

Neoproterozoic Records of the Llanos Orientales Basin, Colombia

Hernando DUEÑAS–JIMÉNEZ^{1*}  and Jorge MONTALVO–JÓNSSON²

Abstract In the Llanos Orientales Basin of Colombia, below thick Tertiary and Cretaceous strata, Paleozoic sedimentary sequences are present, which yield good, diverse, and well-preserved assemblages of palynomorphs. In the northeastern part of the basin in the Arauca Graben, after crossing the unconformity at the base of the Cretaceous sequence, oil wells face the presence of Cambrian and Neoproterozoic (Cryogenian – Ediacaran) sedimentites deposited in low latitudes under shallow marine settings that yield abundant, diverse, poorly preserved, and dark-colored sphaeromorph acritarch assemblages.

In the Chiguiro–1, La Coral–1, and Pato–1 wells drilled in 1985–1986, the presence of Ediacaran palynomorphs was observed for the first time in Colombia. This discovery can be considered to be the oldest sedimentites dated by paleontological methods reported in Colombia. Twenty-six years later, analysis of samples from the Chilacoa–1S, Coralito–1S, Torodoi–1X, and Vaco–1X wells confirmed the presence of Ediacaran sedimentites in the Llanos Orientales Basin. All these wells are located in the Arauca Graben, which is a northeast tectonic depression that extends north, reaching Venezuelan territory.

In the Arauquita–1–Torodoi–1X seismic transect it is possible to observe the presence of a general pinch-out of Tertiary and Cretaceous stratigraphic units towards the east. Under the basal Cretaceous unconformity, all of the stratigraphic units have suffered a great tectonic activity that divides the Arauca Graben into narrow blocks, in which it is possible to observe the presence of a not yet drilled stratigraphic sequence with a thickness of several thousand feet that could involve pre-Ediacaran sedimentites. The detailed palynological analysis of those sedimentites could aid in the interpretation of the evolution of life during (acritarchs) early times.

Keywords: *acritarchs, Ediacaran, Llanos Orientales Basin, Arauca Graben.*

Resumen En la Cuenca de los Llanos Orientales de Colombia, bajo los espesos estratos del terciario y del Cretácico, se encuentran secuencias sedimentarias paleozoicas y neoproterozoicas que tienen abundantes y diversas asociaciones de palinómorfos bien preservados. En el sector nororiental de la cuenca, luego de cruzar la discordancia en la base de la secuencia cretácica, los pozos perforados dentro del Graben de Arauca registran sedimentitas del Cámbrico y Neoproterozoico (Criogeniano–Ediacariano) depositadas en latitudes bajas y en un ambiente marino somero. Estas sedimentitas neoproterozoicas contienen asociaciones de acritarcos esferomorfos abundantes, diversas, pobremente preservadas y oscurecidas.

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En los pozos Chiguiro–1, La Coral–1 y Pato–1, perforados en 1985–1986, se observó por primera vez en Colombia la presencia de palinomorfos ediacarianos. Este descubrimiento se puede considerar como el de las sedimentitas más antiguas datadas por métodos paleontológicos que se han reportado en Colombia. Veintiséis años después, el análisis de muestras de los pozos Chilacoa–1S, Coralito–1S, Torodoi–1X y Vaco–1X confirmó la presencia de sedimentitas ediacarianas en la Cuenca de los Llanos Orientales. Todos estos pozos están ubicados en el Graben de Arauca, una depresión tectónica de dirección noreste que se extiende hacia el norte hasta llegar a territorio venezolano.

En la transecta sísmica Arauquita–1–Torodoi–1X es posible observar un acuñamiento hacia el este de las unidades estratigráficas terciarias y cretácicas. Bajo la discordancia basal del Cretácico, todas las unidades estratigráficas han sufrido una gran deformación tectónica que divide el Graben de Arauca en bloques estrechos. En estos bloques es posible observar una secuencia estratigráfica aún no perforada de varios miles de pies de espesor que podría involucrar sedimentitas preediacarianas. El análisis palinológico detallado de estas sedimentitas podría ayudar en la interpretación de la evolución de la vida (acritarcos) durante los primeros tiempos del planeta.

Palabras clave: *acritarcos, Ediacariano, Cuenca de los Llanos Orientales, Graben de Arauca.*

1. Introduction

The Llanos Orientales is one of the largest sedimentary basins in Colombia and has been a target for oil exploration since the 1940s. Exploratory activity in this basin has been increased in the last decades, but, nevertheless, the basin still holds great possibility for new oil discoveries.

The Llanos Orientales Basin is a lowland area that covers more than 300 000 km² on the eastern edge of Colombia (Figure 1). It is bounded on the west by the Andean Eastern Cordillera and on the north by the Colombia–Venezuela border. It is bounded on the southwest by the serranía de La Macarena and in the southeast and east by outcrops of igneous and metamorphic rocks that belong to the Guiana Shield (Cordani et al., 2016).

The Llanos Orientales Basin is a north trending structural depression adjacent to the Eastern Cordillera. The sedimentary sequences that refill this depression are clearly divisible into three chronostratigraphic units, which have been palynologically dated to the Paleozoic, Cretaceous, and Tertiary. These units are internally separated by well-known regional unconformities and have been considered independently as oil systems.

In the main depocenters of this basin, 3D seismic surveys allow observations of Paleozoic stratigraphic sequences that can reach thicknesses exceeding 15 000 feet (Dueñas, 2001, 2011; Arminio et al. 2013). However, this sequence of marine sedimentites has received very little attention to date, probably because a low hydrocarbon potential has been wrongly assumed (Dueñas, 2002; Arminio et al. 2013).

In the eastern part of the basin (Arauca Graben), the Sun Colombia Oil Company drilled the Chiguiro–1, La Coral–1, and Pato –1 wells in 1985 (Figures 1, 2). After drilling a thick sequence of Tertiary and Cretaceous sedimentites, those wells passed through the basal Cretaceous unconformity facing Cambrian and Neoproterozoic strata (Dueñas, 2001, 2011). Later,

(2011–2012), the Pacific Rubiales Company drilled four wells that confirm the presence of Ediacaran sedimentites in the basin. The Chilacoa–1, Torodoi–IX, and Vaco–IX wells at their bottoms drilled sedimentites of Ediacaran age. Palynological analysis of samples from the Coralito–1S well confirm the presence of Ediacaran sedimentites and suggest the presence of Ediacaran – Cryogenian palynomorphs (Arminio et al., 2013).

Ediacaran palynological associations similar to those reported in the Llanos Orientales have been described in many locations in Europe, Asia, and Africa (Korolev & Ogurtsova, 1983; Baudet, 1988; Palacios & Vidal, 1992; Strother, 1996), but interest in these sedimentites in Latin America has only begun recently (Dueñas, 2001, 2011; Gaucher et al., 2004; Gaucher & Sprechmann, 2009; Gaucher & Poiré, 2009; Ibañez–Mejía et al., 2011; Chigliano, 2013; Chigliano et al., 2015). Unfortunately, the efforts of Feo–Codecido et al. (1984) to study and interpret the Paleozoic rocks of the Venezuelan basins did not continue.

The main objective of this work is to analyze the palynological data obtained from the study of samples from these seven wells and improve our understanding of the diversity of the biosphere during the Ediacaran – Cryogenian in Colombian areas.

2. Palynological Data

In 1985–1986, the Sun Colombia Oil Company carried out a drilling program in the eastern part of the Llanos Orientales Basin. Three of the drilled wells with bottomed cores reported the presence of Ediacaran strata. These three wells are located in what today is known as the Arauca Graben, which is an elongated structure oriented northeast that extends to Venezuelan territory (Figure 1). The Chiguiro–1, Pato–1, and La Coral–1 wells, after crossing thick stratigraphic sequences of Tertiary and Cretaceous sedimentites, passed through the basal unconformity of the Cretaceous and began to perforate Cambrian and

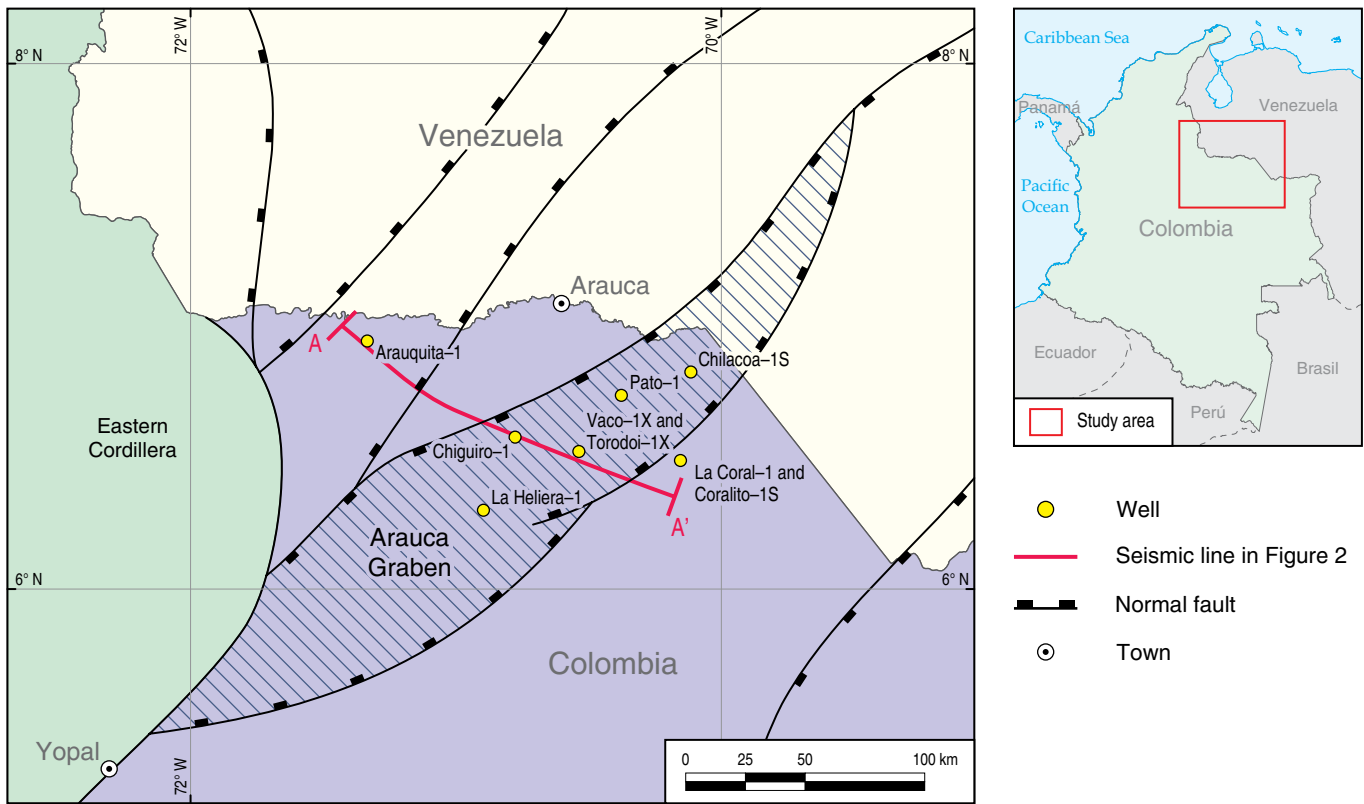


Figure 1. Map of northeastern Llanos Orientales Basin showing the locations of wells included in the text.

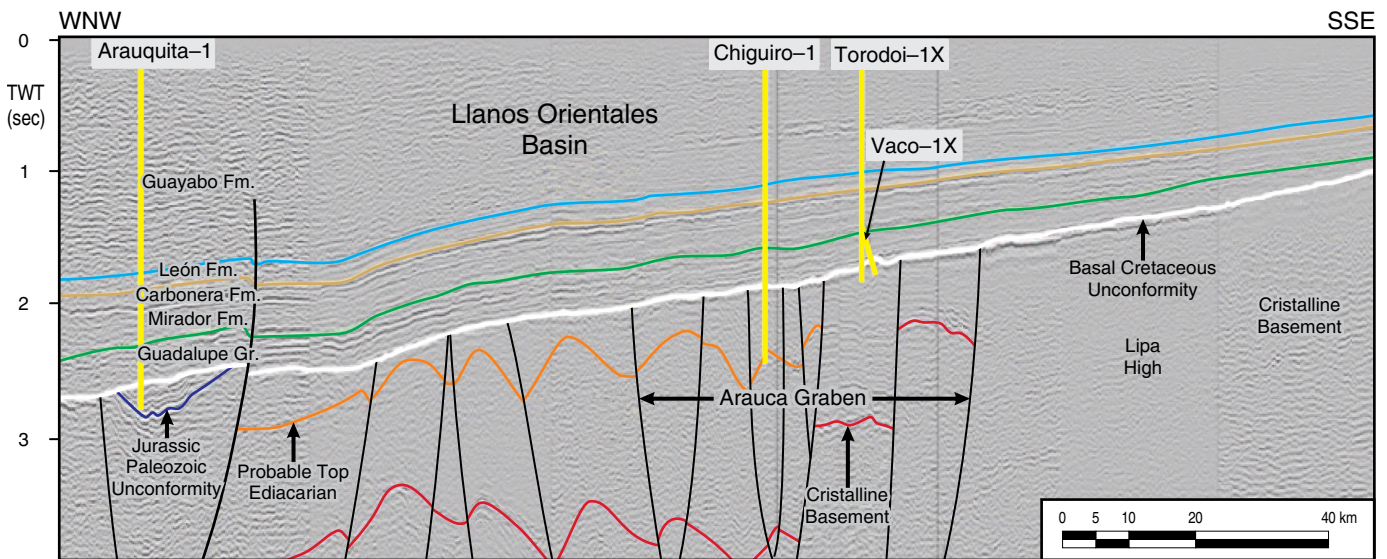


Figure 2. Seismic transect from Arauquita-1 to Torodoi-1X, in which it is possible to observe the regional pinch-out of the Tertiary and Cretaceous units towards the east as well as the tectonics of blocks related to the Arauca Graben. In the Arauquita-1 well, after drilling the unconformity at the base of the Cretaceous, the well drilled a Jurassic sequence before reaching Paleozoic sedimentites. Adapted from Arminio et al. (2013).

Ediacaran sedimentites. The Ediacaran palynological assemblages recovered from those cores samples are comprised of poorly preserved but clearly identifiable acritarch assemblages (Figures 3, 4, 5).

2.1. Chiguiro-1 Well

On 27 January 1985, the Sun Colombia Oil Company carried out a drilling program that commenced with the spudding of

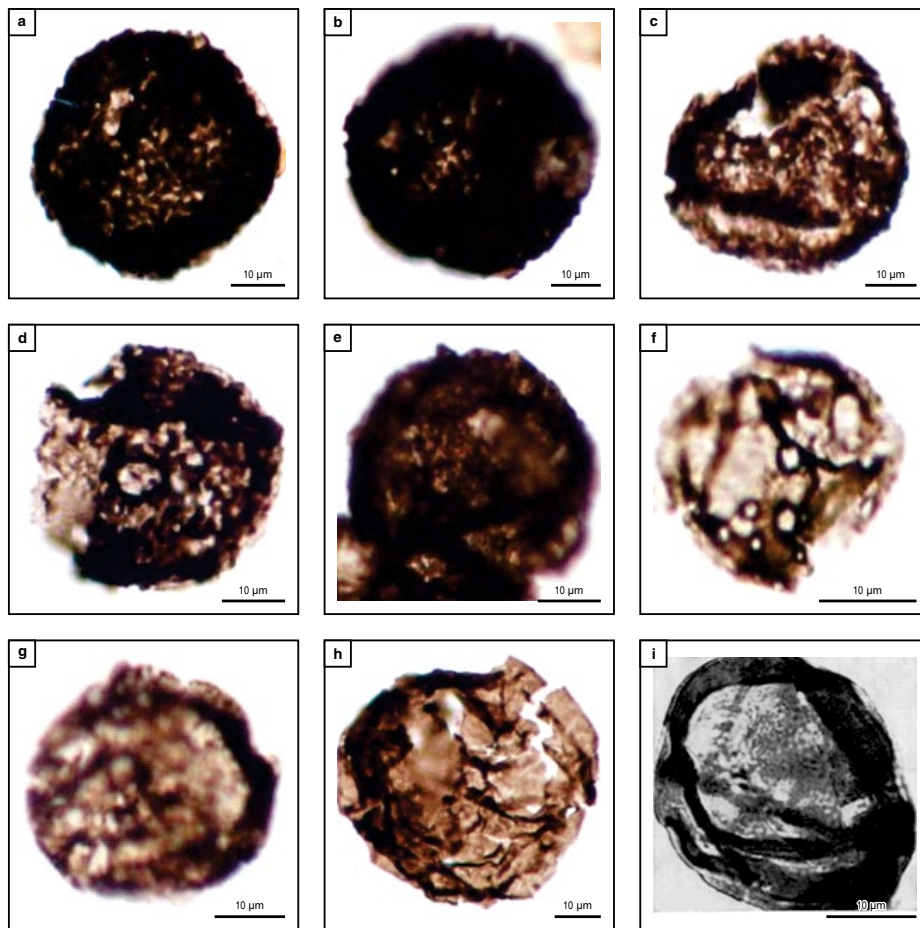


Figure 3. Neoproterozoic acritarchs found in the Llanos Orientales Basin of Colombia. Adapted from Arminio et al. (2013) and Dueñas (2011). Subfigures (a), (b), (c), (d), (e) display *Kildinosphaera cf. verrucata* whereas (f), (g), (h), (i) exhibit *Kildinosphaera chagrinata*.

the Chiguiro–1 well. The primary objective of this well was a large thrust (flowered) anticline that appeared in seismic lines below the regional unconformity of the Cretaceous. The age of the preunconformity section was not known prior to drilling, and speculations ranged from Lower Paleozoic to Lower Cretaceous.

There were no secondary objectives. After drilling 8630' feet of Tertiary and Cretaceous sedimentites, this well passed through a regional unconformity and began to drill fine, blackish, shallow marine sedimentites of Middle to Early Cambrian age and later (11 800) sedimentites of Ediacaran age (Dueñas, 2011).

Sedimentites under the unconformity are constituted by hard bioturbated siltstones with dolomitic and calcite cement. Cuttings samples were taken at 30–feet intervals. Several sidewall cores were taken, and three conventional cores were acquired towards the base of the drilled sequence.

Cuttings samples yielded Cambrian palynological assemblages, including the acritarchs *Granomarginata squamacea*, *Michrhystridium* sp., *Multiplicisphaeridium* sp., *Comasphaeridium strigosum*, *Dictyotidium birvetense*, *Acanthodiacrodium*

constrictum, *Protosphaeridium cf. densus*, *Synsphaeridium conglutinatum*, *Baltisphaeridium pellucidum*, *Dasydiacrodium bicuspidatum*, *Tectitheca additionalis*, *Leiosphaeridia* sp., and *Archaeodiscina cf. umbonulata*. These assemblages also include Chitinozoan fragments. In the uppermost part of this Cambrian interval, the presence of *Timofeevia brevibifurcata* and *Timofeevia lancarae*, species that can reach the Upper Cambrian, was reported.

Samples from the bottom core the 1985 Chiguiro–1 well also yielded palynological assemblages characterized by the presence of *Chuarina circularis* (Figure 4), which is accompanied by *Synsphaeridium conglutinatum*, *Stichtosphaeridium* spp., *Kildinosphaera* spp., *Pterospermopsimorpha* sp., *Synsphaeridium* sp., and *Trematosphaeridium* sp. *Chuarina* is compared with *Leiosphaeridia* and classified with it as a sphaeromorphid acritarch (Wang et al., 2011). The presence of the sphaeromorphid *Chuarina* is indicative of Neoproterozoic strata. *Kildinosphaera* spp. are not known to occur in sedimentites above the Neoproterozoic. This acritarch assemblage is comparable to the Late Ediacarian Leiosphere Palynoflora (LELP).

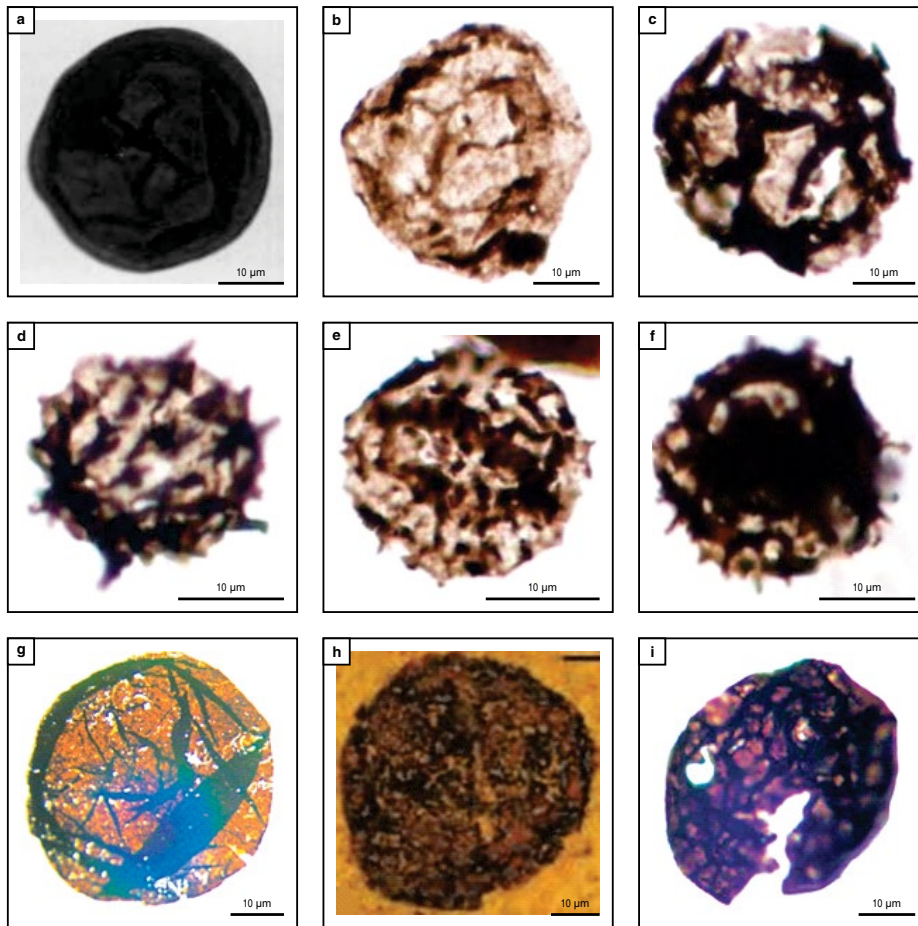


Figure 4. Neoproterozoic acritarchs found in the Llanos Orientales Basin of Colombia. Adapted from Arminio et al. (2013) and Dueñas (2011). Subfigures (a), (b), (c) display *Leiosphaeridia* sp.; (d), (e), (f) show *Michrystridium* sp. and (g), (h), (i) are *Chuaria circularis*.

2.2. Pato-1 Well

The second well drilled by the Sun Colombia Oil Company in the eastern part of the Llanos Orientales was Pato-1. This well was spudded on 19 May 1985. Under the basal unconformity of the Cretaceous, this well penetrated Cambrian – Ediacaran strata. Cuttings samples from the interval 7000'–7165' interval yielded acritarchs of Cambrian age. From the 7170'–7200' (TD) interval, cuttings samples and ten fragments of a conventional core (bottom core) were prepared and analyzed, yielding palynological associations of Ediacaran acritarchs.

Assemblages of acritarchs recovered from fragments of this conventional core include among others *Kildinosphaera chagrinata*, *Kildinosphaera granulata*, *Kildinosphaera lophostriata*, *Lophosphaeridium* sp., *Leiosphaeridia asperata*, *Protosphaeridium* sp., *Synsphaeridium* aff. *conglutinatum*, *Michrystridium* sp., and *Stictosphaeridium* sp. The presence of *Kildinosphaera* spp. are not known to occur in sedimentites above the Ediacaran (LELP). These associations also indicate that these sedimentites were deposited under shallow marine conditions.

2.3. La Coral-1 Well

This well found the top of Neoproterozoic strata at 5650' and reached a total depth of 6492'. A bottom core taken in La Coral-1 encountered a pure sandstone sequence at the top that grades down to bioturbated argillaceous siltstones and sandstones. Very poor assemblages of badly preserved acritarchs were obtained from these sedimentites, which is indicative of high thermal alteration. Recovered acritarchs include *Kildinosphaera* spp., *Michrystridium* sp., and *Leiosphaeridium* spp., which indicate an Ediacarian age (LELP) for core samples.

2.4. Coralito-1S

The Coralito-1S and the Coral-1 wells were drilled close to each other, and are located on the eastern ascending flank of the rift system of which the Arauca Graben form part. Therefore, exhibit similar acritarchs assemblages of *Kildinosphaera* spp. and *Leiosphaeridia* spp., indicating an Ediacaran age, which is either equivalent to the Late Ediacarian Leiosphere Palynoflora (LELP).

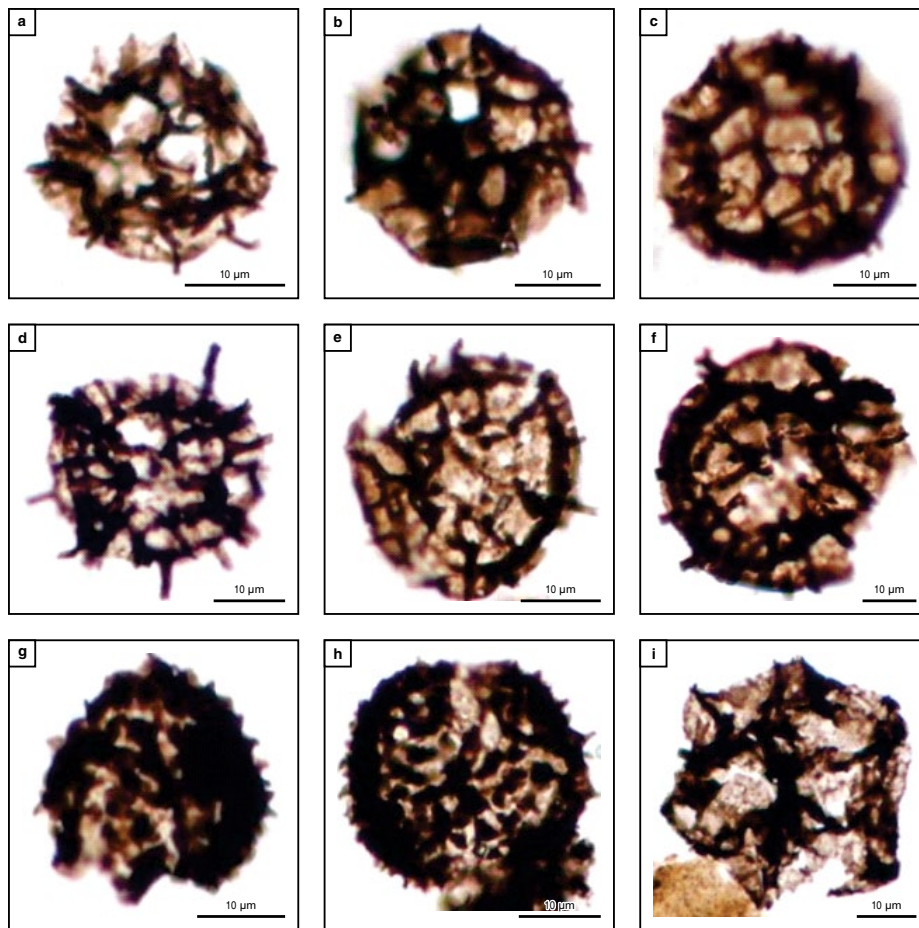


Figure 5. Neoproterozoic acritarchs found in the Llanos Orientales Basin of Colombia. Adapted from Arminio et al. (2013) and Dueñas (2011). Subfigures (a), (b), (c) show images of *Dytiodinium* sp.; (d), (e), (f) display *acanthomorph* acritarch; (g), (h) are *Lophosphaeridium* sp. and (i) *Cymatiosphaera* sp.

2.5. Chilacoa-1S well

The Chilacoa-1S well drilled a total of 6745 feet, by finding the top of Ediacarian strata at 5640 feet (1105). Recovered assemblages include *Cymatiosphaera* spp., *Micrhystridium* spp., and rare *Lophosphaeridium* cf. *tentativum* (Figures 4, 5), suggesting a Late Neoproterozoic very close to the base of the Cambrian (Arminio et al., 2013).

2.6. Torodoi-1X Well

Samples from the interval 7200'–7327' were prepared and analyzed by palynological methods. Good assemblages of poorly preserved acritarchs were obtained from these samples, which are dominated by sphaeromorph forms. Identifiable forms include *Kildinosphaera* spp., (*K. verrucata* and *K. chagrinata*) (Figure 3) and *Leiosphaeridia* spp. This dominance of sphaeromorph acritarchs is characteristic of an Ediacaran age (LELP).

Kildinosphaera spp. (Figure 3) are not known to occur in sedimentites above the Neoproterozoic, but the base of their

range is in the Tonian. Based on the recovered palynomorphs, an Ediacaran age can be assigned to these sedimentites, which were deposited under shallow marine environments.

2.7. Vaco-1X Well

This well was drilled as a sidetrack well of Torodoi-1X. Samples from 8760' to 8880' were prepared and analyzed. The abundant presence of poorly preserved, dark-colored sphaeromorph acritarchs were obtained from these samples. Identifiable forms include *Kildinosphaera* spp. (*K. verrucata* and *K. chagrinata*) with *Leiosphaeridia* spp. This dominance of sphaeromorph acritarchs is characteristic of an Ediacaran age (LELP). The Vaco-1x and Torodoi-1X acritarchs assemblages are similar. Again, *Kildinosphaera* spp. are not known to occur in sedimentites above the Neoproterozoic (Figure 3).

These taxa occur in the Neoproterozoic, certainly within the Ediacaran, but the base of their range is uncertain. A Late Tonian – Ediacaran age has been assigned to these sedimentites, which were deposited under shallow marine environments.

3. Discussion

In the northeastern part of the Llanos Orientales Basin (Figure 1), there is a tectonic depression known as the Arauca Graben. The main faults that control this graben extend towards the northeast, crossing from one side of the frontier with Venezuela to the other.

Dozens of wells have been drilled in the Arauca Graben, but only the Chiguiro–1, Chilacoa–1S, and La Heliera–1 wells were drilled with the main objective of studying the sedimentary sequence below the Cretaceous – Paleozoic unconformity (Figure 2). The other wells drilled in the Arauca Graben immediately touched the Paleozoic ended.

For a long time, Paleozoic sedimentites were mistakenly considered as metamorphic rocks and the economic basement of the Llanos Basin. Palynological determinations have allowed us to determine that both the color and the preservation of palynomorphs recovered from Paleozoic and Neoproterozoic samples are indicative that these sedimentites have experienced thermal alteration but cannot be classified as metamorphic rocks for any reason. It is also important to bear in mind that the presence of both liquid and gaseous hydrocarbons has been reported associated with Paleozoic sedimentites (La Heliera–1) in the Llanos Orientales Basin (Dueñas, 2002, 2011).

In the last two decades, extensive and detailed seismic surveys (2D + 3D) have been carried out in the Llanos Orientales Basin. Those associated with intensive drilling programs have allowed us to observe the presence of a thick Neoproterozoic sequence that could be the basis of proposing a new oil system for the Llanos Orientales Basin.

In the Arauca Graben, core samples from seven wells (Chiguiro–1, Pato–1, La Coral–1, Chilacoa–1S, Coralito–1S, Torodoi–1X, and Vaco–1X) have yielded palynomorphs assemblages indicative of an Ediacaran age and shallow marine settings. The most representative of the recovered Ediacaran acritarchs are *Kildinosphaera* sp. *Leiosphaeridia* sp., and *Chuarina circularis*. These observations should be the subject of future analysis. Undoubtedly, sedimentites analyzed from these seven wells are the oldest ones dated by biostratigraphic methods in Colombia.

From the analysis of the seismic programs obtained in the Arauca Graben as well as from the analysis of samples from the seven wells, it is clear that below the Paleozoic sedimentites there is a sedimentary sequence that until now has been sparsely scratched and that could hold the key to understanding the evolution of Acritarchs in the planet's primary times.

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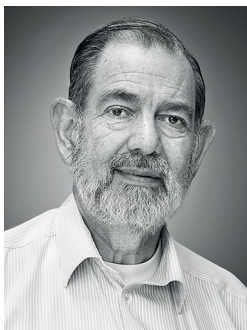
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Explanation of Acronyms, Abbreviations, and Symbols:

LELP	Late Ediacarian Leiosphere Palynoflora	PZ	Paleozoic
		TD	Total depth

Authors' Biographical Notes



Hernando DUEÑAS–JIMÉNEZ studied geology at Universidad Nacional de Colombia, where he graduated in 1972. He later specialized in studies in geology and palynology at the Gemeente Universiteit van Amsterdam, Holland, between 1977–1979 and obtained a PhD in geological sciences in 1986 at the same institution. He was later associated with Servicio Geológico Colombiano leading the Laboratorio de Palinología between 1977 and 1978 and as the Director of the División de Estratigrafía y Paleontología between 1978 and 1980. He was a professor of Palynology in the Departamento de Geociencias, Universidad Nacional de Colombia, Sede Bogotá, between 1979 and 1981, during which time he occupied the position of geologist expert in palynology in Intercol (Exxon group). He was a palynologist in the section of regional works of the Robertson Research INC Company (Houston) between 1982 and 1983, from which he began to practice his profession independently as a consultant geologist in biostratigraphy for the Colombian petroleum industry. In 1978, he was awarded the “Best Geological Research” prize by the Board of Directors of Servicio Geológico Colombiano. He received a

recognition for scientific contribution (San Cayetano Formation) from the Centro de Investigaciones del Petróleo CEINPET, Cuba, in 2003. He held the vice presidency of the Academia Colombiana de Ciencias Exactas, Físicas y Naturales (ACCEFYN) between 2000 and 2002. He is a numerical member of the ACCEFYN and Academia Colombiana de Geografía and a foreign correspondent member of the Real Academia de Ciencias Exactas, Físicas y Naturales de España. He has published more than 80 articles in indexed journals.



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