Evidence for Precambrian Stratigraphy in Graben Basins below the Eastern Llanos Foreland, Colombia*

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Abstract

Deep and extensive graben basins are preserved below the South American sub-Andean foreland basins. These features are the subject of frontier exploration in Colombia and Venezuela. Indeed, "traditional" exploration models were based on the superposition of two Wilson Cycles that considered one or more pre-Cretaceous petroleum systems within pre-Cretaceous grabens. Recently, exploration drilling and new seismic interpretation in the Eastern Llanos Basin of Colombia has yielded evidence for thick sedimentary, non-metamorphosed and well preserved Precambrian (Neoproterozoic) successions that may have filled pre-Paleozoic grabens in at least four locations in the Meta region. These grabens were reactivated and/or continued their uppermost infill until Cambrian times; Late Paleozoic-Mesozoic graben/sag /impactogen reactivations are not discounted, but they are difficult to detect because the entire region is still poorly drilled with deep exploration wells. Biostratigraphic findings include well-preserved examples of acritarchs of the genera Kildinosphaera and Leiosphaeridia asperata, recovered in a section of compact shales and sands as deep as 1000 feet below the Eastern Llanos foredeep unconformity. Chronostratigraphic ages range from Early Cambrian to Ediacaran and Mid-Cryogenian, with color indexes in the range of 3+ to 4- and reflectance results showing that the Neoproterozoic samples are in the upper gas generation window. The evidence collected provides an unexpected window into the early expressions of life on the planet.

Introduction

An increased exploration effort in Colombia, carried out in recent years by many operators, has led to new exploration wells being drilled in both mature and frontier exploration provinces. One of the main exploration areas is the Eastern Llanos Basin, where a number of new exploratory and stratigraphic wells drilled recently in the Arauca region (Figure 1) have yielded new geological and geophysical data that allow building on the current knowledge of the Cretaceous to Tertiary succession that is the main exploration focus. However, penetrations below the Cretaceous, however, have also produced new data that is relevant to the stratigraphic succession contained in graben basins preserved below the Cretaceous to Tertiary wedge that have been mapped, mostly from potential fields, in northern South America from Venezuela to Ecuador, see Figure 2.

Separated by conspicuous basement highs and showing in some cases significant internal deformation and reaching thicknesses of more than 10,000 feet (see map in Figure 3) these basins have been identified as a prospective exploration frontier in the Eastern Venezuela and Colombian Llanos basins by several authors, e. g. Pérez (1985) ,Muñoz – Torres (1991), Goodman et al., 1998 and more recently Audemard and Serrano (2001), Olivares et al., (2002), Mora et al., 2006 , Pinilla et al. (2006), Salazar (2007) and Lugo and Arminio (2008). The geological control of the graben fill is sparse and with very few exceptions is restricted to the shallowest realm immediately below the base Cretaceous unconformity; the ages established, thus far range, depending on authors, from the youngest Ediacaran and earliest Cambrian to Triassic-Jurassic, see Table 1.

Indeed, exploratory wells with pre-Cretaceous target have been only two in the northern Eastern Llanos, drilled by Mobil (HELIERA-1) and Sun Oil (CHIGÜIRO-1) near the Cravo Norte area. All the other penetrations are either controls geologic well controls for TD verification or otherwise extensions of exploration wells targeting Cretaceous and Tertiary collecting strategic data.

The existence of an effective pre-Cretaceous petroleum system, a matter of considerable debate, has been proposed by several authors for the Arauca Graben, e.g. Olivares et al. 2002 and Mora et al. 2006., based on oil geochemical analyses. Traces of bitumen in Ordovician tight sands in HELIERA-1 were reported although no information as to its origin is documented (Quijada, 2012).

With so much exploration interest and such scarce data and information, every new penetration permits the opportunity of gaining additional insight. Such is the case of four wells drilled by Pacific Rubiales Energy in 2011 and 2012 in the Arauca region near Cravo Norte. The wells, named CHILACOA-1S, CORALITO-1S, TORODOI-1X and VACO-1X, penetrated 1,105 feet, 100 feet, 200 and 130 feet of pre-Cretaceous vertical section, through which geochemical and biostratigraphic studies were carried.

Detailed palynological analysis of the four study wells showed conclusive evidence of acritarchs ranging in age from close to the Cambrian/Precambrian boundary down to the Ediacaran and Cryogenian. These results, that could be a first-report of pre-Cambrian life in northern South America, suggest that there are non-metamorphosed sedimentary phases that are older than Early Cambrian, the oldest age previously reported in the exploration area and younger than the oldest sediments known in the region, i.e. the Roraima Basin 1800 Ma (González de Juana et al., 1980) that is well exposed in the Guayana Craton.

The implications for hydrocarbon exploration of this new data are potentially significant:

- Precambrian sediments in the Llanos may open possibilities for additional petroleum systems, given the fact that in Cambrian time and well into the Neoproterozoic extensive marine environments existed around emerged cratons where microbial communities flourished with no predator or bottom – dwelling competition (Gray et al. (1998), England et al. (2002), Mount (1989 and 1991), Nedin and Jenkins (1991), Fedonkin (1992), Gehling (1999), Huddart and Stott (2010).

- Exploration models based on superimposed Paleozoic and Mesozoic - Cenozoic Wilson cycles will require to accommodate a more complex Neoproterozoic and Paleozoic geodynamic evolution for the Llanos region, being part of a west Amazon craton setting that underwent multiple episodes of subsidence and uplift during the Paleozoic (Mišković et al., 2009 and Hartz and Torsvik, 2002).

The new palynological evidence and its exploration implications are discussed in this paper, with a view to update prospectivity issues that could be relevant to exploration in both industry and regulating entities.

General Stratigraphy

Local stratigraphy

The study area is located in the north-central part of the Eastern Llanos Basin, in the Cravo Norte region near the Meta River, 170 km from the Cordillera Oriental piedmont of the Cocuy Massifand 300 km from the western boundary of the Guayana Craton as defined by the Orinoco River, (Figure 1). Here, the thickness of the Cretaceous to Tertiary foreland is in the order of 7,000 feet, (Figure 4) whereas the pre-Cretaceous section has varying thicknesses of more than 10,000 feet where graben basins have been preserved below the base Cretaceous unconformity. Otherwise, the foreland rests on crystalline basement in local highs, e.g. towards the east beyond the interpreted graben shoulder as shown in Figure 5.

Tertiary and Cretaceous

A schematic of the local Tertiary foreland and Cretaceous passive margin fills is shown in Figure 6. The column, based on biostratigraphic analyses carried in well CHILACOA-1S) is representative for the area and correlates with a dozen neighboring wells. In the area, the Mirador and Carbonera sand intervals are present below the regional Leon seal and are the main exploration target. Likewise, the sand-prone Cretaceous interval is the subject of further exploration interest.

Pre - Cretaceous

Well control of the pre-Cretaceous section is sparse and restricted to short sections below the base Cretaceous unconformity as shown in Table 1. This scarcity of rock data highlights the exploration maturity of the Tertiary – Cretaceous section, contrasted with that of the pre-Cretaceous that in fact is a frontier play.

Study well data

The four wells that yielded the data presented in this paper were drilled by Pacific Rubiales Energy in 2011 and 2012 in the Arauca E & P Block and the CPE-1 TEA, all with Cretaceous and Tertiary exploration targets and programmed TD below the Base Cretaceous unconformity.

- TORODOI-1X was drilled vertical in 2011 to a TD of 7,327 feet, targeting and elongated basement structure.
- VACO-1X was directionally drilled in 2011 from the same pad of TORODOI-1X 2011 to a TD of 8663 feet, targeting at Tertiary level.
- CORALITO-1S is a stratigraphic well drilled in 2012 to a depth of 5,620 feet
- CHILACOA-1S is also a stratigraphic well, drilled to a total depth of 6,745 feet in 2012. This well penetrated 1,105 feet below the base Cretaceous unconformity, as part of the investigation plan of the well.

Precambrian Stratigraphy

Palynology: chronostratigraphic age, environment

The palynological samples have been logged quantitatively, with counts of at least 200 specimens made for each sample, and the remaining slide scanned for other significant taxa. Counts that are below 200 specimens represent the entire palynomorph recovery in that preparation. The Precambrian acritarch assemblages are generally of high abundance, and are dominated by poorly preserved dark coloured sphaeromorph acritarchs.

The ranges of Precambrian acritarchs have been taken from a number of published sources, including Baudet (1988), Hoffman and Jackson (1994), Korolev and Ogurtsova (1983) and Palacios and Vidal (1992). Applicable acritarch ranges are summarised in Figure 7 and examples are illustrated in Figure 8.

Identifiable sphaeromorph forms include species of *Kildinosphaera* spp. (*K. Verrucata* and *K. chagrinata*) and *Leiosphaeridia* spp. (including *L. asperata*). Additional acritarchs include cf. *Coneosphaera arctica*, *Cymatiosphaera* spp., *Dictyodinium* spp? *Kildinella* spp. and *Lophosphaeridium* spp., together with *Micrhystridium* spp. and a variety of unidentified acanthomorphs acritarchs.

There are some slight differences in assemblages between the study wells which may be indicating different stratigraphical positions within the Late Neoproterozoic, or which could also be explained as the result of slight variations in the palaeodepositional setting. The exact stratigraphical relationships cannot be determined with certainty, but an educated guess would suggest that the Chilacoa-1S assemblage is the youngest (Late Neoproterozoic, close to the Cambrian boundary), the Torodoi-1X and Vaco-1X assemblages are either equivalent in age to Chilacoa-1S or possibly slightly older, and the Coralito-1S assemblage is probably the oldest.

The Chilacoa-1S assemblages include *Cymatiosphaera* spp. and *Micrhystridium* spp. (Ediacaran and younger), and rare *Lophosphaeridium cf. tentativum* (this species has previously been reported from the Early Cambrian). This association of species suggests a Late Neoproterozoic, Ediacaran age, very close to the Precambrian – Cambrian boundary.

The Torodoi-1X and Vaco-1X assemblages also include a similar association of *Cymatiosphaera* spp., *Micrhystridium* spp. and *Lophosphaeridium* spp., indicating a Late Neoproterozoic, Ediacaran age, which is either equivalent in age to Chilacoa-1S or possibly slightly older.

The assemblages recorded from Coralito-1S include an association of *Kildinosphaera* spp., *Leiosphaeridia* spp. *and Leiosphaeridia asperata*, which suggests a Late Neoproterozoic, Cryogenian to Ediacaran age. Additional and distinct specimens of cf. *Coneosphaera arctica* (previously recorded from the Proterozoic Bylot Supergroup, Baffin Island, Canada (Hofmann and Jackson, 1994), and dated as 1,270 Ma to 750 Ma). This assemblage suggests the sediments in Coralito-1S are the oldest encountered in the four wells, although this cannot be positively proved.

An unequivocal depositional setting cannot be determined with certainty, although comparisons with younger Silurian assemblages suggest that the dominance of sphaeromorph acritarchs could indicate a nearshore, shallow marine or a deep-water offshore setting. It is however noted that the Precambrian acritarch associations are poorly understood and that the dominance of sphaeromorph forms may simply be a function of the simple morphology of most Precambrian acritarchs, which in turn could be unrelated to depositional environment.

Organic maturity

Spore Colour Standard

The colour scale used in this report is based on Pearson (1984) in which the spore colour is directly related to the numerical thermal alteration index (TAI as shown in Figure 9. This scheme is illustrated and discussed in Traverse (1988). Acritarchs have also been used as an indication of thermal alteration (e.g. Duggan and Clayton 2008), particularly in Palaeozoic sediments.

For the Cretaceous samples, the thermal alteration is based on the spore colour of specimens of the spore *Cyathidites* spp. This is a smooth walled, long-ranging taxon, widely used for spore colour determination.

For the Neoproterozoic, there is little alternative to using the sphaeromorph acritarchs, which dominate the assemblages and occur in abundance. For these specimens the colour has been taken from the central area of the specimen, avoiding the thicker outer wall, which distorts the true body colour.

Vitrinite and Acritarch Reflectance

Vitrinite reflectance measurements for the Cretaceous and Tertiary samples (Ro) are based on an abundant assemblage of terrestrially derived vitrinite that was often within coal fragments.

As no higher land plants are known before Ordovician time, no vitrinite maceral is present on which reflectance can be measured as a maturity indicator for the Neoproterozoic samples. Therefore, an alternative approach was applied for the study wells: in this case, reflectance readings were taken not from vitrinite but rather from material that is part of the sphaeromorph acritarch walls, the sporinite-like material that forms the microfossil walls. In polished section, these sphaeromorphs form prominent circular structures with walls that are thick enough for satisfactory measurements. At the elevated thermal maturity level of the Neoproterozoic samples the different macerals (i.e. if as vitrinite was present) would have converged to similar values, and the measurements taken from the acritarchs (Ra) can be considered equivalent to measurements from vitrinite.

Thermal Colour Index (TAI) and Reflectance Results

Colour index and vitrinite reflectance-equivalent readings were taken in all four wells. Well CHILACOA-1S, however, offered the longest pre-Cretaceous investigation and the results of the spore/acritarch colour and vitrinite reflectance analyses are discussed here.

There is a strong contrast between the results from the Neogene and Cretaceous, and the Neoproterozoic samples from the Chilacoa-1S as shown in Figure 10 The colour (TAI) and the reflectance of vitrinite (Ro) and spore/acritarchs (Ra) are presented in Table 2 and Table 3, respectively.

The acritarch colour for the Neogene and Cretaceous samples from CHILACOA - 1S (Table 2) displays a range of 2 to 3- (mainly 2+) which is considered immature to just into the oil generation zone, while Table 3 shows that this section is thermally immature as regards oil generation according to vitrinite reflectance data. This slight discrepancy is not unusual, as there is no exact equivalence between reflectance and spore colour results.

In contrast, the reflectance data (Ra) of the Neoproterozoic in Table 3 shows that samples are overmature for oil generation and towards the upper limit of gas generation i.e. late gas window (Figure 10). This is supported by the acritarch colours shown in Table 2, which are mainly 3+ to 4- (dry gas zone), although it is noted that the acritarch colour shows a slightly lower maturity than the reflectance results. A comparison is shown in Table 4.

Summary

Exploration models

It has been the opinion for some explorers that the interest of pre-Cretaceous successions in the Colombian Llanos relates to the Paleozoic successions contained in the cover of fossilized graben basins. Indeed, authors such as Pérez (1985) and Muñoz-Torres (1991) present maps and well data to support exploration prospectivity of the Paleozoic remnants.

Pérez (1985) describes a thick Paleozoic succession of Cambrian and Ordovician age exposed in the Eastern Cordillera foothills near the Macarena Massif, and the Sierras Chiribiquete and Yuruparí, and attempts to correlate it with findings in the subsurface, namely the Ordovician succession described at Mobil's 1959 well LA HELIERA-1 where in the cored 8,570'- 8,602' where a trilobite specimen was assigned to the genus *Jujuyaspis*, (no species identified). This genus, defined by Kobayashi (1936, is considered to be the marker of Ordovician-Cambrian boundary in many places), has been associated with genus *Elkanapsis* by Kim and Choy (2000) (with extension to Late Cambrian age) in Korea; despite this, these authors maintain their interpretation of assigning lowest Ordovician (Tremadocian) age to the beds with *Jujuyaspis sp.*; this is, however, still an interpretation and the occurrence of *Jujuyaspis* with *Elkanapsis* "…in 9 of 14 localities…" could be associated to a latest Cambrian age in the light of recent studies with more accurate taxa (e.g. achritharcs specia) and taphonomic analysis (Grey and Willman, 2009).

Muñoz – Torres (1991) refers 50 penetrations for the whole Colombian Llanos, quoting ages mostly Ordovician and few (?) Cambrian, with only three confirmed and three questionable Devonian penetrations. Perez (1985) mentions two Jurassic penetrations toward the axis of the Arauca graben in the Arauquita area, west of Caño Limón.

As a general concept for the pre-Cretaceous graben system that extends from eastern Venezuela (Espino Graben) to the Barinas Basin and into the Colombian Llanos, Audemard and Serrano (2001) proposed a conceptual model of superimposed Wilson cycles, the oldest of which would provide a Devonian to Silurian passive-margin derived source and Cambro-Ordovician synrift and Carboniferous to Permian clastic and carbonate reservoirs, see Figure 11.

In this model, conceptualized for Venezuela, the older (Paleozoic) Wilson Cycle rests on crystalline Precambrian basement, and the younger (Mesozoic to Tertiary) was initiated with the Jurassic rift, laid down on the regional unconformity associated with thermal Triassic uplift.

According to the lithospheric behavior expected during rifting and/or elastic bending near collisional boundaries, "sedimentary platforms" on the regional scale for Venezuela and Colombia during the Paleozoic must have been dissimilar, with the sedimentary history in today's Llanos region more related to multiple basin subsidence episodes and long periods of erosion due to thermal or tectonic uplift. For example, from Late Cambrian to Middle Ordovician crustal accretion marked the consumption of Iapetus Ocean beneath the Amazonian Craton. For the rest of the Paleozoic until the Permian the western part of the west Amazonian craton was under convergence geotectonic regimes (Mišković et al., 2009) For this reason, basins by retroarc lithospheric bending (foreland), back-arc extension and/or impactogen rifting (Şengör et al., 1978) must have been more likely to occur than simple rift – passive margin mechanisms.

For this reason, the assignment of "Passive", "Wilson Cycles" to the remnants of sedimentary covers of Paleozoic age in Colombian Llanos Basin is a risky approach, as most of the time between from Cambrian to Permian time the western part of the Amazonian craton was under convergence. This could be a reason why "long-lived" thick Paleozoic sedimentary platforms are preserved in the east-center of the South America Plate instead of the west or the north (see Mišković et al., 2009).

In terms of petroleum systems, those of the Mesozoic to Tertiary Wilson cycle are well-known and documented Venezuela and indeed in Colombia (e.g. Cooper et al. 1995, Sarmiento, 2012). In contrast, scientific knowledge about petroleum system elements in the Paleozoic Cycle is at best basic and preliminary.

Trap

Trapping prospects are provided by numerous, prominent fold and fault structures as well as graben shoulder pinchouts and erosional truncations, all evident from extensive reflection seismic datasets, see also Perez 1985, Audemard and Serrano 2000 and Lugo and Arminio, 2008. This factor is probably the one that has generated most exploration interest.

Reservoir

Regional maps and well data indicate the presence of regional sandstone intervals within the Paleozoic basins in the Colombian Llanos, as almost all the penetrations have reported sandstones. In this context, sandstone porosity could be preserved in a deep realm if hydrocarbon migration was on time to preclude the diagenetic destruction of porosity by cementation processes (Wilkinson and Hszeldine, 2011).

Carbonate build-ups have also been interpreted in the Cravo Norte region, and at least one well, CORAL-1, drilled above an interpreted Cambro – Ordovician carbonate build-up in interpreted
(Sarmiento, 2012).

Overall, risk for presence of sandstone is considered low, but poor reservoir quality is a main reason of concern: almost all penetrations showed tight formations.

Source

In western Venezuela and the Colombia Llanos, oils from the Barinas basin and Arauca region are regarded to be of Cretaceous source, e.g. Cassani et al. 1988. However, a pre-Cretaceous source has been proposed for at least part of the oils trapped in the Barinas basin, (including the Guafita - Caño Limón area), which have been characterized as of mixed Cretaceous and pre-Cretaceous origin, according to 24-norcholestanes (C26 stereane) and 24- nordiacholestanes (Olivares et al, 2002 and 2002, Mora et al., 2006). Indeed, Sarmiento (2012) reports rock geochemistry analyses of Paleozoic units in the Llanos Basin in the range of 0.25% to 3.20% TOC with Tmax 416ºC to 457ºC and Hydrogen Index 19 to 776 mgHC/g TOC. Additionally, tar impregnations were described in compact "Early Paleozoic" sandstones in well LA HELIERA-1.

Additionally, a hypothetical Jurassic petroleum system west of Caño Limón may also be considered if the Jurassic beds mentioned for wells in that region (e.g. ARAUQUITA-1, see Table 1) was to be correlated with source-quality La Quinta lacustrine and marine beds of source quality described on outcrops in the Mérida Andes (Arminio et al., 2004). In addition, biogenic gas might have occurred below the worldwide transgressive shales and biochemical carbonates laid down after the end of the deglaciation of the Cryogenian (ca. 635 Ma, the Marinoan glaciation, see Hoffman, 2011).

Microbial – generated methane below ice caps during glaciation episodes is taking relevance (Hegenberger 1987, Kennedy et al. 2001; Shields et al. 2007, Wadham et al., 2012). These concepts may as well be extended to the "Snowball" episodes in the Cryogenian as well as later glaciations in the 750 to 580 Ma time span (Fairchild and Kennedy 2007).

The Ediacaran time is also favorable for the preservation of organic matter, microbial and microalgae because of the absence of efficient bottom grazers (Gehling, 1999). In general, benthic microbial mats of the Precambrian are potential source rocks due to the diverse states of anoxia that have been reached in both lacustrine and marine environments (Schieber, 1986; Burne and Moore, 1987; Ferry, 1992; Lyons et al., 1994; Gray et al., 1998; Gehling, op. cit.; Graue et al., 2012).

Seismostratigraphic features of "grounding" deformation by ice cap load in the interior of graben basins could be useful to recognize the possible "end of Cryogenian" sequences at the lower graben infills (i.e. Dowdeswell and Fugelli, 2012; Hoffman, 2011) or even at the end of other glacial events during Neoproterozoic. It must be pointed out here that some authors reject non–Cretaceous sources for crude oils in Caño Limon (Schiefelbein et al., 2009), so the idea of a Paleozoic – sourced petroleum system in Colombia is not without controversy.

Migration, charge

If an effective pre-Cretaceous petroleum system is to be considered, it should be contained within the boundaries of the linked graben system. Most authors assume pre-Cretaceous traps to be charged by a pre-Cretaceous Jurassic or Paleozoic source matured in a deeper pod and migrated over relatively short distances.

Updated exploration model: Precambrian petroleum systems

A thick Cryo – Ediacaran succession in the fossil graben basins below the Llanos foreland in eastern Colombia should introduce changes in regional exploration models. One of those would be the insertion of a sedimentary cycle of Precambrian age below the Paleozoic to Jurassic fill already known from well control in the Arauca Graben. Considered this way, a chronostratigraphic framework for northeast Colombia and west Venezuela should accommodate several Precambrian cycles below the Paleozoic Wilson cycle as shown Figure 12.

Reservoir

In terms of exploration prospectivity, a reservoir succession of Proterozoic sandstones in the study area will most certainly carry severe risk of poor quality, given the compaction observed on ditch cuttings and petrophysical logs. For example, in the four studied wells log porosities are in the order of 3% to 5% and Timur permeabilities are as low as 0.1 mD (García 2011 and 2012). Effective reservoirs in Precambrian analogs are always related more with matrix dissolution as porosity – creating mechanism than original porosity (Quijada, 2012).

Source and charge

The presence of a hypothetical Precambrian petroleum system should be added to the prospectivity balance; live oil of older age is known from Mesoproterozoic shales (1,400 – 1,600 Ma) in the McArthur Basin, Australia (Kontorovich et al., 1991 and Craig et al., 2009). Commercial analogs with Proterozoic sources, on the other hand, are not known in South America and are to be taken from the Lena-Tunguska giant oil province in Siberia (Bazhenova et al., 2006) and Oman (Ghori et al, 2009) where source quality rocks have been defined in the Edaicaran – Cambrian time window (Schröder and Grotzinger, 2007).

Commercial petroleum systems are also known in commercial production from Cryogenian carbonates of the Sichuan and Bohai Bay basins in China (Hao and Liu, 1989), and a petroleum system of Archean age in South Africa (Rasmussen et al., 2002).

Precambrian gas has also been discovered recently in the northern Mali portion of the Toudeni basin described by Barber, 2004 to contain in excess of 6000 feet of Precambrian sediments (Amadour, 2008) that contain an organic shale with TOC in the order of 20% (Rahmani et al., 2009).

One key exploration point is that researchers indicate that generation of Precambrian petroleum systems may have taken place at shallow depths earlier in geologic time, i.e. during Precambrian time due to intense crustal heat flow regimes (Kontorovich et al., 2009).

Way Forward

The palynological characterization presented here is a byproduct of otherwise dry exploration and stratigraphic tests. These results are presented in public domain given their intrinsic interest for hydrocarbon exploration, but mostly for scientific and research purposes:

- The sphaeromorp acritarchs of Cryogenian to Ediacaran age identified in the Cravo Norte area allow proposing a Precambrian sedimentary cycle in the 740 Ma – 540 Ma time window that is younger than the Roraima Group of the Guayana Craton and older than the Carrizal – Hato Viejo Early Cambrian succession of the Eastern Venezuelan Basin.
- Further work is suggested to establish or discard a geological correlation of the Cryo-Ediacaran beds identified in the Cravo Norte area with Cinaruco Formation sandstones (Codigo Geológico de Venezuela, 2013) exposed northeast of Puerto Carreño in Venezuela. In the proposed model, the Galeras de Cinaruco would be a geomorphological expression of folded Cinaruco sandstones exposed along the eastern shoulder of the Mantecal Graben (see schematic geotransect in Figure 13).
- The additional complexity that this evidence adds to the geology of the area, suggests that an update may be in order for the exploration concepts of the area, not necessarily toward a pessimistic view.
- The exploration of Precambrian frontier basins in the Colombian Llanos should be subject of Government support and stimulus. In this context, deep stratigraphic wells would be a valid option to bring information from deeper realms of the linked Precambrian to Jurassic Arauca and Mantecal grabens of the Colombian Llanos.

References Cited

Amadou, I., (2008): Petroleum assessment of the intracratonic Taoudeni Basin, Mali. Digital Memoir, XXXIII International Geological Congress, Oslo.

Arminio, J.F., M. Hernández, A. Pilloud and F. Audemard (2004): New Insights on the Jurassic Rift Succession of the Mérida Andes, Venezuela: Implications for New Petroleum Systems in Northern South America. CD-ROM Memoir, AAPG International Conference and Exhibition, Cancun Mexico.

Audemard, F. and I. Serrano, (2001): Future petroliferous provinces of Venezuela. In: Downey M., J. Threet and W. Morgan. (eds.): Petroleum provinces of the twenty-first century. AAPG Memoir 74. p. 353 – 372.

Baudet, D. (1988): Precambrian palynomorphs from northeast Libya. In Subsurface Palynostratigraphy of North-East Libya, Eds: El-Arnauti, Owens and Thusu, Garyounis University
Publications, Benghazi, Libya (SPLAJ), pp. 17-25.

Bayona, G., Cortés, M., Jaramillo, C., Ojeda, G., Aristizabal, J., and Reyes-Harker, A., 2008, An integrated analysis of an orogen-sedimentary basin pair: Latest Cretaceous-Cenozoic evolution of the linked Eastern Cordillera orogen and the Llanos foreland basin of Colombia. Geological Society of America Bulletin, v. 120, p. 1171-1197.

Bazhenova, O., M. Lomonosov, M., T. Bazhekova and N. Fadeeva (2006): Geochemical aspects of Oil-Gas-Bearing capacity of Precambrian deposits ancient Russian platforms. SPE Russian Oil and
Gas Technical Conference and Exhibition.

Colmenares, L. and Zoback, M.D. (2003) Stress field and seismotectonics of northern South America. Geology 31: 721-724.

Cooper, M.A., Addison, F.T., Álvarez, R., Coral, M., Graham, R.H., Hayward, A.B., Howe, S., Martínez, J., Naar, J., Peñas, R., Pulham, A.J., and Taborda, A (1995: Basin development an tectonic history of the Llanos basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia.: AAPG Bulletin, v. 79, p. 1421-1443.

Código Geológico de Venezuela (2013): Formación Cinaruco in http://www.pdv.com/lexico/c1151w.htm as of June 25, 2013.

Craig J., J. Thurow, B. Thusu., A. Whitham and Y. Abutarruma (2009): Global Neoproterozoic Petroleum System. The Emerging Potential in North Africa. Geological Society, Special Publication 326.

Diáz P.,and B. Ramos (2007): Geologic Map of Colombia. ARIANA LTDA Bogota, Colombia.

Dowdeswell, J.A. and Fugelli, E.M.G. (2012) The seismic architecture and geometry of groundingzone wedges formed at the marine margins of past ice sheets. Geological Society of America Bulletin 124 (11-12): 1750-1761.

DeCelles, P.G. and Giles, K.A. (1996) Foreland Basin Systems. Basin Research 8 (2): 105-123.

Dueñas, H. (2001): Paleozoic Palynologycal Assemblages From the Llanos Orientales Basin Colombia. AASP 2001 Palynologycal Meeting, San Antonio, Texas.

Dueñas, H. (2011): The Paleozoic of the Llanos Orientales Basin, Colombia. Pacific Rubiales Energy internal report.

Duggan, M. B. and Clayton, G. (2008): Colour change in the acritarchs Veryhachium as an indicator of thermal maturity. Geo. Arabia Vol. 13, No. 3, pp. 125-136.

England, G.L.; Rasmussen, B.; Krapez, B. and Groves, D.I. (2002) Archean oil migration in the Witwatersrand Basin of South Africa. Journal of the Geological Society (London) 159: 189-201.

Fairchild, I.J. and Kennedy, M.J. (2007) Neoproterozoic glaciation in the Earth System. Journal of the Geological Society (London) 164: 895-921.

Fedonkin, M.A. (1992) Vendian Fauna and the early evolution of Metazoa. In: Lipps, J.H. and Signor, Ph. W. (Edrs) Origin and early evolution of Metazoa. Topics in Geobiology Vol. 10. Plenum Press (N.Y.): 87-130.

Ferry, J.G. (1992) Biochemistry of Methanogenesis. Critical Reviews in Biochemistry and Molecular Biology 27 (6): 473-503.

García, E. (2011): Petrophysical Evaluation of wells Torodoi – 1X and Vaco-1X. Pacific Rubiales unpub. technical report

García, E. (2012): Petrophysical Evaluation of wells Coralito-1X and Chilacoa-1S. Pacific Rubiales unpub. technical report.

Gehling, J.G. (1999) Microbial Mats in Terminal Proterozoic Siliciclastics: Ediacaran Death Mass. PALAIOS (Society of Economic Paleontologists and Mineralogists) 14: 40-57.

Ghori K., J. Craig, B. Thusu, S. Luning, and M. Geiger (2009): Global Infracambrian Petroleum Systems: a Review in J. Craig, J.,Thurow, B. Thusu, A. Whitham and Y Abutarruma (eds) Global Neoproterozoic Petroleum Systems: The Emerging Potential in North Africa. Geological Society, London, Special Publications, 326, pp. 109-136.

González de Juana C. , X. Picard and J. Iturralde (1980): Geología de Venezuela y sus Cuencas Petrolíferas, Vol 1 Editorial FONINVES Caracas 407 pp.

Graterol, V., and Vargas-Gómez, A. (2010): Mapa de Anomalía de Bouguer Total de la República de Colombia V 1.2: Agencia Nacional de Hidrocarburos, Bogotá, Colombia, 2010.

Graue, J.; Engelen, B. and Cypionka, H. (2012) Degradation of cyanobacterial biomass in anoxic tidal-flat sediments: and community changes. ISME Journal 6 (3): 660-669.

Gray, G.J.; Lawrence, S.R.; Kenyon, K. and Cornford, C. (1998) Nature and origin of "carbon" in the Archean Witwatersrand Basin, South Africa. Journal of the Geological Society (London) 153: 1-21.

Grey, K. and Willman, S. (2009) Taphonomy of Ediacaran acritharcs from Australia: significance for taxonomy and biostratigraphy. PALAIOS (Society for Sedimentary Geology) 24: 239-256.

Hao, S. and G. Liu (1989): Precambrian oil and gas in China. Memoirs of the AAPG Annual Convention, San Antonio, USA.

Hartz, E.H. and Torsvik, T.H. (2002) Baltica upside down: A new plate tectonic model for Rodinia and the Iapetus Ocean. Geology; 30: 255-258.

Hegenberger, W., (1987) Gas escape structures in Precambrian peritidal carbonate rocks: Communications of the Geological Survey of South West Africa/Namibia, v. 3, p. 49–55.

Hillier, S.J. and Marshall, J. (1988): A rapid technique to make polished thin sections of sedimentary organic matter concentrates. Journal of Sedimentary Petrology, 58, 754-755.

Hofmann, H.J. and Jackson, G.D. (1994): Shale-Facies Microfossils from the Proterozoic Bylot Supergroup, Baffin Island, Canada. Memoirs of the Paleontological Society, Vol. 37, Supplement to Vol. 68, no. 4 of the Journal of Paleontology, pp. 1-39.

Hoffman, P.F. (2011) Strange bedfellows: glacial diamictite and cap carbonate from the Marinoan (635 Ma) glaciation in Namibia. Sedimentology 58 (1): 57-119.

Huddart, D. and Stott, T. (2010) Earth Environments. Past, Present and Future. John Wiley and Sons Ltd. (N.Y.): 896 p.

Kennedy, M.J., Christie-Blick, N., and Sohl, L.E., 2001, Are Proterozoic cap carbonates and isotopic excursions a record of gas hydrate destabilization following Earth's coldest intervals?. Geology 29: 443–446.

Kim, D.H. and Choy, D.K. (2000) Jujuyaspis and associated trilobites from the Mungok Formation (Lower Ordovician), Yongwol, Korea. Journal of Paleontology 74 (6):Ñ 1031-1042.

Kobayashi, T. (1936) On the Parabolinella fauna from Province Jujuy, Argentina with a note on the Olenidae. Japanese Journal of Geology and Geography 12: 85-102.

Kontonovich, A.E., V.S. Surkov and A. Trofimuk, (1991): The Earth's Upper Proterozoic Deposits – A new prospective level for petroleum exploration. WPC Conference Paper.

Korolev, V. G. and Ogurtsova, R. N (1983): Correlation of Vendian – Lower Cambrian boundary deposits in the Talas-Karatau zone (Malyy Karatau Range) Sections in the East European and Siberian platforms. International Geology Review, vol. 25, issue 5.

Lugo, J. and J.F. Arminio (2008): Exploration potential and foreland development of Andean Basins, north South America. XIV Congreso Venezolano de Geofísica, digital Memoir. SOVG, Caracas Venezuela.

Lyons, W.B.; Hines, M.E.; Last, W.M. and Lent, R.M. (1994) Sulfate reduction rates in microbial mat sediments of differing chemistries: Implications for organic carbon preservation in saline lakes. Sedimentology and Geochemistry of Modern and Ancient Saline Lakes. SEPM Special Publication 50: 13-20.

Marshall, J.E.A. (1991): Quantitative spore colour. Journal of the Geological Society, London, 148, 223-233.

Márquez, X., I. Serrano and F. Audemard (2001): Hydrocarbon - Bearing Paleozoic Rocks: A prediction in Venezuela. CD ROM Memoirs, AAPG Hedberg Conference: New technologies and New play Concepts in Latin America. Mendoza, Argentina.

Mazzuoli, R.; Vezzoli, L.; Omarini, R.; Acocella, V.; Gioncada, A.; Matteini, M.; Dini, A.; Guillou, H.; Hauser, N.; Uttini, A. and Scaillet, S. (2008) Miocene magmatism and tectonic of the easternmost sector of the Calama-Olacapato-El Toro fault system in Central Andes at ~24°S: Insights into the evolution of the Eastern Cordillera. Geological Society of America Bulletin 120 (11-12): 1493-1517.

Mišković A.; Spikings, R.A.; Chew, D.M.; Kosler, J.; Ulianov, A. and Schaltegger (2009) Tectonomagmatic evolution of Western Amazonia: Geochemical characterization and zircon U-Pb geochronologic constraints from the Peruvian Eastern Cordillera granitoids. Geological Society of America Bulletin: 121: 1298-1324.

Mora C., P. Parra and Y. Hernandez (2006): Caño Limón: una anomalía geoquímica que podría representar un sistema petrolifero no convencional en Colombia: evidencias e implicaciones exploratorias. Memoir, IX Simposio Bolivariano, ACGGP Cartagena, Colombia p. 12.

Mount, J.F. (1989) Re-evaluation of Unconformities separating the "Ediacaran" and Cambrian Systems, South Australia. PALAIOS (Society of Economic Paleontologists and Mineralogists) 4: 366-373.

Mount, J.F. (1991) Re-evaluation of Unconformities separating the "Ediacaran" and Cambrian Systems, South Australia.: Reply. PALAIOS 6 (1): 105-108.

Muñoz – Torres, F. (1991): El Paleozoico en los Llanos Orientales: futuro objetivo exploratorio. Memoir, IV Simposio Bolivariano ACGGP, Bogota Colombia, paper no. 12

Nedin, Ch. and Jenkins, R.J.F. (1991) Re-evaluation of Unconformities separating the "Ediacaran" and Cambrian Systems, South Australia: Comment. PALAIOS 6 (1): 102-105.

Olivares, C.O, M. Alvarez and L. López (20021): Are the Apure – Barinas crude oils all Cretaceous – sourced? Annual AAPG-SEPM, Paper Abstract p. A-134.

Olivares, C.O., X. Marquez and F. Audemard (20022): New insights in the application of new petroleum age biomarkers in the Barinas – Apure basin, Venezuela. CD-ROM Memoirs, 8th Latin-American Congress on Organic Geochemistry, Colombia.

Perez, V. E. (1985): Exploración petrolífera del pre-Cretaceo en Colombia: LV Reunión a nivel de Expertos, Quito. Boletin Técnico ARPEL 14 (2): p. 179-191.

Palacios, T. and Vidal, G. (1992): Lower Cambrian acritarchs from Northern Spain; the Precambrian – Cambrian and biostratigraphic implications. Geol. Mag. 129 (4), pp. 421-436.

Pearson, D. L. (1984): Pollen/spore colour standard, version 2. Phillips Petroleum Company, privately distributed.

Pinilla C., E. Castro and L. Araque (2003): Paleozoico, play no explorado en Colombia. Memorias and CD ROM IX Simposio Bolivariano de Exploración, ACGGP Cartagena Colombia p. 143.

Quijada, C. (2012): Análisis Exploratorio del Precretácico en el Norte de la Cuenca de Los Llanos, Colombia. MSc Thesis, Universidad Simon Bolívar 126 p.

Reid, A.R. (1972) Stratigraphy of the type área of the Roraima Group, Venezuela. In: Memoria, Conferencia Intergeológica Interguianas, 9th, Puerto Ordaz, Venezuela: Ministerio de Minas e Hidrocarburos (Caracas), Boletín de Geología, Pub. Esp 6: 343-353.

Reis, N.J. and Yánes, G. (2001) O Supergrupo Roraima ao longo da faixa fronteiriça entre Brasil- Venezuela (Santa Elena de Uairén-Roraima Mountain), in Reis, N.J. and Monteiro, M.A.S. (edrs) Contribuçâo à Geologia da Amazônia, Volume 2: Manaus, Brazil, Sociedade Brasileira de Geologia: 113-145.

Sarmiento, L. F. (2012) Geology and Hydrocarbon Potential of the Llanos Basin Llanos Basin. Petroleum Geology of Colombia series Vol 9 F. Cediel (ed) Agencia Nacional de Hidrocarburos 184 p.

Shufen, S. and Wenxing, L. (1998): Micropalaeoflora of the Metasedimentary Formation of Wudangshan Group in Yunxi Province and its Stratigraphical Significance. Progress in Precambrian Research, Issue 1, pp. 56-64.

Schieber, J. (1986) The posible role of benthic microbial mats during the formation of carbonaceous shales in shallow Mid-Proterozoic basins. Sedimentology 33: 521-536.

Schiefelbein C., C. Urien, W. Dickson, M. Odegard and J. Zumberge (2009): Petroleum Systems of Western South America Assessed from Oil Geochemistry and Basin Redefinitions. X Simposio Bolivariano de Exploración, ACGGP Cartagena Colombia.

Schneider Santos, J.O.; Potter, P.; Reis, N.J.; Hartmann, L.A.; Fletcher, R. and McNaughton, N.J. (2003) Age, source, and regional stratigraphy of the Roraima Supergroup and Roraima-like outliers in northern South America based on U-Pb geochronology. Geological Society of America Bulletin 115 (3): 331-348.

Şengör, A.M.C.; Burke, K. and Dewey, J.F. (1978) Rifts at high angles to orogenic belts: tests for their origin and the Upper Rhine Graben as an example. American Journal of Science 278: 24-40.

Shields, G.A., Deynoux, M., Strauss, H., Paquet, H., and Nahon, D., 2007. Barite-bearing cap dolostone of the Taoudéni Basin, northwest Africa: sedimentary and isotopic evidence for methane seepage after a Neoproterozoic glaciation. Precambrian Research 154, 209-235.

Thomson, S.N. (2002) Late Cenozoic geomorphic and tectonic evolution of the Patagonian Andes between latitudes 42°S and 46°S: An appraisal based on fission-track results from the transpressional intra-arc Liquiñe-Ofqui fault zone. Geological Society of America Bulletin. 114 (9): 1159-1173.

Traverse, A. (1988): Paleopalynology. Unwin Hyman Ltd., ISBN 0-04-561001-0, pp. 1 – 600.

Ulloa C., V. Pérez and B. Baldis (1982): Unidades Litoestratigráficas del Ordovícico de los Llanos Orientales de Colombi. V Congreso Latinoamericano de Geología, Argentina.

Wadham, J.L.; Arndt, S.; Tulaczy, S.; Stibal,M.; Tranter, M.; Telling J.; Lis, G. P.; Lawson, E.; Ridgwell, A.; Dubnick, A.; Sharp, M.J.; Anesio, A.M. and Butler, C. E. H. (2012) Potential methane reservoirs beneath Antarctica. Nature (Letter Research) 488: 633-637.

Wilkinson, M. and Haszeldine, S. (2011) Oil charge preserves exceptional porosity in deeply buried, overpressured, sandstones: Central North Sea, UK. Journal of the Geological Society (London) 168: 1285-1295.

Yule, B.L., Roberts, S. and Marshall, J.E.A. (2000): The thermal evolution of sporopollenin. Organic Geochemistry 31: 859-870.

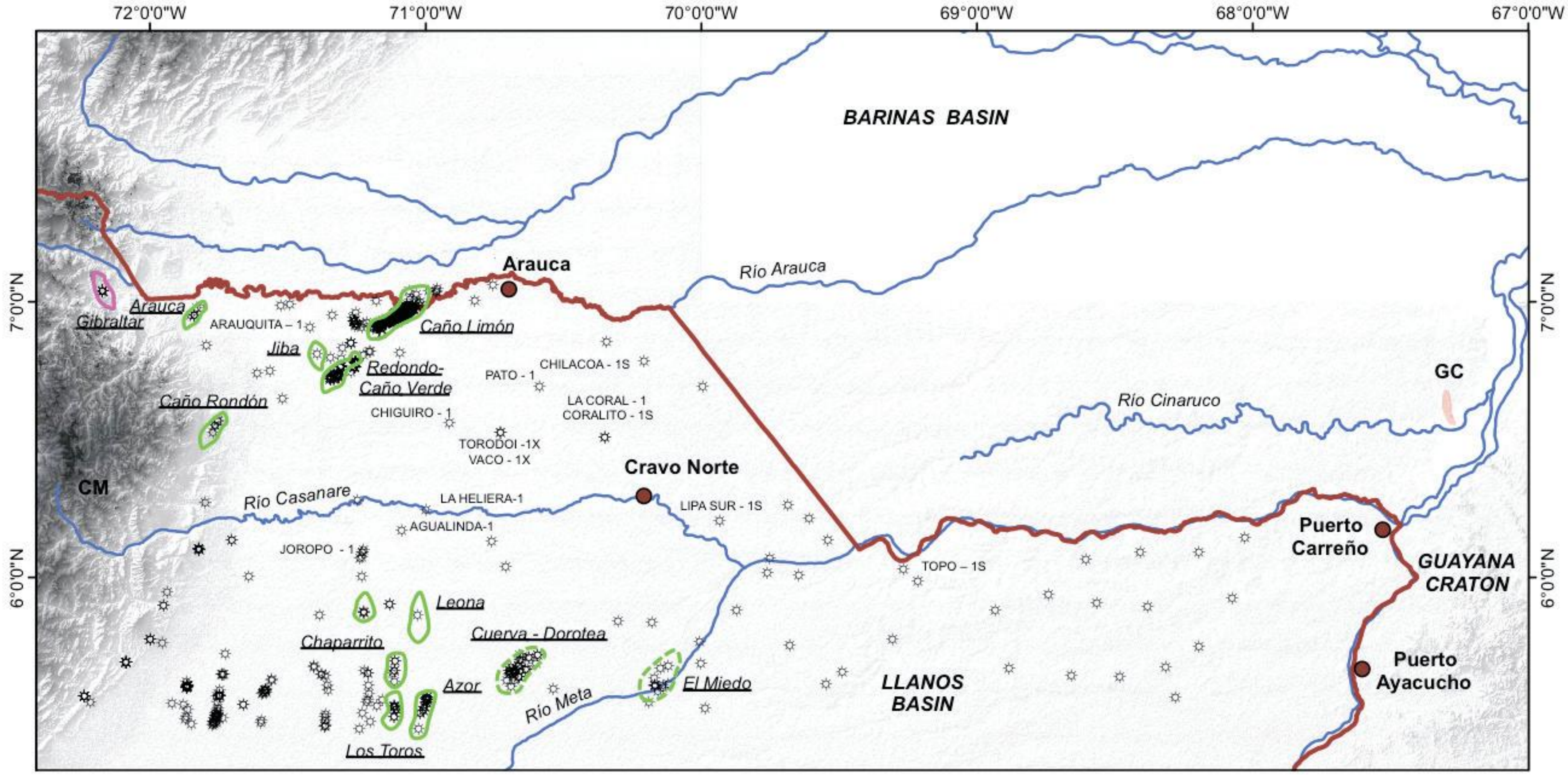

Figure 1. Regional map showing location of wells, including those mentioned in the text. Commercial fields in solid green outline (oil) and purple (condensate). Oil discoveries in dotted green outline. The digital elevation model shows the Cocuy Massif of the Cordillera Oriental (CM) and the Galera de Cinaruco (GC), highlighted in red.

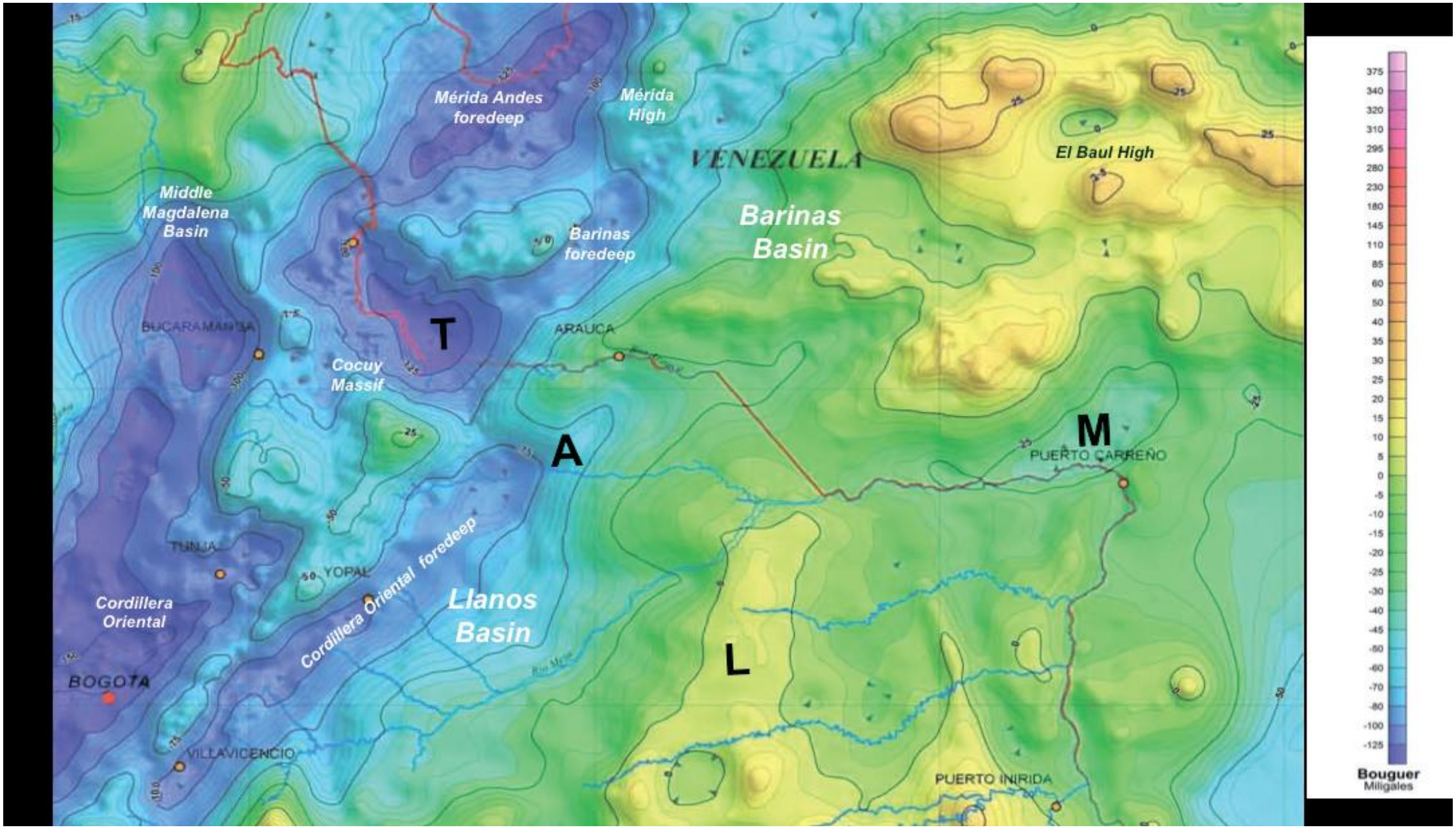

Figure 2. Bouguer anomaly map of northern area showing the main pre-cretaceous graben basins. Contours from -125 mG (darkest blue) to +175 mG (red) A: Arauca graben; M: Mantecal graben T: Táchira graben. Notice the masking effect of the superposition of the Cordillera Oriental and Barinas foredeeps on the Arauca and Tachira grabens Contour map by Graterol and Vargas - Gómez (2010).

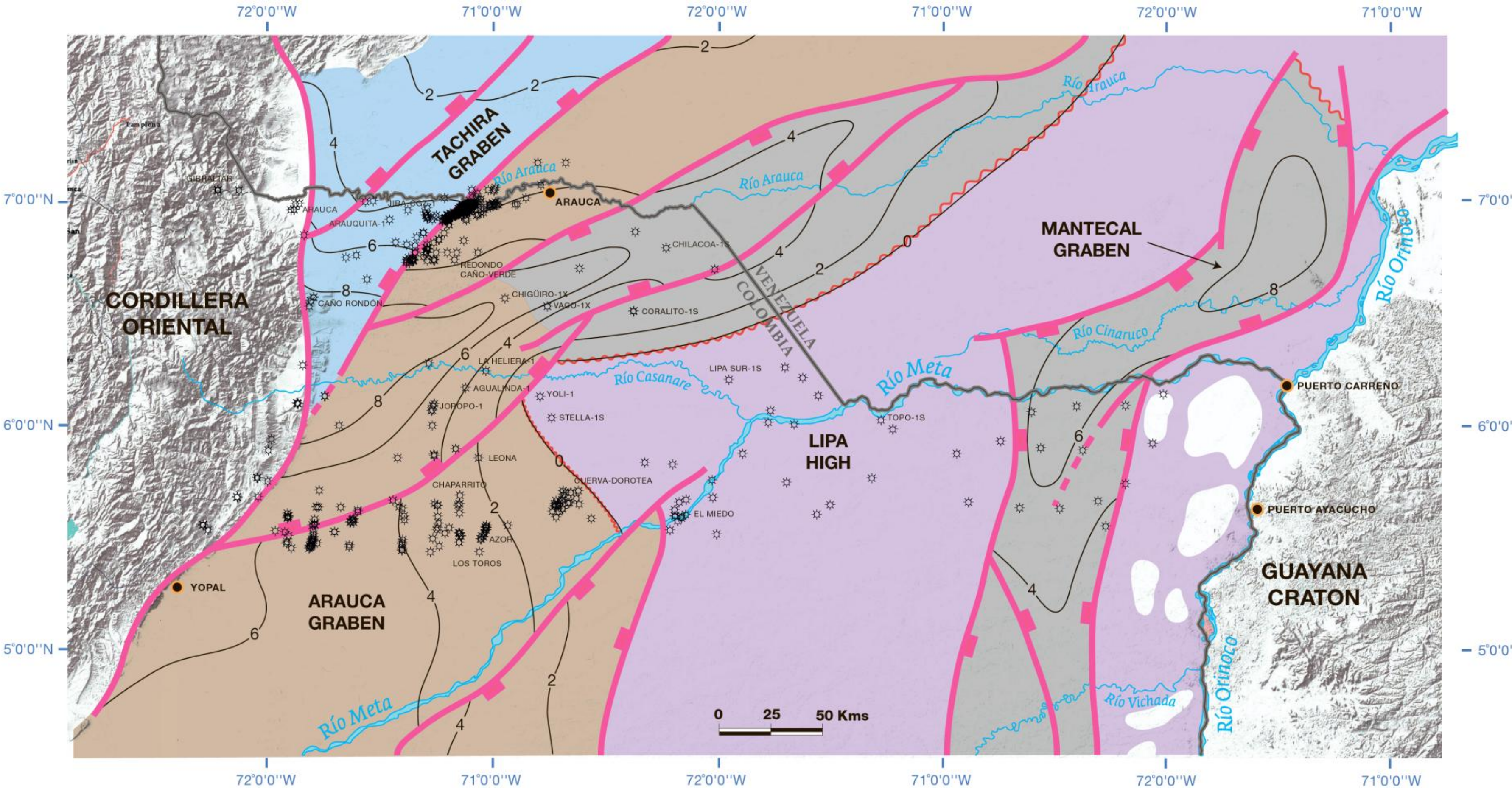

Figure 3. General framework of pre-Cretaceous grabens below the Llanos foreland in the Arauca – Cravo Norte region of eastern Colombia. Colour-coded subcrop patterns below the base Cretaceous unconformity: Triassic – Jurassic (blue) Paleozoic (brown), Neoproterozoic (grey) and Precambrian basement (purple), white areas are cratonic outcrops in the east and Cordillera Oriental in the west. Isopach contours in thousands of feet are of total pre-cretaceous graben fill. All graben faults are normal with variable tectonic inversion. The map incorporates interpreted seismic and magnetogravimetry. Modified from Muñoz (1991), Lugo (unpub. map 2009) and Quijada (2012). Surface geology from Díaz and Ramos – ARIANA (2007) and Código Geológico de Venezuela (2013).

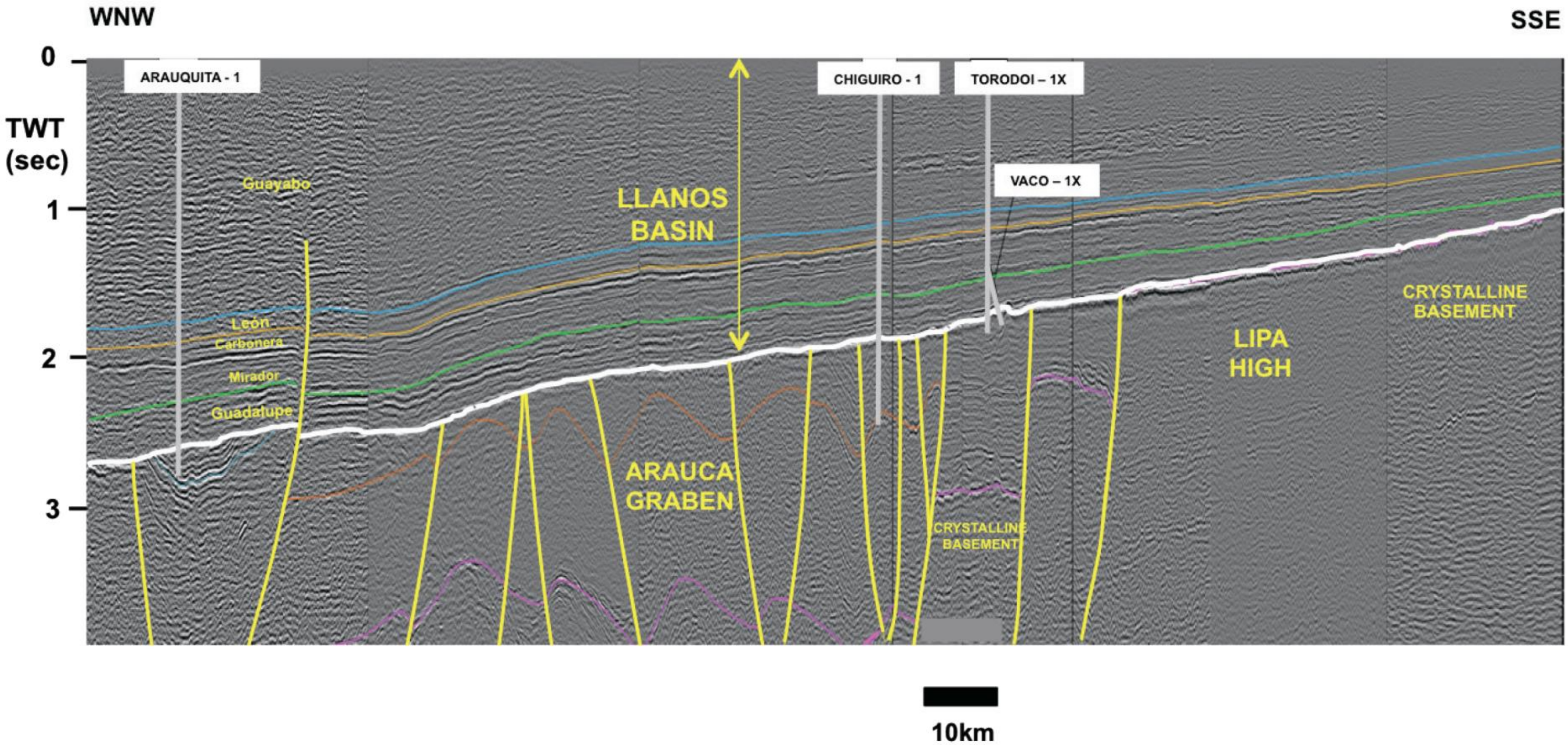

Figure 4. Seismic transect showing the general basin style of the study area. Notice the Llanos foreland above the pre-Cretaceous section of the Arauca graben. The angle of projection distorts the actual distance between deviated wells drilled from the same surface location. In the center of the image, the foreland is 7,000 to 8,500 feet thick.

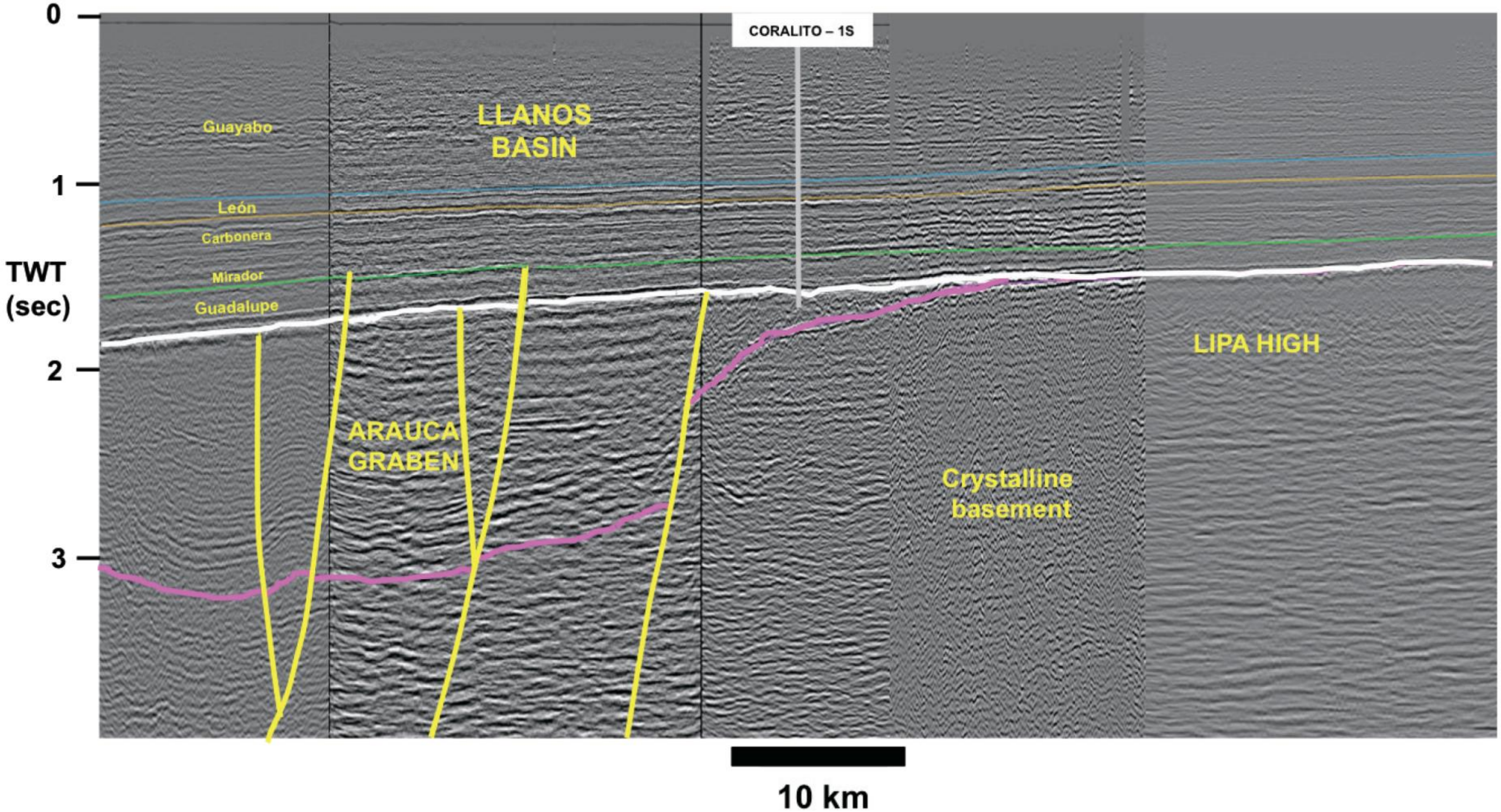

Figure 5. Seismic transect oriented west to east showing the truncation of the pre-Cretaceous sedimentary section onto the eastern shoulder of the Arauca graben.

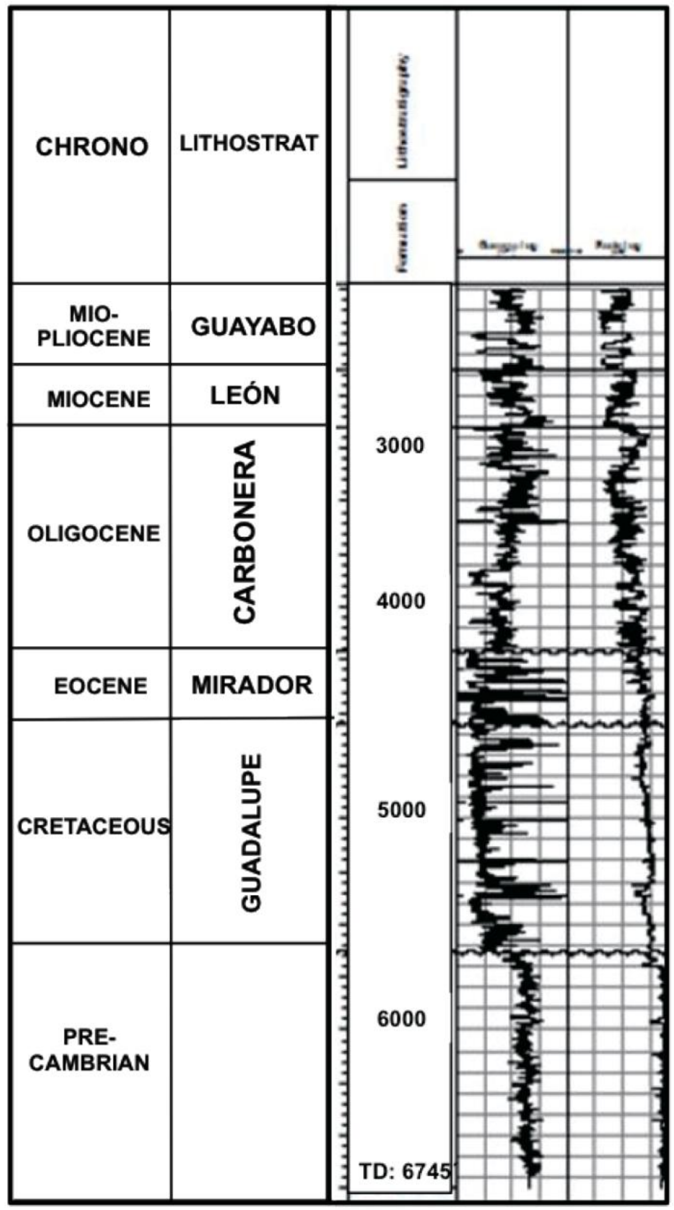

Figure 6. General lithostratigraphic column of the Llanos basin in the Cravo Norte area, based on the CHILACOA - 1S well.

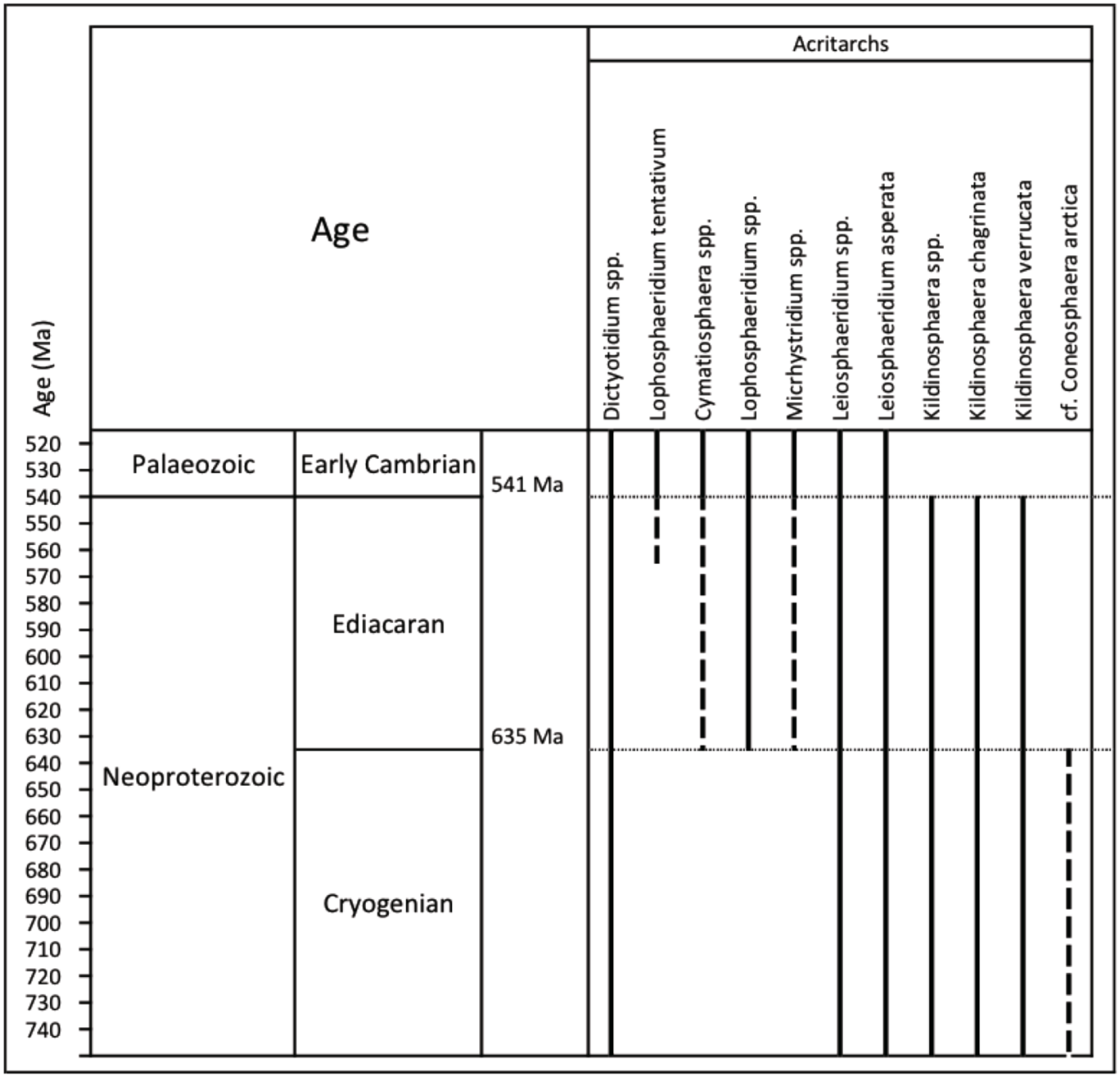

Figure 7. Ranges of selected acritarchs for the Late Neoproterozoic to the Early Cambrian (Gradstein et al., 2012).

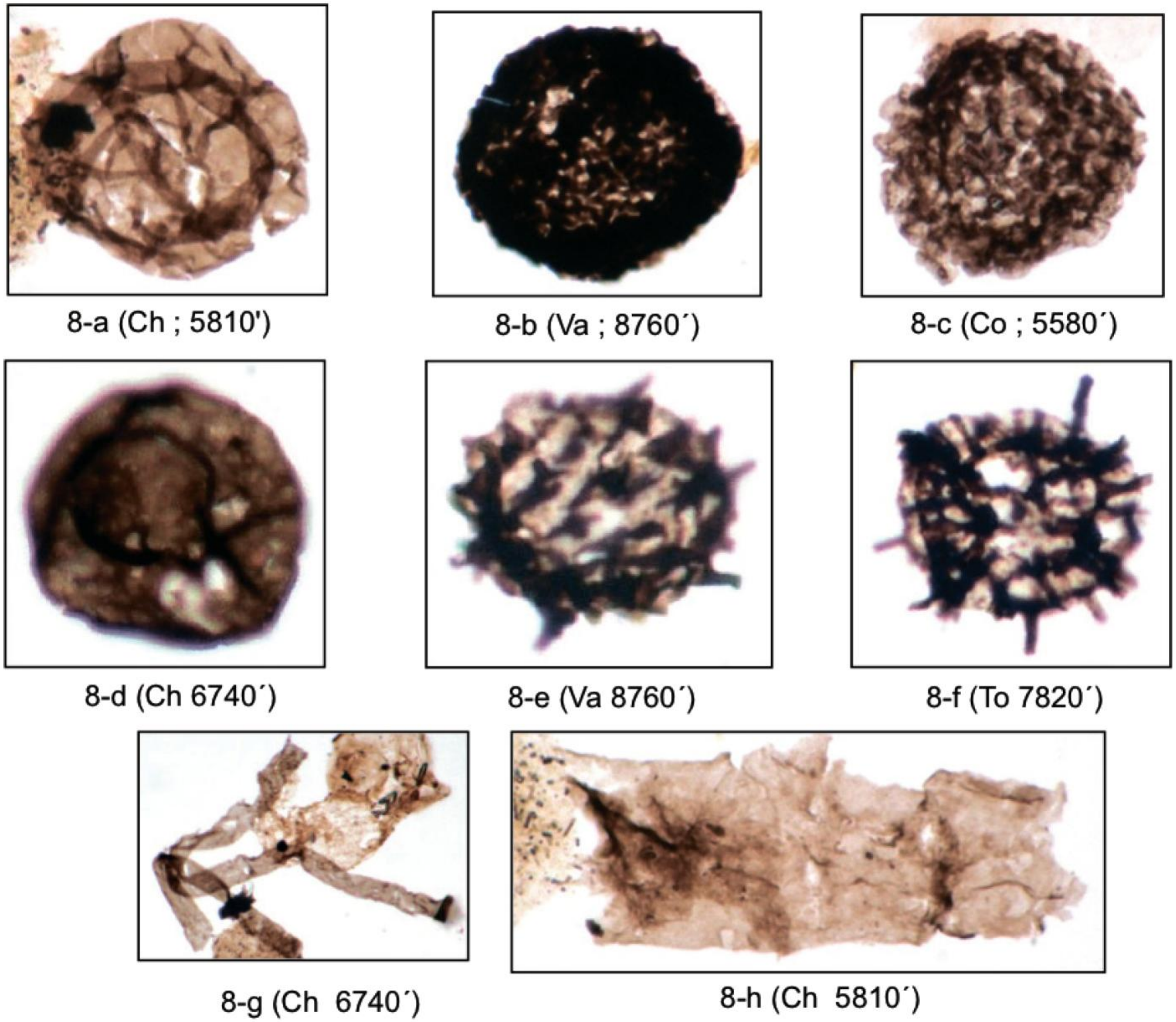

Figure 8. Images of sphaeroacritarcs of Neoproterozoic age recovered in the Cravo Norte region of the Llanos Orientales, Colombia. Ch = Chilacoa-1S; Va = Vaco-1X; Co = Coralito-1S; To = Torodoi – 1X. Depths in feet MD 8-a Leiosphaeridia asperata'), 8-b Kildinospahera cf. Verrucata, 8-c cf. Coneosphaera arctica 8-d Sphaeromorph acritarch 8-e Michrystridium sp.8-f Acanthomorphs acritarch 8-g and 8-h, Filaments Specimens size: 8-a to 8-f approx. 27mm x 27mm; 8-g 7 mm x 94 mm and 8-h 35 mm x 88 mm.

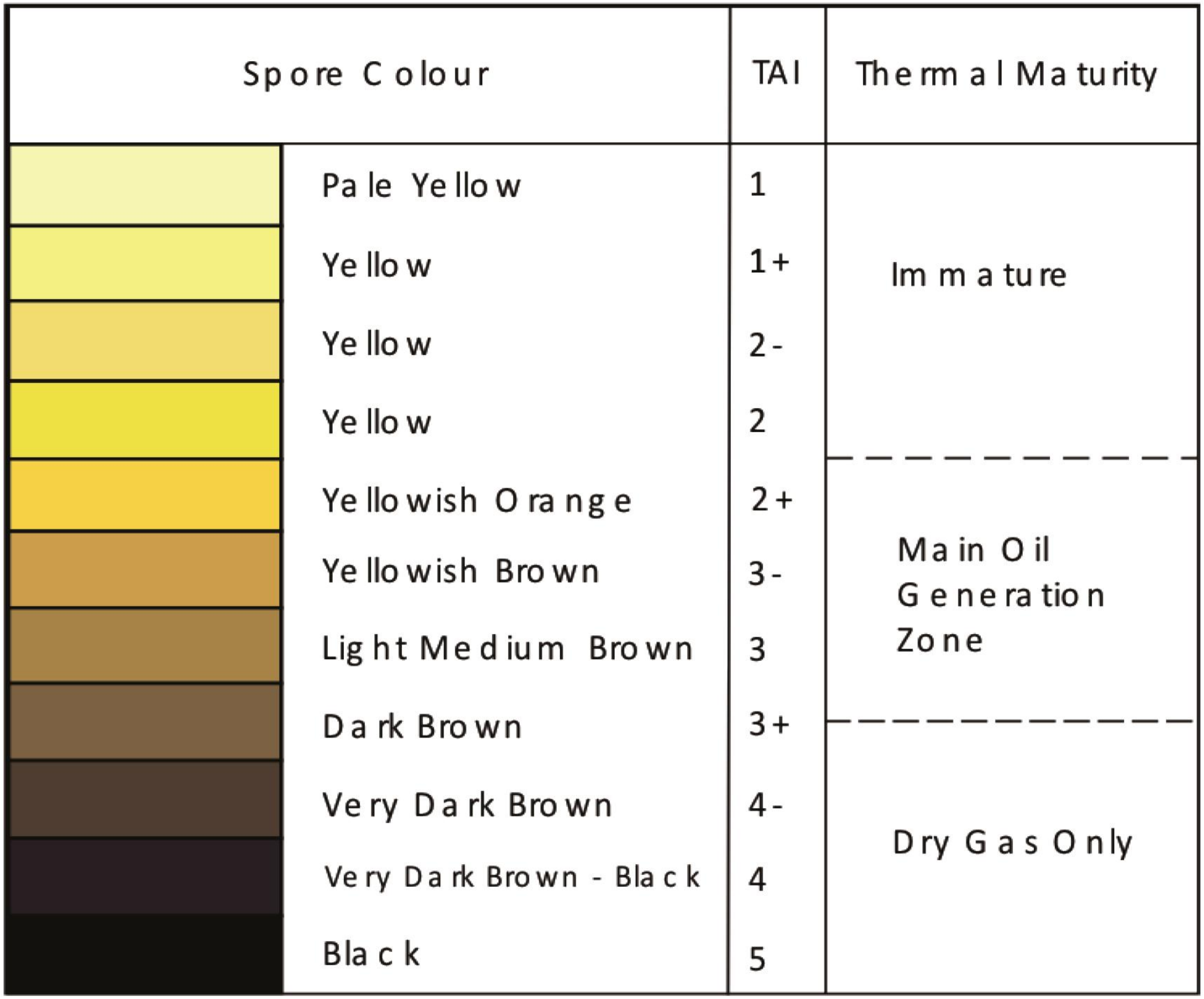

Figure 9. Thermal alteration color Indices (TAI) applied in this paper (Pearson, 1984).

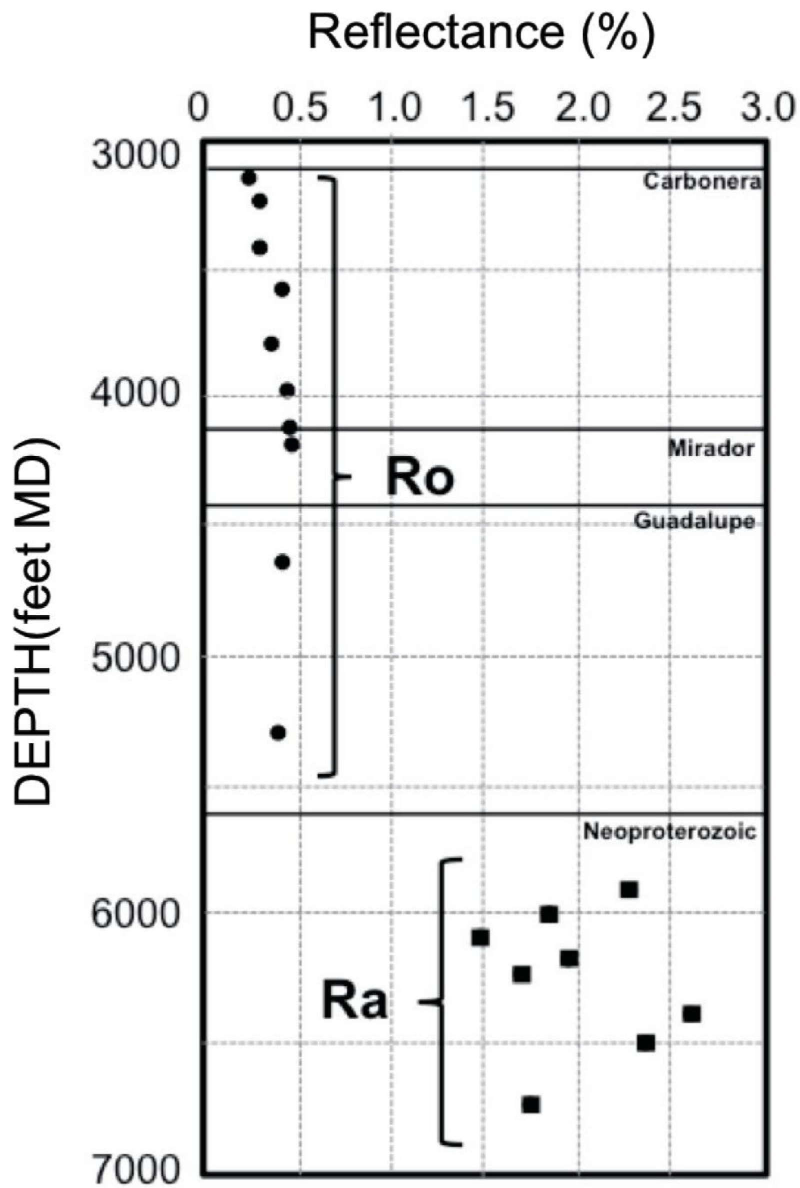

Figure 10. Results of vitrinite reflectance (Ro, black dots) and achritarch reflectance (Ra, black squares) for Chilacoa-1S.

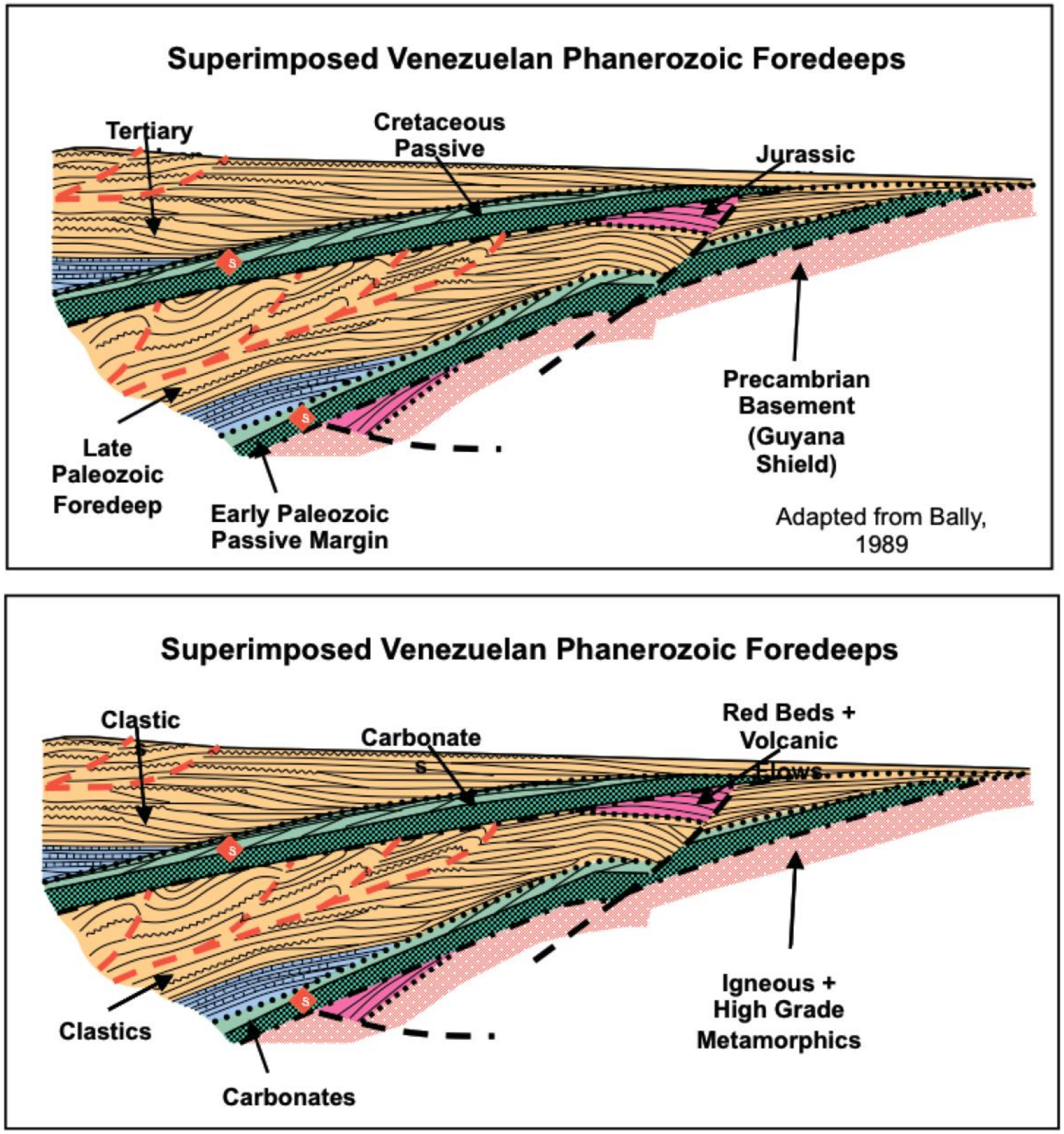

Figure 11. Double Wilson cycle exploration model for pre-Cretaceous below the Eastern and Barinas (Llanos) basins as proposed by Audemard and Serrano (2001).

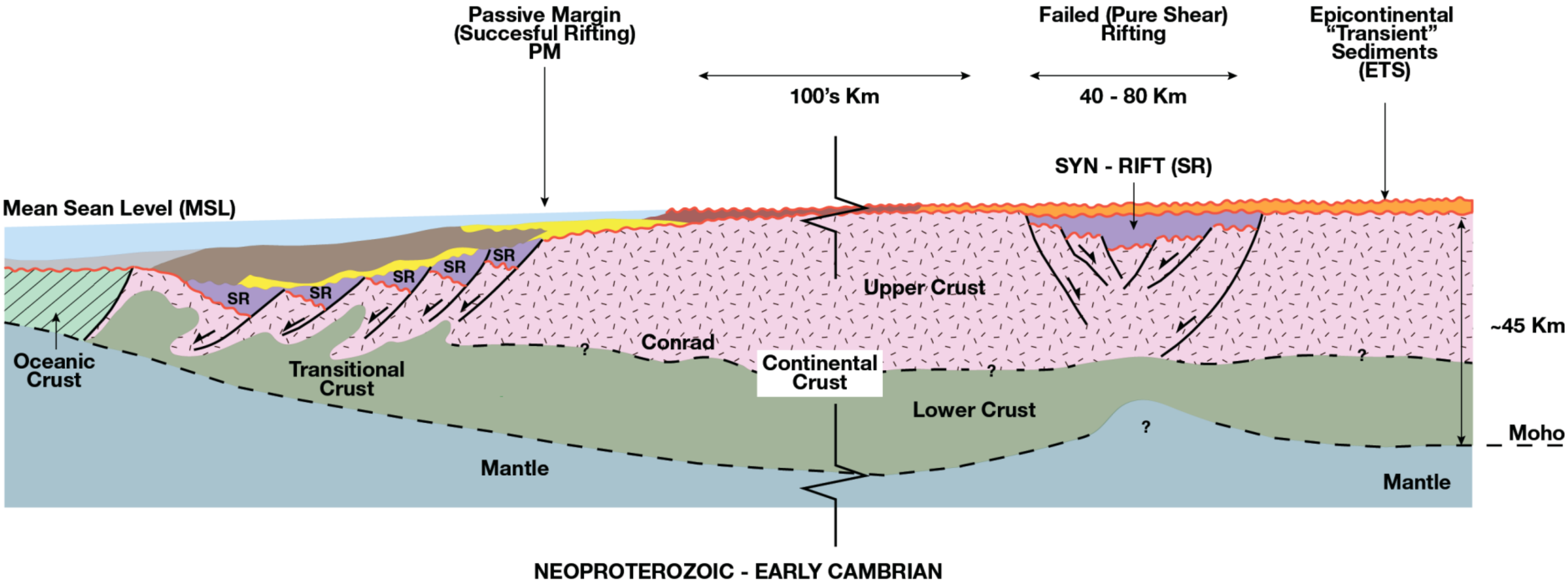

Figure 12a. Conceptual model of the sedimentation framework in the NW margin of Amazonia-Rio Negro, today´s South America (see text) during Neoproterozoic to Early Cambrian. Towards the Iapetus Ocean was a passive margin, product of the separation of Laurentia and Amazonia - Río Negro. In the South American craton, one or more aborted rifting episodes e.g. the Arauca and Mantecal grabens were filled mainly in Precambrian times. See Miskovic et al., 2009

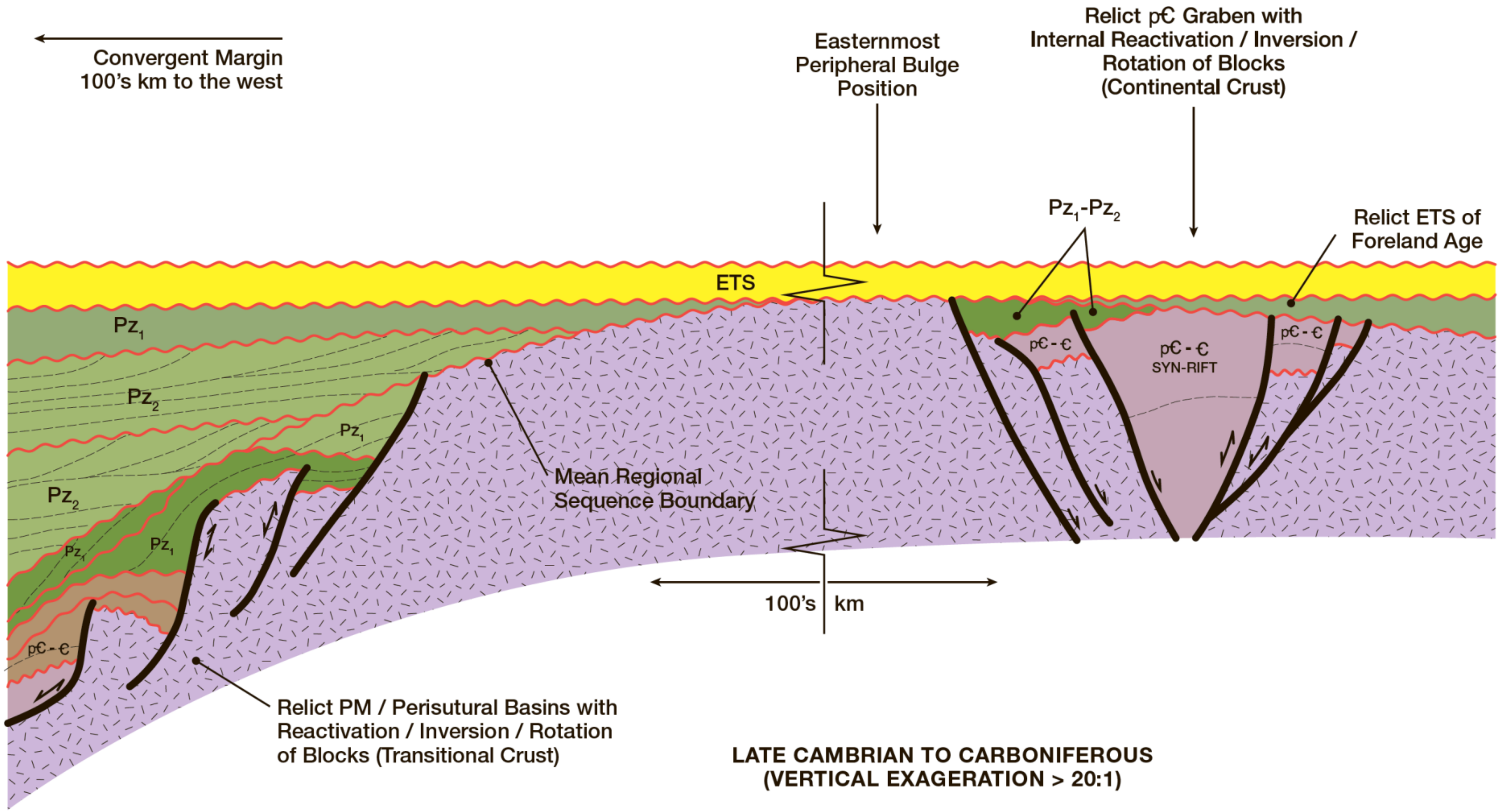

Figure 12b. The late Cambrian to Carboniferous evolution was complex in the W border of Amazonia, dominated by convergence (the terrain of Paracas-Arequipa was accreted during this time and on the NE edge Avalonia separated and the Rheic ocean opened in Middle Ordovician. In the NW of Amazonia, foreland - type lithospheric bending and fault reactivation probably took place in repeated episodes. In Late Ordovician, transtensional basins probably formed. The Carboniferous to Permian was marked by Ouachita convergence. (See Miskovic et al., 2009).

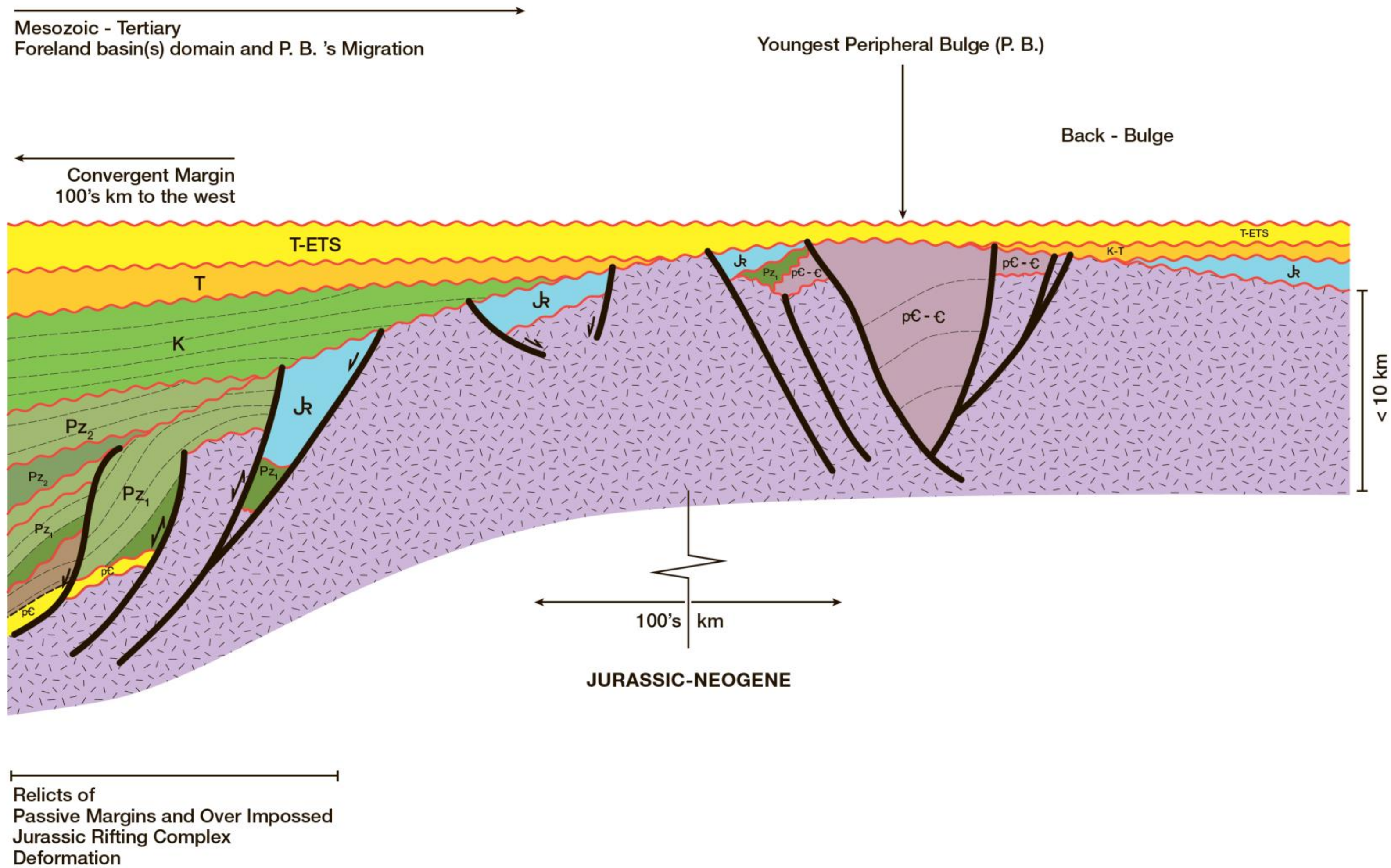

Figure 12c. Inferred stratigraphic location of the aborted Precambrian grabens in the locus of a first passive margin. A simple Paleozoic Wilson cycle of crustal attenuation and subsequent thickening by the Ouachita convergence was complicated by strike-slip and local thinning related with incipient back-arc rifting. Thus, the Arauca and Cravo Norte regions preserve relics of thick Precambrian graben fill over which Paleozoic and Jurassic normal faulting was superimposed, thus explaining why intensely deformed Neoproterozoic beds are contained within normal graben boundaries that seldom extend upwards and only show mild inversion. Toward the west of Figure 12c, the Mesozoic passive margin, together with the existing Jurassic and Paleozoic, is involved in the Cordillera Oriental orogen. In this context, the thickest sediments are Neoproterozoic while relatively thin Jurassic and Paleozoic are interpreted to be part of pre-Mesozoic grabens or Paleozoic / Mesozoic impactogens. Thus, the Cordillera Oriental at large coincides with Jurassic rift relics developed over attenuated Precambrian crust and overlying Paleozoic (Figure 12a, Figure 12b). See Bayona (2008).

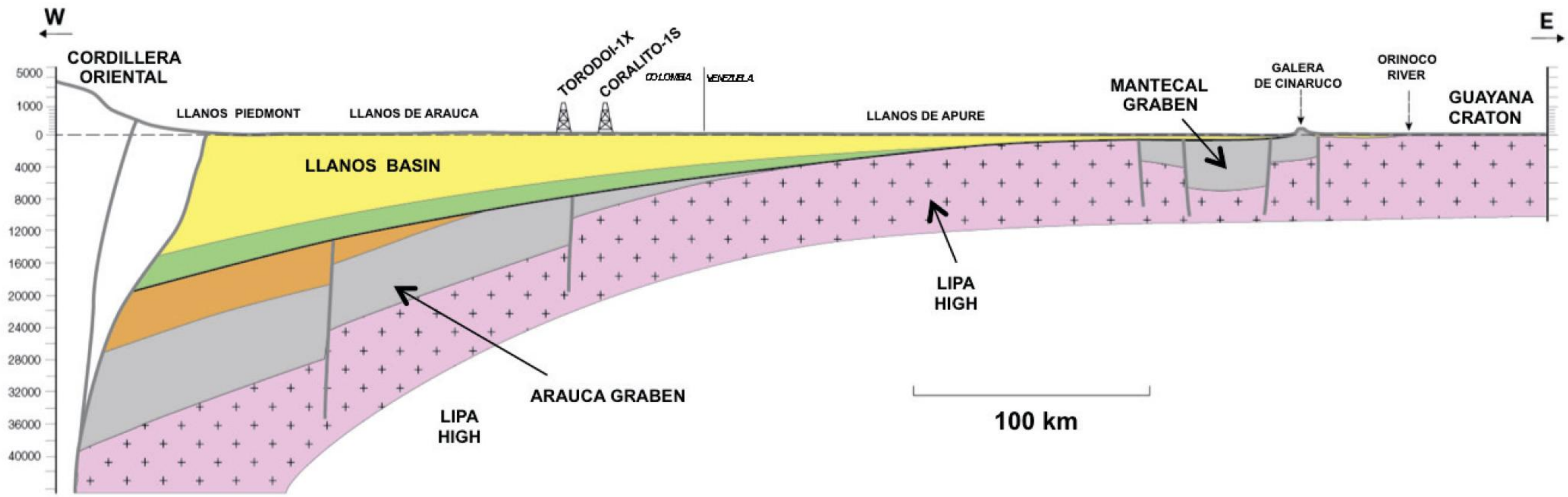

Figure 13. Schematic geotransect across the Llanos Basin, showing the Llanos foreland superimposed to the "fossilized" Arauca and Mantecal pre – cretaceous grabens. Fault geometry and internal graben deformation appear simplified. The interpretation suggests that the Galera de Cinaruco is a geomorphological expression of outcropping Neo-Proterozoic, probably younger than the Roraima beds exposed elsewhere in the Guayana Craton. Depths are approximate. The topographic surface was derived from GIS elevation model and the geological relations and color codes correspond with the map in Figure 3.

WELL	OPERATOR	YEAR	PENETRATION (feet)	AGE @ TD
LA HELIERA-1	Mobil	1959	747	Ordovician – Tremadoc (Ulloa *et al* 1982)
CHIGÜIRO-1	Sun	1985	3,549	Cambrian (top) Precambrian Ediacaran? (bottom) (Dueñas 2011)
LA CORAL-1	Llanos	1988	800	Mid – Late Cambrian (Dueñas, 2011)
ARAUQUITA-1	Oxy	1982		Triassic - Jurassic (Pérez 1985)
JOROPO-1	Oxy	1985	952	Ordovician (Dueñas, 2011)
PATO-1	Sun	1985	272	Cambrian (top) (min 165 ft) Ediacaran (bottom) (min 30 ft) Dueñas (2011)
AGUALINDA-1	Lasmo	1985	390	Undiff Paleozoic (Dueñas 2011)

Table 1. Pre-Cretaceous well control and selected references of the northern Llanos, Colombia.

DEPTH (feet MD)	**1**	**1+**	**2-**	**2**	**2+**	**3-**	**3**	**3+**	**4-**	**4**	**5**
3150	1			10	18	2					
3270				3	14	7					
3420			1	6	14	5					
3570				3	5	1					
3780				3	8	14	1				
3990	1			2	21	5					
4110				5	12	9					
4170			1	5	18	6					
4640			1	7	14	8					
5300				1	7	1					
5330											
5660								4			
5780								8	6		
5810								8	6		
5900								11	4		
5990								8	7		
6080								7	12		
6170								18	9	1	
6230								9	6	2	
6320								14	8		
6380								11	4		
6500								14	14	1	
6620								3	5	1	
6740								14	14	2	

Table 2. Thermal Alteration Index (TAI) well CHILACOA-1S.

DEPTH	Ro	n	st dev	min	max
3150	0.24	84	0.03	0.17	0.30
3240	0.30	78	0.05	0.21	0.37
3420	0.30	81	0.05	0.22	0.40
3570	0.41	70	0.03	0.35	0.45
3780	0.35	85	0.03	0.28	0.42
3960	0.45	63	0.04	0.39	0.51
4110	0.46	79	0.03	0.40	0.51
4170	0.46	70	0.03	0.40	0.51
4640	0.42	23	0.05	0.35	0.50
5300	0.39	39	0.03	0.34	0.43
5330	-				
5660	-				
5780	-				
5810	-				
	Ra				
5900	2.27	21	0.56	1.17	2.92
5990	1.85				
6080	1.48	20	0.29	0.85	2.14
6170	1.95	8	0.47	0.79	2.07
6230	1.71	19	0.35	1.09	2.37
6320	-	4	0.07	1.65	1.79
6380	2.60				
6500	2.36	22	0.37	1.84	3.49
6620	-	8	0.42	1.79	2.83
6740	1.74	1			

Table 3. Reflectivity results, well CHILACOA-1S.

DEPTH feet MD	AGE	REFLECTANCE (%)	TAI	MATURITY
3150 – 4170	Neogene	Ro = 0.24-0.46%	2 to 3-	immature to marginal mature
4640 – 5300	Cretaceous	Ro = 0.42 - 0.39%	2 to 3-	immature to marginal mature
5660 – 6740	Neoproterozoic	Ra = 1.48 - 2.6%	3+ to 4-	overmature for oil and mature for gas

Table 4. Comparison of measured reflectances Ro and Ra with measured Thermal Alteration Index (TAI), well CHILACOA-1S.