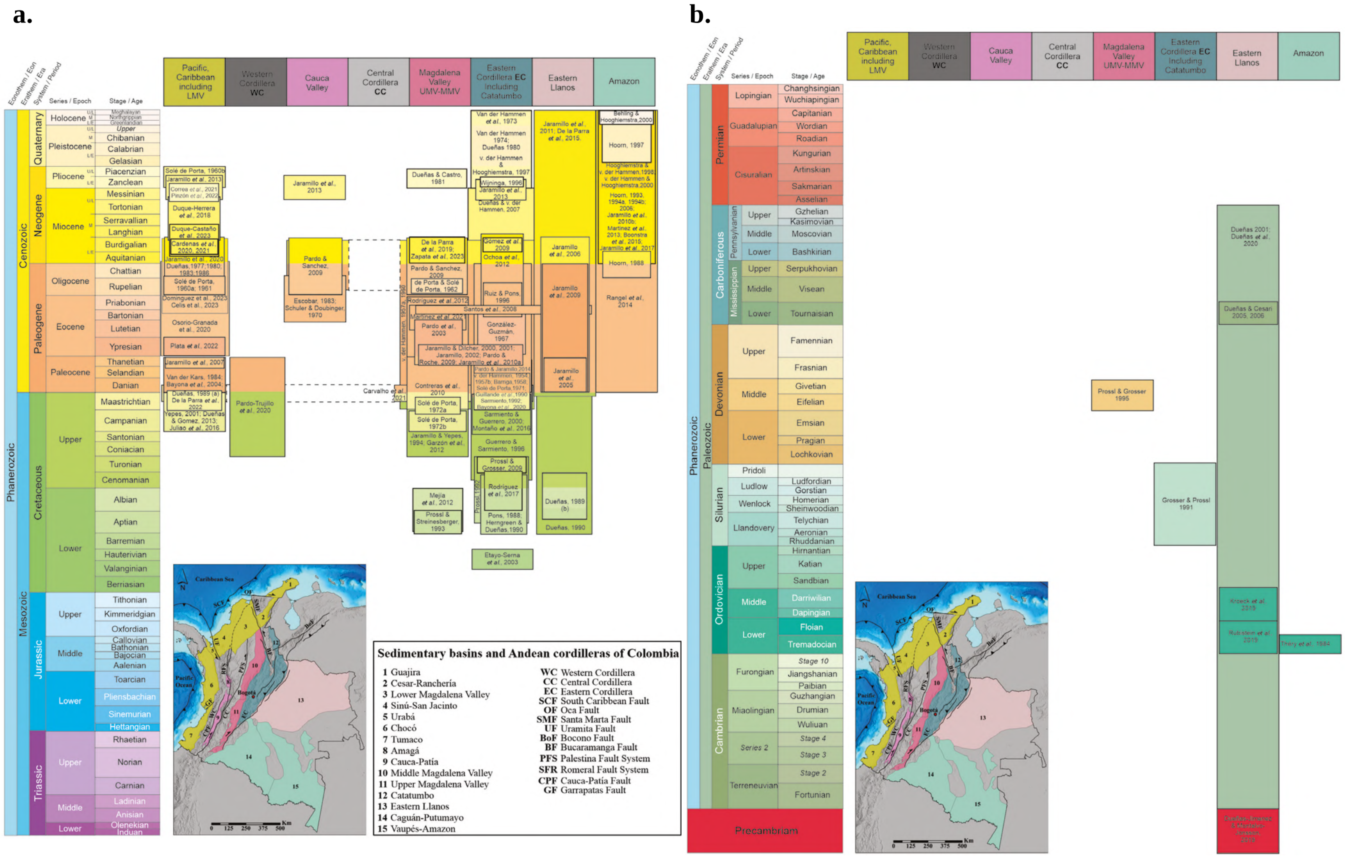

Figure 1. a. Temporal distribution of palynological studies published for the Cretaceous and Cenozoic in Colombia. The regions mentioned in the chart are in different colors on the basin map (modified from **Barrero *et al.***, 2007). For detailed references, see Table 1s. **b.** Temporal distribution of palynological studies published for the Precambrian and Cenozoic in Colombia. The regions mentioned in the chart are in different colors on the basin map (modified from **Barrero *et al.***, 2007). For detailed references, see Table 1s.

Palynological zonations

In the late 1950s, the first scheme of pollen and spores stratigraphic distribution in deposits from the Maastrichtian to the Pliocene in the Eastern Cordillera was proposed. Known as the PAF diagram, an abbreviation for palms (P), angiosperms (A), and ferns (F), it related the percentage variations among the different palynological groups to regional changes in flora and, therefore, allowed the subdivision of the sedimentary record into chronostratigraphic units (**van der Hammen,** 1957a) whose validity was questioned (**de Porta & Solé de Porta**, 1962) and is not currently used. Later, **Germeraad *et al.*** (1968) proposed a zonation for tropical areas encompassing the upper Cretaceous to the Quaternary using palynological data from South America (including Colombia), western Africa, and Borneo. On their part, **Regali *et al.*** (1974) presented a zonation calibrated with foraminifera and nannofossils spanning the Mesozoic and Cenozoic and based on the palynology of sedimentary basins from Brazil. In Colombia, some palynomorph assemblages are similar to those reported in this zonation. Later, a palynological zonation was proposed for northern South America spanning the Cretaceous and Cenozoic that included palynological data from Colombia (**Muller *et al.***, 1987). This zonation correlated with others previously proposed (e.g., **Germeraad *et al.***, 1968; **Regali *et al.***, 1974) including those proposed for Guyana by **van der Hammen & Wimstra** (1964) and **Wimstra** (1971) and another one for Africa. For the Miocene, detailed palynological zones have been proposed in Venezuela (**Lorente**, 1986) and the Amazon basin (**Hoorn**,1993), which are also used in Colombia.

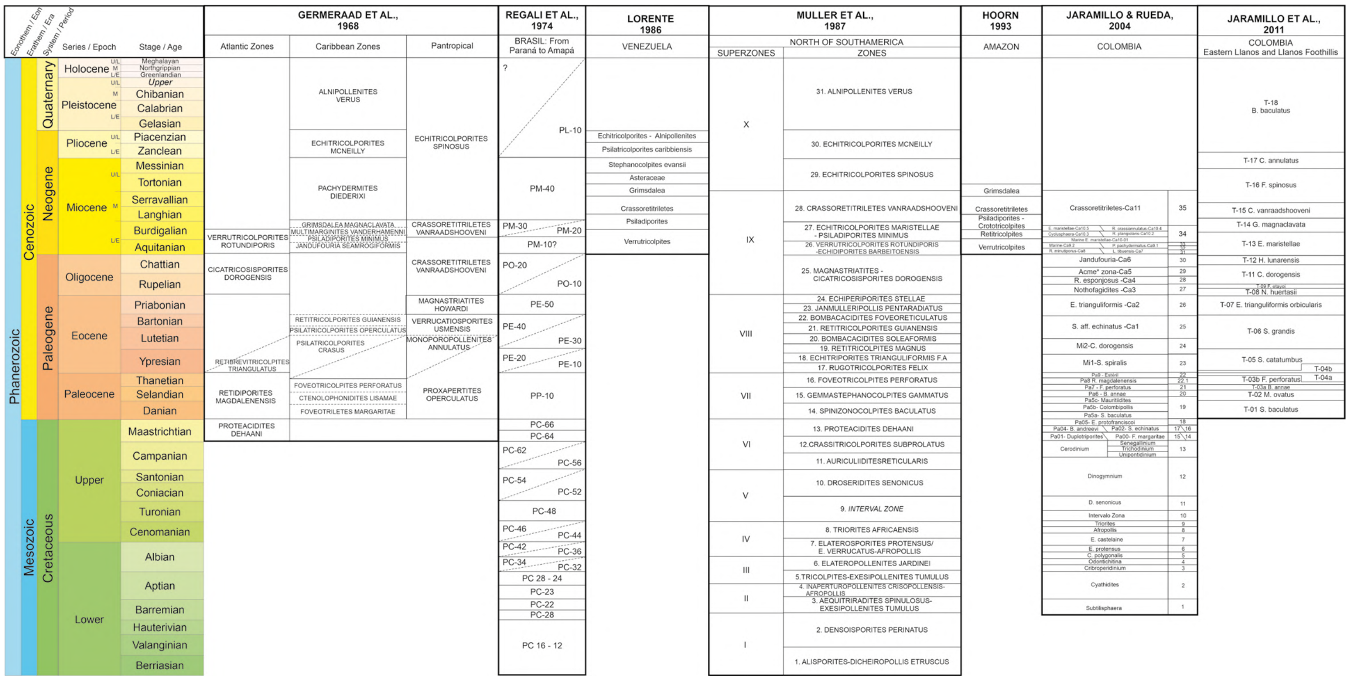

Figure 2. Comparison of palynological zonations from the Cretaceous to the Quaternary proposed for northern South America including those published for Colombia (**Jaramillo & Rueda**, 2004; **Jaramillo *et al.***, 2011).

Cuartas *et al.* (2009) conducted an evaluation of palynological data from publications and the petroleum information bank (EPIS). They determined that the Eastern Llanos basin has the greatest palynological information followed in order by the Middle (VMM) and Upper Magdalena (VSM) valleys, the Eastern Cordillera, and the Catatumbo basins. Despite the existence of a greater volume of palynological data in the VMM, as of 2021, the number of published palynological works for the Eastern Cordillera has increased. Also, the publication of the first data for the Caribbean, Pacific, and western Colombian areas is notable (**Figure 1 a-b**). The extensive palynological data from several Colombian basins has allowed for a preliminary palynological zonation spanning from the Aptian to the middle Miocene (**Jaramillo & Rueda**, 2004) and one for the Cenozoic calibrated with isotopic data and planktonic foraminifera (**Jaramillo *et al.***, 2011). These zonations have been tested in various areas of the country with optimal results and have become fundamental tools for hydrocarbon exploration (**Jaramillo & Rueda**, 2004; **Pardo *et al.***, 2022, **Plata-Torres *et al.***, 2022). The division of the Oligocene into four palynological zones, for example, is a notable contribution of the zonations proposed for Colombia (**Jaramillo & Rueda**, 2004; **Jaramillo *et al.***, 2011) compared to those published for Northern South America (**Figure 2**).

Palynology in Colombia through time

Precambrian-Paleozoic

Published studies on the Paleozoic including palynology, lithostratigraphy, and geochemistry on sediments traditionally considered metamorphic have shown a potential for hydrocarbon generation that has recently sparked industry interest as an alternative to acquiring new reserves for the country (**Dueñas-Jimenez *et al.***, 2020).

Precambrian rocks are mostly igneous and metamorphic and are distributed mainly in the Orinoquia-Amazon, the Eastern Cordillera, and the Sierra Nevada de Santa Marta (**Gómez-Tapias *et al.***, 2015). In the Amazon region, some sedimentary deposits have been reported in the Tunuí Group (**Renzoni**, 1989) and La Pedrera Formation (**Galvis *et***

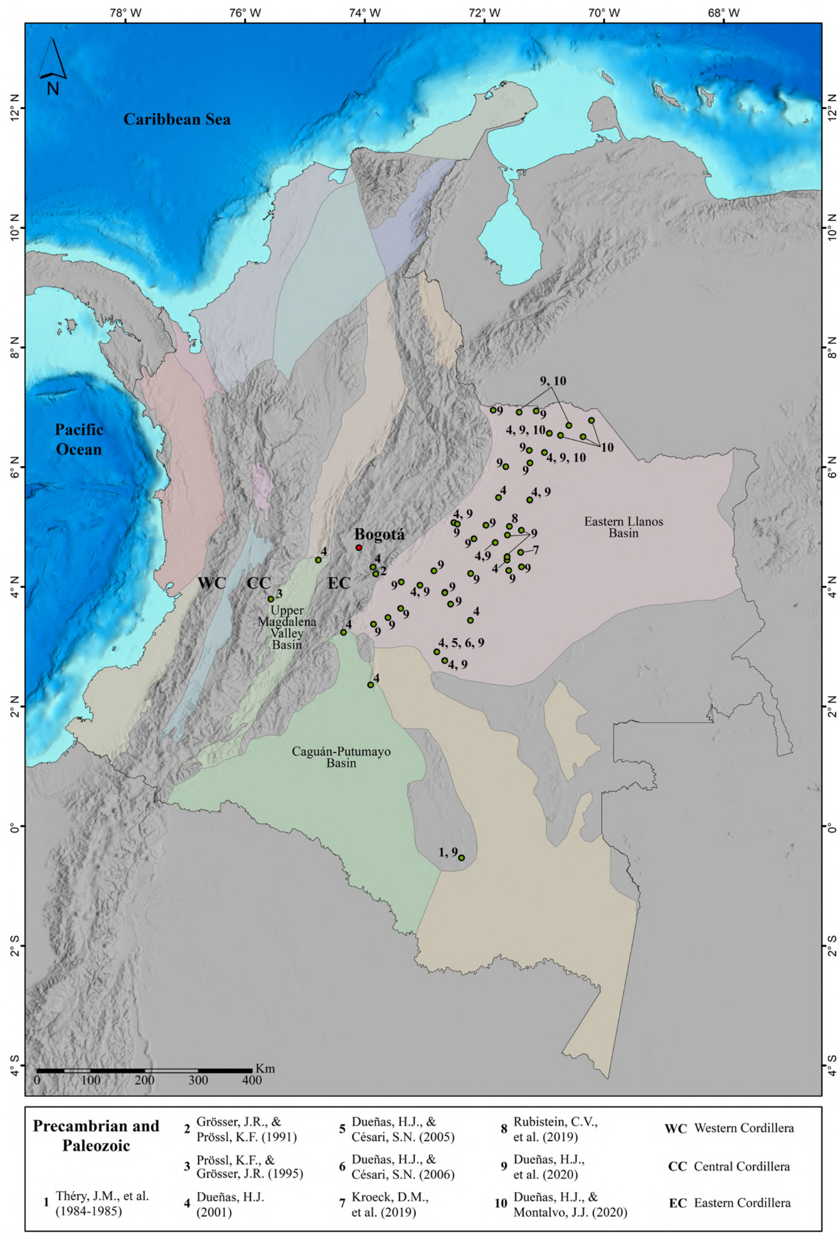

Figure 3. Map of sedimentary basins in Colombia indicating the locations where Precambrian and Paleozoic palynological publications have been made. For detailed references, see table 1s.

al., 1979), but there are no micropaleontological studies on these rocks. In contrast, an abundant and diverse association of Ediacaran acritarchs has been described for the so-called "Arauca Graben" in the Eastern Llanos (**Arminio *et al.***, 2013; **Dueñas-Jiménez & Montalvo-Jónsson**, 2019).

The world's palynological record of Cambrian to Devonian deposits is composed of a diverse association of acritarchs, chitinozoans, scolecodonts, algae, cyanobacteria, and spores. The first pollen grains were reported for the end of the Devonian through the Permian with acritarch, spore, and megaspore associations still dominant (**Traverse,** 1988). In Colombia, the palynomorph associations described for the Paleozoic deposits contain abundant and diverse acritarchs, spores, and some chitinozoans; however, pollen grains have not been reported.

The Paleozoic sedimentary deposits are mainly located in the Eastern region of Colombia (**Gómez-Tapias *et al.*,** 2015). Cambrian to Devonian deposits of shallow marine environments have been reported on igneous and metamorphic rocks of the Amazonian Craton in the Eastern Llanos and the Amazon (**Dueñas,** 2001). Cambrian and Silurian rocks in the low-grade metamorphosed Quetame and Floresta massifs are reported to the south of the Quetame-Mérida terrain extending from the northeast of the Eastern Cordillera to western Venezuela while sedimentary rocks accumulated in coastal, fluvial, and marine environments present a diverse macrofossil fauna and flora (**Moreno-Sánchez *et al.*,** 2020). To the south and west of the country, Paleozoic sedimentary deposits with a lower degree of metamorphism are found on a Precambrian Grenvillian metamorphic basement in the Eastern Cordillera and the Magdalena Valley (**Bayona *et al.*,** 2010; **Moreno-Sánchez *et al.*,** 2020).

The oldest Paleozoic deposits (Cambrian) studied with palynology (**Figures 1b and 3**) are found in the Eastern Llanos, on the Arauca sector, where a very diverse association of acritarchs from shallow marine environments is described (**Dueñas**, 2001, 2002; **Dueñas-Jiménez *et al*.**, 2020). Early Ordovician (Arenigian) acritarchs have been reported in the Araracuara Formation in the south of the Chiribiquete mountain range (**Théry *et al*.**, 1984); other palynological data from the Ordovician describing well-preserved associations of acritarchs and chitinozoans come from wells drilled in the Eastern Llanos (**Dueñas**, 2001; **Dueñas-Jiménez *et al*.**, 2020). Recent studies in this region indicate the presence of the Peri-Gondwana palynological province of the Ordovician (**Kroeck *et al*.**, 2019; **Rubinstein *et al*.**, 2019).

Silurian palynomorphs have also been found in the Eastern Llanos (**Dueñas-Jiménez *et al*.**, 2020) and on the eastern flank of the Eastern Cordillera in the Quetame-Mérida terrain (**Grösser & Prössl**, 1991). Palynological data from the Devonian and Devonian-Carboniferous have been reported in the Eastern Llanos (**Dueñas**, 2001; **Dueñas & Césari**, 2005, 2006; **Dueñas**, 2011; **Dueñas-Jiménez *et al*.**, 2020) and on the eastern flank of the Central Cordillera in shales of the Amoyá Formation (**Prössl & Grösser,** 1995). The Permian, mainly described in the Santander massif in the Eastern Cordillera, presents a diverse marine fauna, but no palynological studies have been published on these rocks.

Mesozoic

In the Permian-Triassic, the vegetation around the world was dominated by conifer or conifer-like gymnosperm. Palynologically, this separation between the Late Permian and the Early Triassic is not easy because at this time the pollen record was dominated by striate bissacates pollen (**Traverse**, 1988). During the Triassic, the palynofloras experimented a high provincialism associated with latitude and by the Late Triassic and Early Jurassic, the palynoflora consisted mainly of non-striated bisaccate pollen grains. The palynoflora of the Jurassic shows a more cosmopolitan record (e.g. *Classopollis*) with latitude-associated variations in their abundance. The dinoflagellates record suggests a high provincialism at this time (**Traverse**, 1988).

During the late Paleozoic and early Mesozoic, compressive tectonics associated with the formation of Pangea have been recorded in Colombia. Later, its fragmentation during the Triassic resulted in the opening of the proto-Caribbean (**Spikings & Paul**, 2019). Extensive sedimentary deposits were accumulated during the Jurassic in shallow marine and continental environments associated with extensional basins in areas such as La Guajira, the Perijá and San Lucas Mountain ranges, the Eastern Cordillera, the Magdalena Valley and Putumayo extending to Ecuador (**Mojica & Kammer**, 1995; **Bayona *et al*.**, 2020). The dominant presence of red sandstones, conglomerates, and mudstones accumulated in oxidizing environments (e.g., Bocas, Jordán, and Girón units), hinders the preservation of organic matter microfossils and limits palynological information from the Triassic-Jurassic to very few locations (e.g., Bocas and Girón Group formations in Santander) (**Remy *et al.***, 1975; **Pons**, 1983).

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Cretaceous

During the Cretaceous, a major change in the composition of the world's flora occurred due to the emergence and diversification of angiosperms. The oldest record of this group in both hemispheres is from 130 Ma, Barremian (**Jaramillo,** 2019). The paleobotanical records suggest that from their appearance and through the Cretaceous, angiosperms' diversity and abundance progressively increased until they came to dominate terrestrial ecosystems surpassing other plant groups (e.g. pteridophytes, cycadophytes, coniferales) in the Paleocene (**Jaramillo,** 2023; **Crane & Lidgard,** 1989, 1990).

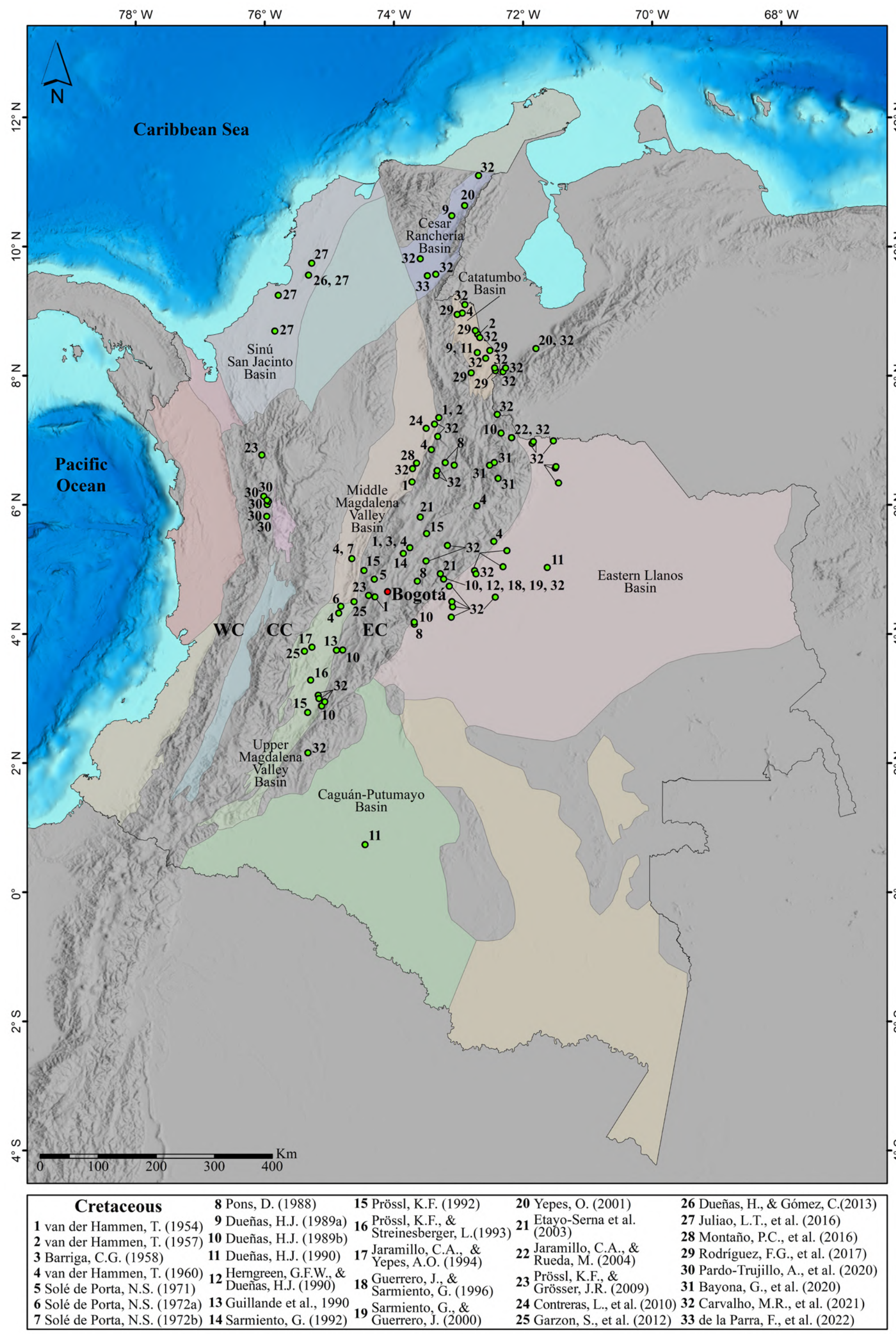

Figure 4. Map of sedimentary basins in Colombia indicating the locations where Cretaceous palynological publications have been made. For detailed references, see table 1s.

Rocks from the Cretaceous period in Colombia are exposed in the Western Cordillera, Central Cordillera, Magdalena Valley, Eastern Cordillera, some areas in the Caribbean (La Guajira and Sinú-San Jacinto basins), the Eastern Llanos, and the Amazon (**Barrero *et al.***, 2007; **Gómez-Tapias *et al.***, 2015). During the Early Cretaceous and until the Turonian, the sea progressively advanced and occupied the entire eastern region of Colombia (**Etayo-Serna *et al.***, 1969; **Sarmiento-Rojas *et al.***, 2006); its regression at the end of the Cretaceous generated extensive coastal and fluvial deposits (**Sarmiento**, 1992a) where the palynomorphs were well preserved. Systematic flora and microflora studies are limited, despite the dominance of ferns and gymnosperms on the mainland and a few angiosperms (**Jaramillo**, 2019). In contrast, the influence of the sea led to paleontological studies of marine macrofossils in areas of the current Magdalena Valley and Eastern Cordillera (**Etayo-Serna**, 1964; **Etayo-Serna**, 1979; **Gómez-Tapias *et al.***, 2015; **Patarroyo**, 2020).

Publications on Cretaceous palynology mainly focus on the Eastern Cordillera, the Magdalena Valley, and the Eastern Llanos (**Figures 1a and 4**). Palynological studies on Lower Cretaceous rocks from the central zone of the Eastern Cordillera (Cundinamarca) show a high thermal alteration index as a result of deep burial and tectonics associated with the uplift of the Andes, which destroyed or hinder the recognition of palynological associations (**Fabré & Delaloye**, 1983; **Dueñas**, 1989, **Prössl**, 1992; **Prössl & Grösser**, 2009). Likewise, in the Barremian-Aptian deposits of the Villa de Leyva area (Eastern Cordillera), where fossil macroflora is reported, palynomorphs have not been recovered due to their high thermal maturity (**Prössl**, 1992). In contrast, the record of relatively well-preserved marine and continental palynomorphs dates from the Aptian and extends through the Upper Cretaceous (**Dueñas**, 1990; **Dueñas**, 1989a). A study of the Batá Formation on the eastern flank of the Eastern Cordillera over the Quetame massif contains a palynological association of the Valanginian-Hauterivian (**Etayo-Serna *et al.***, 2003).

Palynological associations from the Aptian have been reported in sedimentary deposits of the Upper Magdalena Valley in the Yaví Formation (**Prössl & Vergara-Streinesberger**, 1993; **Vergara *et al.***, 1995), and from the Aptian-Albian in the Alpujarra, Ocal, and Caballos formations (**Mejía-Velásquez *et al.***, 2012). Studies from deltaic deposits in the Caballos (Upper Magdalena Valley) and Une Formations in the eastern sector of the Eastern Cordillera present palynology dating from the Albian to the Cenomanian (**Herngreen & Dueñas-Jiménez**, 1990). Despite the high thermal maturity observed in the palynomorphs, an Albian-Cenomanian age has been indicated for the Aguardiente and Capacho formations in the Catatumbo basin (**Rodríguez-Forero *et al.***, 2017).

In the Upper Cretaceous of the Eastern Cordillera, a succession covering the Cenomanian to Paleocene interval has been described including, from bottom to top, the Une (upper part), Chipaque and San Antonio Sandstones, the Aguacaliente Shales, the San Luis de Gaceno Sandstones, and the Guaduas and Lower Socha formations. This succession exhibits a changing palynological spectrum between marine and terrestrial palynomorphs allowing the determination of relative sea-level changes (**Guerrero & Sarmiento**, 1996; **Sarmiento & Guerrero,** 2000). In the western part of the Eastern Cordillera, the palynology of a marine sequence from the early Maastrichtian age has been studied in the Guadalupe Formation, where the report of marine palynomorphs is scarce but that of fungi is abundant suggesting very humid environments and high temperatures (**Gillande *et al*.,** 1990). A high diversity of pollen and spores morphotypes has been described in Maastrichtian-Paleocene sedimentary deposits also in the Eastern Cordillera and in the Guadalupe and Guaduas formations (**Solé de Porta,** 1971; **Sarmiento,** 1992b). Recently, very early Maastrichtian to early Eocene deposits in the north of the Eastern Cordillera in the Cocuy region were dated using palynology (**Bayona *et al*.,** 2020).

In the Upper Magdalena Valley, Santonian-Maastrichtian dinoflagellates from the Olini Group have been studied (**Jaramillo & Yepes-Amézquita**, 1994; **Garzón *et al.***, 2012), as well as terrestrial palynology from the Upper Cretaceous deposits of the Honda-Guaduas region (Cimarrona Formation) and Guataquí (**Solé de Porta,** 1972a; 1972b) in the Middle Magdalena Valley. Palynological associations of pollen, spores, and dinoflagellates from the

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Maastrichtian have been described for the Molino Formation in the Cesar-Ranchería Basin and in the upper part of the Colón Formation in the Catatumbo Basin (**Dueñas-Jiménez**, 1989b). Additionally, dinoflagellates have been studied in the Colón Formation (Río Molino section) in northern Colombia and the Mito Juan Formation (Río Loro section) in western Venezuela from the Maastrichtian-Danian age (**Yepes**, 2001). Recently, the first continental record of the Colón Formation in the Cesar-Ranchería Basin was published including the palynology of the Cretaceous-Paleogene boundary (**de la Parra *et al*.**, 2022). Campanian-Maastrichtian marine and terrestrial palynomorphs accumulated in both shallow and deep marine environments have been reported in the Cansona Formation of the Colombian Caribbean (**Dueñas-Jiménez & Gómez-González**, 2013; **Juliao-Lemus *et al*.**, 2016).

The Quebradagrande complex, located on the western border of the Central Cordillera, contains organic mudstones that exhibit fossil plants with ages from the Hauterivian, possibly the oldest from the Cretaceous in Colombia (**Lemoigne,** 1984; **Maya & González,** 1995; **Jaramillo,** 2012; 2019). Efforts to recover palynomorphs from the Quebradagrande complex have been unsuccessful due to thermal alteration, which hinders their preservation (**Pardo *et al*.,** 2022). Similarly, the recovery of palynomorphs in Upper Cretaceous marine sediments from the Western Cordillera has been limited given the intense tectonic activity there, which results in a high degree of thermal alteration in the rocks (**Pardo-Trujillo *et al*.,** 2020).

Cenozoic

Significant eustatic changes and climatic variations occurred during the Cenozoic (**Zachos *et al*.,** 2001). In Colombia, the uplift of the Central and Eastern cordilleras (**Pindell & Kennan,** 2009; **Pardo-Trujillo *et al*.,** 2020) resulted in the development of mostly continental sedimentary deposits in the interior of the country drastically altering ecosystems. These events also contributed to the current configuration of tropical forests (**Jaramillo,** 2012).

Palynological studies in Colombia have revealed that at the end of the Cretaceous period, there was an extinction of at least 75% of plant species, which gave rise to new floras dominated mainly by tropical angiosperms during the Paleocene epoch (**van der Hammen**, 1958; **Jaramillo *et al*.**, 2006; **de la Parra**, 2009; **Jaramillo**, 2012, **Carvalho *et al*.**, 2021). From the Paleocene to the Eocene, the rate of new species appearance was higher than the extinction rate indicating an increase in diversity that continued until the middle Eocene (**Jaramillo *et al*.**, 2010). During the late Eocene-Oligocene, a drastic decrease in diversity was followed by a new increase during the Oligocene and early Miocene. This increase was not as high as the one observed during the early-middle Eocene but it did allow for the differentiation of tropical floras with specific composition and structure for the Paleocene, Eocene, and Oligocene-Miocene early forests (**Jaramillo *et al*.**, 2006; **Jaramillo *et al*.**, 2010).

The formation of new continental environments generated changes in the diversity, abundance, and replacement of floristic species. Such events are studied in palynostratigraphy and turned palynology in Colombia one of the most commonly used tools in Cenozoic hydrocarbon exploration (**Kuyl *et al.***, 1955; **van der Hammen**, 1954a, 1954b, 1957b). Since its beginnings in the 1950s, this has led to the description and illustration of pollen and spores (**van der Hammen**, 1954a, 1954b, 1956a, 1956b, 1957b, 1961; **van der Hammen & García-de Mutis,** 1965**; Solé de Porta**, 1960a, 1961, 1963, 1970, 1971; **Kedves & Solé de Porta**, 1963), as well as the development of specific Colombian palynological zonations (**Jaramillo & Rueda**, 2004; **Jaramillo *et al*.**, 2011).

Paleogene: Paleocene-Eocene-Oligocene

The Paleogene period has a considerable amount of palynological data from regions in the Magdalena Valley, the Eastern Cordillera, and the Eastern Llanos, and to a lesser extent, the Caribbean (Cesar-Ranchería and Sinú San Jacinto basins) (**Figures 1a and 5**). In the western part of Colombia, published works are limited. There are no reports of Paleogene sedimentary deposits in the Central Cordillera. In the Western Cordillera, the Paleocene, sedimentary rocks occur in very few localities and have a high degree of thermal maturity that hinders the preservation of palynomorphs (**Pardo-Trujillo *et al*.,** 2020).

The available palynological information for the Paleogene mainly comes from continental deposits such as fluvial and lacustrine sediments, as well as from littoral environments in the northern part of the country including the Eastern Cordillera, the Magdalena Valley, and the Cesar-Ranchería basins. During this period, the coastline was located towards the Pacific, the Caribbean, the northeast of Colombia, and the west of Venezuela (**Moreno-Sánchez & Pardo-Trujillo**, 2003). At some point during the Eocene, the sea advanced into the continent and moved to the Eastern Llanos and the current location of the Eastern Cordillera (**Santos *et al.***, 2008; **Pardo & Jaramillo**, 2014).

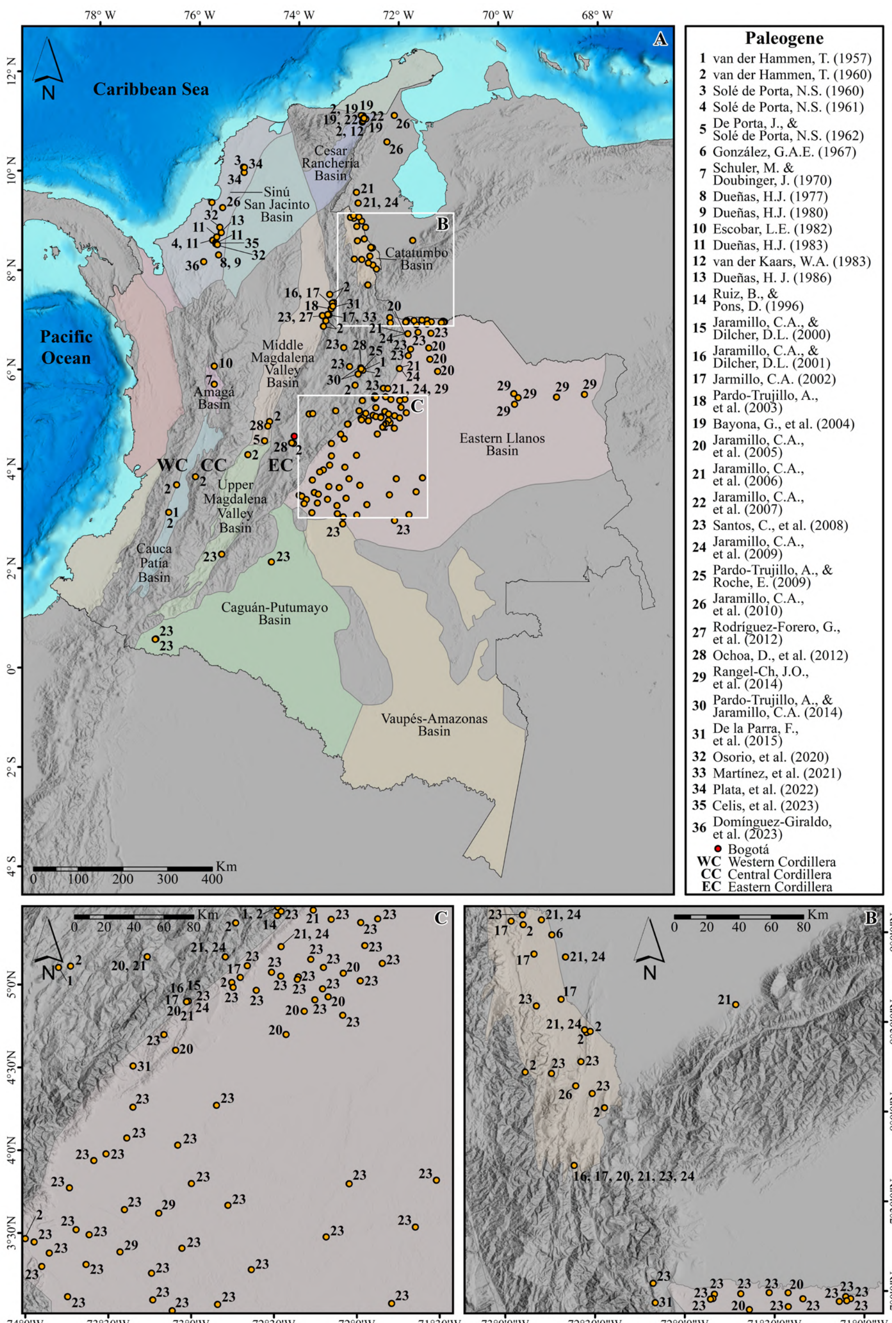

Figure 5. Map of sedimentary basins in Colombia indicating the locations where Paleogene palynological publications have been made. For detailed references, see table 1s.

Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales.
47(183):412-438, abril-junio de 2023. doi: https://doi.org/10.18257/raccefyn.1913

An informal palynological scheme has been proposed for the Middle Magdalena Valley based on high-quality palynological data on the Cretaceous to the Middle Eocene obtained from multiple wells drilled for the industry (**Contreras *et al.***, 2010). Additionally, detailed palynostratigraphic studies of the Paleocene-Eocene have been conducted including analyses of organic matter in sections of the Middle Magdalena Valley, the Eastern Cordillera, and the western part of Venezuela (**Jaramillo & Dilcher**, 2001; **Pardo-Trujillo *et al.***, 2003; **Pardo-Trujillo & Roche**, 2009). Studies have also been conducted in the Nuevo Mundo syncline for the Eocene Esmeraldas Formation (**Rodríguez-Forero *et al.***, 2012) and in two sections on the eastern flank of the Nuevo Mundo syncline where the macro and microflora of the Esmeraldas Formation and the lower part of the Mugrosa Formation have been studied (**Martínez *et al.***, 2021).

Palynological research on the Paleocene-Eocene in the central area of Colombia covering sections of the Middle Magdalena Valley, the Eastern Cordillera, Catatumbo, and the Eastern Llanos has revealed diversity variations and allowed for the description of a large number of new pollen and spore species (**Jaramillo & Dilcher,** 2000; 2001; **Jaramillo**, 2002; **Jaramillo *et al.***, 2010). Sedimentary deposits in the Eastern Cordillera have been extensively studied with palynology in the Cretaceous-Paleogene transition in the Sabana de Bogotá, El Cocuy, and the Llanos foothills (**Solé de Porta**, 1971; **Sarmiento**, 1992b; **Guerrero & Sarmiento**, 1996; **Bayona *et al.***, 2020).

The Early to Middle Eocene palynology of the Catatumbo basin has shown changes in palynological associations possibly linked to relative variations in sea level (**González-Guzmán**, 1967) and similar to findings reported for the late Eocene in the Eastern Llanos, the Eastern Cordillera, and the Putumayo basins, where changes in the content of marine and terrestrial palynomorphs have been associated with marine incursions (**Santos *et al.***, 2008). The reworked palynomorphs found in the Eastern Llanos and the Eastern Cordillera have been used to understand tectonic activity during the Cenozoic in Colombia (**de la Parra *et al.***, 2015). Palynological associations and sedimentary environments of the Usme, Concentración, and Santa Teresa formations in the Eastern Cordillera, which span in the range of Late Eocene-Early Miocene, were studied to understand changes in sedimentary deposits as a result of Andean orogeny centered on the deformation of the Eastern Cordillera (**Ochoa *et al.***, 2012). Previous studies on the Cenozoic zonation (**Jaramillo *et al.***, 2011) describing part of the biostratigraphic palynology in the Eastern Llanos and the Llanos foothills were conducted on the Late Paleocene-Early Eocene of the Los Cuervos Formation (**Jaramillo *et al.***, 2005) and the Eocene in the Mirador formation (**Jaramillo *et al.***, 2009).

During the Paleocene, sedimentary deposits in the Colombian Caribbean describe palynological associations of coastal environments of tidal plains in the Cerrejón Formation (Cesar-Ranchería basin), in the Guajira sector (**van der Kaars**, 1983; **Bayona *et al.***, 2004; **Jaramillo *et al.***, 2007). Recently, a detailed palynological assemblage of the Early Eocene (Ypresian) was described from two core wells drilled in the San Cayetano Formation in the Sinú-San Jacinto Basin (**Plata-Torres *et al.***, 2022). For the Oligocene-Early Miocene of the Planeta Rica sector in the Ciénaga de Oro Formation, in the San Jerónimo and San Jacinto anticlines in the Caribbean, coastal environments characterized by mangroves with variations in the coastline have been described (**Sole de Porta**, 1960a; 1961; **Dueñas**, 1977; 1980a, **Dueñas-Jiménez**, 1983; 1986). In the Cauca Valley basin, palynology of the Amagá Formation has been described in the department of Antioquia, suggesting a middle Eocene-Oligocene age (**Schuler & Doubinger**, 1970; **Escobar**, 1982-1983).

Neogene: Miocene-Pliocene

The Neogene period (Miocene-Pliocene) was a time of significant changes in the configuration of terrestrial and marine ecosystems in South America, driven by a series of global events. The closure of the Central American Seaway (CAS) brought important changes in oceanic circulation and the formation of a new system of currents known as the heat conveyor belt, which had important consequences for global climate patterns. At the same time, the great American biotic interchange occurred, resulting in the exchange of flora and fauna between North and South America. The Neogene also saw the record of the largest amount of Antarctic ice, which had a significant impact on global sea level and oceanic circulation. Finally, the uplift of the Andes had a profound effect on the climate of the region, with modifications in the location and intensity of the Intertropical Convergence Zone (ITCZ) and the formation of distinct ecological zones along the elevation gradient of the mountain range.

The study of these events has allowed an increase in the number of publications in geosciences since the 1980s aimed to understand the history of the Neogene (e.g. **O'Dea *et al.***, 2016; **Bacon *et al.***, 2015; **Cione *et al.***, 2015; **Montes *et al.***, 2015; **Woodburne**, 2010; **Lessios**, 2008; **Schmidt**, 2007; **Webb**, 2006; **Bacon *et al.***, 2015; **Coates *et al.***, 2004, 1992; **Coates and Obando**, 1996; **Duque Caro**, 1990 a, b; **Keigwin *et al.***, 1982). From a botanical point of view, plant fossils from this period are related to current plant communities through comparative taxonomy. Therefore, the study of Neogene pollen spectra is mainly used in research on paleoclimatic and paleoecological reconstructions, in many cases associated with the configuration of the Andes and the global events mentioned above.

During the Miocene-Pliocene in Colombia, the uplift of the Andes formed a natural phytogeographic barrier that gave rise to the tropical forests of Chocó, the Magdalena Valley, and the Amazon, each with its own floristic characteristics, suggesting that the high diversity recorded in the Colombian tropics is the result of a Neogene inheritance rather than Quaternary processes (**Hooghiemstra & van der Hammen**, 1998). Neogene sedimentary deposits are found in all the country's basins, however, most of the palynological publications for this period are from the Eastern Llanos, the Eastern Cordillera, and the Orinoquia (**Figures 1a and 6**).

Palynological studies have been conducted in the Colombian Amazon region, particularly in the area between Araracuara and Isla Cristina, where Late Oligocene-Early Miocene floodplain deposits have been described (**Hoorn**, 1988). Additionally, near Araracuara in the Caquetá River basin, Early-Middle Miocene fluvial deposits have pollen and spore assemblages characteristic of tropical forests with swamp and riparian vegetation (**Hoorn**, 1994a). Sedimentological and palynological studies of Middle-Late Miocene fluvial-lacustrine deposits in the Upper Amazon region suggest that the origin of the Amazon River system is a consequence of the uplift of the Eastern Cordillera (**Hoorn**, 1994b; **Hoorn *et al.***, 1994). Palynological data from the Miocene in the Amazonian region of Perú, Brazil, and Colombia report mangrove vegetation associated with marine incursions due to eustatic changes, subsidence in the periphery of the Guyana Shield, and rapid subsidence in the sub-Andean zone (**Hoorn**, 1993; **Hoorn**, 2006; **Bonstra *et al.***, 2015). In the lower Apaporis River deposits, the presence of mangrove vegetation and dinoflagellates, which fluctuated with palm vegetation during the Late Middle-Late Miocene, constitute palynological evidence of marine incursions (**Hoorn**, 2006). In contrast, dinoflagellate and foraminiferal studies of Lower-Middle Miocene deposits suggest changes in salinity in the northeast Amazon region, indicating that marginal marine conditions extended at least 2000 km inland from the Caribbean. Later, during the Pliocene-Pleistocene, a drop in sea level and a change in the tectonic regime ended the marine incursions in the Amazon basin (**Bonstra *et al.***, 2015). The duration of marine incursions in the Llanos and Amazon/Solimões basins to the northwest of the Amazon suggests two short-lived marine flooding events: one in the Early Miocene and one in the Middle Miocene (**Jaramillo *et al.***, 2017), rather than a single event during the entire Miocene as previously suggested by some authors (**Webb**, 1995; **Räsänen**, 1995).

Miocene palynology in the Eastern Llanos and the Llanos foothills has been presented in zonations and diversity models published by **Jaramillo & Rueda** (2004), **Jaramillo *et al.*** (2006), **Jaramillo *et al.*** (2011), and **de la Parra *et al.*** (2015). However, it has been observed that palynological reports of marine dinoflagellates in this area of the country often show heterochrony with their global distribution due to local marine conditions (**Pinzón *et al.***, 2022; **Cárdenas *et al.***, 2020).

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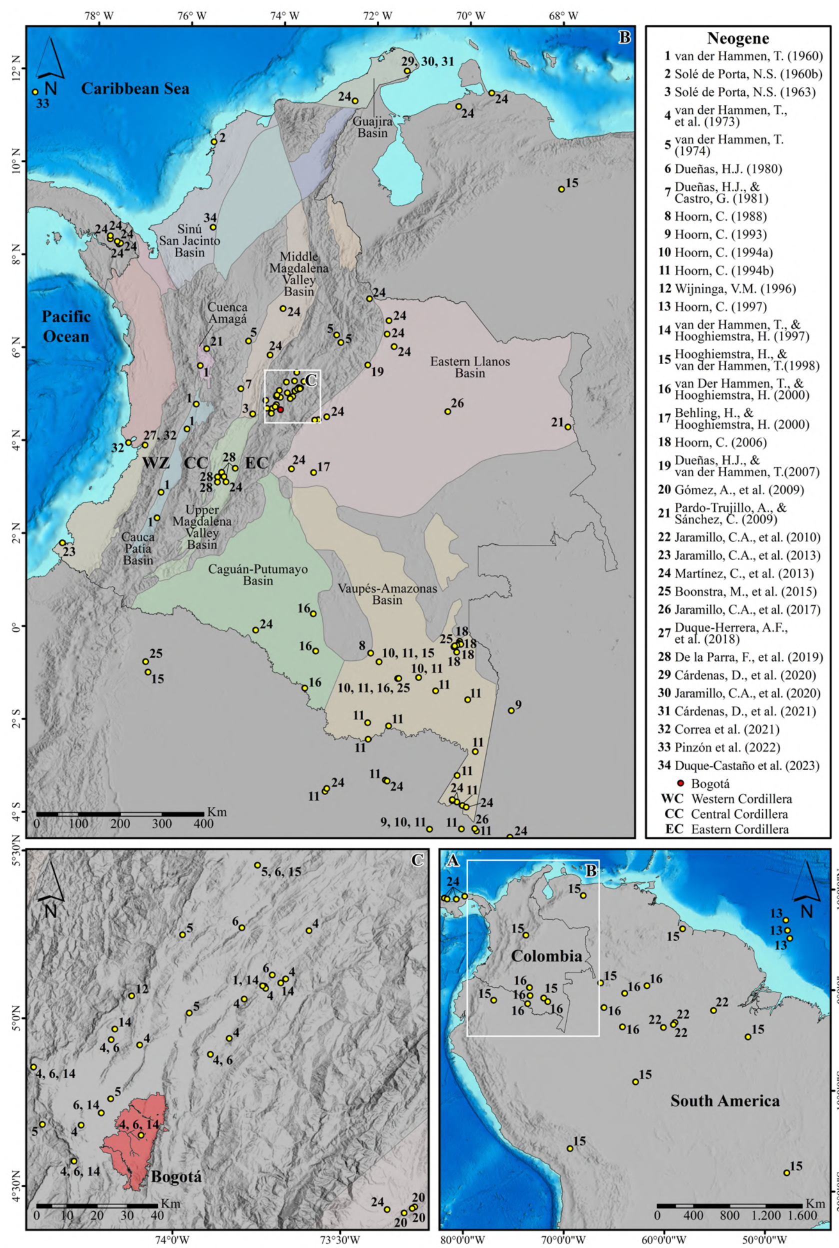

Figure 6. Map of sedimentary basins in Colombia indicating the locations where Neogene palynological publications have been made. For detailed references, see table 1s.

In the Llanos foothills, north of Yopal, the palynological content has been studied from Early Miocene marine sediments in the lower Diablo Formation previously considered to be from the Oligocene (**van der Hammen**, 1960) and the Middle to Late Miocene San Fernando Formation (**Dueñas-Jiménez & van der Hammen**, 2007). In this study, vegetation changes related to fluctuations between marine-influenced lacustrine and fluvial environments were interpreted (**Rangel *et al.***, 2014). Multi-tool studies using mollusks and palynology have interpreted lakes of up to 10 km extent with marine incursions for the eastern edge of the Eastern Cordillera in the Early Miocene Carbonera C2 Formation (**Gómez *et al.***, 2009).

In general, the Neogene period, and especially the Pliocene-Quaternary deposits, have been extensively studied in the Eastern Cordillera with palynological research in the Tilatá, Subachoque, and Sabana formations in the Sabana de Bogotá, where the end of the uplift of the Eastern Cordillera has been described, as well as the enrichment of the local flora with the arrival and establishment of Holartic and Antarctic floristic immigrants in the Colombian Andes (**van der Hammen & González**, 1960; **van der Hammen**, 1957a, 1961, 1966; **van der Hammen *et al*.**,1973). These pioneering works by van der Hammen were later summarized in a monograph (**Dueñas**, 1980b). In the following years, important paleobotanical research (macro and microflora) continued in localities near the Sabana de Bogotá and its surroundings (**van der Hammen**, 1974; **Hooghiemstra**, 1984; **van der Hammen & Cleef,** 1986; **Hooghiemstra**, 1989; **Wijninga & Kuhry**, 1990, 1993; **Hooghiemstra & Cleef**, 1995; **Wijninga**, 1996a, b, c, d; **Torres**, 2006), which allowed to understand the evolution of the Andean forest and its relationship with the Andean orogeny (**Hooghiemstra *et al*.**, 2006).

For the Pliocene and Quaternary in the eastern zone of Colombia, chronostratigraphic units have been established based on pollen and spore content including Tequendamian, Facatativan, Sisganian, Chocontanian, Engativan, Funzanian, Fuchanian, Cotanian, Subanian, Bacatanian, and Fuquenian (**van der Hammen & Hooghiemstra,** 1997). These authors also made significant contributions to the phytogeographic knowledge by proposing a hypothesis of the establishment and development of the diverse Neotropical forests during the Neogene as a response to changes in drainage patterns and the isolation of new dynamic ecotones (e.g. Amazon, Magdalena Valley, and Chocó), originated with the uplift of the Andes. As in the Orinoquian-Amazonian region, marine fluctuations would be responsible for an ecosystemic pressure that would be crucial in evolutionary processes reflected in the richness and decrease of species. The authors also affirmed that during the Quaternary, the extinction of plant species was a common phenomenon since the current species diversity appears to be lower than that observed in the palynological diversity diagrams of the Miocene-Pliocene. Besides, according to the authors, during the last glacial period in the Quaternary, the Amazon basin in different sectors and times maintained its rainforest vegetation cover, or it was replaced by savannas, depending on the climatic conditions (**Hooghiemstra & van der Hammen**, 1998).

Miocene palynology in the Magdalena Valley has been conducted in the La Cira Formation, municipality of Jerusalén-Cundinamarca (**Solé de Porta**, 1963), and in the Barzalosa Formation, where extensive lacustrine systems during the Early Miocene have been described and correlated along the Middle and Upper Magdalena valleys (**Zapata *et al*.**, 2023; **de la Parra *et al*.**, 2019). In the Falan region, department of Tolima, palynological associations related to altitudinal changes during the Pliocene have been studied in the Las Palmas Member of the Mesa Formation (**Dueñas & Castro**, 1981). The palynology of Cerro La Popa in Cartagena presents two different floristic assemblages associated with altitudinal changes, where the presence of *Alnus* could indicate sedimentary deposits from the Upper Pliocene to Pleistocene age (**Solé de Porta**, 1960b).

Recently, studies have been conducted on the palynology of the Miocene in western Colombia including the Pacific and the Caribbean. In the Patía sub-basin sector of the Cauca Valley, the sedimentology and palynology of the Burdigaliano-Early Langhian Morales Formation have been described (**Gallego-Ríos *et al.***, 2020). In the Pacific, at least three sedimentary cycles of transgression-regression have been described using dinoflagellates from the Buenaventura 1-ST-P well (**Duque-Herrera *et al*.**, 2018), while in the Ladrilleros Juanchaco sector, an increase in primary productivity during the Serravalian-Tortonian was demonstrated by dinoflagellate (**Correa *et al*.**, 2021) and other microfossils studies (**Vallejo *et al.***, 2016; **Plata *et al*.**, 2018). Towards the Caribbean sector, in the Cocinetas Basin on the Guajira Peninsula, heterochrony has been recognized in relation to high latitude data in Lower Miocene dinoflagellates leading to the proposal of a dinoflagellate biostratigraphy for the Late Chattian-Early Burdigalian, as well as the description of new species of acritarchs and dinoflagellates (**Cardenas *et al*.**, 2020; **Cárdenas *et al*.**, 2021). Also, in the Cocinetas Basin, an integrated study was conducted to understand changes in the vegetation from the Late Oligocene to the Early Miocene, where an age model of marine micropaleontology including dinoflagellates was presented (**Jaramillo**

et al., 2020). Integrated palynological studies with calcareous microfossils in the DSDP 502A in the Colombian Caribbean during the Late Miocene-Pliocene show synchrony in some dinoflagellates and highlight the importance of including terrestrial palynomorphs in the study of deep-sea sediments (**Pinzón *et al.***, 2022). In the Sinú-San Jacinto Basin, sedimentary deposits spanning de Ciénaga de Oro (CDO) and Porquero formations were studied from a core using integrated micropaleontological tools; due to the environments there, only palynomorphs were recovered to CDO; in contrast, for the Porquero formation, the recovery of marine calcareous microfossils allowed to calibrate some palynomorph ages (**Duque-Castaño *et al.***, 2023).

Additionally, palynological publications reviewed the taxonomy, phylogeny, stratigraphic distribution, and biogeography of some microfossils with current representatives within the Araucariaceae, Chloranthaceae, Fabaceae, and Palmae families, such as *Cyclusphaera* sp., *Clavainaperturites microclavatus*, *Striatopollis catatumbus*, and *Mauritia* sp., respectively. The aim was to understand their origin and radiation using modern optic techniques of taxonomic identification and advanced computer programing (Software R) (**Rull**, 1998; **Pardo-Trujillo & Sánchez**, 2009; **Jaramillo *et al.***, 2013; **Martínez *et al.***, 2013; **Romero *et al.***, 2020; **Bogotá *et al.***, 2021).

Overview of palynological advances in the Colombian Caribbean

Currently, the Colombian Caribbean is considered a frontier basin due to its high number of oil and gas seeps, which suggests a high potential for hydrocarbon exploration (**Barrero *et al.***, 2007). However, palynological studies in this sector are scarce (**Figure 1**). In recent years, the National Hydrocarbons Agency (ANH) has conducted studies including regional seismic lines, core drilling, geological mapping, and different types of sample analyses. In this context, the University of Caldas has carried out micropaleontological studies including the palynology of drill cores covering the interval from the Maastrichtian to the Pliocene (**Figure 7**). In the Cesar-Ranchería Basin, wells ANH-La Loma 1, ANH-La Estación-1, ANH-Carretalito-1, ANH-Cañaboba-1, ANH-La Loma 2 have been studied and in the Sinú-San Jacinto Basin, wells ANH-La Estrella-1X, ANH-Piedras Blancas-1X, ANH-San Cayetano-1, ANH-La X-1A, ANH-Mohambo-1X, ANH-San Antero-1X, ANH-Nueva Esperanza-1X, ANH-Tierra Alta-2X-P, ANH-San Jacinto-1, ANH-La Cantera-1, ANH-Costa Azul-1, P18, ANH-San Antonio-1X, and ANH-Los Pájaros-1X.

Palynology data from the San Cayetano, Chengue, San Jacinto, Ciénaga de Oro, and Porquero formations spanning Early Eocene (Ypresian) to Early Miocene have been published recently by **Osorio-Granada *et al.*** (2020), **Plata-Torres *et al.*** (2022), **Castaño-Duque *et al.*** (2023), **Domínguez-Giraldo *et al.*** (2023) and **Celis *et al.*** (2023).

Based on the Llanos and the Llanos Foothills zonation (**Jaramillo *et al.***, 2011), a preliminary overview of the palynology of the Caribbean (**Figure 7**) (**Table 2S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3371; **Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3372) showed that the Maastrichtian-Paleocene boundary has been documented in the ANH-La Loma-1 well. The middle and late Paleocene and the Paleocene-Eocene boundary have been recognized in the ANH-La Estación-1, ANH-Carretalito-1, ANH-Cañaboba-1, and ANH-La Loma-2 wells, respectively, all located in the Cesar-Ranchería Basin. In the latter, reworked Cretaceous palynomorphs were observed. There is no clear evidence of Paleocene deposits from the palynological data in the Sinú-San Jacinto Basin. A discordant Maastrichtian- Paleocene(?) with Eocene deposits was observed in the ANH-La Estrella-1X well. Early Eocene deposits were examined in ANH-Piedras Blancas-1X, ANH-San Cayetano-1, ANH-La X-1A, ANH-Mohambo-1X, and ANH-San Antero-1X wells. Middle-Late Eocene palynomorph associations were observed in the ANH-La Estrella-1X, ANH-San Jacinto-1, ANH-La Cantera-1, and ANH-Tierra alta-2X-P wells. The Oligocene was reported at the top of the ANH-La Estrella-1X and ANH-San Jacinto-1, and at the base of ANH-La Cantera-1, ANH-Costa Azul-1, ANH-Nueva Esperanza-1X, ANH-Tierra alta-2X-P, P18, and ANH-San Antonio-1X, at the top of which Miocene deposits were identified. The

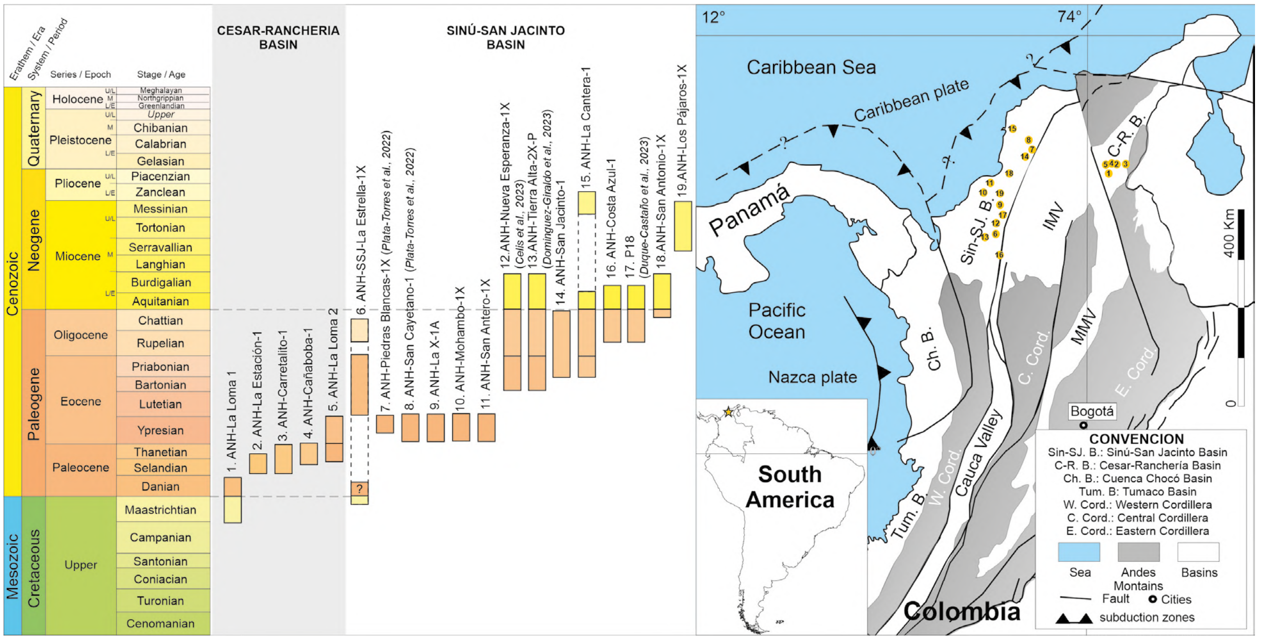

Figure 7. Localization of 19 exploratory wells studied in Colombia and distributed through time. Some of their palynology has been published.

Miocene-Pliocene was recovered in the ANH-Los Pájaros-1X well, where the reworked Maastrichtian palynomorphs were reported (**Table 2S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3371; **Appendix 1,** https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3372).

Palynological highlights for the Caribbean include: 1) Biostratigraphic range extension to the Ypresian (Early Eocene) of some palynomorphs described in the Oligocene (e.g. *Grimsdalea minor*) by **Dueñas-Jiménez** (1986) and from the Miocene (*Grimsdalea magnaclavata*) by **Germeraad *et al.*** (1968); 2) global marine events reported during the Early Eocene were observed in the Caribbean (e.g. *Adnatosphaeridium multispinosusm* Acme); 3) diacronism of marine palynomorph events reported to the Llanos and the Llanos foothills (**Jaramillo *et al.***, 2011) while in the Caribbean the marine events are more consistent with global reports than with those proposed in the zonation; 4) the palynology of the Early Eocene from the Caribbean is similar to that reported in the Catatumbo basin, with a high diversity of palmae and bombacoideae types (**González-Guzmán**, 1967); 5) discordances: deposits from the Maastrichtian discordant with the Eocene (agree with **Duque-Caro**, 1971), probably discordances into Eocene-Oligocene boundaries, however more research is needed regarding these epochs; 6) reworked palynomorphs from the Cretaceous in the Miocene deposits and Oligocene reworked in Early Miocene deposits in the Sinú-San Jacinto Basin, as well as Cretaceous reworked palynomorphs in Late Paleocene deposits in the Cesar-Ranchería Basin; 7) the applicability of the Llanos and the Llanos foothills zonation (**Jaramillo *et al*.,** 2011) in the Caribbean Basin is good, but some minor variations and the occurrence of new species could be improved.

Final reflections and conclusions

Palynology in Colombia has been mainly focused on the needs of the hydrocarbon sector, geological mapping, stratigraphy, and vegetation evolution. The Paleozoic, with 10 publications and 63 localities, has been studied mainly in wells and sections in the eastern Llanos and the Amazon basin. The Cretaceous, with 32 published papers, covers 70 localities distributed in the Eastern Cordillera, the UMV, the Cesar-Ranchería, Catatumbo, and the Colombian Caribbean basins. The Paleogene has 35 publications about a large number of localities (210) among the wells and sections distributed in most of the sedimentary basins of the country, but no publications in the southern region and the Colombian Pacific. Like the Paleogene, the Neogene also has 34 publications and 168 localities, with publications in the Amazon region and the first reports of palynomorphs in the Pacific standing out.

In the last decade, the publication of the first palynological zonation for the Cenozoic in Colombia and the progress made in western Colombian (e.g., Cauca Valley and Pacific basins) has been outstanding. In frontier basins such as the Caribbean, the role of the ANH and the recent collaboration of the University of Caldas, has allowed for a complete compilation of the palynological record of the Sinú-San Jacinto and Cesar-Ranchería basins through the drilling of exploratory wells and some of the results have been published and disseminated in different academic scenarios. However, much remains to be explored, especially in regions of the country where access is limited due to public security issues and geographic challenges. These sectors include some areas of western Colombia and the Caribbean.

Colombia continues training palynologists while the development of new artificial intelligence technologies opens for palynology new research pathways that will allow the exploration of Neotropical diversity through database management and help from the oil and gas industries. Additionally, increased knowledge of climate change issues promotes the development of strategies for CO_2 capture through the integration of palynology with fields such as stratigraphy and structural geology.

Supplementary material

Tabla 1S. References used in the maps (Figures 3-6) and localities of palynological studies from the Paleozoic to Neogene. See the table 1S in https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3370

Tabla 2S. Palynomorph distribution chart of Colombian Caribbean. New data. See the table 2S in https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3371

Appendix 1. Palynomorphs recovered in Colombia spanning the Cretaceous to the Neogene. See the Appendix in https://www.raccefyn.co/index.php/raccefyn/article/view/1913/3372

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Authors' contributions

A.Pl-T.: Conceptualization, investigation, methodology, writing of the original draft, visualization, review, and editing; A.P-T.: Supervision, conceptualization, writing - review & editing; C.G-G.: Review & editing; J-A.F.: Supervision, review & editing.

Conflicts of interest

The authors declare that they do not have any conflict of interest about the content of this work or its financial support.

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