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# Potential of Unconventional Hydrocarbons in the Paraguayan Chaco: Carandayty Sub-Basin Case

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***Abstract:*** *The current dependence on the automotive fleet and certain sectors of the oil industry, the impact on the national energy matrix and the unsuccessful search for conventional hydrocarbons in the country's territory, stimulates the search and eventual exploitation of unconventional hydrocarbons that added to current technological progress, especially for the extraction of shale gas by method of hydraulic fracturing (Fracking), opens up new energy opportunities for the country. The geology of Paraguay reveals the existence of large sedimentary basins with hydrocarbon potential not yet productive due to the lack of persistence in terms of exploration. The sedimentary sequences of the Carandayty subbasin in almost their entirety consist of Paleozoic sediments with high possibilities of gas concentration between their pores. This research was largely dictated by the available information based on stratigraphic data, geological correlation and regional outcrops, observations and interpretation of exploratory and palynological data from the Carandayty Sub-basin, in the Western region of Paraguay. The areas with non-conventional hydrocarbon potential are the Devonian marine shales and Silurico sandstones. Potential shale gas deposits exist in the Kai Formation (Devonian) with 8200 feet thickness, composed of black shale rich in organic matter.*

***Keywords*** *– Energy, Geology, Unconventional Hydrocarbon, Potential*

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## I. Introduction

The energy matrix of Paraguay is characterized by a high supply of primary energy from renewable and local sources, specifically hydrogenation and biomass. According to the energy balance of 2012, 57% of this supply corresponded to hydroelectricity and 27% to biomass (firewood, charcoal and vegetable waste). The remaining 16% were hydrocarbons. However, analyzing the final consumption, biomass occupies 46% of the energy consumed in the country, 16% electricity and 38% hydrocarbons (see Figure 1). Paraguay imports 100% of its demand for hydrocarbons, whether in crude oil, gas, fuels and derivatives, which means foreign currency disbursements close to US $ 240 million per year. There is no national production of hydrocarbons yet [1].

Since the 40s of the last century, both the Eastern and the Western region, the latter also known as the Paraguayan Chaco, in search of hydrocarbons applying conventional methods of research, trying to locate structural entrapments, or stratigraphic anomalies that could eventually contain oil or gas or both, however the commercial findings of conventional hydrocarbons have not been successful to date. The development of the hydrocarbon sector, specifically exploration and its eventual exploitation, is considered among the objectives of the energy policy, fostering the participation of companies in the search for oil and gas in the country [2].

The development of a stratigraphic framework based on paleontological analysis, outcrop studies and interpretation of seismic and well information allowed the revision of the potential of unconventional hydrocarbons in the shales of the Paleozoic sequence, mainly in the Siluric and Devonian sequences, in the Sub-basin of the Carandayty in the Paraguayan Chaco [2].

The evolution of the Chaco's stratigraphy and tectonics is based, both on outcrops and in the subsoil data from hydrocarbon exploration wells and groundwater. There are several water wells built in the Chaco region that provide data on the geology of the subsoil, which added to the exploration of hydrocarbons along the sub-basins are complemented with more than 15,000 km of seismic lines and general coverage by aeromagnetic studies of the Southwest , west and north of the Chaco.

The definitions for unconventional hydrocarbons are varied depending on the perspective from which the subject is analyzed. In general, the descriptions vary from the point of view of the origin, through the types of unconventional hydrocarbons to the description of the process and costs involved in its exploitation. In general, unconventional hydrocarbon deposits are reservoirs of very low permeability natural gas or sedimentary formations containing very high viscosity oil, which makes it difficult to flow into wells [3] (see Figure 2).

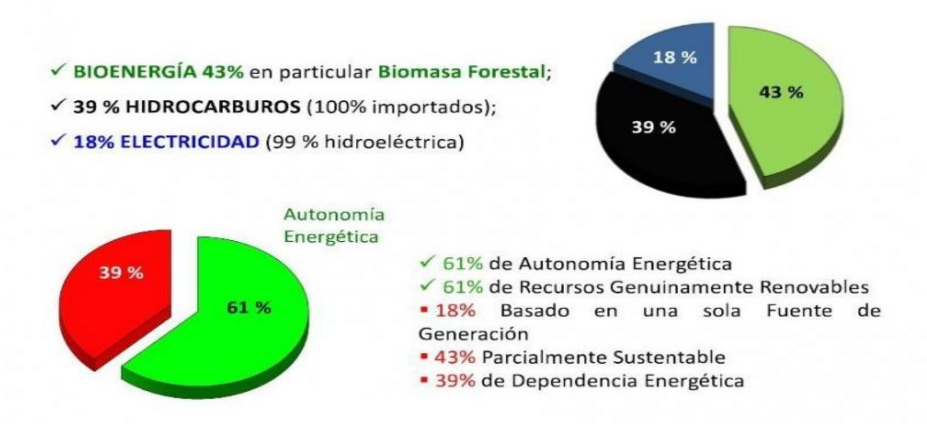


**Figure 1. Current Situation. Energy Consumption Matrix.**

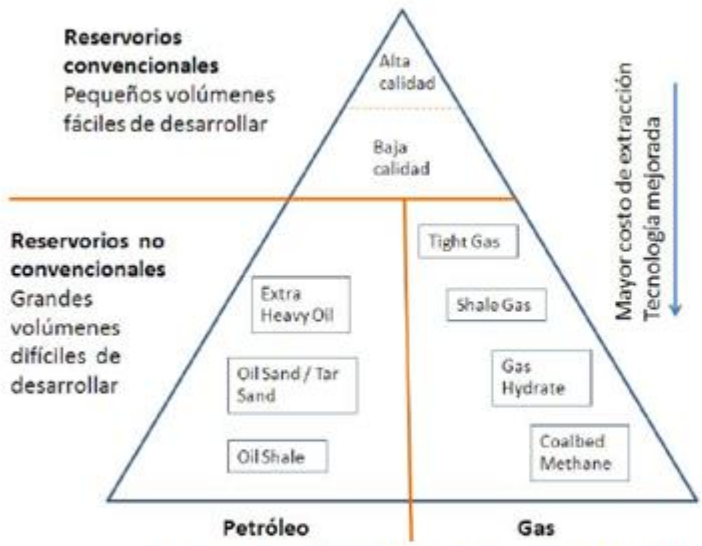


**Figure 2. Potential Hydrocarbon Triangle.**

## II. Theatrical Framework

The deference between conventional and unconventional gas lies fundamentally in its genesis. The conventional gas is inside a porous and permeable deposition rock and mostly does not need stimulus for its exit; A well is drilled and it seeks to come out naturally. As for shale gas, it develops within an impermeable clayey rock compressed by overlaying sediments accumulated during long geological times transforming into shale gas. These rocks are so impermeable that gases are trapped inside them, unable to migrate towards deposits. This makes it necessary to set up a whole extraction process, more complex that normally is much more expensive nowadays. During these last years, the increase in total gas resources worldwide is attributed to this gas, which has been the object of intense exploration-production efforts.

Figure 3 shows the definitions for unconventional hydrocarbons which are presented below: Extra Heavy Oil is a crude whose API grade is less than 10 and a voscosidad below 10,000 centipoise and flows to reservoir conditions. Natural bitumen (Oil sands/Tar sands), Like the extra heavy crude oil, this hydrocarbon has an API grade of less than 10, however its viscosity is higher than 10,000 centipoise, so under reservoir conditions, it does not have fluency or mobility. It is contained in sands or porous rocks formed mainly of carbonates and is mixed with inorganic compounds.

Shale oil or schist (Oil Shale) is an organic compound called kerogen contained in thin-porous, fine-grained rocks (shales) has intermediate properties between oil and mineral coal, is insoluble in organic oil and precursor of petroleum in sedimentary rocks. The kerogen is of energetic interest because when it is anaerobically heated up to 500 ºC, it becomes oil. The gas of low permeability sandstones (Tight Gas), is a gas contained in sandstones and carbonates of very low permeability, may or may not have fractures. The gas flows slowly among its pores so that economic recovery volumes can not be obtained without resorting to hydraulic fracturing. Shale gas or schist (Shale Gas), is located in natural fractures and pores of schists or low permeability sedimentary clay rocks. Known by the name of slate gas as tight gas requires hydraulic fracturing for economic recovery. Gas in hydrates (Gas Hydrate) They are methane molecules trapped in permanent layers of ice forming crystalline structures with water molecules. They are located in regions of very low temperature and high pressure, mainly in the Arctic at depths greater than 200 meters and marine sediments at depths of more than 500 meters. Although the estimated energy potential of this resource is enormous. Coal mineral gas or gray gas (Coalbed Methane) (Coalbed Methane), It is methane-rich natural gas that is mainly absorbed in the internal surface of the mineral coal and to a lesser extent trapped as free gas in the pores and fractures of this mineral [3].

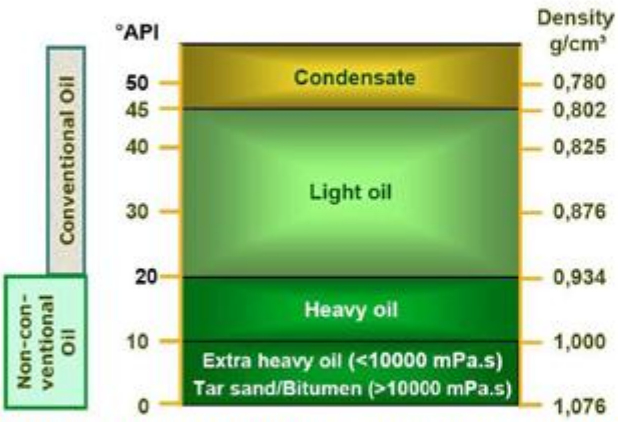


**Figure 3 Classification of oils according to their API grade**

Since mineral coal is the most abundant fossil energy resource in the world, the potential of coal mineral gas is also very significant, being one of the unconventional hydrocarbons of greater production in North America. Another term for bituminous slate oil or kerosene refers to a mixture of solid hydrocarbon and other organic components containing nitrogen, oxygen and sulfur. It is extracted, by heating, from a rock called oil shale, with a yield of between 68 to 227 liters of oil per ton of rock [4].

The economic cost of extracting unconventional hydrocarbons is currently prohibitive, which is why they are considered to be oil and natural gas that have advantages in terms of the large volume found but located in deposits and complex physical characteristics that make it impossible to exploit them with technologies traditional companies demanding special procedures for their recovery. One of the known methods of extraction is hydraulic fracturing, which involves injecting high pressure water directly into the rock containing the gas with the intention of fracturing or breaking it so that the hydrocarbon can flow to the wellhead.

According to the report published by the U.S. Energy Information Administration, from April 2011, 48 sedimentary basins were evaluated in 32 countries and 14 regions of the world, estimating a volume in situ shale gas of 670 Tmc, from which we can tell are technically recoverable only 28 % (187 Tmc) [3]. The region of Latin America and the Caribbean, is characterized by being very rich in both fossil and renewable energy resources, being clearly an exporter. However, these resources, mainly fossils, are completely asymmetric with respect to their geographic distribution, concentrating in very few countries and making the largest number of countries energetically dependent on imports [3]. The Latin America "South Cone" has great potential for shale gas, now starting to be verified. This potential for shale gas is present at the complex borderline Basin of Chaco-Paraná in Brazil and Paraguay. This is an intracratonic pre basin globally similar to the Neuquén Basin and other South American basins east of the Andes Mountain Range. It contains a thick sequence of essentially marine Paleozoic rocks overlaid essentially by continental Mesozoic deposits

The Chaco-Paraná Basin extends from the southeastern part of northern Argentina and southern Bolivia with an area in Paraguay of about 400 thousand km2. Geochemical studies conducted in this basin have resulted in the order of 10 billion barrels of unconventional crude and 10 Tpc of gas in the layers corresponding to the Lower and Permico Paleozoic. According to estimations of the U.S. Energy Information Administration, Paraguay has 62 Tpc of shale gas reserves technically recoverable in its position in the Chaco Paraná Basin of a total in situ of 249 Tpc [3]

Paraguay constitutes an extensive region of sedimentary basins that indicate an important potential that with persistence in the exploration will be able to reach the success. The Paraguayan Chaco, is an extensive Quaternary plain, occupies an area of approximately 246 thousand km2, with an average elevation of about 160 m above sea level, is part of the so-called Gran Chaco of South America and includes fractions of Argentina, Bolivia and Paraguay. A series of basins located east of the Bolivian Andean Belt, where the sub-basins known as Carandayty, Curupayty, Pirity and Pilar are located, which together with the Paraná basin in the Eastern region of Paraguay, form part of a single basin upto the Mesozoic known as

Chaco-Paranaense [5]. The subsoil of the Paraguayan Chaco records the entire geological column that spans from the EoCambrico to the present, with powerful strata of sandy facies and shale gas or Paleozoic shales considered as hydrocarbon potential. The Curupaity and Carandaity sub-basin are essential Paleozoic depocenters, while the Pirity and Pilar sub-basins are attributed to the Mesozoic extension (see Figure 4).

Systematic studies of the stratigraphic column, paleontological and palynological determinations and exploration well logs reveal levels of shale and shale gas with high possibilities of gas concentration between their pores. In Paraguay, the shale gas develops within an impermeable clay layer compressed by the superposition of sediments accumulated in large basins and for a long time, such as Silurian and Devonian (Paleozoic), which are transformed into shale gas. Due to the high impermeability of the rocks, the gases are trapped inside them, without the possibility of migrating towards geological traps or deposits. This situation requires complex extrusion processes compared to a conventional hydrocarbon drilling that currently represent very high costs and in many cases are impractical.

**II. 1. Regional Geological Tectonic Framework**

The Pericratonic Basin of the Chaco was developed on rocks of the Precambrian, thus forming the great South American Chaco. The Chaco basin belongs to a series of modern foreland basins east of the Andean belt that extend from the Pampas in central Argentina to the Llanos in eastern Venezuela. These basins are located between the Andean Belt and the shields of Central Brazil and Guayan(see Figure 5).


**Figure 4. Paraguay's structural map Figure**

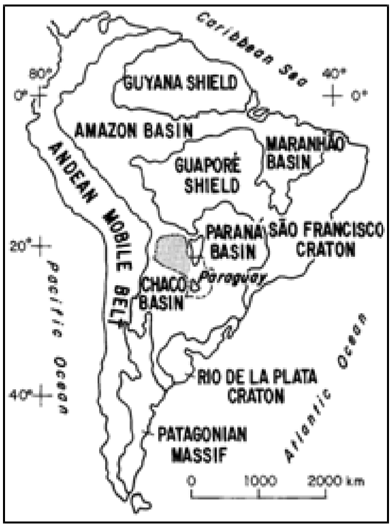


**Figure 5. Map of South America Chaco basin**

The tectonic history of the Phanerozoic basin of the Chaco of Paraguay begins during the intense Brazilian thermo tectonic cycle (680-450 Ma), when the carbonatitic and clastic sequences of the EoCambrico belonging to the Itapucumi Group are deposited associated with extensional and compressive events (Zalan, 1987 ). The Brazilian basins evolved through extensional and compressional phases, pushing along the edges of the basins an acidic magmatism (680-580 Ma) affecting the southeast and northeast of Paraguay. This Brazilian event marks the beginning of the collapse of the Chaco and Paraná watershed, establishment of the northwest-southeast and northeast-southwest structural framework [6].

The Chaco Basin is characterized by a style of structural lineaments oriented northwest and northeast of origin of the Eocambrian Brasiliano cycle. The four phases of subsidence results of the differential reactivation occurred in the Fanerozoic are the so-called Early Paleozoic, Late Paleozoic, Late Mesozoic and Cenozoic. It is important to note that these subsidences or phases are separated by erosive discordances and non-deposition area or simply by little sedimentation. While the paleozoic phases reflect a slight subsidence and local structural readjustments, the mesozoic basins were subjected to a general reorganization of the structure styles by extension oriented along predominantly northeast-related lineaments with the Atlantic opening. Finally, a Cenozoic phase was caused by they orogeny of the Andes and accompanied by regional structural adjustment.

The geological events that occurred in the Chaco basin in the Fanerozoic and that characterized the stratigraphy and mode of sedimentation are: 1. Deposition of Paleozoic clastic sediments (From the late

Proterozoic to Early Permian) occurred in marine and continental environments in shelf and basins sunk locally 2. Secondly, clastic terrigenous and carbonated sedimentation of the Upper Jurassic-Early Cretaceous- until the middle Eocene formed thick continental fillings in rift basins, with local marine transgression from Simplified lithostratigraphic column of the Paraguayan Chaco Basin [5]. 3. Deposition of continental and marine sediments in a basin environment from the Eocene to the present. Facies changes from marine to coastal and continental environments are progressive from the west in the Bolivian region to the east in the region of Paraguay. It is important to consider that the sub-Andean zone is characterized by intense decreasing faults to the east. The tectonic character of this region produces a compressive force that decreases in the Paraguayan Chaco where only subvertical faults are found with some possible vertical movement.

**II.2. Geological Configuration**

The Paleozoic history of the Paraguayan Chaco has much in common with the region of Bolivia and it is important to understand this relationship. Similar depositional environments are observed between the belt of the sub-Andean belt of Bolivia to the west, and to a lesser degree, the area of Roboré-Santiago de Chiquitos (Serranías de Santiago and San José) to the north, in the east of Bolivia. Many of the lithological units found and defined in Bolivia, in the western part of the belt sub-Andean, are similar or equivalent in Paraguay, although the changes in the depositional environments in the region of Paraguay are notorious.

The sedimentary section penetrated in the Paraguayan Chaco varies from Lower Ordovician to Lower Pennsylvanian and Upper Permian to Lower Triassic. In the Subandean Belt of Bolivia, shaly and sandy sequences from Ordovician to Tertiary are present. Important lithologic differences are found between the pre-Devonian sequences in Paraguay and those in the Subandean Belt to the west ofthe study area. The section found in the central portion ofthe Southem Subandean Belt of Bolivia in the Serrania Sararenda (Sararenda Hills), on the Parapeti River, is similar to the sequence found in the Carandaity and Cumpaity subbasins of Paraguay [5]. The area of the Robore Basin or Serranias Chiquitanas (Chiquitos Hills or Serranias Santiago y San Jose) in easternmost Bolivia is of relatively less importance to the study of the Paraguayan Chaco than the Subandean Belt, because of its different facies characteristics. The Chaco area is located west of the Brazilian Shield. Sediments derived from this shield were deposited in the Chaco in a relatively undisturbed continental to marine shelf environment dipping gently towards the west.

Reconstruction of pole migration during the Paleozoic indicate high to polar latitudes for the study area, and help to relate the lithologies found with likely climatic conditions. There are very few scattered outcrops in the Paraguayan Chaco. The oldest rocks are probably attributed to the Cerro León Formation of the Ordovician - Siluric, composed of hard quartz sandstones and strongly fractured. The Silurian System is

widely distributed in Bolivia and in the Chaco and eastern Paraguay. Two formations occur in the Subandino Belt of Bolivia. These are the Cancañiri Formation and the Kirusilla Formation [2]. Both arise in the central and southern sections of the Subandino Belt, and the Kirusillas Formation is also found in the subsoil of the South Sub-Andean Belt [7].

The Kirusillas Formation consists almost totally of a monotonous succession of black shales with a "high organic content" and rare interbeds of fine-grained gray micaceous sandstones. Its upper contact in the western Subandean Belt is determined only through palynology, because ofthe identical namre ofthe Lower Devonian shales that overlie it in this area. The Formation reaches a thickness of 300 to 450 meters (984 to 1,476 feet). The age, as determined by macrofossils and palynology, is Early to Late Silurian (Llandoverian to Ludlovian; Berry and Boucot, 1972; Crowell et al, 1980). None of the lithologies found in these two formations in Bolivia extends to the Paraguayan Chaco due to facies changes. The Silurian period is marked by the migration of the pole from NE to SW through South America, and this paleomagnetic data is reflected in the tilloids of the Cancañiri Formation in Bolivia. [5].

Texaco geologists (1975) produced a composite stratigraphic column of the southwestern flank of the Cerro Leon outcrop. The basal section consists of 100 meters of homogeneous light gray quartzite with thin streaks of hematitic quartzite along bedding planes, very well bedded, with beds of 0.5 to 3 meters thick. Some beds have well developed cross bedding. Abundant fossil casts, including fragments of corals and crinoids were reported in the uppermost beds. Overlying the quartzites, in apparently gradational manner, are 25 meters of light gray micaceous sandstones, bedded in 10- to 30- centimeters-thick units containing fossil casts. These sandstones are apparently missing in some areas, and an erosional unconformity was inferred. Overlying the gray sandstones are 25 meters of pink to brick red quartzose sandstones, fine to medium grained, with "subrounded to subangular, fairly well sorted grains with little silty matrix. Very friable, very porous, well bedded 50 cm thick beds" [5].

The Devonian Period as a whole is characterized by a generally transgressive sea in South America, and is reflected in widely distributed shales. However, in certain areas, stages within the Devonian Period also represent rises and falls of sea level. The lower San Alfredo Group reflects shore zone to shallow marine environments. White, crossbedded quartz arenites and less mature sandstones up to 300 m thick contain intercalated siltstones and shales, indicating a variety of sedimentary facies. The presence of leiospheres and chitinozoans in the northwestern Chaco exploration wells and corals, bryozoans, and crinoids at the Cerro León massif are indicative of a marine depositional environment. Wolfart interpreted Favosites sp., Leptocoelia flabellites, Chonetes falklandicus, and Tentaculites stubeli at Fortin Aroma and the Lagerenza high as evidence for an Early Devonian age. Terrestrial spores at the central Chaco uplift show that sandy coastal facies rimmed the arched areas. The upper San Alfredo Group is represented by dark, thick, fossiliferous, shallow marine shales. It grades upward into a regressive sequence of continental deposits. Late San Alfredo shale deposition were restricted largely to the Curupaity and Carandayty depocenters. Tentaculites, brachiopods, and crinoids indicate shallow marine facies. Subsequent tectonism and burial maturation have resulted in Devonian shales that range from immature (Carandayty and Curupayty subbasin) to lowgrade metamorphic (Lagerenza and Fuerte Olimpo highs) [6]. The local Devonian transgressive deposited the San Alfredo Group in the west and north of Chaco. Outcrops of siltstones and shales of this Group are observed in outcrops in Sierra Leon and Line 42. For much of the Paleozoic, the Chaco basin was part of a relatively stable area of shallow marine and continental sedimentation south of the Brazilian shield The Paleozoic succession is dominated by terrigenous clastics. An almost complete Ordovician sequence of the Cerro León Group is preserved in the Don Quixote-1 well in the Carandayty subbasin.

Carboniferous rocks represented by gray-green sandstones and diamictites appear in the area of Palmar de las Islas and Cerro León in the north of the western region. The broadscale geology suggests that a large sedimentary platform was established in the Ordovician and persisted until the Mesozoic. Only the Curupaity, Carandaity, and San Pedro depocenters experienced continuous subsidence, apart from the main Paraná basin. A pronounced angular unconformity separates the Devonian and Carboniferous successions in much of the northwestern Chaco. Subsequent tectonism resulted in movement of structural basement blocks and local erosion across uptilted crests where Upper Carboniferous continental glacial sediments and Lower Permian shallow marine sequences of the Palmar de las Islas Group have an erosional contact. Locally the Permian rests on Devonian shales. Only in the deeper western parts of the Carandayty subbasin is a complete section of Devonian Upper Carboniferous and Lower Permian sedimentary rocks preserved.

The outcrops in the Palmar de las Islas zone, is related to rocks of the Carboniferous, however we consider that in this region, sediments very different from those described for the Carboniferous. These rocks vary between fine-grained sandstones and sandstone of the dry lagoon which are sporadically distributed in the middle of a flat surface. The structural values (heading and dip) that these outcrops present are variable. This behavior is probably due to the arrangement of tilted blocks, associated with normal failures, of a distensive type. There are no elements that indicate the effects of compressive deformation.

The outcrops north of the Chaco, in the vicinity of the San José ranch, are located on the western edge of the lagoon. The polimictic conglomerates with thick edges to media of pink granite, white quartz, black shales and porphyritic rocks and quartzites represent the San José Formation (The Lower Carboniferous) [8]. Local discordances and variable thicknesses (up to 800 m in the Carandayty subbasin) are characteristic. The presence of conglomerate sandstone in the Tarija basin (Bolivia) is mainly associated with the thicker and more friable texture roots that make up several of the formative units (Tupambi, Chorro, Escarpment) of the Carboniferous in the Andean region. Thick texture sediments, are visibly consolidated and silicified with diagenetic processes show a moderate reaction to HCI. This unit is assigned to the interval between Early Carboniferous and Early Permian. The typical places of this unit are located between the towns of Palmar de Islas and Adrian Jara, along the high Lagerenza. According to the same author, this classic succession has a thickness of 1,600 m and presents good characteristic as reservoir rock [6].

The Upper Carboniferous–Lower Permian, Cabrera Formation has a transitional contact with the underlying San José Formation and is a sandstone-dominated sequence with local basal conglomerates.

Mezozoic. Fluvial and eolian sedimentation during the Triassic filled depressions in the northern Chaco, the environment changed gradually to a desert landscape, blanketing the remaining topography. These strata are included in the lower Adrian Jara Formation. A major Mesozoic extensional event corresponding to the opening of the South Atlantic (230–65 Ma) is recorded for the main Adrian Jara Formation in the Curupaity subbasin. Its equivalents in the Pirity subbasin are the Berta, Palo Santo, and Santa Barbara formations.

The tectonic style reflects pervasive extension from Early Cretaceous to middle Eocene time. The geometry of the former subbasins and highs was modified substantially. The Carandaity and Curupaity subbasins became relatively stable, with only low sedimention rates. Further uplift of existing highs established new depositional centers. Three new subbasins subsided along northeast- southwest axes: the Pirity and Pilar

subbasins and the Bahía Negra platform. Continental sedimentation was widespread. Basic to alkaline magmatism (135–108 Ma and about 70 Ma) is characteristic. Mesozoic rifting is believed to have established the principal structures and initiated maturation of potential source rocks for hydrocarbon generation [9].

Cenozoic. The formation and uplift of the Andean mountain ranges to the west of the Chaco basin (50-35 Ma) initiated a process of sedimentation whose new source of sediments excluded the marine influence from the direction of the Cordillera. As a remnant of inverted cracks, the blocks of Asuncion and San Ignacio register local nephlastic magmatism (49-40 Ma). The sub-basins and highs of the Chaco basin that were established during the Mesozoic were covered by the thick continental layer of the Chaco Formation. The slight reactivation of structures in the Mesozoic is attributed to tertiary tectonism. That some of these structures are still active is evidenced by internal drainage patterns in the Bahía Negra-Pantanal area and weak seismic activity.

## III. Analytical Framework

III.1. Stratigraphy of the carandayty subbasin end potential de hidrocarburos no convencionales

The Carandayty sub-basin, is located in the northwest corner of the Paraguayan Chaco, is separated from the Curupayty by the Alto de Cerro León (izozog as it is known in Bolivia), Northeast-Southeast direction, and Pirity by the Alto de Boquerón, direction Northwest-Southeast and is part of the Tarija basin of Bolivia. Geologically it is constituted by Paleozoic rocks (Silurian and Devonian) that behave as generators and reservoirs respectively, as they can be verified by the numerous Bolivian and Argentine productive fields and by the discovery of gas from the Independencia 1 well of the Paraguayan company Cano Martínez. The Silurico-Devónico cycle is constituted by clastic sediments of marine origin of Silurian and Devonian age, where clearly you can see sandy and clayey facies.

The stratigraphy of the Carandayty sub-basin, with respect to the Ordovician, according to observations made in the lithological profile in the Don Quixote well, presents marine shales from the middle Ordovician to the superior in the western part of the Paraguayan Chaco. In the eastern part of the mentioned Sub-basin, in the Parapiti-1 well, the shales range from the Lower Ordovician to the Middle. The Ordovician shales are black to very dark gray, firm, silty and siliceous in parts, partly fissile, piriticas, very micaceous, interspersed with sand. The interspersed sand is white to medium gray, silty and partly micaceous, very fine to fine, predominantly friable and sometimes firmly cemented by silica; with occasional anhydrite stringers, occasionally slightly calcareous [5]. The most superior contact of Ordovician seems to be transitory to the silts and slates of the Middle and Upper Ordovician. This shale sequence is informally called the Don Quixote Formation [5] (see Figure 6).

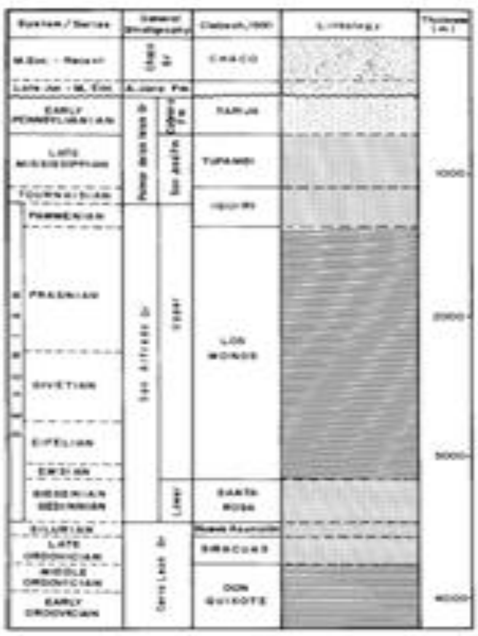

**Figure 6. Simplified stratigraphy of the Carandaity subbasin, western Paraguayan Chaco basin. Modified by F. Wiens, 1.995**

The more distal facies of the Ordovician sediments in Paraguay, unlike the Subandino Belt, indicate that the deepest part of the Ordovician Sea between the Subandino Belt and the Brazilian Shield was found in the western Paraguayan Chaco. The Asunción-1 well, in the San Pedro channel in eastern Paraguay, penetrated palaeontologically with date. Middle to upper cycle linked to the geodynamic evolution of the Early Paleozoic

Pacific margin. Although the lowest levels of the Ordovician reached in the Chaco basin contain dark marine shales and siltstones with lingula [10]. The lowest Ordovician is the La Paz Formation, which in the northwest of the Chaco is an interval of black slate and pyrite with interbedded siltstones and sand stones.

The Silurian strata which are Car encountered in the Chaco Basin of NW Paraguay and eastern Bolivia are indicative of passive margin con deposition, starting with the Lower Silurian deeper the water organic rich source rocks of the La Paz (pro Formation (Kirusillas Formation in Bolivia) (see Figure 7). These are a sout primary source rock and are mature present day to the west in the Andean foreland. Geochemical data from dep the Parapity 1 well and Pennzoil's Don Quijote well in inclu Paraguay reveal that these rocks are also in the gas generating window in Paraguay. Deep water turbidites and fractured novaculite (chert) beds of the Lower Santa Rosa Formation (Sara sandstones of the Carb Carmen Formation in Bolivia), above the La Paz source rocks, are reservoirs in the Upper Silurian [11] (see Figure 7)

Outcrops of the Silurico observed in the northwestern part of the Chaco, in the rocky massif of Cerro León, an elevated structure that contrasts with the almost flat topography of the terrain. White, yellowish-white sandstones with crossed stratification were identified, in the basal part they are arcosicas determined as Cerro Leon Formation. In more tectonized areas of Cerro Leon, the sandstones pass to quartzites with development of phaneritic quartz crystals, which indicates the hydrothermal action. The relief has an elongated north-east-southeast shape and its length in this direction is approximately 35 km. The altitude of the hill is approximately 600 meters above sea level. The fractures are mainly of north-south directions, existing others of NW-SE and NE-SW. The presence of gaps or faults between the stratification planes indicates that there was horizontal displacement, in addition to the normal faults of large size. This section represents a transgressive and regressive Chaco. The Cerro León del Silurico Group, was detected in the Carandayty Sub-basin and has a lithology similar to the Cerro León massif

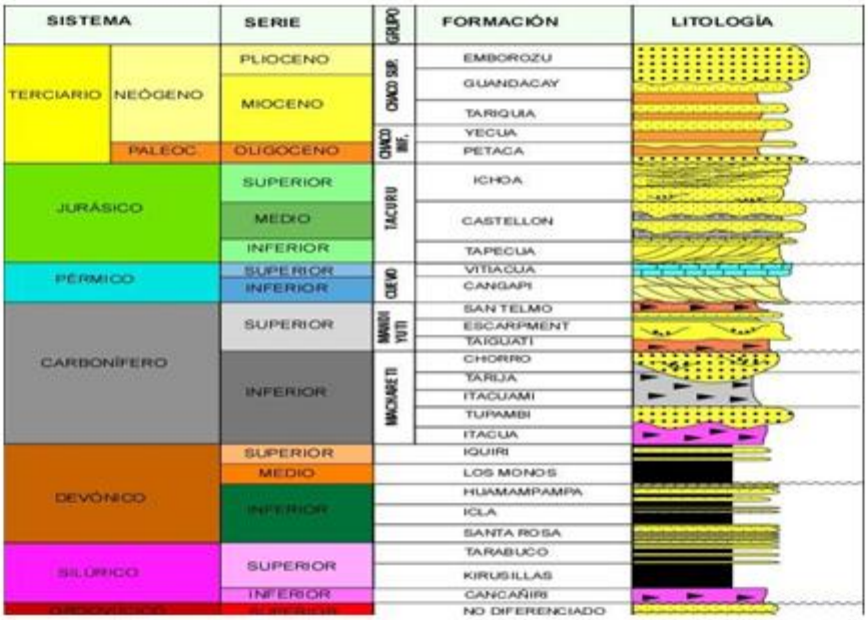


**Figure 7. Generalized stratigraphic column of southern Bolivia**

The levels of the Silurico are observed, at certain intervals in the Don Quijote-1 well, for example, 2,327 to 2,346 meters (7,636 to 7,700 feet) macro-fossils, particularly the crinoid stems replaced by pyrite [5]. Samples from 2,338 to 2,347 meters (7,670 to 7,700 feet) contain up to 25% pyrite [12]. The superior contact with the Santa Rosa Formation seems conformable. The well Don Quijote-1 penetrated a total of 135 meters (442 feet) of siluric sediments, while the Parapiti-1 well penetrated a total thickness of 335 meters (1,100 feet). In the Pure Lagerenza-1 well, the palynological samples of up to approximately 2,316 meters (7,600 feet) gave an early Devonian age; below this depth, the fossils are charred and are not identifiable. The marine regression persisted throughout the Silurian, depositing thick sandstones with intercalations of shales. These gradational deposits are the highest formation of La Paz and the Santa Rosa Formation. Wolfart, reports arthrophycus, brachiopods and gastropods from the thickest intervals near the top. A llandoverian age is suggested [12].

The outcrops of the Devonian, constitute Shales, siltstones and micaceous sandstones of very fine grain that were observed in semi-covered outcrops, with very little possibility of obtaining information about facies and sedimentation environments. The localities where these outcrops were recognized are known by Sierra León and the hill of Line 42 and correspond to the San Alfredo Formation [13]. The black clays that are shale were deposited in a lower energy environment in the center of the Carandayty Sub-basin. On some occasions these fine facies can be constituted as regional stamps. The black shales are known for their potential as a source rock for hydrocarbons, on the Bolivian side, in the Tarija basin, where they are called Los Monos Formation.

Comparatively, on the Bolivian side, the stratigraphic column contained in the Tarija basin is generally divided into two groups of reservoir levels, with the Devonian being considered gas carriers, while the supra-Devonian reservoirs produce oil and / or gas. The quartz sandstone facies of the known formations in Bolivia such as Santa Rosa, Icla Huamampampa and Iquiri are reservoirs, mainly for gas. They are quartzitic sandstones that produce mainly by fracturing, deposited in coastal marine environment and external platform (see Figure 7).

Although the stratigraphy can be differentiated, due to the change of facies, in the Carandayty Sub-basin on the Paraguayan side, it is not ruled out that the lithological behavior in certain sectors and levels are similar to that of the Tarija basin of which the sub-basin forms a part of the Carandayty. The scope of this investigation does not contemplate a detailed study of the facies and lithological characteristics of the mentioned Formations. The lithological distinction between the Santa Rosa, Icla and Huamampampa formations of the western part of the sub-Andean belt of Bolivia is not easily observed in Paraguay. The sequence is similar to the one found in the eastern part of the sub-Andean belt of Bolivia in the Sierra Sararenda and northwestern Argentina. That is to say, the Santa Rosa Formation that goes from Gedinnian to Emsian (Early Devonian) in Paraguay is covered by shales of the Los Monos Formation [5]

The behavior of the Devonian in the Paraguayan Chaco is conditioned by the depth of the basin in general. This characteristic influenced the variations in the entrance of clastic sediments. The transgressive character of the sea in the Devonian period allowed the wide distribution of the shales. The sequence of black clays, shales of greater granulometry detonates the deep environment. In the Devonian, the sea levels have undergone changes oscillating of rises and downs in sectors and depths that influenced in the deposits and types of sediments what prevents to generalize the behavior of the sediments in the Carandayty Basin object of the present study.

The lithological unit of sandstone, siltstone and shales interspersed in the Carandayty Sub-basin is palynologically dated in the Don Quijote-1 well as in the Upper Ordovician to the lower Devonian and in the Parapiti-I well as the Upper Ordovician to the Lower Devonian. They reported that the presence of leiosfras and Schizocvstia sp, the latter fragmented, indicate that this sedimentary package correlates with the Icla Formation of the western part of the sub-Andean belt of Bolivia. In general, the homogeneous sequences of shades of dark gray to black of marine origin extend from the Emisian to the Frasnian in the Sub-basin of Caranadayty. This thick sequence of Devonian shale is known as the Los Monos Formation in Bolivia and is contained in the San Alfredo Group in Paraguay. The Devonian shales are dark gray to black, firm, micaceous to very micaceous, partly fissile, with layers of siltstone. In this study we propose the name of Kai Formation to this Formation. The marine sands corresponding to the Santa Rosa Formation underlie the sequence of shales of the Los Monos Formation. The upper part of this unit has an Emsian palynological age in the Don

Quijote-1 well, correlated with the Huamampampa Formation of the western part of the Bolivian Subandino Belt [5]. Well La Paz-1, 2.210 meters deep, penetrated at least 91 meters from Devonian shales dark sea with about 335 meters from interbedded shales, sandstones, siltstones and quartzites assigned to the ages of the Devonian, Silurian and Ordovician. Approximately 1,300 feet (396 meters) of dark marine shales of possible Ordovician age continue to full depth.

The greatest thickness of the Devonico registered in the sub-basin of Carandayty is 2,542 meters, of which correspond to the marine shales of the Kai Formation of 2,500 meters. The San Alfredo Group is of Early-Late Devonian age. Nearly all the exploration wells have been found with Devonian sections, as have the groundwater surveys in the north of the Chaco [14] (see Figure 8).

The Carboniferous Geological units are represented in the Palmar Group of the Islands (Early Carboniferous-Early Permian by two Formations, San José and Cabrera Separated by the High Structural of the Central Chaco and Lagerenza.

In the Carandaity subbasin, scattered samples extending to the lower section of the redbeds provided fossils mainly from Toumais and some of the early Pennsylvanian years. The early Mississippian section,

which extends to the redbeds, would be the equivalent of the Tupambi Formation in Bolivia. The first ages of Pennsylvania would indicate the presence of the Tarija continental formation in the sub-basin of Carandayty.

In Bolivia, in the Tarija basin, the reservoirs are found in the Permian, Mesozoic, and Tertiary base (Fm. Petaca) cycles. They are Sandstones of wind and fluvial origin of glacial, periglacial and continental environment that produces by primary porosity, with values that oscillate between 12 and 30%. The traps are mostly structural, and the purely stratigraphic entrapment is not common. Some accumulations in the Tertiary, where the reservoirs are ephemeral fluvial sandstones of marked lenticularity, possibly have a strong stratigraphic influence in the entrapment. The main migration routes are linked to failure and fracture systems [7]. It is not ruled out that the geological conditions and the lithological characteristics of these cycles are prolonged in this sub-basin sub-basin. Only in the deepest western parts of the sub-basin of Carandaity there is a complete section of the Upper Devonian-Carboniferous.

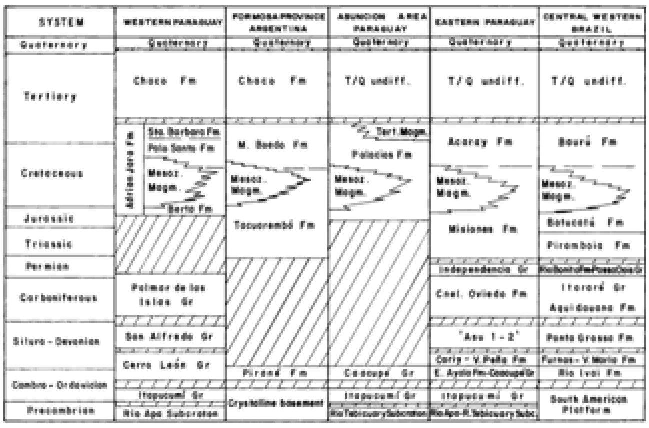


**Figure 8. Comparative stratigraphic chart of the Paraguayan Chaco basin, western Paraguay, with adjacent correlative areas in eastern Paraguay, Argentina, and Brazil.**

Organic geochemical study, conducted in the well Don Quixote-1 drilled in order to determine the source of the quality of hydrocarbons and thermal maturity of the penetrated sediments allowed to perform interpretations according to levels from surface to total depth.

Zone A (Surface at 1650 feet). This area, like the section up to 2450 feet in the Katerina-1 well, has a very poor hydrocarbon source character. This section includes unconsolidated sand and minor intercalations of green mudstones (only 0.04% organic carbon). Only biogenic methane gas (produced by bacteria) can be expected in any reservoir trap in this area. The well cuts mainly threw methane (more than 99% of the C1 - C4 gases) by our analysis of gc C1 - C7. Zone B (1650 to 5850 feet). This grayish-gray lake like section is the mature counterpart of the shale section found in the Katerina-1 well during the interval of 2450 to 3747 feet. Like the latter, this area has an excellent character as an oil source, but, unlike the latter, it has experienced a greater degree of thermal maturation. The shale in the Katerina-1 well exhibits several geochemical characteristics of an immature organic facies that include a pale yellow kerogen color, the presence of porphyrin pigments and an odd carbon preference of the C15 heavy paraffins. On the contrary, the shales of Zone B in the Don Quixote well are mature and have undergone the oil generation phase. While the shales in well 1 of Katerina are classified as Stage 1 to 1+, in the Don Quijote well they are classified as Stage 2 in the upper part of Stage 3+ in the lower part of the zone. The mature nature is reflected by the absence of the odd carbon preference in normal paraffins, the kerogen color from orange to dark brown and the absence of porphyrin pigments.

Zone B in the Don Quixote well appears to represent the same organic facies as those already mentioned in the Katerina-1 well on the basis of similar ic4ac4 proportions. This ratio varies between 0. 2 and 0.5 in both cases. Zone B is finely distinguished from the underlying Zone C by an abrupt change in the geochemical characteristics of the organic. Zone C has a decidedly different and considerably higher difference (values of 0.8t vs 0.3 of iC4 / nC4) we interpret a limit of organic circles at 5,850 feet that could consciously coincide with a disagreement

Zone C (5850 to 9496 feet): Top slate section (5850 to 6980 feet): This section comprises dark gray micaceous shales that have a lithological appearance of the shales of Zone B. They are not very different in the total organic matter content. Based on the composition differences of cold light that are difficult to dehydrate, they seem to represent an organic facies different from Zone B. This upper section of shale is a very mature

organic facie. It has had a good source character, but due to local geothermal conditions it has passed to the advanced stage of thermal maturation. The increase in the geothermal maturation of these sediments is shown

by the progressive decrease with the depth of the moisture percentage of the gas, the C4-C7 hydrocarbon and the C15 + hydrocarbon content. During this interval, the shales have a relatively constant organic carbon content and show a uniform type of organic kerogen. Any hydrocarbon reservoir found in association with this particular section, in this place of the well, would contain a high gravity oil near the top that progresses to moist gas and condensed to the base. This section contains a lot of pyrite that can relate directly or indirectly to its anomalous geothermal history; Medial Sand Section (6980 to 8100 feet), this section, which we assume was one of the objectives of this deep test, in this particular location of the well, can at least be best described as a disappointment. There are thick sands and siltstones within this section but they are nom porous. Although they were clean quartz, very fine sand and silt at the same time, they are good due to the silica cementing. Second, even if they were porous, they are inside a very mature facie and would contain gas instead of oil; Lower shale section (8100 to 9496 feet), this section of shale represents a very mature organic facies (Stage 4 at 8400 feet). Only gaseous hydrocarbons would be stimulated in any reservoir (if present) within this section at this well location. In fact, in the lower 600 feet where the shales have a slate-like appearance (they sound like slate), the gas would contain mainly methane.

This study has delineated two essential conditions that must be met in this exploration area to find oil:

1. The favorable area is probably peripheral to the hot area also tested by Don Quixote. In this area, the shales of Zone C located immediately above the sand would have a wide thermal history for the generation of oil and, however, do not have enough temperature for the destruction of liquid hydrocarbons
2. The favorable area should contain uncemented sands from Zone C. It is expected that away from the anomalous hot area drilled by Don Quixote the lower temperatures would have hindered the pressure solution and the associated silica cementation of these sands [15].

## IV. Potential for exploration of unconventional hydrocarbons

The potential of unconventional hydrocarbons in the Caranday sub-basin is related to the Paleozoic marine shales (see Figure 6). They belong to the Silurian-Devonian Cycle and indistinctly have generators behavior as reservoirs of oil and gas. The black clays or shales of the Carandayty belonging to the San Alfredo Group are the most promising. The target consists of the Upper Devonian and Mississippian transitional sands. The Iquiri Formations (Missisipian), Kai (Denomination given in this study to the Los Monos Formation (Upper Devonian) and Santa Rosa (Lower Devonian) belong to this Group, the Kai Formation serves as a source rock, the sandy horizons within the area of shales of the Formation are considered as oil accumulators because they are surrounded by source rocks The formations correspond to the Frasnian, Givetian, Eifelian and Emsian of the Upper, Middle and Lower Devonian respectively The Silurico is represented by the Nueva Asunción and Siracusa Formations and Don Quixote of the Ordovicico all of them from the Cerro León Group.

Local wells in the Caranday Basin were studied with greater emphasis: Don Quixote-1, Parapiti-I, (see Figure 9).Katerina-1 and La Paz-I, the first two reaches sediments of the Lower Paleozoic penetrating to the rocks of the Ordovician age Medium and Early del Parapiti over 1,300 meters (>4,265 feet) of the Devonian Los Monos Formation, in the Don Quixote-1 well, have source character (0.5% TOC) with shales that were subjected to an oil generation phase generated high gravity oil near the top and wet gas and condensate towards the base. Ordovician shales (0.5% TOC), in the Don Quixote-1 well ofthe Carandaity Subbasin, are in a very mature organic facies (stage 4-) and generated only gaseous hydrocarbons (methane).

Paleozoic marine shales and carbonates reach nests of 2,500 m in the sub-basin of Carandaity, representing excellent hydrocarbon source rocks. The shale units of the Cerro Leon Group (TOC content of 0.5 wt. %, Don Quijote-1) may represent secondary source rock; in Argentina and Bolivia there are producing fields in this interval. The organic material in the upper portions of the succession in the less deformed interior parts of the sub-basins (eg, well Katarina-1) tends to be immature. In the deepest parts of the section and along the margins of the sub-basins, the level of organic maturity varies from mature to excessively mature (for example, the Don Quijote-1 well). The increase in geothermal energy maturity with depth produces a decrease in the humidity of the gas. The increase of geothermal gradients, fractures and magmatisms produced a saturation of the sedimentary rocks, reaching conditions of low grade metamorphism. The wells (wells Mendoza-1 and Mendoza-2) of the Carandayty sub-basin present gas and dry oil.

Potential prospects existing in the country will receive greater attention and importance, if by means of geological modeling and basin analysis the volume of hydrocarbons economically recoverable will be indicated. The carburiferous potential of the Carandayty sub-basin is given by: Subbasin of Carandayty: Generators: La Paz Formation; 1.5 - 2.0% TOC; San Alfredo Group; 2.5 - 3.5% TOC Reservoirs: Sta. Rosa

formation; 11 - 13% porosity. San Alfredo Group; 3 - 15% porosity; Palmar de las Islas Group: 10 - 20% porosity. Oil window: 750 - 1220 m Main structures: Paleozoic domes; Stratigraphic / structural disagreements.

| Simple Depth (in feet) | Age | Environement | Remarks |
|---|---|---|---|
| 1400-1600 | Early Frasnian Minimun age | Near shore marine. Restricted circulation | Aproximately correlative wiht 2500 feet in Pure Mendosa well |
| 1600 - 3200 | Givetian | Near shore marine. More | Abrupt preservation change |

| | | | |
|---|---|---|---|
| | | open marine at 2300 to 3200 feet | which may be thermally related May possibly indicate an unconformity |
| 3200 - 4500 | Eifelian | Shallow marine open circulation | Abundant spiny acritarchs of the Balthis phaeridium Type. |
| 4500 - 6800 | Emsian Devonian | Marine open circulation | Preservation of fossil spores is such that they can be recognized only as spore |
| 6800 - 7900 | Silurian | Shallow marine Restricted circulation | Chitinozoa and acritarch assemblage. Predominantly small arcitarchs |
| 7900 - 9100 | Middle Ordovician | Shallow marine | Chitinozoa area predominant fossil. Few arcitarchs |
| 9100 - 9296 | Lower Ordovician | Shallow marine | Chitinozoa area predominant fossil. Few arcitarchs |

**Figure 9. Determinacion paleontológicas de la edades de la columna de sedimentos del Pozo Parapiti**

The Lagerenza well encountered Devonian gas shows while drilling. The Mendoza 1R Well DSTd at 3.0 MMCFGD from a 13m zone, which yielded a whole core containing a 1/8 inch (3mm) open fracture, although partly filled with calcite crystals. These whole cores from the Devonian were reported as mostly shale and siltstone, containing some sandstone laminations too thin to resolve on wireline logs.

This unconventional reservoir requires the proven vertical fractures to connect the sand Sour laminations and allow for profitable production. The existi recent CAS International report and core analysis from predic the CDS-GM-05-5001 well suggest that this 3.0 prese MMCFGD DST rate in the Mendoza 1R well was probably limited by old drilling techniques, including high mud weights leading to formation damage. CAS International also concludes that fracture stimulation would probably increase flow rates from the Devonian occurr significantly.

This is particularly critical in tight and other 'unconventional' reservoirs historically not considered as reservoir, such as the Barnett Shale in Texas, USA.

This is also in some ways an analogue the ga for possible CDS Devonian production. CAS International's mean estimate of Devonian gas potential is 15 Bcf per km2.

## V. Conclusion

The potential of hydrocarbons in the Carandayty basin in the Paraguayan Chaco is mainly related to the Paleozoic marine shales of the Silurico-Devónico cycle (San Alfredo Group). The Lower Ordovician Group of the Cerro León Group and the upper Devonian shales of the San Alfredo Group are source rocks in this sub-basin.

The possible deposits of shale gas exist in the Los Monos Formation with 2, 500 meters of thickness of shales rich in organic matter, deposited in marine areas. The generation of oil is inferred for the lower parts of the sequence in the center of the sub-basin and along the flanks of the upper reaches of the margin of the basin.

The Chaco basin in Paraguay remains largely unexplored; the geology suggests that it has a significant hydrocarbon potential. The counterparts of the Carandayty sub-basin on the Paraguayan side of Bolivia and northern Argentina are the main producers of oil, gas and condensate.

The efforts for the discovery of hydrocarbons in Paraguay are still insufficient. It requires a greater investment in prospecting / exploration programs to advance in the knowledge of the geological complexity and increase the possibilities of obtaining in greater detail the information that can indicate us aerial with commercial potential of oil exploration.

The country needs to incorporate into its energy matrix this valuable resource that will be achieved through strong investments in the sector in the medium and long term. It is necessary a finished study of the comparative costs of the exploitation of unconventional hydrocarbons in the country, in order to evaluate the competitiveness of an eventual entry with the other sources of energy allowing the increase of the diversification of the Energy Matrix.

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