Llanos N-S Petroleum System Variation (Columbia)*

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Geological Setting

The basement of the Llanos is cover by Paleozoic series, not all very well dated but that include silicoclastic Siluro-Devonian deposits. Strong unconformities separate these locally highly deformed series from the Cretaceous series. The Lower Cretaceous sediments present in the Eastern Cordillera and deposited in an extensional context are absent in the Llanos. In westernmost Colombia the compression that leads to the Andes formation started during the Cretaceous, the first accretion started during the Aptian (Amaine terrain, now Western Cordillera) whereas subsidence continued eastward with the deposition of the Une, Gacheta and Guadalupe Formations which pinchout in the Llanos Oriental (Casero et al., 1997; Sarmiento, 2001). Subsequent accretion took place in the west at the end of the Maestrichian resulting in the onset of uplift for the Central Cordillera and the first inversion in the area of present day Magdalena Valley. The Llanos subsidence continued in a very poorly tectonic basin (Barco, Cuervo and Mirador Formations deposits – Cooper et al., 1995, Bayona et al., 2008). A compressive context predominated thereafter in the Eastern Cordillera since the Eocene. After the inversion of the Mesozoic extensional grabens, a more classical thrust regime developed, the Llanos basin became a classical, but rather external, foreland (Carbonera and Leon Formations deposits). The Eastern Cordillera is a double verging mountain belt: the western flank in the Magdalena Valley was initially the more active one but the compressive front has now shifted to the Llanos where the Miocene foreland is currently affected by the compression that propagates eastward. As a result, the Guayabo Formation deposits (Late Miocene to Quaternary) are deformed and partially eroded westward (Parra et al., 2008).

The easternmost prominent thrust is the Yopal. One in the central Llanos and the structure that corresponds to the former Early Cretaceous basin edge is the Guaicaramo thrust (Bayona et al., 2008).

Petroleum System

Numerous source rocks are present, most of them shales, some with a sealing role. There are also numerous reservoirs, all the sands, the more productive ones being the Une, the Guadalupe, the Mirador and the Carbonera C7 Formations. The producing structures are the noses of subtle faulted blocks due to normal faulting, often east-verging, that affect the Upper Cretaceous and Tertiary series. The small offsets on these faults result in small size fields. On the contrary, near or within the foothills, large compressive structures have been successfully drilled and host almost all the large fields of the area (e.g. Cusiana, Cupiagua, Volcanera). Eastward, over the wedge of the Oligocene-Early Miocene basin, non structural traps have also been successfully drilled; they may contain large reserves (e.g. Rubiales).

Exploration Issue

All explorationists working in the Colombian Llanos have noted the variability of the fluids discovered in the numerous fields in API degree as in chemical content. In order to understand this variability a regional synthesis has been carried out. As just resumed, the Llanos basin is the current foreland of the northern part of the Andes, as a result the sediments, particularly source rocks and carrier beds, get thinner eastward, except the Leon Shale that displays a rather constant thickness and constitutes the regional seal. Therefore, the burial history varies from west to east resulting in the expulsion of various fluids at various level of maturation. This explains in part the mixture of fluids found in the HC fields. In addition some reservoirs are, or were when they were charged, shallow and cold and so biodegradation happened. Today, eastward the basin remains thin, the reservoirs are at shallow depths and biodegradation continues on, and heavy oils are found, like in Rubiales. However the correlation ºAPI-reservoir temperature is far for being simple in the Llanos and a general model of maturation-migration-accumulation is required to frame data understanding in an acceptable pattern. We did that at the regional scale to model in 3D the maturation-migration history. Special attention has been given to predict the temperature in the reservoir when the hydrocarbons arrived. A lot of the low API may be finally explained by a paleobiodegradation that took place during the Miocene. An important point is the timing of the arriving of the first pulse of HC and on this issue the northern and southern parts of the Llanos present very different characteristics. Within this short paper we will focus the discussion on these north-south differences.

Workflow

After the compilation of all available data, more that 8000 samples of source rocks and fluids, a regional synthesis has been carried out. It includes the mapping of the richness of the various source rocks, temperature and paleotemperature as well as a 3D model of the petroleum system (multisurfaces).

Source Rocks and Fluids

The study highlights that there are various good source rocks in the Llanos. The "official" main one is the Gacheta Formation from the Upper Cretaceous however its potential decreases eastward (especially the HI), the Los Cuervos Formation (Maestrichian-Paleocene) and all the Tertiary shales (Carbonera and Leon Formations) display an equivalent high potential in the Oriental Llanos. Analyzing our data, the initial potential of the Gacheta Formation in the Llanos will be S2 of about 10 mgHC/g with a HI of 300. The Cuervos Formation S2 is smaller, about 6 mgHC/g. The Leon Shale and Carbonera shaly Formations (especially the C6) initial S2 are both around 10 mgHC/g. The Paleozoic shales have also remaining TOC content up to 2% with remaining HI up to 400 for samples in the oil window. The Fomeque Formation has been modeled with an initial potential of 12 mgHC/g (HI=450) extrapolating data from the Cordillera.

The Fomeque Formation, Lower Cretaceous, is known in the Eastern Cordillera, it is not present in the Llanos since the edge of the Cretaceous extensional basin was located westward. However, the HC isotope characteristics on the Llanos do suggest an influence of this marine carbonate source rock; it has so been modeled, limiting its presence below the Cordillera (Figure 1b). Biomarkers allow tracing the presence of oil from Tertiary source rocks (Dzou et al., 1999). The authors suggested mainly the Cuervo Formation as source rock but we consider the Carbonera shales as a possible alternative.

Maturity History

The source rocks, except the Paleozoic ones, are poorly mature eastward and the HC are coming from the deepest part of the basin westward. In the kitchen usually all levels of maturity are present from the gas window in the Paleozoic to immature in the Leon shales. The expected fluids in the traps are a mixture of the different type of HC expelled from these different source rocks.

In term of maturity history, the Llanos foreland could be roughly divided into 3 zones, that we will call south, central and north. The specificities of each are summarized in Figure 2 (see the location of the profile, Figure 1) and could be synthesized as follow:

- **South**: **early maturation**: all over the Llanos foreland the Carbonera Formation (Oligocene) is too thin to allow the Cretaceous to be mature during its deposition except southward in the Apiay-Chichimene area. There, the maturation started during the Miocene and so the age of the structure may influence the charge risk. The Carbonera and the Leon Formations are rather thick and the Curvo and the bottom of the Carbonera Formations are mature in the western part.

- **Centre**: **thinner Tertiary burial and limited current kitchen**: The Carbonera and the Leon Formations are thin in the central part. They remain immature and the only Tertiary source rock that reaches the early oil window is the Cuervo Formation.

Maturation of the Cretaceous source rocks started at the lower Miocene. During the Quaternary, due to the shortening, the Yopal thrust bound the drainage area of the central structures.

- **North**: **Leon Shales partially mature**: in the north, the Guayabo Formation is up to 4km thick and therefore thick enough to allow the bottom of the Carbonera Formations and the Leon Formation to be mature, and the deepest source rocks to be in the gas window. The maturation happens during the Guayabo deposition, i.e. during the last 10 Myr. The maturation of the youngest source rocks facilitate the charge of youngest reservoirs and indeed the few fields that produce from the C5 and C3 sandstones are in this part of the Llanos; migration pathway is obviously more complex and is out of the scope of this paper.

Biodegradation

Heavy oils have been found in the Colombian Llanos, the low API gravities are there known to be due to biodegradation. This phenomenon may happen when the temperature on a reservoir is less than about 80ºC. Fresh water is also necessary but in a foreland it is usually the case. A quick quantification of the biodegradation risk can so be done by modeling the temperature versus time in the reservoirs. It has been done for the Llanos.

Three of the computed maps, concerning the C7 reservoir, are shown (Figure 3). One may note that almost overall in the Llanos, the C7 Formation was too cold to allow preservation of the light oil during the Middle Miocene. At the opposite, currently the risk of biodegradation is limited to the eastern part. Through time, these results show that the first arrived oil has been likely biodegraded whereas the current pulse may remain light in the western part of the basin. In the southern area where the maturation of the source rock has started earlier the model predict a very high probability of finding biodegraded oil, mixed or not with a younger intact one.

Conclusion

Strategically, one may conclude the no part of the Llanos can be excluded from being prospective. From a purely geochemical perspective, HC could be found everywhere in the Oriental Llanos although the charge risk must be qualified for possible low gravity fluids, and other components of the petroleum systems must be considered. However, we are dealing with a multi-system, more complex than previously thought, deserving a specifically local approach for prospect evaluation.

The presented study did not aim to model the migration pathway and as a result the mixture of the different fluids in the reservoirs cannot be assessed; however qualitatively, one may conclude that up to 5 source rocks are mature in the HC kitchen of the Llanos. The expected fluids cannot be a simple, mono source rock one. Biodegradation of the fluids expelled during the Early Miocene, may have happen almost everywhere. It is the case for the fluid expelled from the Cretaceous source rocks in the southern part of the Llanos.

Acknowledgments

The 1D basin modeling has been done with Genex, the 3D model with Petromod, the integration of the data and the visualization of the results with GOCAD. We thank B. Duval for useful comments of the first version.

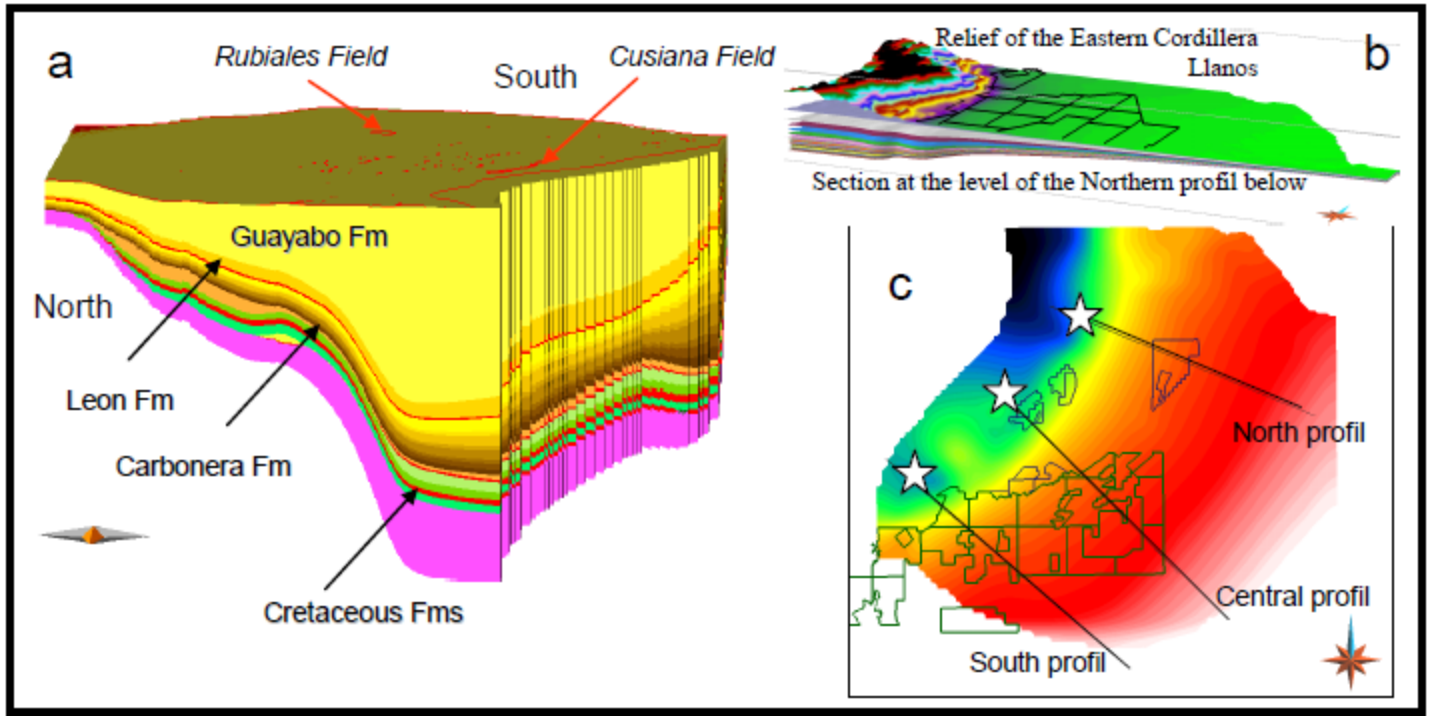

Figure 1. Location of the main features.

(a) N-S view of the 3D model showing the thickness change of the various formations. At the surface in red the main fields, the red line westward is the position of the Guaicaramo thrust.

(b) Oblique view, towards the north to show the relative depth of the foreland versus the Eastern Cordillera elevation and the simplifications made under the thrusts to model equivalent kitchens using software allowing only vertical displacements.

(c) Top view with the position of the 3 profiles shown in Figure 2, the blocks are the exploration areas. White stars: location of the fictive wells presented in Figure 2.

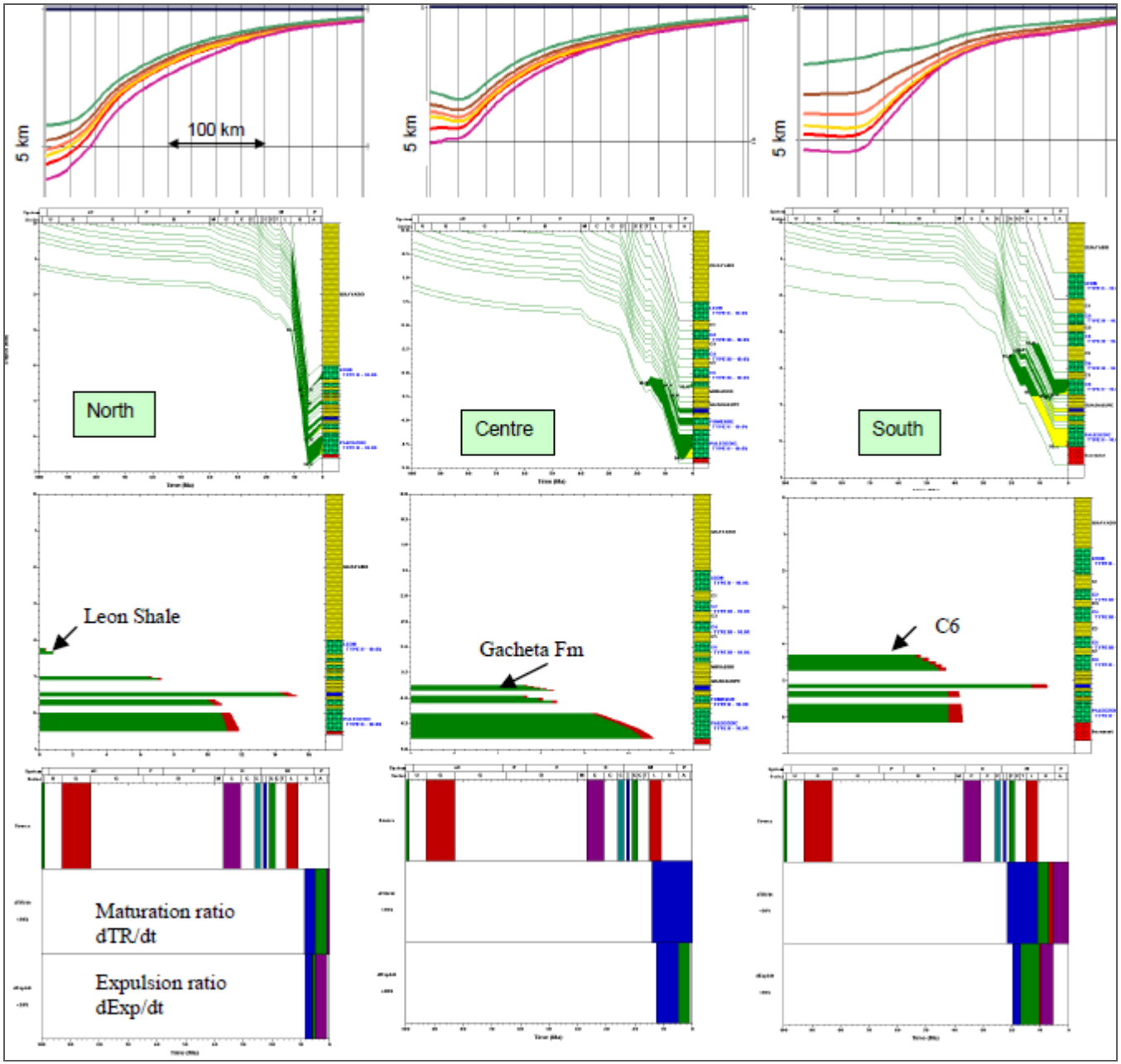

Figure 2. Profiles, maturation versus time, expulsed HC in a vertical well in the western part of the profile (see location Figure 1) and synthesis of the petroleum system for the 3 areas. The name of the youngest mature source rock has been highlighted on the third line that shows the expelled quantity for each main SR in a deep part of the kitchens. The deeper one is the potential Paleozoic SR.

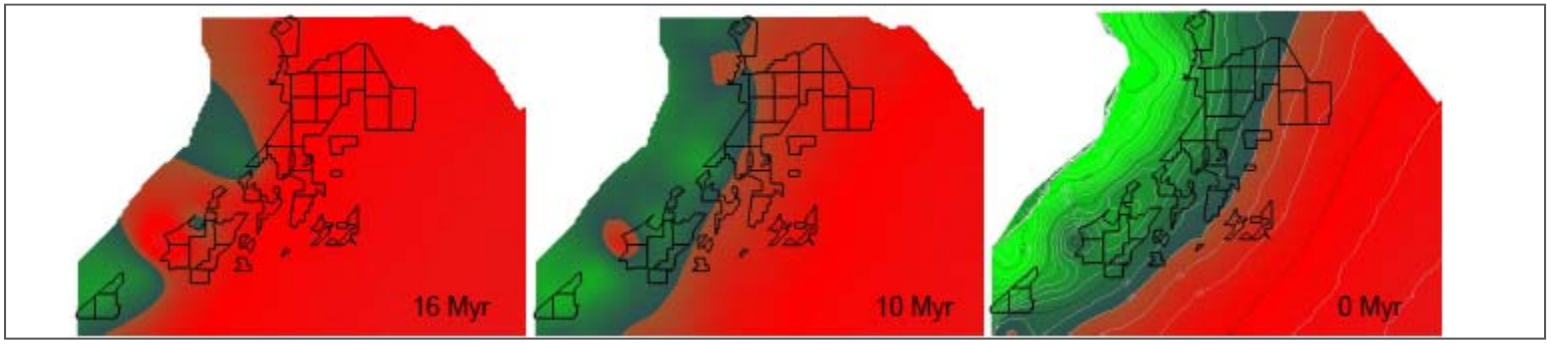

Figure 3. Evolution of the temperature is the C7 reservoir. The sharp color change highlights the 80ºC and so the threshold for the biodegradation possibility.

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