Cenozoic Petroleum Systems of the Sinú – San Jacinto Basin. Exploratory Perspectives of a Promising Frontier.

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Abstract

The Sinú San Jacinto Basin (SSJ) although the abundance of oil and gas seeps, is an under-explored and poorly understood basin, especially on the dynamics of the petroleum systems. A long lasting exploratory paradigm about the basin is the absence of source rocks for liquid hydrocarbons in the Cenozoic sequence and that the oil found in wells and seeps has provenance from upper Cretaceous rocks (Cansona Fm.).

However, recent studies of source rock quality show that in the Cenozoic sedimentary succession, particularly of Paleocene age, there are intervals with source rock characteristics appropriate for generation of liquid hydrocarbons, which is corroborated by detailed studies of biomarkers from rock extracts, crude oils and seeps in the basin, suggesting that the input of hydrocarbons sourced from units deposited during the Cenozoic is more important than previously believed for the basin, being probably the most important source.

Similarly generation models of some depocenters, calibrated with thermal maturity data (Tmax and% Ro) and biomarkers, indicate that the Cenozoic sequence, especially Paleogene rocks, can reach maturity conditions suitable for hydrocarbons generation similar to those estimated from biomarkers from crude oils in the basin. These results open a new spectrum of exploration opportunities in conventional and unconventional petroleum systems associated with the Cenozoic, increasing the prospectivity potential of this under-explored basin.

Introduction

An exploration paradigm in the basin is that if the potential source rocks of Cenozoic age, based on ditch samples, are indicative of type III kerogen and there are so many oil seeps in the area, the only source rock that could produce liquid hydrocarbons should be relicts of the Cretaceous Cansona Formation. However this affirmation is confronted by the fact that crude oil analysis for the Floresanto-1, Perdíces-1 and San Sebastián-1 wells drilled in the Sinú area (Halliburton, 2007) shows that the first two have high values of oleanane, a biomarker used as source input and age marker formed from angiosperms, which indicate terrestrial organic matter origin and its concentration increases in Tertiary oils (Moldowan et al, 1994).

Taking this in mind, these oils could be more representative of a Tertiary than a Cretaceous source rock, but additional evidence on this subject came from slim holes data (Universidad de Caldas – ANH, 2009), which prove the existence of a potential source rock in the Paleocene (Arroyo Seco Formation), that has not only type III but type II kerogen samples, and the potential to generate not only gas but crude oil.

Because of this and to better understand the genesis of the hydrocarbons in the basin a detailed geochemical characterization of 17 crude oil seeps, 2 condensate seeps, 11 bituminous sands, and 110 mud volcanoes was made. Analytical procedures included bulk parameters (API/density, Ni, V, S), SARA fractionation, GC/FID for saturate and aromatic fractions, SIM-GC/MS for saturate and aromatic biomarkers after molecular sieve isolation, and SIM-GC/MS for diamondoids compounds.

Geologic Framework

The Sinú-San Jacinto Basin is located in the northwestern corner of Colombia, and it is the most prolific area in oil and gas seeps among Colombian basins. This under-explored basin limits to the east with the Romeral fault system; to the north with the Oca Fault, to the northwest with the South Caribbean Deformation Belt deformation front; to the southwest with the Uramita fault system, and to the south with the cretaceous sedimentary and volcanic rocks of the Western Cordillera. The structural development of the basin is linked to the transpressional-transtensional deformation generated by displacement of the Caribbean Plate.

The oldest sedimentary rocks in the area, corresponds to relatively shallow marine deposits, of the Cansona Formation (Campanian - Maastrichtian), which were deposited unconformably on a basement of continental to transitional nature. This unit is unconformably overlaid by conglomerates, fluvial-deltaic sandstones and shallow marine mudstones with abundant molluscs of the Arroyo Seco Formation (early Paleocene - middle Eocene), which are unconformably overlaid by deltaic deposits and platform carbonates of the Toluviejo Formation formed by bioclastic limestones with macroforams, echinoderms, oncolites and molluscs, which interdigitate with fossiliferous calcareous sandstones and mudstones of deltaic and shallow marine environments of the Chengue Formation, deposited during the late Eocene –

Oligocene. Mudstones with marine molluscs and crustaceans of the El Floral Formation and fossiliferous sandstones interbedded with intervals rich in organic matter of the Ciénaga de Oro Formation (late Oligocene - early Miocene), represent the onset of a regional transgressive event that extends until middle Miocene and flooded the Lower Magdalena Valley (LMV), to the east. During late Neogene, were deposited in successive sequences, unconformably between themselves, sandstones with abundant molluscs of the El Cerrito Formation (late Miocene); sandstones, limestones and conglomerates of fluvial-deltaic and shallow marine environments of the Sincelejo Formation (Pliocene) and recent fluvial-lacustrine to coastal deposits (Pliocene - Pleistocene).

Geochemistry results from seeps in the basin

The geochemical data of the oil seeps and bitumen extracts of bituminous sands and mud volcanoes were interpreted in order to establish the organic matter source, depositional environment, thermal maturity and biodegradation in the basin, describe the geological and stratigraphic setting, identify the source rock that generated the oil seeps, and characterize the petroleum systems present in the Sinu-San Jacinto basin.

The oil seeps and condensates are moderate to normal mature, while organic matter from mud volcanoes and bituminous sands appear to have low to medium maturity; this is supported by results obtained for Methylphenanthrene index (MPI-1), calculated vitrinite reflectance (Ro,%), Ts/(Ts+Tm), methyldibenzothiophene ratio, C29-Sterane (20S/(20S+20R), C29-Sterane (ββ/αα+ββ) and 3- & 4-methyldiamantanes.

The presence of Oleanane in variable concentrations in the samples suggests that the organic matter was deposited in a marine or marine deltaic environment during the Tertiary and/or in the Late Cretaceous. Lower values of Oleanane might also indicate that some of the rocks could be deposited in low terrestrial input environments during the Tertiary and/or Late Cretaceous.

In general, C27 and C29 steranes are observed to dominate over C28 in oil seeps and mud volcanoes; however, C28 seems to be dominant in bituminous sand samples. The relative proportions of C27, C28 & C29 regular steranes of most of the samples correspond to source rocks deposited in estuarine to marine environments as shown in the ternary diagram (figure 1), which indicates an important input of terrestrial organic matter in most samples with input also of marine organic matter

Evidence for moderate to severe biodegradation in the basin is based on the presence of n-alkane profiles with n-C12 to n-C36 distribution to n-alkanes completely absents, presence of a medium to severe unresolved complex mixture (UCM), low molecular weight hydrocarbons/high molecular weight hydrocarbons LMWH/HMWH> 1, Not Pr, Ph and light isoprenoids present in some samples, regular steranes in low concentration, low ββ-steranes, and medium to high concentration of tricyclic terpanes. This is also confirmed by geochemical correlations, such as MA/A and MD/D (Diamondoids) (figure 2) and the presence of 25-norhopanes, especially NH, BNH and TNH.

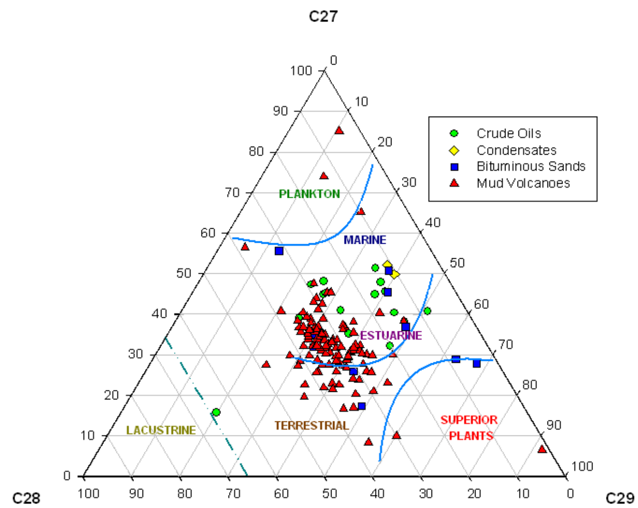

Figure 1 Ternary diagram of relative abundance of C27, C28 and C29 of ββ-Steranes (*m/z* 218) from Sinu-San Jacinto basin

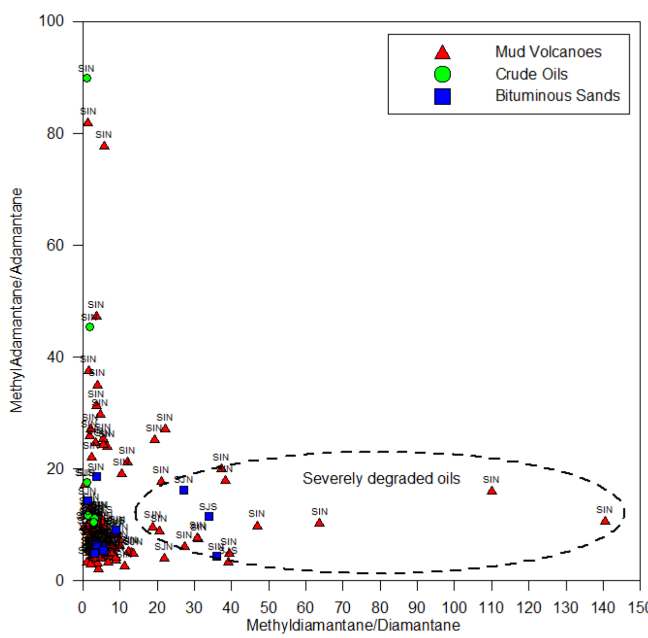

Figure 2 Plot of MA/A vs MD/D in the Sinu-San Jacinto basin.

Kerogen characterization of potential source rocks in the basin

The Oxygen Index vs Hydrogen Index diagram (Van Krevelen diagram) shows that rock samples from the Paleocene Arroyo Seco Formation have type II oil-prone kerogen. For the rest of the Cenozoic units (San Cayetano, Toluviejo, Chengue, El Floral, Luruaco, Ciénaga de Oro and Sincelejo formations) their samples are indicative of type III gas-prone kerogen to type IV kerogen (Figure 3) (Aguilera et al, 2010).

The presence of a source rock with type II kerogen (Arroyo Seco Formation) in the basin as shown by the pyrolysis data, suggests that the many oil seeps reported in the basin could have origin , at least in part from this formation, and is good agreement with the Cenozoic origin suggested by the biomarkers from the oil seeps and bitumen extracts from mud volcanoes and bituminous sandstones.

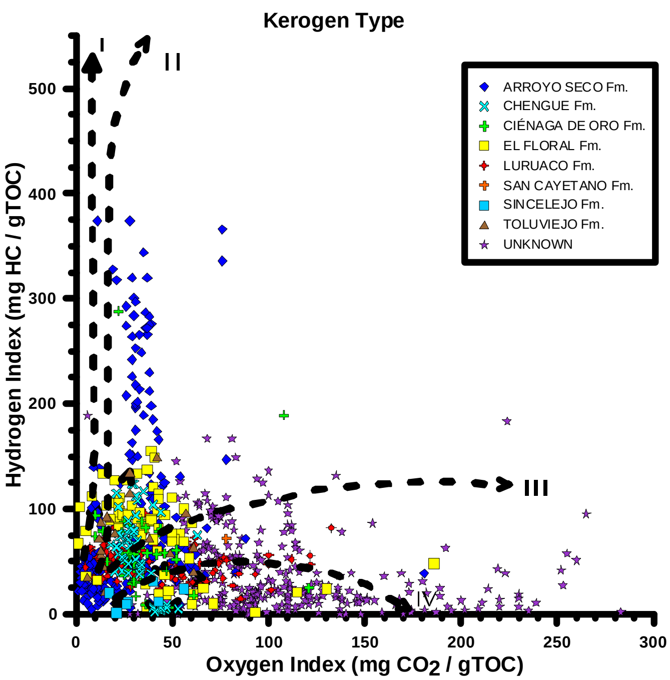

Figure 3 Van Krevelen Diagram of ditch samples from the SSJ Basin, showing that the predominant kerogen type in the basin is type III gas-prone, with the presence of type II kerogen in samples of the Paleocene Arroyo Seco Fm. (From Aguilera et al., 2010).

Petroleum Systems characterization of the Sinú – San Jacinto Basin.

The Pristane/Phytane vs Oleanane/C30 Hopane (Oleanane Index) graph shows that oils from the San Sebastián-3, San Sebastián-2 and Río Sinú-4 wells have low oleanane index values (<0.2) and Pr/Ph values (<2), and correlate well with rock extracts from the Arroyo Seco, Toluviejo and El Floral formations, suggesting that these units are the sources for the hydrocarbons found in those wells. The oil from the San Sebastián-1well has higher Pr/Ph value (>4) and seems to correlate well with rock extracts from the Arroyo Seco Formation (Figure 4) (Aguilera et al., 2010).

The Phytane/nC18 vs Pristane/nC17 graph shows good correlation between the crude oils found in the San Sebastián-1, San Sebastián-3, Perdices-10 and Floresanto-6 wells with rock extracts from samples of the Arroyo Seco, Ciénaga de Oro, El Floral and Toluviejo formations. Indicating that the oils have origin from terrestrial organic matter and to a minor extent from mixed kerogen (type II-III), but additionally that the crudes and rocks have similar thermal maturities (Figure 5) (Aguilera et al., 2010).

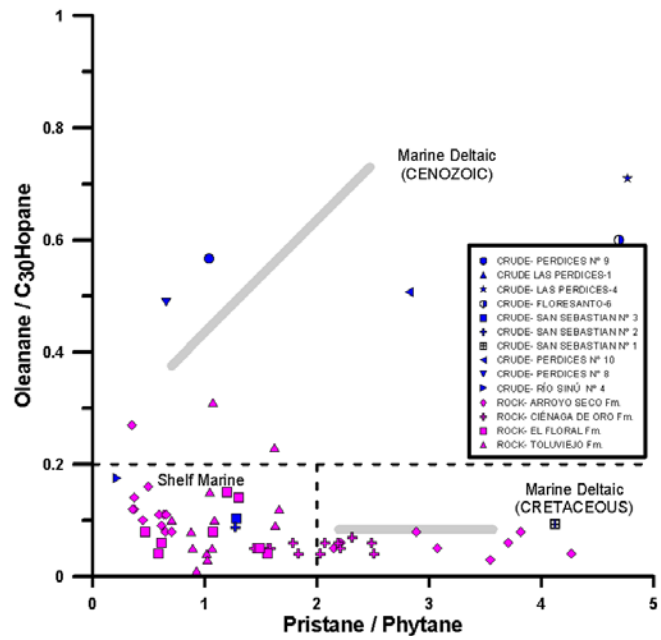

Figure 4 Pristane/Phytane vs Oleanane/C30 Hopane (Oleanane Index) graph showing the correlation between crude oils and rock extracts from samples analized in the basin (From Aguilera et al., 2010).

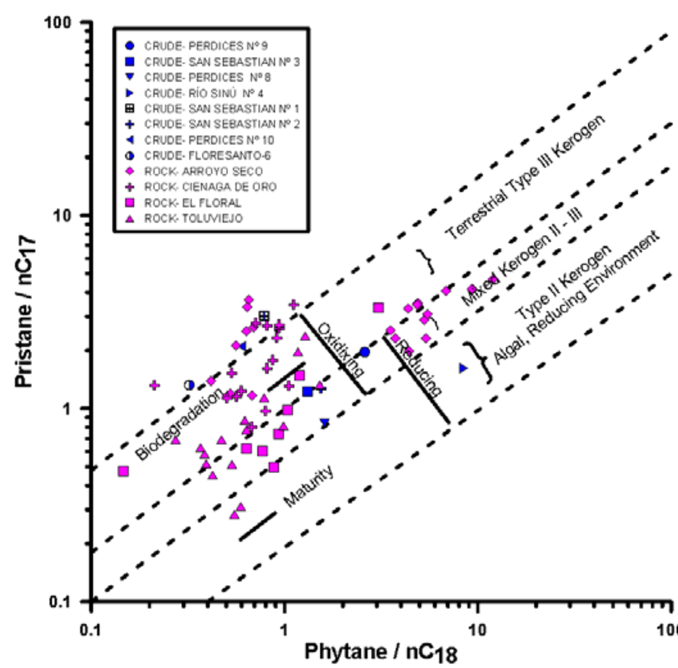

Figure 5 Phytane/nC18 vs Pristane/nC17 graph showing the correlation between crude oils and rock extracts from samples in the SSJ basin (From Aguilera et al., 2010).

From the existing geochemical information at the basin some hypothetical petroleum systems can be postulated (*sensu* Magoon & Dow, 1994): Arroyo Seco (.), Arroyo Seco–Chengue (.), Arroyo Seco – Toluviejo (.), Arroyo Seco – Ciénaga de Oro (.), Toluviejo (.), Toluviejo – Chengue (.), Toluviejo – Ciénaga de Oro (.), Ciénaga de Oro (.).

Exploratory perspectives for the SSJ Basin.

Regarding prospectivity, having multiple formations with generation potential for oil and gas also creates many opportunities at different stratigraphic levels and the presence of mudstones sealing multiple structures locally and regionally increasing the chances of finding commercial accumulations in the area.

The geochemical information indicates that not only the Late Cretaceous Cansona Formation but the Paleogene Arroyo Seco Formation can generate liquid hydrocarbons, and that the Neogene stratigraphic sequence is gas prone.

The presence of multiple oil and gas seeps at the surface (figure 6), indicate the existence of an active petroleum system in the Sinú – San Jacinto Basin, but the lack of information from these seeps precludes determining which of the potential source rocks is actively generating hydrocarbons in the basin.

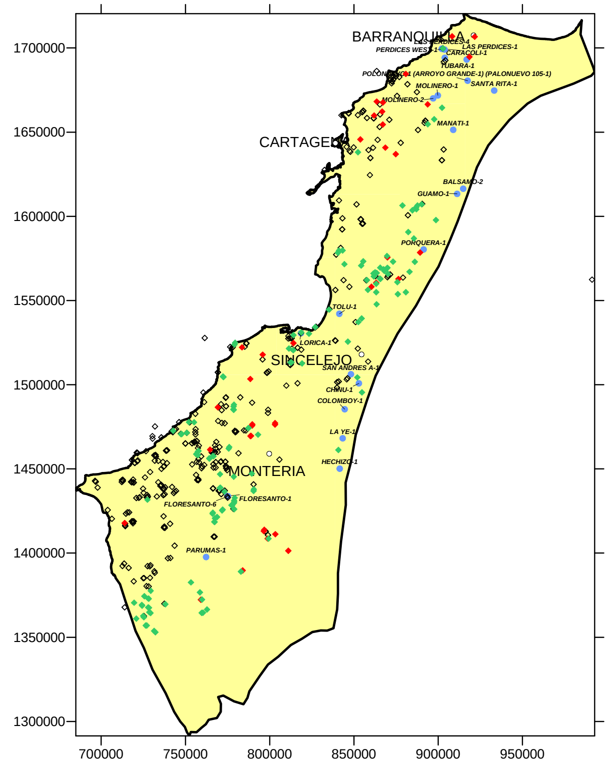

Figure 6 Seeps map of the SSJ Basin. Blue dots are wells with geochemical data, green rhombs are oil seeps, red rhombs are gas seeps and hollow rhombs are undetermined seeps. (From Aguilera et al., 2010).

For the onshore part of the Sinú Fold Belt, the following types of plays can be considered (Figure 7):

- Folds associated with early stages of the formation of diapirs which do not completely break the sequence. A favorable aspect of these kinds of folds is that, according to the extent of the folds associated with mud diapirs from surface geology, they could be laterally extensive, ranging in length from 5km to 20 km approximately.
- Folding and truncation of the reservoirs against the diapirs (drag folds), which considering the lateral extension from surface geology of the mud diapir systems could create structures of considerable extent within the synclines (mini-basins).
- Truncation of reservoirs and sealing by syndepositional unconformities to the flanks and within the synclines, caused by the deformation associated with the vertical movement of the mud diapirs.
- Folding associated with faulting (fault propagation folds).
- Although seismic imaging is not good enough to establish the presence of a sedimentary sequence below the possibility of a Sub-Mud play cannot be discarded.

Conclusions

In summary the geochemical data allow to establish the following regarding the source rocks generating hydrocarbons at the basin:

The source rock is mainly siliciclastic (shales) deposited in a low salinity, shelf marine to fluviodeltaic environment under suboxic to oxic conditions, with variable input of terrestrial organic matter. The expected kerogen types are type II oil-prone and type III gas-prone.

There is a clear separation of at least two source rocks from Pr/Ph values, one with high terrigenous input and high Pr/Ph values, and other with lower terrigenous input, in which probably predominates algal marine or mixed organic matter and low Pr/Ph values. This is concordant with the known stratigraphy of the basin, especially for the Tertiary sequence which has been deposited under fluvio-deltaic and coastal marine environments.

The geochemical information indicates that not only the Late Cretaceous Cansona Formation but the Paleogene Arroyo Seco Formation can generate liquid hydrocarbons, and that the Neogene stratigraphic sequence is gas prone.

The possibility of having multiple formations with generation potential for oil and gas also creates many opportunities at different stratigraphic levels and the presence of mudstones sealing multiple structures locally and regionally increases the chances of finding commercial accumulations in the area.

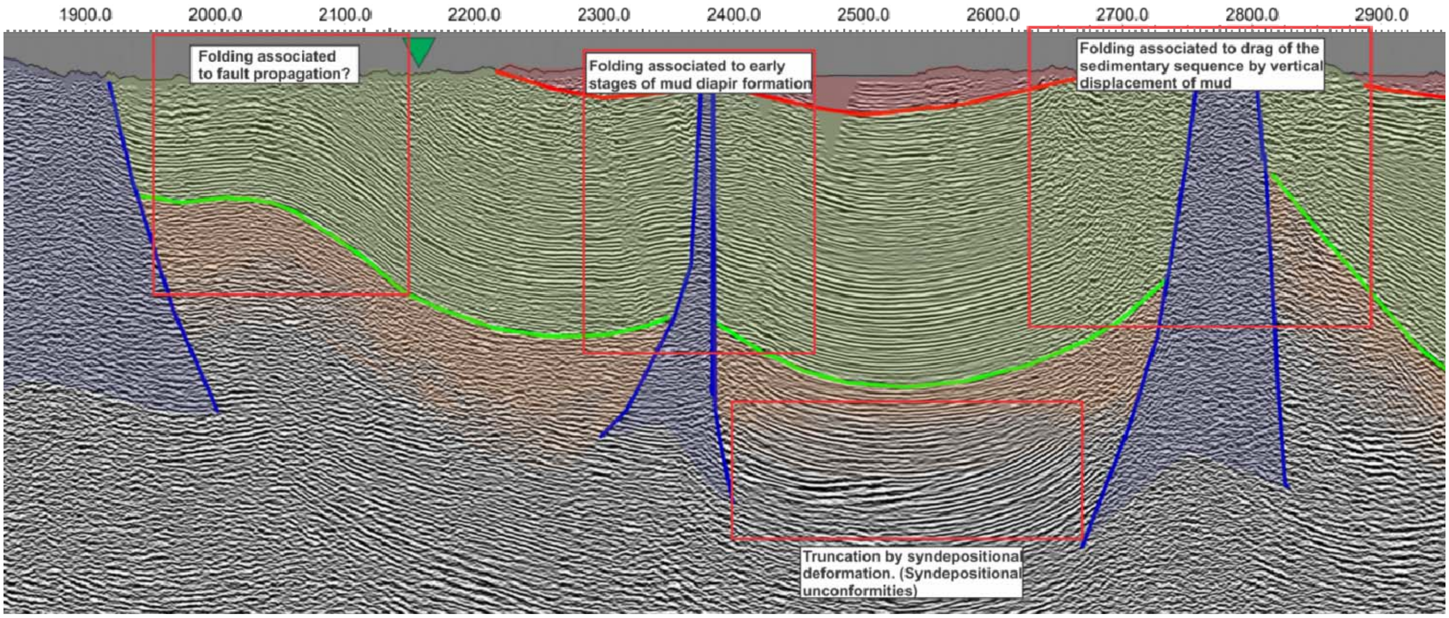

Figure 7 . Type of plays in the onshore part of the Sinú Fold Belt.

References

1. Aguilera, R., Sotelo, V., Burgos, C., Arce, C., Gómez, C., Mojica, J., Castillo. H., Jiménez. D., & Osorno, J. (2010). *Organic Geochemistry Atlas of Colombia – Second Edition. Earth Sciences Research Journal.* Vol. **14** Special Edition. 180 p.

2. ANTEK S.A. – RA GEOLOGIA E.U. (2010). *Sinú – San Jacinto Basin, Colombia. Oil Seeps and Petroleum Systems Evaluation SINÚ –Multi-client, Non-exclusive Project*. **2** Vols. **8** Annex. 211 p.

3. Halliburton. (2007). *Informe ejecutivo proyecto "Consultoría para realizar la evaluación (geología del petróleo), la integración, interpretación y reinterpretación de la información suministrada y la que deba ser consultada para generar los paquetes de información técnica requeridos para llevar a cabo la Ronda Caribe"*. Reporte interno a la ANH. 97p.

4. Magoon L, & Dow W., (1994) *The petroleum system. In: The Petroleum System from Source to Trap* (eds. Magoon L & Dow W.). American Association Petroleum Geologist Memoir 60, p. 3-24.

5. Moldowan, J.M., Dahl, J., Huizinga, B.J., et al., (1994). *The molecular fossil record of oleanane and its relationship to angiosperms*. Science, Vol. 265, p. 768-771.

6. Universidad de Caldas - ANH (2009) *Estudio integrado de los núcleos y registros obtenidos de los pozos someros tipo ¨Slim Holes¨ en la Cuenca Sinú.* Universidad de Caldas. ANH. **2** Vols. **6** Annexes. 171 p.