Petroleum Systems Charged by Tertiary Source Rocks: New Exploration Opportunities in northern South America

DAVID A.WAVREK (Petroleum Systems International, Inc. Salt Lake City, UT) and
DENISE M. BUTLER (PennzEnergy, Houston, TX)

ABSTRACT

Petroleum systems research in northern South America indicates that the volumetric contribution of hydrocarbons from Tertiary source rocks is greater than traditionally thought. This conclusion is based on results of new oil-based biomarker technologies that define the effective source rock facies in terms of geologic age and position within a depositional sequence. A case study in the Falcón basin also demonstrates the diversity of hydrocarbons generated from Tertiary petroleum systems and how certain oils could be mistakenly assigned to the Upper Cretaceous petroleum system. Accurate petroleum system assignments will become increasingly important as exploration programs target low sulfur crude oils, non-associated gas, and gas-condensates in northern South America as a result of market pressures.

INTRODUCTION

It is generally assumed that the source rocks of the Upper Cretaceous (La Luna and its stratigraphic equivalents) are responsible for the hydrocarbon accumulations in northern South America. Indeed, these Upper Cretaceous source rocks rank as world class in terms of quality and quantity, and are responsible for numerous giant to super-giant oil fields. The first geologist to fully appreciate this oil-source rock relationship was Hollis Hedberg (1931), a conclusion that has been reinforced by subsequent studies (Bockmeulen et al., 1983; Zumberge, 1984; Talukdar et al., 1985, 1986, 1988; James, 1990; Audemard, 1993; Talukdar and Marcano, 1994; Parnaud et al., 1995; Stoufer et al., 1998; and Ramon and Dzou, 1999). What is less appreciated, however, is the contribution of Tertiary source rocks to the overall hydrocarbon reserves of northern South America. The purpose of this paper is three-fold: to review evidence in prior reports that Tertiary source rocks contribute to hydrocarbon reserves of northern South America, outline the strategy used to define and quantify Tertiary contributions, and demonstrate the potential impact on oil and gas exploration programs. The results indicate that the volumetric contribution of hydrocarbons generated from Tertiary source rocks is probably greater than previously thought. This revelation will become increasingly significant as exploration programs target low sulfur crude oils, as well as gas and gas-condensate resources in the region.

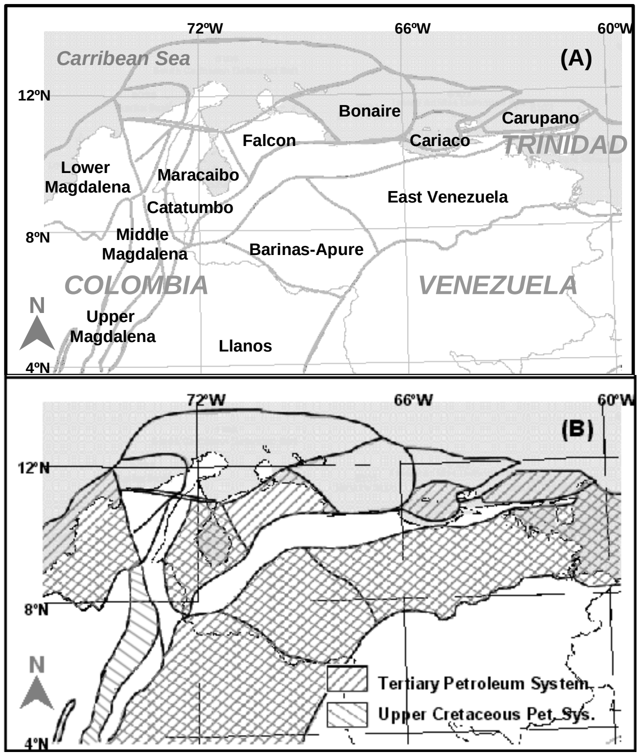
DISCUSSION

Synthesis of Recent Studies

The literature pertaining to petroleum systems of northern South America contains numerous accounts of Tertiary source rocks contributing to the total hydrocarbon charge (Figure 1). Using the Maracaibo basin as a typical case, Talukdar et al. (1985, 1986) identified three oil types in the region: an oil derived from a marine kerogen that correlates to the La Luna formation; an oil derived from a terrestrial kerogen presumed to correlate to Paleocene shales or coals; and a third type that is interpreted to be a mixture of marine and terrestrial oil. The Tertiary sourced oils that are enriched in terrestrially derived organic matter are estimated to contribute between 2 and 5 percent of the reserves in Maracaibo basin (Gallango et al., 1985; James, 1990; Talukdar and Maracano, 1994). Although this pales in comparison to that attributed to the Upper Cretaceous, it should be emphasized that the volume of Tertiary sourced oil in this single basin is in the range of 1 billion barrels which remains a significant volume by any global standard.

A survey of other producing basins in northern South America indicates that oils attributed to Tertiary source rocks are volumetrically significant. Yurewicz et al. (1998) extended the coverage from the southwest of Maracaibo into the Catatumbo sub-basin of Colombia to confirm that the Upper Cretaceous marine source rocks contribute the bulk of the oil charge, but that the terrestrial source rocks of the Paleocene were responsible for the waxy oils. Yurewicz et al. (1998) also speculates on the gas potential of the Tertiary sequences, and suggests that they are responsible for the gas discovered at Cerrito field.

Figure 1- Map of northern South America showing producing basin names (A) and age of source rocks (B) contributing to the petroleum systems.



Carlson and Moldowan (1998) report that both Upper Cretaceous and Tertiary source rock intervals contribute to the hydrocarbon charge in Trinidad, although they do not comment on the respective volumes. These authors also extrapolate their conclusions back into Venezuela by proposing a positive correlation between the Tertiary sourced oils of Trinidad and the highly similar oils (waxy, terrestrial) of the Maturin region. The conclusion that the waxy oils in other parts of East Venezuela (e.g., Las Mercedes, Oficina) are sourced from Tertiary rocks has also been reported by a number of previous investigators (Cassani et al., 1988; James, 1990; Tocco et al., 1994). In addition, the giant (8 Tcf) Yucal-Placer gas field of East Venezuela is presumed to be sourced from the Tertiary (Aymard et al., 1985). In the Barinas sub-basin of Venezuela, Cassani et al. (1988) attributed the source rock to be the Upper Cretaceous, a conclusion that is reinforced in the report by Gil (1998). Extending the coverage into the Apure State, Lopez et al. (1998a,b) clearly documents an additional oil type (paraffinic-naphthenic vs. typical aromatic-naphthenic) but they fail to make a definitive statement as to the significance of this new data. In the Falcón basin, the source rocks are presumed to be Tertiary in age based on consideration of the oil composition and the assumption that the Upper Cretaceous source rocks of this region are over mature (James, 1990). It is noted that Ahlborn (1998) recently suggested some evidence that the Upper Cretaceous may have contributed a paleo-hydrocarbon charge to the region, but this is not expected to represent a significant volume of oil. In the Llanos basin of Colombia, Rangel et al. (1997) established that both Upper Cretaceous and Tertiary source rocks contribute to the hydrocarbon charge, based on the results of oil-based biomarker analysis. This result was re-confirmed by Moldowan et al. (1998). The Lower Magdalena onshore has both Upper Cretaceous and Tertiary sourced hydrocarbons, whereas the offshore seems to be restricted to Tertiary sources (Arteaga, 1995; Schamel et al., 1998; Deckelman and Huizinga, 2000). The source rocks for the other offshore basins, including Carupano and Cariaco, are reported to be in the Tertiary sequences based on geologic circumstances of thermal maturity (James, 1990).

Petroleum System Assignment Bias

The preceding synthesis reveals that a bias exists concerning the criteria for identifying oils sourced from Tertiary source rocks. That is, the oils identified as being generated from Tertiary source rocks have the general traits of being waxy with low total sulfur contents. On a molecular basis, the oils typically display abundant C20+ n-alkanes with a convex profile and a relatively high pristane to phytane ratio. The biomarker fraction is generally dominated by molecular signatures associated with organic matter input from higher plant debris such as oleanane and relatively low tricyclic terpane concentrations, but displaying an enhanced C19/C23 tricyclic terpane ratio. Molecular indicators of increased oxicity and/or siliciclastic lithology of the depositional system are commonly emphasized, such as enhanced diasterane/sterane and Ts/Tm ratios. These are, in fact, physical properties and/or molecular traits in distinct contrast to that commonly cited for the oils sourced from the Upper Cretaceous La Luna and lateral equivalents.

There are cases where oils generated from marine source rocks are assigned to the Tertiary section (e.g., offshore Lower Magdalena, Cariaco and Carupano), but this occurs in circumstances where the Upper Cretaceous marine source rocks are over mature and/or completely absent. The source rock assignment bias is also not justified on the basis that a significant portion of the Tertiary sedimentary section across the northern margin of South America has been deposited in a marine depositional system (e.g., Pindell et al., 1998). It is thus proposed that oils sourced from marine sequences in the Tertiary can be erroneously assigned to the Cretaceous petroleum system. Likewise, the organic facies variation of the Upper Cretaceous source rocks is not adequately constrained, although it is known that these sequences can have a significant percentage of higher plant debris. As a result, it is quite feasible that waxy oils assigned to the Tertiary could actually be generated from the Cretaceous petroleum system. The solution to this dilemma is to adopt a rigorous approach to the petroleum system assignments by including additional parameters in the analytical program, including the incorporation of age-specific biomarkers.

Biomarkers are defined as organic compounds detected in the geosphere whose basic carbon skeleton suggests an unambiguous link to a contemporary natural product (Mackenzie, 1984). These molecules allow a direct link to be established between organic matter input to a source rock and the correlative crude oil. The time span from the Cretaceous into the Tertiary marks important changes in the flora and fauna, changes that are recorded in the molecular record. These changes include the appearance of new species, as well as the diversification and radiation of others. Examples include the appearance of dinoflagellates in the Triassic, a group that continued to diversify and radiate through the Mesozoic into the Tertiary. The organic matter input of these organisms is recorded in the molecular record by 24-norcholestanes and 24-nordiacholestanes (Moldowan et al., 1996, 1998; Holba 1998). In addition, the molecular fossil identified as oleanane parallels the evolution and radiation of flowering plants (angiosperms) through the Cretaceous into the Tertiary, with the highest relative amounts recorded in Tertiary oils (Moldowan et al., 1994). The application of the oleanane index to crude oils, however, must be restricted to those sourced from marine to marine-deltaic depositional environments as the depositional/diagenetic environment can have a profound influence on the fate of the oleanoid precursors (Murray et al., 1997). The application of these techniques to the Falcón basin of Venezuela provides an interesting case study for investigating the diversity of oils generated from the Tertiary petroleum systems and allows a demonstration of the technique to aid in the accurate petroleum system assignments. This will become more important as exploration targets low sulfur oils, and gas/gas-condensate accumulations.

Case Study of Falcón Basin (Venezuela)

The Falcón basin is located in northwestern Venezuela, and essentially occupies the entire State of Falcón (Figures 1 and 2). It is an elongate east-west oriented structural basin that contains sedimentary sequences from Eocene to the Pleistocene. The complex structural architecture is the result of east-west movements of the Caribbean and South American plates, creating three distinct structural provinces. The

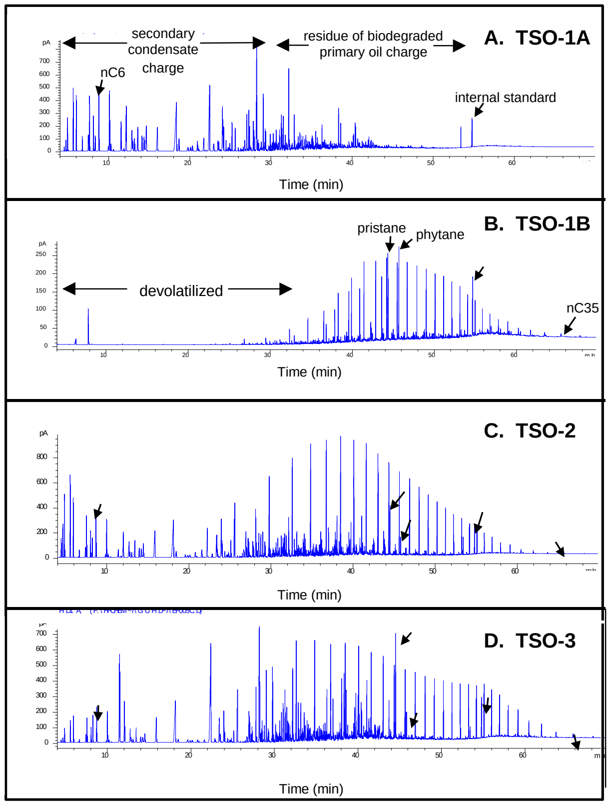
Figure 2 – Map of the state of Falcón (Venezuela) with the distribution of oil types discussed in text.

active tectonism of this area, in turn, greatly influence the sedimentary processes producing significant discontinuities and sediment deformities. The Tertiary source rocks are believed to have been deposited during a transgression in the late Eocene to early Miocene and a regressive cycle in the middle Miocene (Boesi and Goddard, 1991). The complex structural and stratigraphic framework of this basin has made correlation across the basin very difficult. This also gives rise to the problem of compartmentalized reservoirs, making the issues of hydrocarbon charge, expulsion, and migration even more complicated. There is also some debate concerning the existence and extent of Upper Cretaceous sediments in the basin. A few wells have penetrated Paleocene sediments and possibly the Upper Cretaceous, but they are not considered to be important from a source rock perspective due to the advanced thermal stress experienced by these sequences.

In order to assess the compositional variation of oils derived from the Tertiary interval within the Falcón basin (Figure 2), a total of 34 crude oils were analyzed. The samples from East Falcón included representatives of the Cumarebo, La Vela, Riecito, and Mene de Acosta oil fields plus surface seeps collected near Riecito, Buenos Aires, and El Saman. Where applicable, this data set is supplemented by information in the public domain. These alternative data sources allow us to extrapolate conclusions to West Falcón (e.g., Tiguaje field; Boesi and Goddard, 1991; Molina, 1993) and the offshore La Vela Bay (Miranda field; Young, 1973). For comparison sake, representative samples from Maracaibo and East Venezuela are included to constrain interpretations to the Upper Cretaceous petroleum systems.

The results of this work establish that the oils can be divided into at least 3 major types (Figures 2 and 3) that correlate to different source rocks within the Tertiary sequences. The tentative assignments for these three oil types are the Middle Miocene Agua Salada mixed marine carbonate/clastics (TSO-1), the Early Miocene Agua Clara marine shales (TSO-2), and the Early Miocene Cerro Pelado coals (TSO-3). A condensate fraction has also been identified as mixed with the produced oils at Mene de Acosta (Figure 3A) that is probably generated from deeper (possibly Oligocene Pecaya) source rocks. It is significant to emphasize that the oils sourced from the marine source rocks could be easily mistaken for being part of the Upper Cretaceous petroleum system if a rigorous analytical program were not in place.

Figure 3 - Representative gas chromatography (GC) traces of the end-member oil types identified in the Falcón basin. Correlative source rocks and alternation mechanisms are briefly discussed in the text.



Application to Exploration Programs

The successful use of petroleum system logic in exploration programs relies on a team of individuals making integrated interpretations related to the processes of hydrocarbon generation, migration, and accumulation. A key aspect is the accurate assignment of the petroleum system, as well as identifying the effective components and peocesses active *within the petroleum system*. It is not only important to assign the hydrocarbons to the correct large scale petroleum system (Upper Cretaceous vs. Tertiary), but also to be able to identify the correlative source rock within the marine sequences of the Tertiary (e.g., Agua Salada and Agua Clara formations of the Falcón basin). A comprehensive molecular program is required to accomplish this task since routinely used molecular parameters (e.g., conventional steranes and hopanes) have multiple origins that do not yield formation specific correlations, especially in fluvial-deltaic depositional systems. The complications associated with identifying effective source rocks in deltaic systems are related to their being dominated by higher plant debris deposited in a wide variety of environments (flood plain, lacustrine, paralic, deltaic, and marine). This is particularly important from the migration-accumulation perspective since accurate identification of the effective source rock facies will directly influence the charge risk within the complex Tertiary sequences. The charge risk in these systems is primarily due to limited drainage area and connectivity of the migration conduits. In the case of the widespread TSO-3 oils that correlate to Cerro Pelado coals of the Falcón basin, the specific position of the effective coal deposits are determined to be those coal measures that had a marine influence during the depositional process and/or during very early diagenesis. This information is advantageous for exploration in this Tertiary basin since the source rocks should be associated with the coarse-grained sediments within the nearshore marine system. In this way, the near shore marine sands will act as efficient expulsion/migration conduits for the hydrocarbons leaving the juxtaposed coal beds. This conclusion is based on detailed molecular characterization that includes analysis of alternative pathways of the oleanoid precursors (Murray et al., 1997). This information is also useful in the re-assessment of coal-derived oil volumes on a global scale.

Another key point with exploration significance is the interpretation of condensate phase genetic origin. It is usually assumed that a condensate originates from hydrocarbon generation at thermal stress levels intermediate between oil and gas. This is an important process, and explains the secondary hydrocarbon charge at Mene de Acosta (Falcón basin). There are alternative mechanisms for generating condensate and these are important in other parts of northern South America. Examples include the in-situ reservoir cracking of oil to gas-condensate in Maracaibo, and vertical migration of light hydrocarbons after partial vaporization of deeper oil accumulations in some of the offshore basins. It is noted that this latter process is significant in Tertiary basins throughout the world, and that the differentiation of the condensate formation mechanism in a particular basin is an important aspect in the petroleum systems analysis since it will indicate whether or not oil, gas, or dry holes can be expected from deeper drilling programs.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Devon Energy Corporation and Pennzoil Venezuela, S.A. for permission to publish selected parts of this paper. We particularly wish to acknowledge Dr. E.G. (Skip) Rhodes and Dr. Robert W. Spoelhof (Pennzoil Venezuela, S.A.) for their support and encouragement throughout the course of this study. Dr. Santosh K. Ghosh (PDVSA) is also acknowledged for his assistance in navigating the stratigraphic nomenclature of the region. Finally, Ms. Carole McCalla and Susan Nguyen of Petroleum Systems International Inc. are acknowledged for their efforts in preparation of this manuscript, as well as the subsequent oral presentation.

BIBLIOGRAPHY

Ahlborn R.C. (1998) Eocene plays and cretaceous hydrocarbons in Western Falcon, Zulia and Falcon States, Venezuela. *AAPG Annual Convention Abstracts*, Salt Lake City, Utah.

Arteaga O.L. (1995) Petroleum systems of the lower Magdalena Valley basin, NW Colombia. *Organic Geochemistry: Dev. and Appl. to Energy, Climate, Environment, and Human History*, Donostia-San Sebastian, Spain. 94-95.

Audemard F. (1993) Generation and migration of heavy oils from Guarico and southern Maturin subbasins. *AAPG Bull*., 77, 303.

Bockmeulen H., Barker C. and Dickey P.A. (1983) Geology and geochemistry of crude oils, Bolivar Coastal fields, Venezuela. *AAPG Bull*., 67, 242-270.

Boesi T. and Goddard D. (1991) A new geologic model related to the distribution of hydrocarbon source rocks in the Falcon basin, northwestern Venezuela. In K.T. Biddle (ed.) *Active Margin Basins: Case Histories and Examples,* AAPG Memoir 52, 303-319.

Carlson R.M.K. and Moldowan J.M. (1998) Genetic and maturity relationships of two distinct oil types and organic-rich Naparima Hill formation shales, Trinidad. *ALAGO Proceedings*, Margarita Island, Venezuela, 6p.

Cassani F., Vallejos C., Gallango O., de Toni B. and Talukdar S. (1988) Geoquimica organica de los crudos Venezolanos. *III Simposio Bolivariano, Exploracion Petrolera de Cuencas Subandinas,* Caracas, 612-637.

Deckelman J.A. and Huizinga B.J. (2000) Seabed piston coring: A cost effective means of assessing petroleum charge, offshore Colombia. *AAPG Annual Meeting Abstracts*, New Orleans, LA.

Gallango O., Talukdar S. and Chin-A-Lin M. (1985) Caracteristicas de los crudos marinos en la Cuenca de Maracaibo, Venezuela Occidental: *Memoir, Sixth Venezuelan Geological Congress*, Caracas, Venezuela, 3, 1661-1693.

Gil E.E. (1998) Indicadores geoquimicos asociados a las facies organicas que generacion los crudos del area de Barinas, Venezuela. *ALAGO Proceedings*, Margarita Island, 6p.

Hedberg H.D. (1931) Cretaceous limestone as petroleum source rock in northwestern Venezuela. *Bull. AAPG*, 15, 229-246.

Holba A.G., Dzou L., Masterson W.D., Hughes W.B., Huizinga B.J., Singletary M.S., Moldowan J.M., Mello M.R. and Tegelaar E. (1998) Application of 24-norcholestanes for constraining source age of petroleum. *Org. Geochem*., 29, 1269-1283.

James K. (1990) The Venezuelan hydrocarbon habitat. In J.Brooks (ed.) *Classic Petroleum Provinces*, Geol. Soc. Spec. Pub. No. 50, 9-35.

Lopez L., Lo Monaco S., and Richardson M. (1998a) Use of molecular parameters and trace elements in oil-oil correlation studies, Barinas sub-basin, Venezuela. *Org. Geochem.*, 29, 613-629.

Lopez L., Lo Monaco S., Labastida E. and Lira A. (1998b) Correlacion de crudos de la subcuenca de Barinas, Venezuela. *ALAGO Proceedings*, Margarita Island, Venezuela, 4p.

Parnaud F., Gou Y., Pascual J-C., Truskowski I., Gallango O., Passalacqua H. and Roure F. (1995) Petroleum geology of the central part of the eastern Venezuelan basin. In A.J. Tankard, R. Suarez S., and H.J. Welsink (eds.) *Petroleum Basins of South America*, AAPG Memoir 62, 741-756.

Mackenzie A.S. (1984) Applications of biological markers in petroleum geochemistry. In J. Brooks and D. Welte (eds) *Advances in Petroleum Geochemistry, Volume 1*. Academic Press, London, 115-214.

Moldowan J.M., Dahl J., Huizinga B.J., Fago F.J., Hickey L.J., Peakman T.M. and Taylor D.W. (1994) The molecular fossil record of oleanane and its relation to angiosperms. *Science*, 265, 768-771.

Moldowan J.M., Dahl J., Jacobson S.R., Huizinga B.J., Fago F.J., Shetty R., Watt D.S. and Peters K.E. (1996) Chemostratigraphic reconstruction of biofacies: Molecular evidence linking cyst-forming dinoflagellates with pre-Triassic ancestors. *Geology*, 24, 159-162.

Moldowan J.M., Dahl J., Brooks P.W. and Mello M.R. (1998) Characterization of South American oils to determine source rock age and provenance using new high resolution biomarker methods. *ALAGO Proceedings*, Margarita Island, Venezuela, 3p.

Molina A. (1993) Tiguaje field-Venezuela. In N.H. Foster and E.A. Beaumont (compilers) *Structural Traps VIII*, Atlas of Oil and Gas Fields, AAPG, Tulsa, 295-303.

Murray A.P., Sosrowidjojo I.B., Alexander R., Kagi R.I., Norgate C.M. and Summons R.E. (1997) Oleananes in oils and sediments: Evidence of marine influence during early diagenesis. *Geochim. Cosmochim. Acta*, 61, 1261-1276.

Pindell J.L., Higgs R. and Dewey J.F. (1998) Cenozoic palinspastic reconstruction, paleogeographic evolution and hydrocarbon setting of the northern margin of South America. In J.L. Pindell and C.L. Drake (eds.) *Paleogeographic Evolution and Non-Glacial Eustasy, Northern South America.* SEPM Special Publication No. 58, 45-85.

Ramon J.C. and Dzou L.I. (1999) Petroleum geochemistry of the Middle Magdalena Valley, Colombia. *Org. Geochem.*, 30, 249-266.

Rangel A., Brooks P.W. and Giraldo B. (1997) Petroleum geochemistry of oils in the foothills of the Llanos basin, Colombia. *EAOG Proceedings*, Maastrict, The Netherlands.

Schamel S., Allen R.B., Schelling D., Wavrek D.A., Laverde M. and Ballesteros C. (1998) Hydrocarbon potential of the Sinu-San Jacinto region of northern Colombia. *AAPG Convention Abstracts*, Salt Lake City, Utah.

Stoufer S., Chigne N., Sanchez J.H. and Mello M.R. (1998) Cretaceous and Tertiary petroleum systems of the northwest region of the East Venezuela basin. *AAPG Bull.*, 82, 1971.

Talukdar S, Gallange O. and Chin-A-Lien M. (1986) Generation and migration of hydrocarbons in the Maracaibo basin, Venezuela: an integrated basin study. *Org. Geochem.*, 10, 261-279.

Talukdar S., Gallange O. and Ruggiero A. (1985) Formaciones La Luna y Querecual de Venezuela: Rocas madres de petroleo: *IV Congreso Geologico Venezuela*, 3606-3642.

Talukdar S., Gallange O. and Ruggiero A. (1988) Generation and migration of oil in the Maturin subbasin, Eastern Venezuelan basin. *Organic Geochemistry*, 13, 537-547.

Talukdar S. and Marcano F. (1994) Petroleum systems of the Maracaibo basin, Venezuela. In L.B. Magoon and W.G. Dow (eds.) *The Petroleum System – from Source to Trap.* AAPG Memoir 60, 463-481.

Tocco R., Alberdi M., Ruggiero A. and Jordan N. (1994) Organic geochemistry of the Carapita Formation and terrestrial crude oils in the Maturin Subbasin, Eastern Venezuelan Basin. *Org. Geochem.,* 21, 1107-1119.

Young W.A. (1973) Organic geochemical study of oil and core samples from the 23-Miranda-2X, 23-Miranda-3X, and 23-Miranda-4X wells, Gulf of La Vela, Esso Production Research Report.

Yurewicz D.A., Advocate D.M., Lo H.B. and Hernandez E.A. (1998) Source rocks and oil families, Southwest Maracaibo Basin (Catatumbo Subbasin), Colombia. *AAPG Bull.*, 82, 1329-1352.

Zumberge J.E. (1984) Source rocks of the La Luna Formation (Upper Cretaceous in the Middle Magdalena Valley, Colombia). In J.C. Palacas (ed.) *Petroleum Geochemistry and Source Potential of Carbonate Rocks: Studies in Geology No. 18.* AAPG, Tulsa, 127-133.