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Short Communication

Pre-Cretaceous sedimentary sequences of Llanos Orientales Basin, Colombia

Secuencias sedimentarias pre-Cretácicas de la cuenca de los Llanos Orientales, Colombia

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ABSTRACT

Sedimentary deposition in the Llanos Basin (LLO) began in open basins of very freezing waters during the Cryogenian-Ediacaran, continued as deposition in cold open basins during the Cambrian, Ordovician and Silurian, and ended with the deposition in warmer waters during the Devonian and Carboniferous.

In the Chiguiro 1 well, it could be observed that there was a continuous sedimentation, passing from the Ediacaran to the Lower Cambrian. The Cambrian- Lower Ordovician was deposited without obstacles throughout the Basin (LLO). After a strong tectonic period, sedimentation continued only in the Meta Sunbasin, where small sedimentary patches of Ordovician (Floiano-Darriwilian), Silurian, Devonian and Carboniferous ages have been reported. Permian sediments have not been observed in the LLO and probably represents a period of non-deposition or erosion.

Keywords: Play Tectonics, Basin Evolution, Stratigraphy, Palynology

RESUMEN

El depósito sedimentario en la Cuenca de los Llanos (LLO) se inició en cuencas abiertas de aguas muy frías durante el Criogénico-Ediacariano, continuando como depósitos en cuencas abiertas frías durante el Cámbrico, el Ordovícico y el Silúrico, finalizando como depósitos en aguas más cálidas durante el Devónico y el Carbonífero.

En el pozo Chigüiro 1 se pudo observar que existió una sedimentación continua, pasando del Ediacariano al Cámbrico Inferior. El Cámbrico-Ordovícico se depositó sin obstáculos a lo largo y ancho de la Cuenca LLO. Posterior a un fuerte periodo de actividad tectónica, la sedimentación solo continuó en el extremo sur occidental en la Subcuenca del Meta, en donde se ha reportado la presencia de pequeños parches sedimentarios de edades Ordovícico (Floiano-Darriwiliano), Silúrico, Devónico y Carbonífero. El Pérmico no ha sido reportado en la Cuenca de los Llanos y posiblemente represente un periodo de erosión o sin depositación.

Palabras clave: Tectónica de placas, Evolución de la cuenca, Estratigrafía, Palinología.

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1. INTRODUCCIÓN

Colombia occupies the northwest corner of South America (SA), framed by the Pacific Ocean, the Caribbean Sea, Venezuela, Brazil, Peru, and Ecuador. The most outstanding physiographic feature is the Andean Cordillera, which has three branches, the Western, the Central, and the Eastern Cordilleras (Fig.1). The Llanos LLO is a structural depression located toward the east of the Eastern Cordillera,

being the most hydrocarbon prolific (more than 250 oil fields) and the largest sedimentary basin in Colombia covering about 230.000 km² (Guerrero et al. (2022). Bounded on the west by the Andean Cordillera and limited to the south by outcrops of the igneous-metamorphic rocks belonging to the Guyana Shield, the LLO contains some of the most extensive oil discoveries in Colombia including; Caño Limon, Cupiagua, Cusiana, Apiay, Chichimene, Rubiales and others, and it is still considered as a potential basin for big and medium-size discoveries.

In a joint effort between the National Hydrocarbons Agency (ANH) and the Colombian Geological Services (SGC) during the last few years, new information has been acquired (from surface and wells), seismic information has been interpreted and laboratory analysis (petrography, geochemistry, XRD and radiometry) has been performed. This new information has been used to rethink the evolution model of the Eastern Llanos basin. This work shows the exercise carried out with palynological samples from some wells in the study area.

2. GEOLOGICAL SETTING

For long geologic time, the Caribbean, Cocos, and Nazca tectonic plates have been colliding with the South American plate producing an uplift of the Andes Cordillera. The last collision of the plates occurred during the Late Miocene and was very intense, producing the uplift of the Eastern Cordillera by more than 2.000 meters. Due to orogenic movements in Palaeozoic, the LLO was exposed to transpressive deformation.

The resulting compressive structures in the Llanos Basin are large and widespread and could have a strong potential for the entrapping of hydrocarbons.

According to paleogeographic maps for the different Paleozoic Periods produced by Scotese (2014), the Paleozoic sediments in the current Llanos basin (LLO) were deposited in seas with very freezing waters to cold waters. Figure 2 presents the location of South America during the Early Carboniferous 356 Ma.

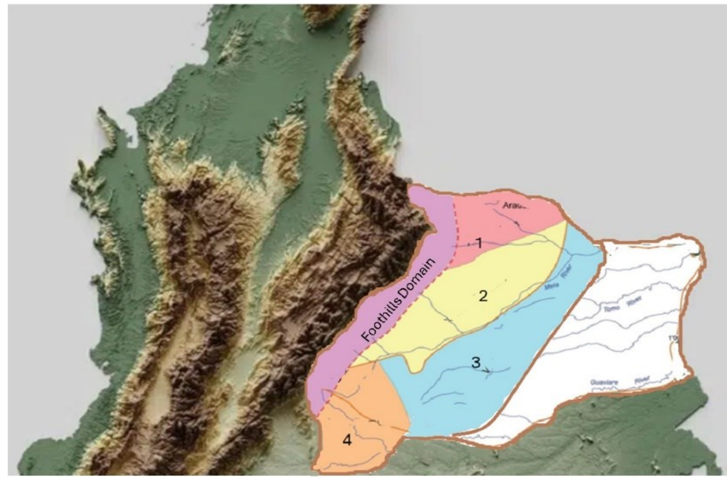

Figure 1: Paleozoic Sub-Basin Llanos Basins (LLO) 1. Arauca Sub-Basin 2. Casanare Sub-Basin 3 Vichada Sub-Basin 4. Meta Sub-Basin. Adapted from Miguel Valenzuela, 2021.

Sharing the same area in surface, the LLO has two overlapping basins; the lower one includes Neoproterozoic and Paleozoic sediments that preserved the impressions of the separation of Pangea; the upper basin, was deposited during the Mesozoic and Cenozoic. The two basins share the compressional history of the collision of the tectonic plates during the Andean orogenies.

During the Triassic and Jurassic, the main tectonic movements took place relating to the destruction of Pangaea. North America and South America separated leaving on both sides rift scars. Today these features are seismically observed in the basement of the LLO.

Sediments from the Berriasian to Aptian have not been reported in LLO (Vayssaire et al., 2014), (Figure 3) The upper Mesozoic sequence is abruptly suspended at the top of the Campanian and locally reestablished during the Paleocene and Eocene. Of the 252 Ma that makes up the Mesozoic-Cenozoic stratigraphic sequence, about 65% were not deposited or eroded in the LLO.

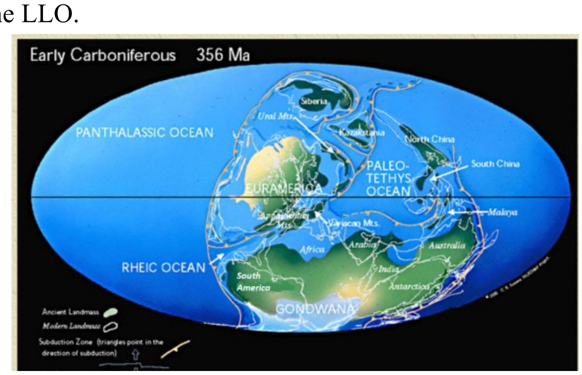

Figure 2: Paleogeographic location of South America block during the Early Carboniferous. Taken from Scotese, 2014.

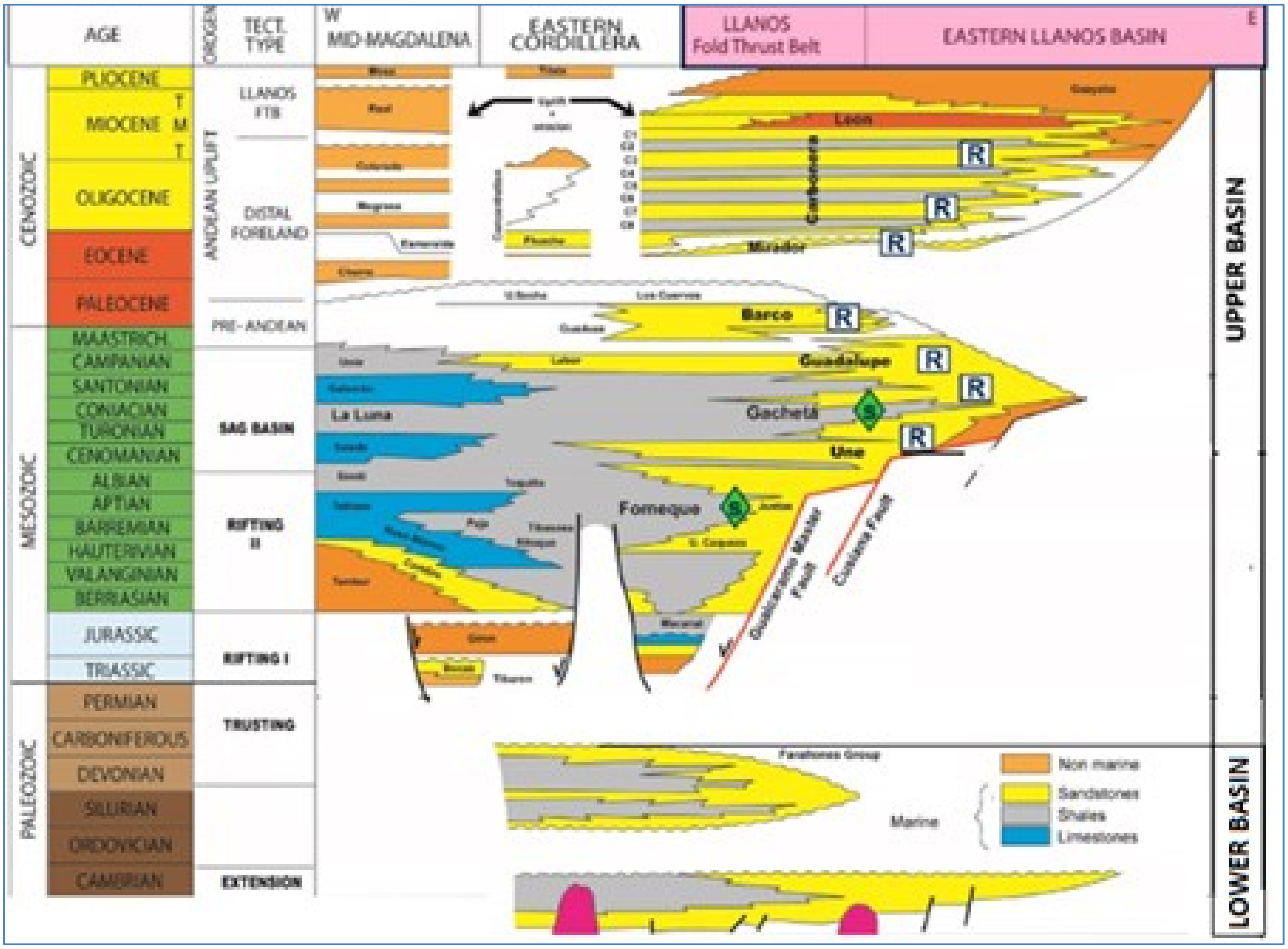

Figure 3: Stratigraphy chart for Llanos Orientales Basin, Adapted from Vayssaire et al., 2014.

The lower Llanos Basin involves Neoproterozoic and Paleozoic sediments (1.000-298 My) that overlie an igneous-metamorphic basement that forms part of the Amazonian Craton shield (Dueñas (2001), Dueñas (2002), Dueñas (2011) . Dueñas and Montalvo (2020) and Arminio et al (2013). The basement is densely fractured and presents a rift-like tectonic system, where seismically narrow and elongated engravings can be observed with east-west orientation. In the deepest part of these engravings very old sedimentary sequences (Ediacarian-Tonian) have been protected from erosion.

Unlike the Upper Basin, which has been densely drilled and intensively studied, with outcropping sequences in the Eastern Cordillera, the Lower basin has been sparsely drilled and its sediments studied in a very basic way. It should be noted that unlike the sediments of the Upper Llanos Basin, the sediments of the Lower Basin do not outcrop in the Eastern Cordillera (Figure 3). To study the sediments of the Lower Basin, it is necessary to analyze samples from oil wells (ditch, conventional cores and sidewall cores).

For this study nineteen wells were selected which locations can be observed in (Figure 5). Samples from the wells shown in Figure 5 were selected for palynological analysis.

3. METHOD

As part of the evaluation of the LLO and the eastern foothills of the Cordillera Orientals, 15,086 km of 2D and 3D seismic data were interpreted, previously reprocessed by the ANH to obtain the best possible image of the Paleozoic interval. To control the pitting of the Paleozoic horizons, 80 wells were used.

During the seismic interpretation, 10 horizons were defined, and their age was based on biostratigraphy data available (Rubinstein et al., 2021, Dueñas, 2022 and Dueñas et al., 2022).

For the depth conversion, information from wells was used to calibrate and tie the reflectors.

The interpreted seismic horizons correspond to: (1) Top of Paleozoic (Base of Mesozoic or Cenozoic, Unconformity), (2)Top of Carboniferous (Hiatus) (3) Top of Devonian (Base of Carboniferous), (4) Top of Silurian (Hiatus) , (5) Base of Silurian (Hiatus) , (6) Base Middle Ordovician (Hiatus), (7) Top of Early Ordovician (Hiatus), (8) Top of Cambrian, (9) Top of Precambrian (Ediacarian) and (10) top of Basement. The generalized Paleozoic stratigraphic column is shown in Figure 6.

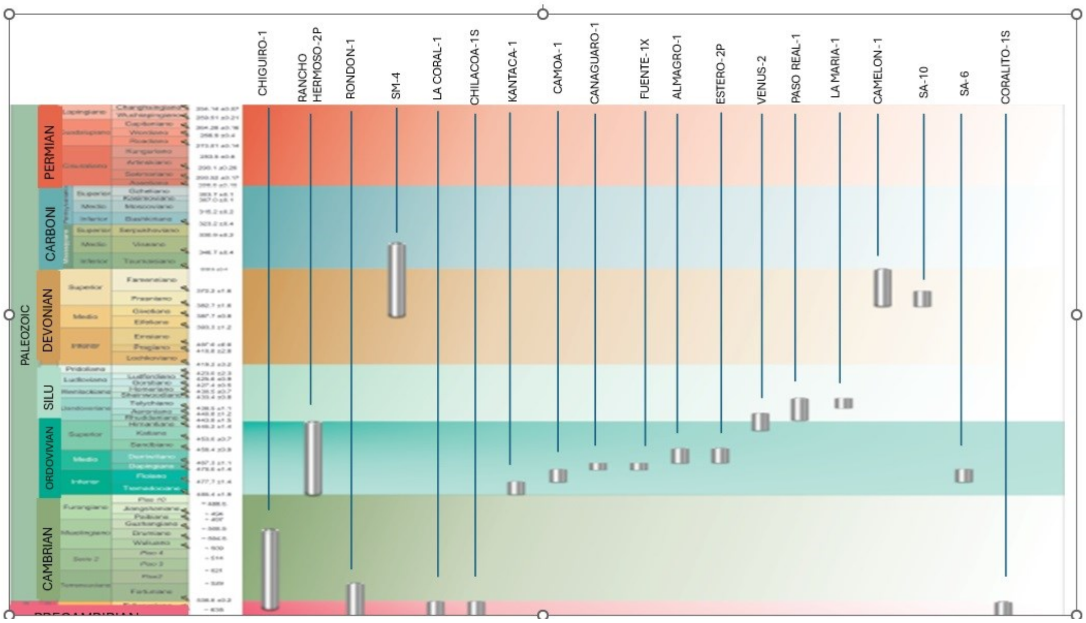

Figure 4. Stratigraphic range established for Paleozoic sections drilled in selected wells.

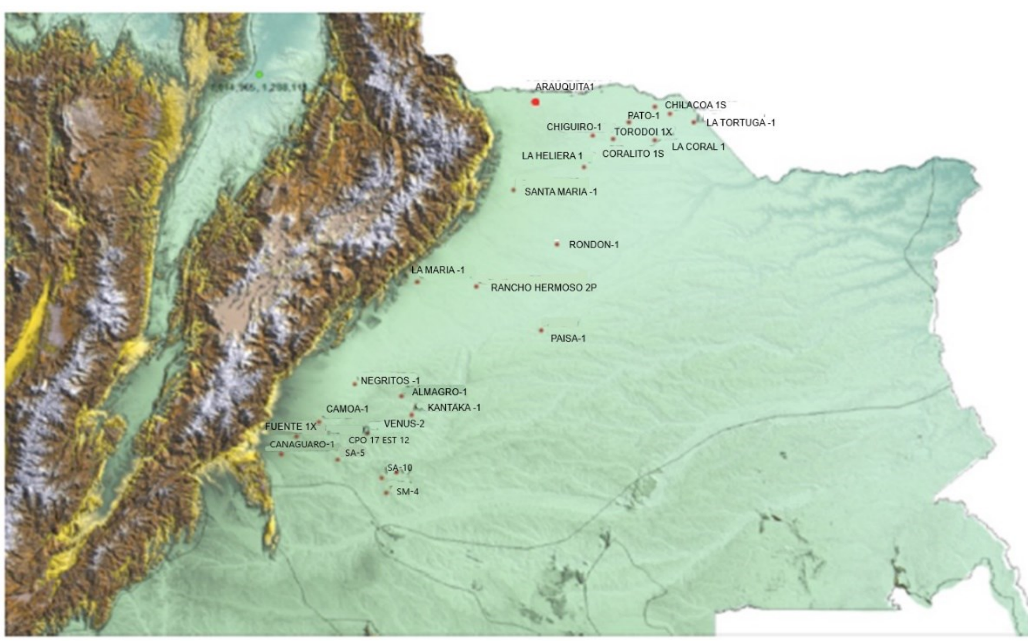

Figure 5: Location of wells selected for this study

4. RESULTS

Of the thousands of wells drilled in the LLO basin, only 115 crossed the unconformity at the base of the Cretaceous (or Tertiary) and less than 30 drilled more than 100 ft of the Paleozoic sediments (rat holes). For this study stratigraphic columns were constructed for 24 wells in the basin from cores and drill cuttings. And finally, nineteen of the Paleozoic sections have been analyzed palynologically and their results are used to elaborate Figures 4 and 6.

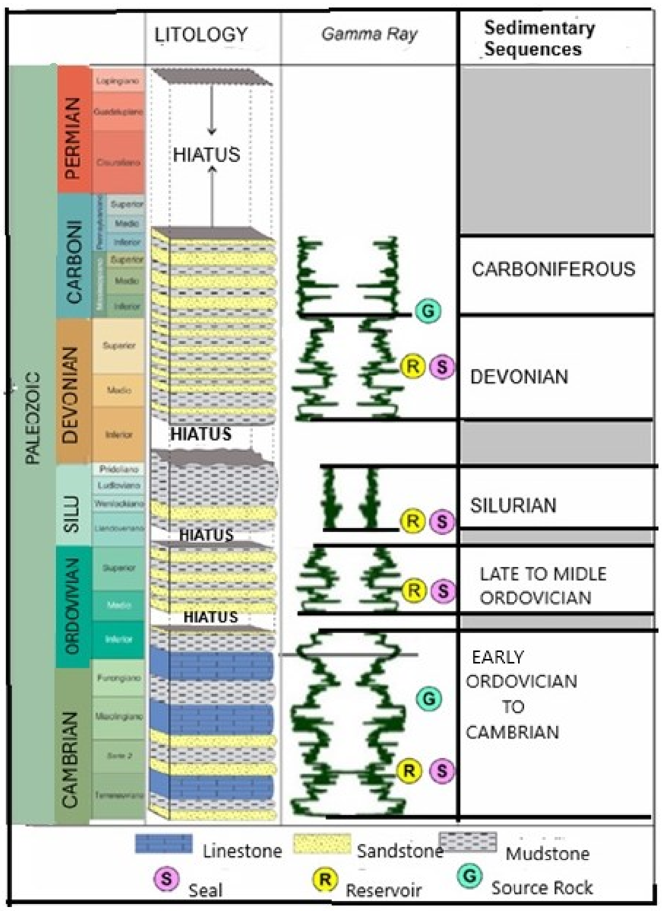

Figure 6: Generalized Paleozoic stratigraphic column in the LLO

After seismic interpretation it was clear that Paleozoic intervals are not uniformly distributed in the basin, deposition and subsequent preservation were mainly controlled by structural deformation. In the northern part of the basin, in the Arauca Graben (Arauca Sub-basin) some wells drilled Ediacaran sediments. The Cambrian, Lower and Middle Ordovician are widely distributed in the basin. They deepen towards the foothills of the mountain range and towards the east they truncate against the Paleozoic unconformity, which puts Paleozoic sediments in contact with Mesozoic rocks.

For the Upper Ordovician, its distribution is in small patches caused by erosion, it is present to the west of El Viento fault (Figure 7) and in the surroundings of La Maria-1 well. The Silurian are only present to the south, west of Viento fault, in the Paso Real-1 and San Juan-1 wells. Being the Silurian a little more extended; for a more detailed description see Guerrero et al. (2022). The Devonian and Carboniferous had been only reported in the SM-4 well (Dueñas and Cesari (2005).

The thickness of the Paleozoic sequence appears in Figure 7. This map is also showing the main trends of faults that are affecting the Paleozoic. At least three different domains can be identified. Toward the north these faults are SW-NE oriented, in the middle they are SSW-NNE and to the south they are more N-S. This south block regime is limited at the east for the El Viento Fault (Figure 7), a main structure that controlled the sedimentation of the basin, from the beginning of the Paleozoic. The máximum thickness (around 7200 ft.) of the Paleozoico, appears at the Norte, near the Arauca Graven. According to the available data, thethickness of the Paleozoic sequence extends into Venezuela. To enhance the accuracy of the model, it is recommended to incorporate seismic and well data from the venezuelan Barinas- Apure Basin.

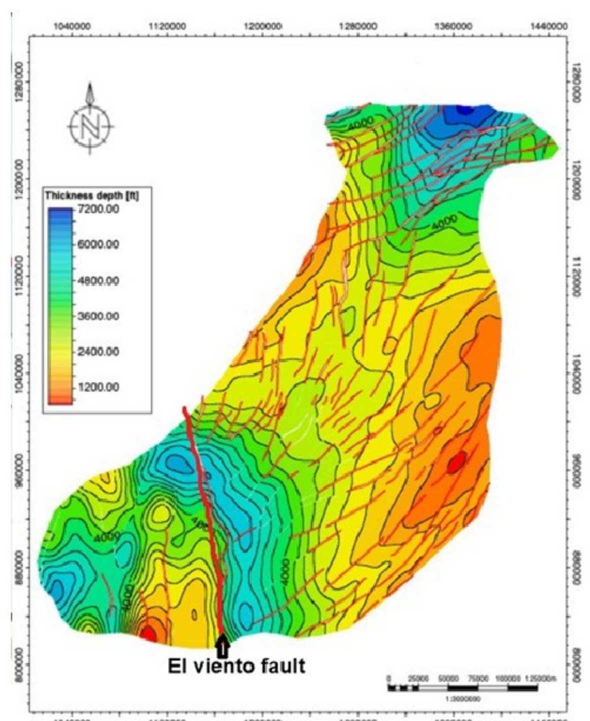

Figure 7: Thickness map of the Paleozoic sequences Eastern Llanos Basin.

4.1 Palynological Data

Neoproterozoic

In the wells Palma Real-1, Chilacoa-1S, La Tortuga- 1, Coralito-1S, La Coral-1, Vaco-1X and Torodoi-1X 4 (Figure 8), Neoproterozoic sediments have been analyzed, reporting the presence of Ediacarian- Cryogenian acritarchs assemblages (Arminio et al 2013, Dueñas 2001. Dueñas 2002. Dueñas 2011 Dueñas and Montalvo 2020). These wells are in the most northeastern part of the LLO (see Figure 5).

The acritarch assemblages reported by Armio et al. (2013) includes: *Kildinosphaera verrucata, Kildinosphaera chagrinata, Leiosphaeridia asperata, Leiosphaeridia spp., Coneosphaera cf. arctica, Cymatiosphaera spp, Dictyodinium spp, Lophosphaeridium spp. and Micrhystridium spp*. among several others. The reported acritarch associations indicate the presence of Cryogenian and Ediacaran sediments (Figure 8).

In the Chiguiro 1 and Pato 1 wells, acritarchs associations confirmed that sediments of Cambrian age were drilled below the unconformity at the top of the Paleozoic, and subsecuent basal cores taken from these wells have also yielded Neoproterozoic acritarchs

Análisis of Samples from the Chilacoa-1S, Torodoi-1X, and Vaco-1x wells, (Arminio et al 2013) reported the presence of acritarchs assemblages that included Cymatiosphaera spp., Micrhystridium spp. and Lophoesphaeridium cf. tentativum that are palynomorphs that have also been reported in sediments from the Early Cambrian age, suggesting that the sediments of these wells may be located close to the Ediacaran- Paleozoic boundary. These acritarchs exhibited dark colors related to the dry gas generation window (Fig. 8).

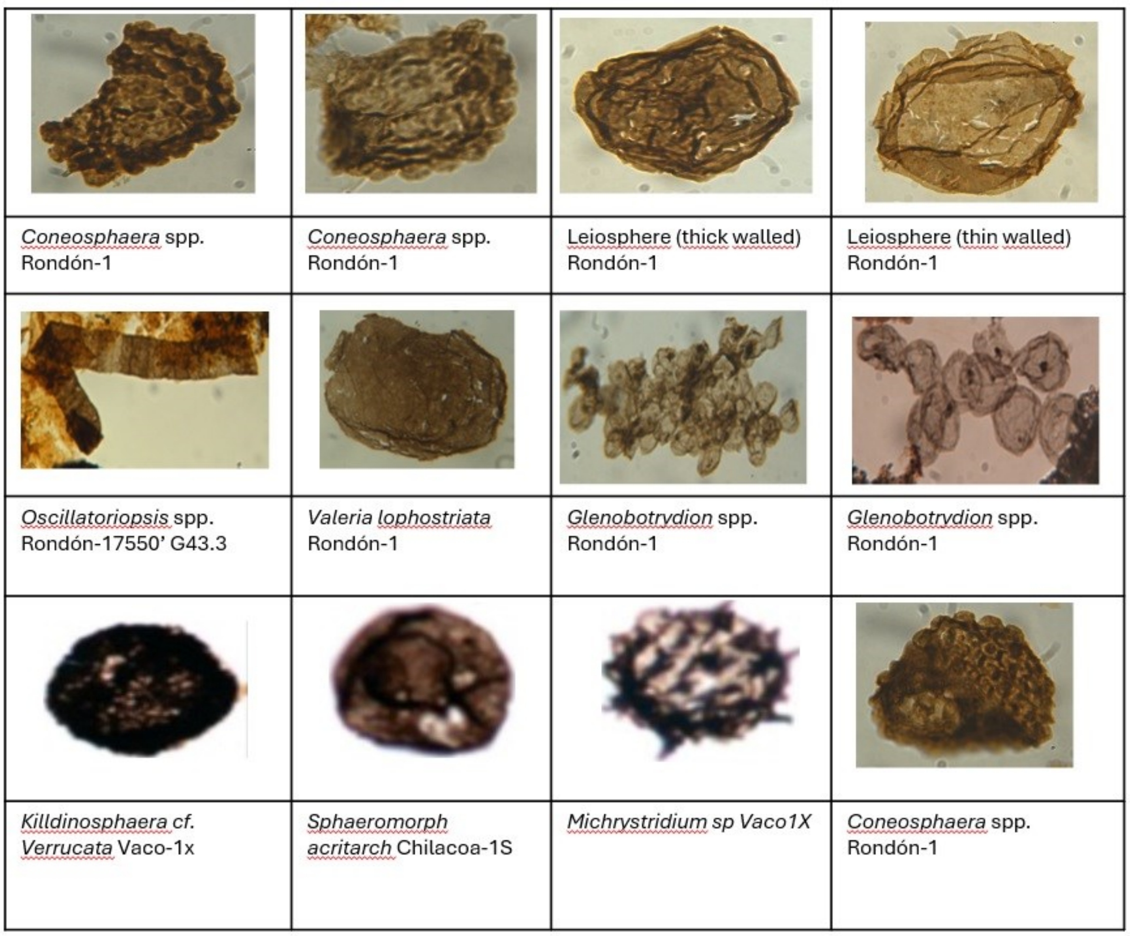

Figure 8: Neoproterozoic palynomorphs in Rondon-1(Ecopetrol 2014), Chilacoa-1S and Vaco-1X (Arminio 2013) wells.

In the Rondon-1 well (Ecopetrol-Petrostra 2014,) located in the central part of the Basin, sedimentation that include Tonian to Ediacaran ages has been reported. In the interval 7,430'- 7,850', the presence of the algae Siphonophycus spp. and thinwalled leiospheres have been reported. A Cambrian- Neoproterozoic age has been assigned to this interval. Samples from the 7910'-8090 interval are characterized by the presence of sparse assemblages involving the acritarches *Coneasphaera artica, Valeria lophostriata, and Lophosphaeridium spp* that allows an assignment to the Cryogenian to Tonian age. Some of the palynomorphs in Figure 8 have dark colors, but it is possible to observe their main morphological characteristics. These dark colors are indicative that the sediments containing them have undergone thermal alteration but in no way can they be classified as metamorphic sediments. (Fig. 8).

Cambrian

The Chiguiro-1 well reported the most complete Cambrian stratigraphic sequence (Dueñas, 2011, Ecopetrol-Icron, 2010)). In this well, the top of the Cambrian is reported at 8,361' and the total depth. was 11.910'. The recovered assemblages are dominated by the common presence of Crystallinium cambriense and the presence of Adara alea, Vulcanisphaera lanugo, and Eliasum llaniscum. The 8.400'-8.530' interval has been interpreted as Late to Middle Cambrian. From 9.620' to 11.750' as Middle to Early Cambrian and the basal core (11.845' to 11,906') as Ediacarian. The color of the acritarchs indicates that these sediments are within the hydrocarbon generation window (Fig. 9).

Ordovician

So far, the most complete Ordovician section has

been reported in the Rancho Hermoso 2P well. This well drilled in the central part of the LLO encountered an unconformity at the top of the Paleozoic at 10.030' and the top of the igneous-metamorphic basement at 12.820' (Rubinstein et al 2021 and Rubinstein 2019). Between 10,167' and 10,246 palynomorph associations include Villosacapsula setosapellicula, Veryhachium trispinosun group, Veryhachium lairdi, Leiofusa litotes, Orthosphaeridium spp, Acanthodiacrodium spp, Baltisphaeridium spp. to which a Late Ordovician age was assigned.

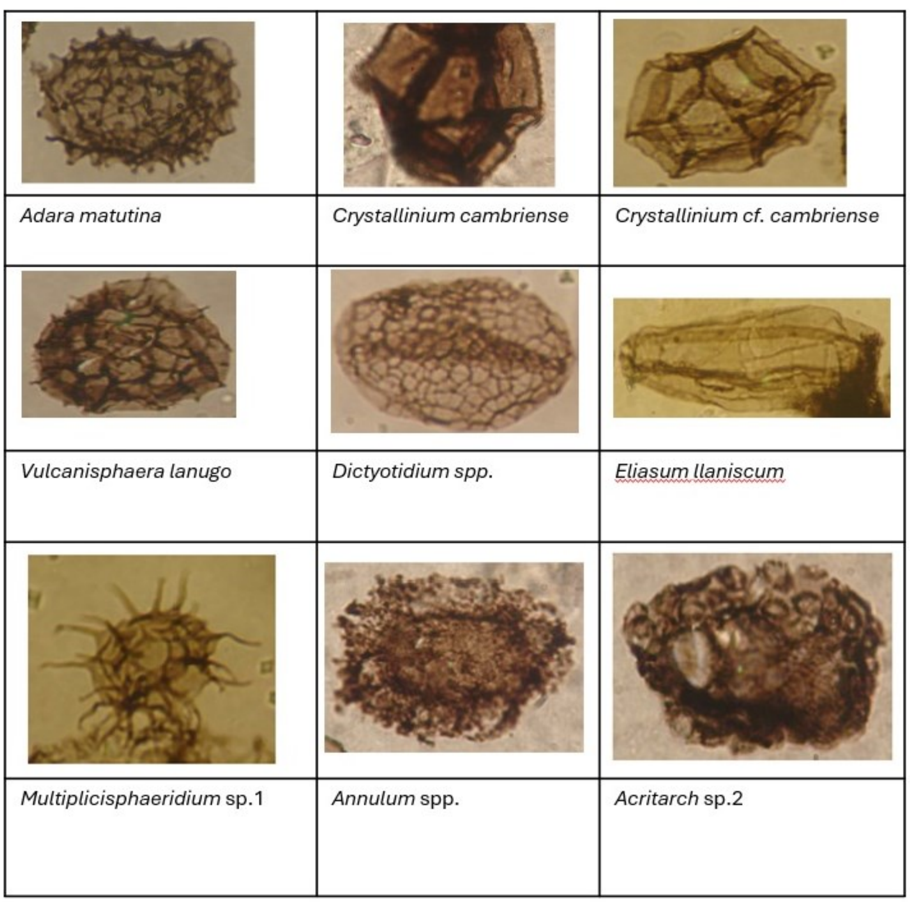

Figure 9. Cambrian palynomorphs, in Chigüiro-1 well (Ecopetrol 2010 Dueñas et al 2021).

Between 10337 and 10578 the recovery of acritarchs increased with the entry of Striatotheca principalis var. parva, Striatotheca cf. frequens, Orthosphaeridium tematum, Striatotheca quieta, Frankea sartbemardensis, Dicrodiacrodium ancoriforme, and Stellechinatum uncinatum. The associations between 10,646’ and 11,175’ include as new elements the acritarchs Cymatiogalea spp., Peteinosphaeridium armatum, Arbusculidinium filamentosum, Poikilofusa cf.

plethysticha, and Ammonidium multipugiunculatum among others. This association is assigned a Darriwilian to Dapingian age. This interval is also characterized

by the presence of black claystones considered as source rock. The deepest interval of this well, 11237’-11637’ is characterized by an acritarch assemblage formed by Petaloferidium florigerum, Striatotheca transformata, Comatiogalea spp, and Pachyspaeridium rhabdocladium, assigned a Floian age and whose acritarch colors are indicative that these sediments are within the oil generation zone (Fig. 10).

Silurian

Silurian sediments have been reported in the Paso Real-1 and La Maria-1 (Ecopetrol-Icron (2010) , Ecopetrol-Petrostrat (2014). From the short section drilled in the Paso Real - 1 well (2,140- 2,360’), it was possible to recover acritarch assemblages characterized by the presence of Neoveryhachium carminae, Dactylofusa spp., Tylotopalla cf. caelmenticutis,

Villosacapsula spp., Eupoikilofusa cabotii, Dactylofusa marahenis, and Baltisphaeridium tenuata. Based on the acritarchs associations obtained from these sediments, a Llandovery age has been assigned to these sediments that according to the color of their acritarchs are in the oil generation zone. Cuttings samples located at 17,300’ from the La Maria- 1 well, yielded an acritarch association characterized by the presence of Dactylofusa estillis, Diexallophasis denticulata, Diexallophasis sanpetrensis, Gerongerrillus nudus, Multiplicisphaeridium cladum, and Veryhachium trispinosum among others. This acritarch association assigning a Llandovery age to these sediments that despite their depth are in the mature zone for hydrocarbon generation (Fig. 11).

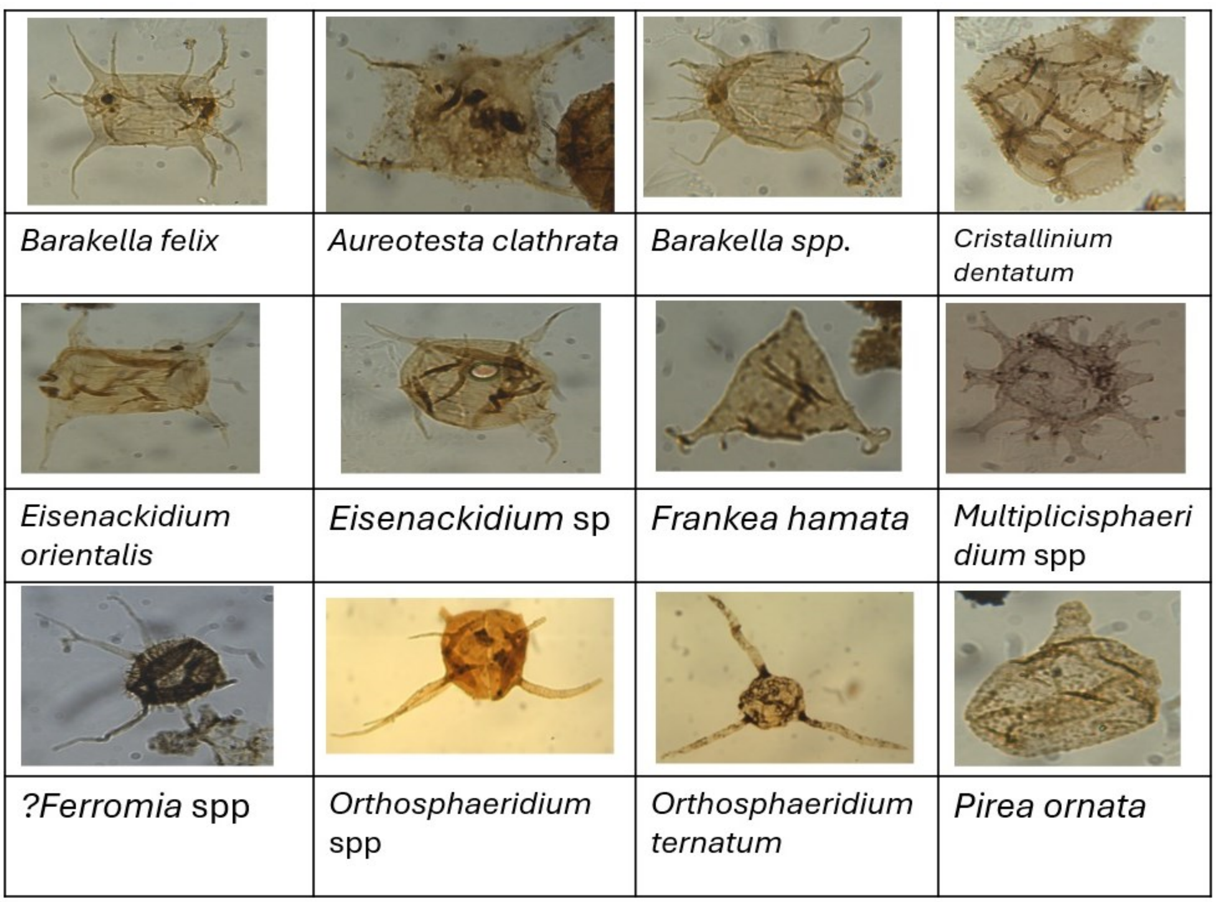

Figure 10. Ordovician palynomorphs in Rancho. Hermosos-2P well (Ecopetrol 2014, Rubistein et al 2019).

Devonian-Carboniferous

In the SM-4 well, located in the southwestern part of the LLO, Carboniferous and Devonian sediments were drilled (Dueñas 2001, 2006., Dueñas and Cesari, (2006). In the interval 2000' to 2350' palynomorph associations are dominated by trilete spores, while in the interval 2390'- 2990' the presence of trilete spores decreases as the recovery of acritarchs increases.

At a depth of 2350', there is a clear paleoenvironmental boundary from brackish continental to shallow marine sedimentation, which is also indicative of the boundary between the Carboniferous and the Devonian (Fig. 12).

The palynomorph associations of the Carboniferous are characterized by the presence of Grandispora spiculifera, Auroraspora solisorta, Retusotriletes crassus, Apiculiretusispora multiseta, Anapiculatisporites concinnus, and Spelaeotriletes spp. The palynomorphs reported above allow us to assign a Mississippian- Tourmaisian age to these sediments and included the presence of Verrucosisporites nitidus, Maranhites spp. among others. Sediments from 2390 to 2990' show an association of acritarchs Characterized by the presence of; Ammadium inornatum granulate, Cymatiosphaera peligroso, Cymatiosphaera winderi, Cymbosphaeridium sp. A, Daillydium sp, Diexallophasis triangulata, Domasia spp, Exoxhoderma irregulare among many others.

Very good associations of Acritarchs, Algae, and spores were recovered from the 2690' to 2719' interval in the Camelon-1 well (Ecopetrol-Petrostrat 2014). The acritarch association is characterized by the presence of Daillydinium pentaster, Gorgonisphaeridium spp, Navifusa bacillum, Palacanthus ledanoisii, Stellinium comptum, Verihachium lairdii, and Veryhachium trispinosum among others. The most abundant spores are Apiculiretusispora spp, Retusotriletes spp, Verrucosisporites bulliferun, Grandispora spp, Ancyrospora spp, and Samarisporites triangulatus among others. The most abundant algae are Maranhites mosesii. The palynomorphs cited above, allow us to assign a Late Devonian L Frasnian age to these sediments (Fig. 12).

Permian

No Permian strata have been reported in the LLO. The Permian was probably a time of nondeposition or intense erosion. Recent seismic studies have allowed us to observe that the basement of the basin is densely affected by rift faults that have compartmentalized the basin making it too complex to explain the distribution of Neoproterozoic and Paleozoic sediments.

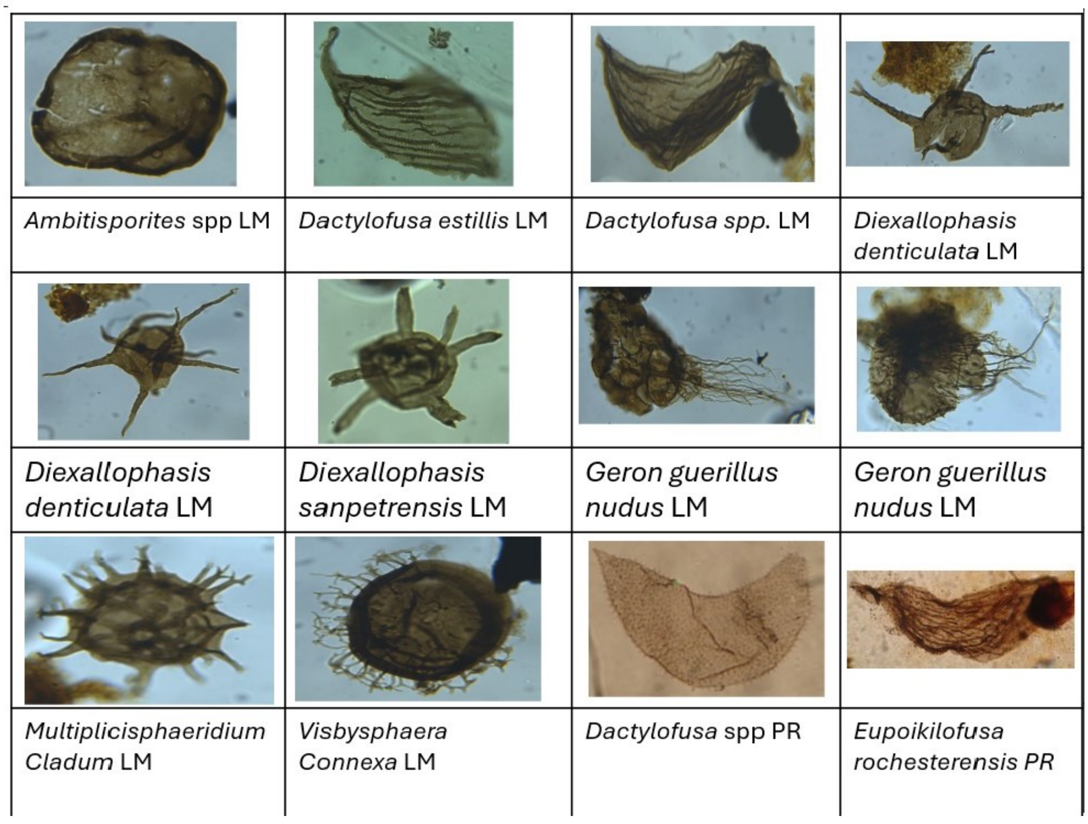

Figure 11. Silurian palynomorphs in La Maria-1 and Paso Real-1 wells. (Ecopetrol 2010 and 2014)

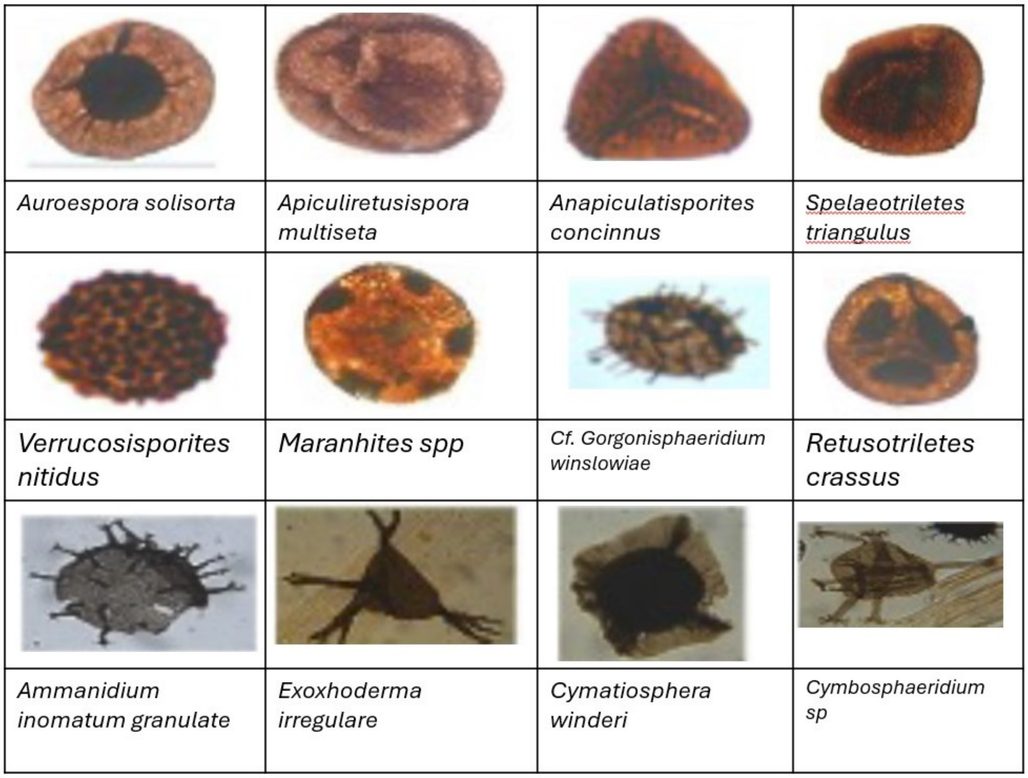

Figure 12. Carboniferous and Devonian palynomorphs in SM-4 well. Dueñas & Cesari 2005

5. CONCLUSIONS

The Precretaceous stratigraphy in the LLO includes thick sequences of Neo-Proterozoic (Cryogenian-Ediacaran), Cambrian and Ordovician sediments, that cover a large part of the central and eastern part of the LLO and were deposited in shallow seas with very cold waters and generally show moderate thermal alteration.

Only to the west of the El Viento fault, the Late Ordovician, Silurian, Devonian and Carboniferous sedimentary are present in the form of sedimentary patches. Permian sediments have not been reported in the LLO and were probably not deposited or were eroded.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no financial interests or personal relationships that could have influenced the work reported in this article

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