

Biogenic Gas Potential Offshore Guajira Peninsula, Colombia

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ABSTRACT

Within the Guajira region of Colombia, several trillion cubic feet (TCF) of gas have been discovered, with the potential for additional reserves. Most of the discovered gas is present in two producing fields, Chuchupa and Ballena. Geologic considerations, including the nature of the stratigraphic column and low regional geothermal gradients, suggest that these gas accumulations are biogenic in origin. The geochemical character of the gas, which is both dry and isotopically light, further supports such an origin. A regional assessment suggests that future exploration also will be directed largely toward biogenic gas accumulations.

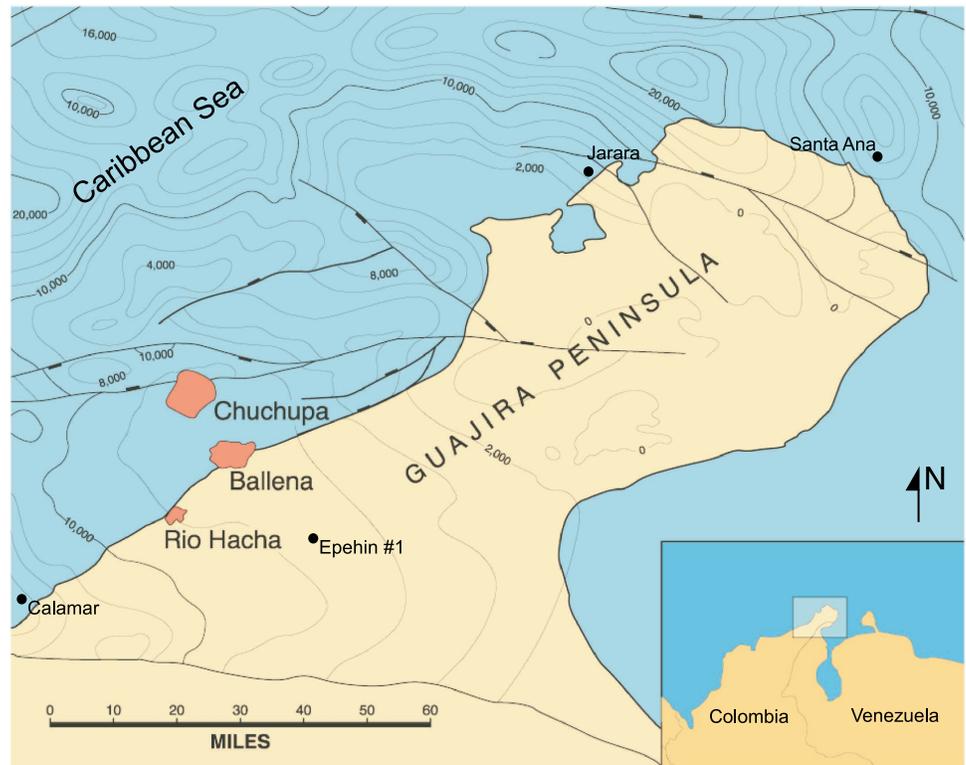
Unlike many assessments of hydrocarbon exploration potential that focus on trap capacity, this study examines the availability and character of hydrocarbon charge. The volume of hydrocarbons was estimated using a geochemical model in which the amount of bacterially produced gas is a function of organic enrichment and temperature history. The volume of gas available was constrained further by comparing the timing of gas generation to that of trap development. The overall expulsion, migration, and trapping efficiency of the hydrocarbon system was established through a statistical assessment of known gas accumulations in the Guajira region and ranged up to ~3.2%. The estimated efficiency of the Guajira region hydrocarbon system is considered a minimum because of trap-capacity limitations. Using the trap-volume constrained system efficiency factor, the gas available to individual leads ranges up to ~4 TCF. Additional upside potential may exist, given the uncertainties of the estimates. The presence of multi-TCF charge estimates clearly indicates the potential for additional commercial gas accumulations in the area.

INTRODUCTION

The “Greater Guajira Region” is a transform margin located in northern Colombia (Figure 1). The sedimentary sequence, which approaches 2400 m (8000 ft) in the vicinity of the gas accumulations

and may exceed 4800 m (16,000 ft) to the north of the producing area, ranges in age from Paleogene through Quaternary (Figure 2). The stratigraphic section is dominated by siliciclastics, although Miocene carbonates have proven to be important reservoir targets.

Figure 1. Index map for the Guajira study area, with generalized total sediment thicknesses displayed. Contours are in feet.



Exploration in the “Greater Guajira Region” has proven-up reserves in excess of 7 TCF of gas, with much of this gas being present in two producing fields (Chuchupa, 5.7 TCF, and Ballena, 1.2 TCF gas in place). Recently acquired seismic data have revealed the presence of additional prospective targets in the offshore region, extending the potential play into deep water. The focus of this study was an examination of the risks associated with hydrocarbon charge of these offshore prospects. The assessment was accomplished by examining the source-rock potential and thermal maturity of the penetrated section, the geochemical character of produced gases, and modeling the volumes of hydrocarbons that may ultimately be available for entrapment.

eration potential using Rock-Eval pyrolysis. Total organic carbon (TOC) content ranged from less than 0.1% to almost 25% (Figure 3). Above-average levels of organic enrichment (TOC > 1.0%) are considered one of the prerequisites for classification as a possible oil-source rock (Bissada, 1982). However, source-rock

SOURCE-ROCK POTENTIAL

As part of the assessment of the hydrocarbon charge potential of the Guajira region, more than 1200 subsurface samples were screened geochemically for hydrocarbon source-rock potential, through a determination of organic carbon content and hydrocarbon-gen-

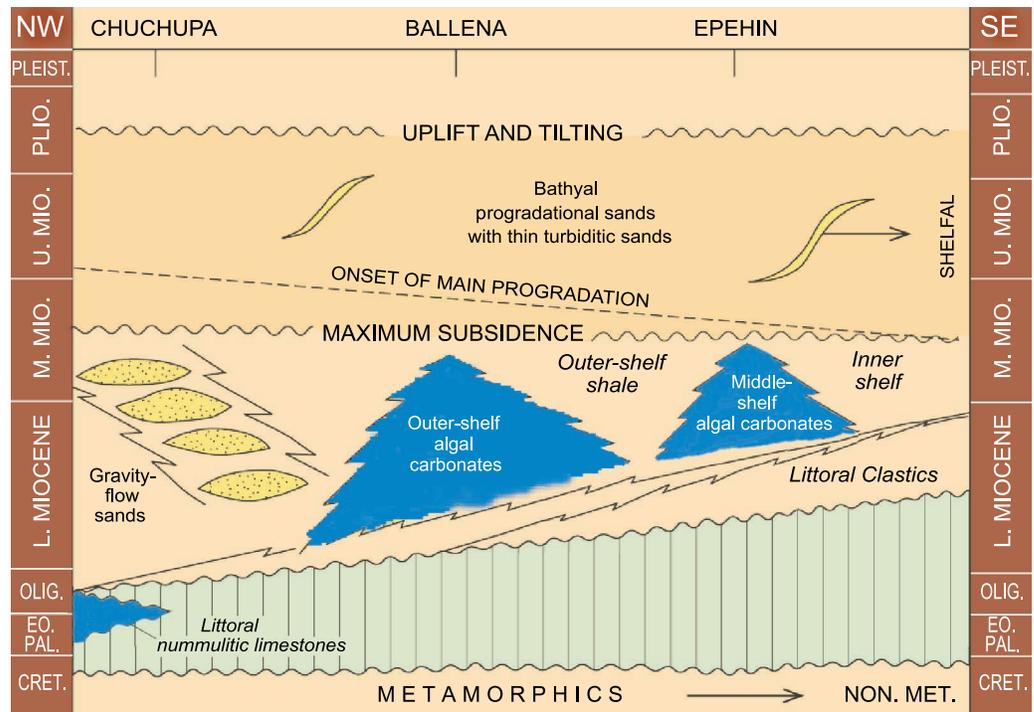


Figure 2. Stratigraphic cross section for Guajira study area.

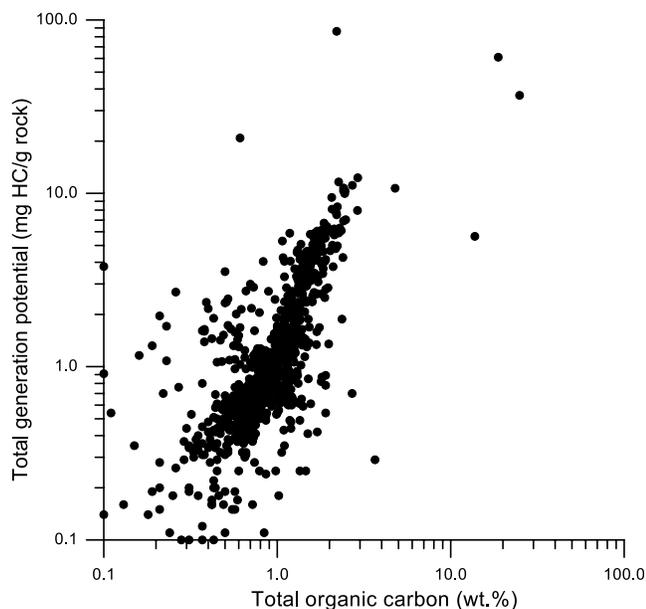


Figure 3. Relationship between total organic carbon content and total pyrolytic hydrocarbon yield ($S_1 + S_2$), revealing that a significant number of samples contain above-average levels of organic carbon and had above-average hydrocarbon yields.

thresholds as low as 0.5% TOC are considered possible for gas sources (Rice and Claypool, 1981). This difference in threshold criteria for oil- and gas-prone source rocks results from differences in expulsion mechanisms. Oil is expelled as a separate phase and is driven by pressure and capillary forces (Mackenzie et al., 1988). In contrast, gas typically leaves the source-rock system by diffusion and is driven by concentration gradients (Leythaeuser et al., 1987). More than 80% of the samples analyzed contain more than 0.5% organic carbon and could, therefore, act as a gas source, with approximately 50% of the samples containing more than 1.0% organic carbon, and could potentially be an oil source, if the appropriate kerogen is present and hydrocarbon yields are adequate.

Hydrocarbon-generation potential was rather modest, with most samples having $S_1 + S_2$ yields of less than 2.5 mg HC/g rock (Figure 3). Total hydrocarbon yields greater than 2.5 mg HC/g rock is the second prerequisite for classification as a possible oil-source rock (Bissada, 1982). Although the low hydrocarbon yields most probably would preclude the expulsion of liquid hydrocarbons, they do not restrict gas expulsion, which, as noted above, is diffusion driven. A significant number of samples did have elevated hydrocarbon yields. Most of the

samples with elevated hydrocarbon yields, however, display evidence to suggest that their elevated yield (and probably their elevated TOC) is a result of contamination by drilling fluids. The presence of non-indigenous organic matter is suggested by the elevated free hydrocarbon to organic carbon ratio (S_1/TOC) (Figure 4) and inconsistencies between the production indices ($S_1/[S_1 + S_2]$) and T_{max} (temperature of peak pyrolytic hydrocarbon yield; Figure 5). The presence of contaminants in the samples would result in an overestimation of the sedimentary section's hydrocarbon source potential.

In addition to hydrocarbon yield, organic matter characterization was accomplished through the use of Rock-Eval pyrolysis (Espitalié et al., 1977). Characterization is typically established through an examination of the relationship between the hydrogen (mg " S_2 " HC/g TOC) and oxygen (mg CO_2/g TOC) indices, as presented on a modified van Krevelen-type diagram. An examination of the contaminant-free population suggests that the analyzed samples are largely gas-prone (Figure 6), plotting near or below the type-III reference curve. A number of samples display very low hydrogen indices (< 50 mg HC/g TOC) and represent type-IV or inert organic matter. This material would have very limited capability to generate any hydrocarbons. A few samples do display slightly elevated hydrogen index values (> 300 mg

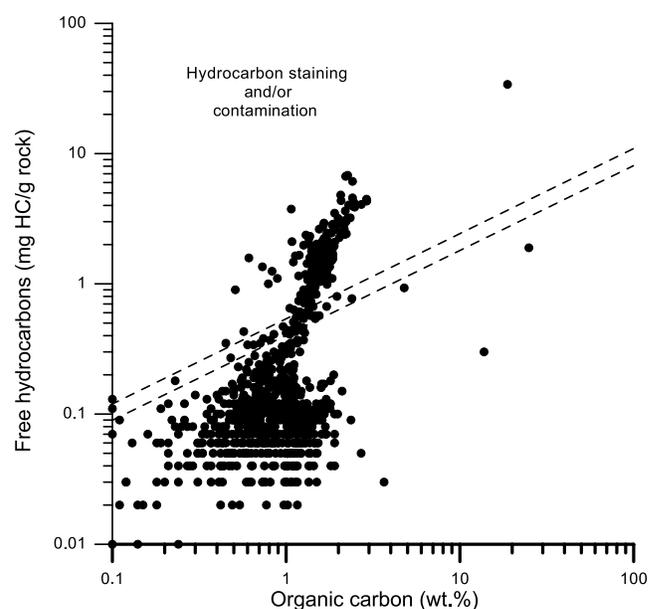


Figure 4. Relationship between the free hydrocarbon content (S_1) and total organic carbon content, suggesting that a significant number of samples with organic carbon contents greater than 1.0% are contaminated.

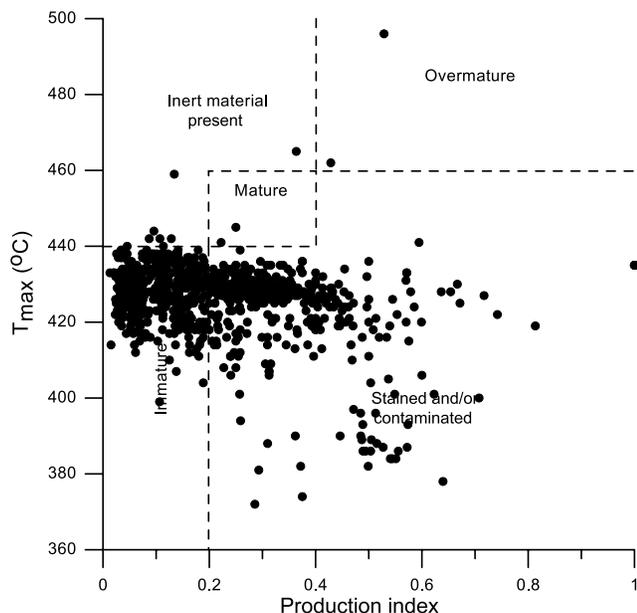


Figure 5. Relationship between the production index and T_{max} , confirming both the thermal immaturity of the sedimentary sequence and the contaminated nature of many of the samples.

HC/g TOC) and suggest the presence of minor oil-source potential. It should be noted, however, that the “gas-proneness” of the section might be slightly overstated through the use of the Rock-Eval indices because of the low organic carbon content of the samples (Katz, 1983).

THERMAL MATURITY

Vitrinite reflectance (R_o) was used to establish the thermal maturity of the penetrated section. A rep-

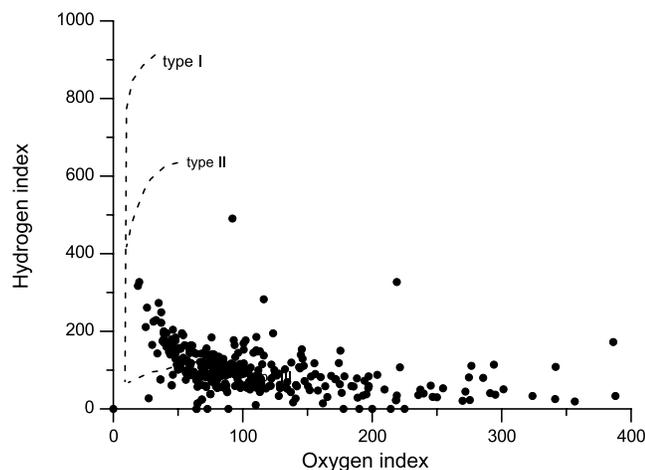


Figure 6. Modified van Krevelen–type diagram for contaminant-free samples displaying the largely gas-prone character of the penetrated sequence.

representative vitrinite reflectance profile is presented in Figure 7. Available data suggest that the top of the main stage of hydrocarbon generation and expulsion ($R_o = 0.68\%$) is located at a depth of ~ 3500 m ($\sim 11,500$ ft) subsurface. These data, along with the regional isopach data (Figure 1), indicate that much of the sedimentary sequence is thermally immature, suggesting that the region’s hydrocarbon potential is largely limited to biogenic gas.

A more detailed examination of the raw reflectance data also reveals the presence of a significant amount of recycled organic matter in some of the samples. The presence of this recycled material is a partial explanation for the low hydrogen indices observed for some of the samples.

GAS CHARACTER

A number of gas samples were available for analysis from three fields from the study area — Chuchupa, Ballena, and Rio Hacha. Both the molecular and isotopic compositions of these gases were determined. Molecular composition is a function of source rock character, thermal maturity, and alteration history. Gas wetness ($100 \times C_{2+}/[C_1 + C_{2+}]$) values range from 0.28 to 0.45% (Figure 8). According to Schoell (1983), dry gases have wetness index values less than 5%. Therefore, all of the gases studied from the region are classified as dry. Dry gas may have either a bacterial ($R_o < 0.5\%$ or sediment temperature $< 70^\circ\text{C}$) or

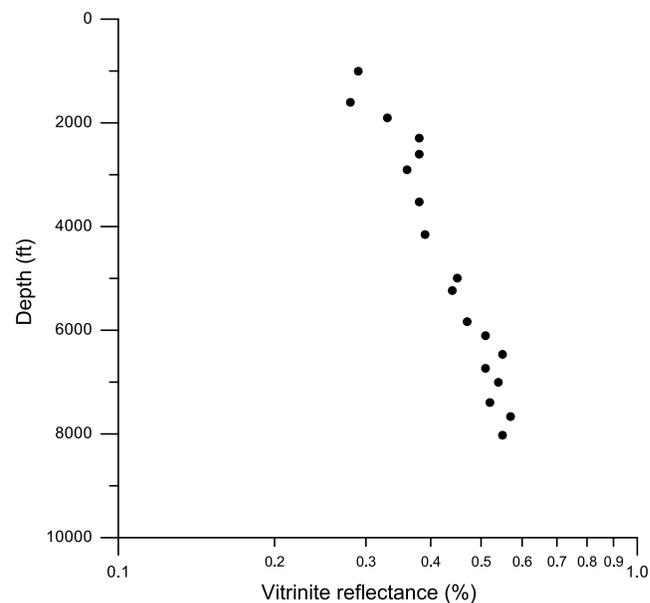


Figure 7. Vitrinite reflectance profile for the Epehin #1 well.

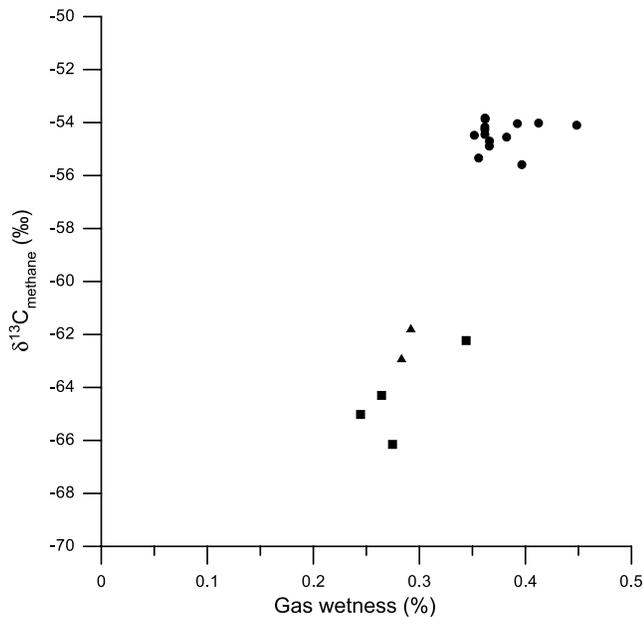


Figure 8. Relationship between methane stable carbon isotope composition and gas wetness (Chuchupa ● – Ballena ■ – Rio Hacha ▲) depicting the clear differences in gas composition between Chuchupa and the Ballena and Rio Hacha fields.

a thermal origin associated with an advanced level of thermal maturity ($R_o > 2.0\%$). Typically, ethane and the heavier hydrocarbon gases are assumed to have a thermogenic origin; therefore, trace quantities of these gases often are thought to indicate either minor mixing of biogenic and thermogenic gases or the onset of thermogenic processes. Oremland et al. (1988) has shown, however, that trace quantities of ethane (less than 1%) also may be explained by bacterial processes. Therefore, additional data are required to establish the mode of gas formation.

The mode of gas formation is more commonly established through an examination of the stable carbon isotopic composition of its hydrocarbon components. “Primary” biogenic gas is isotopically light (i.e., $\delta^{13}\text{C}_{\text{methane}} < -55\%$; Schoell, 1983). The methane-stable carbon isotope data suggest that the Ballena and Rio Hacha gas samples have a “pure” biogenic origin (Figure 8). The isotopic composition of a gas increases (i.e., becomes heavier or less negative) with increasing thermal maturity (Stahl, 1977). The methane from the Chuchupa samples is about 10‰ heavier than the methane from Ballena and Rio Hacha (Figure 8). Isotopic compositions of methane similar to those observed at Chuchupa often are assumed to represent a mixed biogenic-thermogenic origin (Schoell, 1983).

As a result of the low concentrations of ethane, only a limited amount of isotope data is available. The available ethane values are all lighter than -43.5% . Such isotope values suggest either bacteriogenic ethane and/or ethane associated with incipient thermogenesis (Taylor et al., 2000).

These data, therefore, confirm a largely biogenic origin for the region’s commercial gas accumulations. Such a mode of formation is significant in that it requires an approach to exploration different from that associated with exploration for thermogenic hydrocarbons. Because “primary” biogenic gas forms early in a sedimentary sequence’s history, exploratory targets (both reservoirs and trapping mechanisms) need to form early (Rice and Claypool, 1981). This contrasts with thermogenic accumulations, which are less sensitive to the timing of trap formation because much of the thermogenic gas generation occurs late in the basin’s history.

MASS-BALANCE MODEL

There are several approaches to hydrocarbon resource estimation. Historically, these approaches have focused on trap capacity, incorporating such elements as the volume of rock under closure and the reservoir’s porosity. When such approaches are used, either a tacit assumption that sufficient hydrocarbons are available to fill the trap is made or some arbitrary fill-up factor is invoked. An alternative approach examines the amount of hydrocarbons available for entrapment (Katz and Kahle, 1988). Although such an approach is typically used to estimate oil and thermogenic gas potential, it can be adapted to estimate biogenic gas potential.

The approach developed for this study to estimate biogenic gas resource potential has several well-defined steps. The first step is to estimate the maximum amount of gas that could be generated by the sediments within each generative prism. The areal extent of each generative volume is established through an analysis of the basin’s structural configuration. In biogenic gas systems, lateral migration is thought to play an important role in the formation of economic accumulations because the volume of gas present typically exceeds that which could be generated within the area of the trap (Brown, 1997). Therefore, the generative prism normally extends beyond the geographic limits of an individual accumulation. Gas yield per volume of rock within the generative prism is a function of source-rock richness and methanogenic bacterial activity, which

itself is largely a function of temperature (Köning, 1992). The previously discussed organic carbon data can be used to estimate the maximum potential biogenic gas yield (Clayton, 1992). Assuming maximum biogenic gas production (i.e., the sediment has reached temperatures approaching $\sim 60^{\circ}\text{C}$) and a yield of $4.9 \text{ ft}^3 \text{ gas}/\% \text{ TOC}/\text{ft}^3 \text{ sediment}$ (Clayton, 1992), the organic carbon data suggest biogenic methane yields ranging from 2.6 to $10.7 \text{ ft}^3 \text{ gas}/\text{ft}^3 \text{ sediment}$. Gas yield as a function of maximum burial temperature can then be calculated (Figure 9; Katz, 1995). The ultimate gas yield in the generative prism is then reduced through an examination of the thermal history of the source(s) within each structure's fetch area. This analysis is performed as a time series so that only the gas formed after the development of a viable trap is quantified, with the gas yield being defined by the sediment's maximum exposure temperature.

The amount of gas formed within the generative prism significantly exceeds that which may ultimately be trapped. Prior work by Katz et al. (1998) suggests that there are significant post-generation gas losses. For example, they calculated that in Central Sumatra, less than 20% of the gas generated after trap development would be available for entrapment. Therefore, once the amount of gas gen-

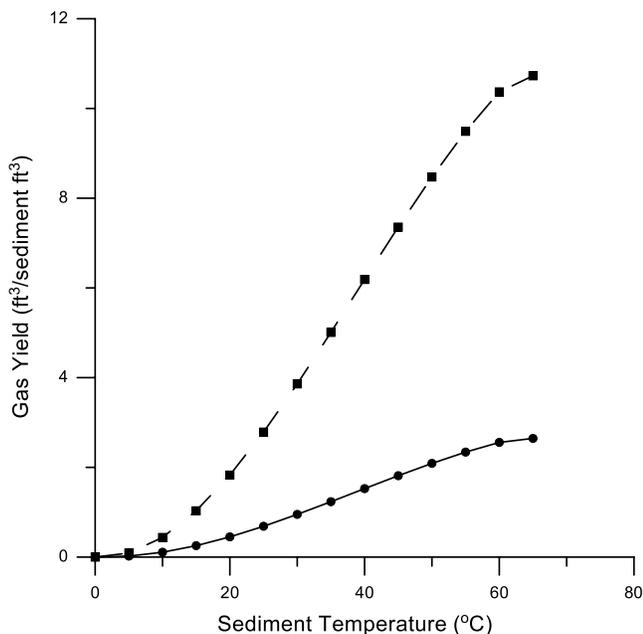


Figure 9. Biogenic gas yield range as a function of temperature for the maximum (■) and minimum (●) observed organic carbon contents, excluding the limited coaly intervals.

erated is established, potential gas losses from and to the system should be estimated. Ideally, one would like to directly calculate any and all of these gas losses. The difference between the calculated gas produced and that lost from the system would be the amount of gas available for entrapment. The gas available for entrapment includes the known gas accumulations in both commercial and sub-commercial reservoirs and the remaining exploration potential. Calculated gas losses would need to take into consideration the gas retained in solution in the pore waters and oil contained in the effective source rock, gas lost to formation waters and oil in the carrier and reservoir network, and gas lost through diffusion across the seal, as well as any catastrophic losses associated with seal failure. The nature of these calculations assumes that in order for a gas accumulation to form, a free-gas phase exists throughout the generative prism and that migration occurs in a gas phase. Because of the relatively limited volumes of water typically moving through any given lead, prospect, or trap, only a limited amount of gas is thought to migrate in solution. Brown (1997) had previously suggested the importance of such a migration mechanism.

Unfortunately, the information necessary for the calculation of each of these losses is not readily available in an undrilled or poorly drilled basin or subbasin. For example, the estimation of the volume of gas retained by the source rock requires an understanding of the effective source-rock volume, source-rock porosity, temperature, pressure, gas and oil saturation, and pore-water salinity. Furthermore, these factors are not static but vary through time as a function of the development of sedimentary overburden, generation of hydrocarbons, and basin hydrodynamics. For example, fluid flow in a basin may increase significantly the number of pore-water volumes that the generated gas may be exposed to.

Because a rigorous calculation of gas loss is precluded, the approach taken was based on an overall hydrocarbon system expulsion/transfer efficiency factor. In this approach, the expulsion/transfer efficiency factors of known commercial and sub-commercial accumulations are determined, and their probability of occurrence is established. The efficiency factor is the percentage of gas formed in a gathering area present in its associated structure. The calculated efficiency factors for the Greater Guajira Region and their probability of occurrence are presented in Figure 10. These data suggest P_{10} , P_{50} , and P_{90} efficiency factors of 0.44%, 1.78%, and 3.20%, respectively.

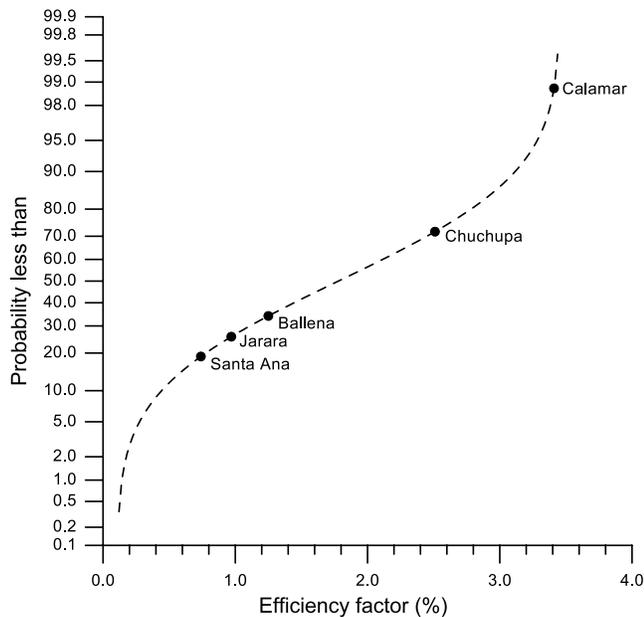


Figure 10. Calculated gas-transfer-efficiency factors for the Greater Guajira Region. These values assume that trap capacity was not a limiting factor.

This method of establishing the transfer efficiency factor assumes that the availability of hydrocarbons and not trap capacity is the primary gas volume-limiting factor. In the Greater Guajira Region, with some traps apparently filled to the spill-point, trap capacity may be a limiting factor. Under such circumstances, the estimated efficiency factors are reduced, and the system effectiveness may be higher for prospects not limited by trap capacity. An analysis of available data suggests that the efficiency factors for traps not limited by trap capacity may be more than double that calculated.

HYDROCARBON EXPLORATION POTENTIAL

An examination of a regional seismic grid revealed the presence of at least 11 leads and/or prospects within the Greater Guajira area. As outlined above, the fetch area for each of these potential targets was defined based on the structural framework during the time of gas generation. The amount of biogenic gas generated was calculated for each stratigraphic level by time slice. The volumes of gas generated for each time slice after trap development were combined to estimate the "maximum" gas available in each generative prism. The previously established efficiency factors were then used to reduce the generated volume to that available for entrapment. Using the trap-capacity-limited effi-

ciency factors, the P_{50} values for the identified leads ranged up to ~ 4 TCF (Figure 11), with P_{90} gas volumes potentially exceeding 7 TCF. A comparison of the volume of biogenic gas available for entrapment with that of the trap capacity could then be made in order to assess objectively the hydrocarbon charge risks. This approach suggests that five of the leads and prospects have potential gas reserves in excess of 1 TCF.

CONCLUSIONS

Source-rock potential for liquid hydrocarbons appears to be very limited in the study area. Hydrocarbon-generation potentials are typically below the threshold for oil expulsion, and the organic matter is largely gas-prone. However, there is clear evidence to support significant gas-generation potential throughout the stratigraphic column.

The stratigraphic section in the study area generally is thermally immature. Therefore, hydrocarbon potential is limited largely to biogenic gas. Any thermogenic hydrocarbon potential would result largely from lateral migration from more distal portions of the current study area, where sediment thicknesses exceed ~ 3500 m ($\sim 11,500$ ft).

The analysis of gas samples from the region confirms that the region's known resource base is almost exclusively biogenic gas. This conclusion further implies that the more viable exploration targets would have formed early in the basin's history, allowing for maximum accessibility to hydrocarbon charge.

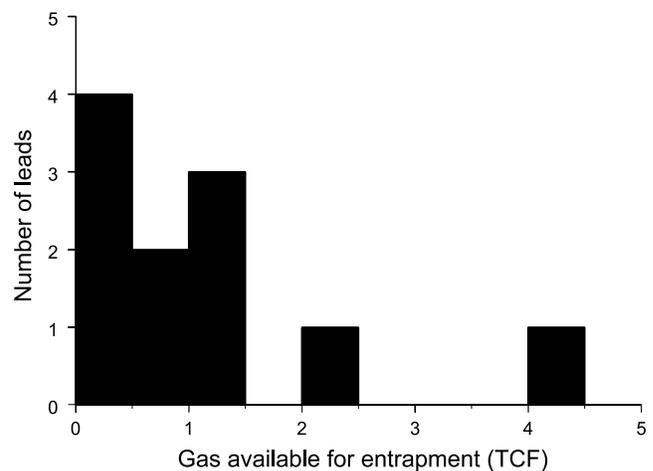


Figure 11. Histogram of P_{50} hydrocarbon values for leads and prospects in the Greater Guajira Region.

A detailed quantitative assessment of gas losses could not be performed because of the number of unknowns and the range of uncertainty associated with each of the variables required for such calculations. However, the overall gas-transfer efficiency from generative prism to trap could be estimated using the region's known commercial and sub-commercial gas accumulations. These estimates suggest that the transfer efficiency is less than 4%. These calculated efficiency factors may not be fully representative of the system's overall efficiency because of trap size limitations.

Eleven leads and/or prospects had been identified in the Greater Guajira Region. The integration of available data and model results suggests that several of these leads have gas potential in excess of 1 TCF and could have commercial viability.

The use of this approach permitted an objective assessment of hydrocarbon charge. It also permitted the ranking of identified prospects based on charge rather than just trap capacity.

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REFERENCES CITED

- Bissada, K. K., 1982, Geochemical constraints on petroleum generation and migration — a review: Proceedings, Association of Southeast Asian Nations Council on Petroleum (ASCOPE) '81, Manila, The Philippines, p. 69–87.
- Brown, A., 1997, Migration controls on the occurrence of economic bacterial gas accumulations, *in* R. J. Krui-zenga, ed., Proceedings, Applications of emerging technologies: Unconventional Methods in Exploration for Petroleum and Natural Gas V: Institute for the Study of Earth and Man, Southern Methodist University, Dallas, Texas, p. 84–106.
- Clayton, C., 1992, Source volumetrics of biogenic gas generation, *in* R. Vially, ed., Bacterial Gas: Paris, Editions Technip, p. 191–204.
- Espitalié, J., M. Madec, B. Tissot, J. J. Mennig, and P. Leplat, 1977, Source rock characterization methods for petroleum exploration: Proceedings, Offshore Technology Conference, Houston, Texas, p. 439–443.
- Katz, B. J., 1983, Limitations of Rock-Eval pyrolysis for typing organic matter: Organic Geochemistry, v. 4, p. 195–199.
- Katz, B. J., 1995, Biogenic gas — its formation and economic significance: Proceedings, Indonesian Petroleum Association 24th Annual Convention, Jakarta, Indonesia, v. 1, p. 461–474.
- Katz, B. J., W. R. Almon, C. Atallah, M. Schoell, and Y. Tang, 1998, Gas resource quantification — a supply-side approach: Proceedings, Indonesian Petroleum Association Conference on Gas Habitats of SE Asia and Australia, Jakarta, Indonesia, p. 1–6.
- Katz, B. J., and G. M. Kahle, 1988, Basin evaluation: A supply-side approach to resource assessment: Proceedings, Indonesia Petroleum Association 17th Annual Convention, Jakarta, Indonesia, v. 1, p. 135–168.
- Köning, H., 1992, Microbiology of methanogens, *in* R. Vially, ed., Bacterial Gas: Paris, Editions Technip, p. 3–12.
- Leythaeuser, D., R. G. Schaefer, and M. Radke, 1987, On the primary migration of petroleum: Proceedings, 12th World Petroleum Congress, Houston, Texas, v. 2, p. 227–236.
- Mackenzie, A. S., T. M. Quigley, D. Leythaeuser, M. Radke, and P. Muller, 1988, The movement of hydrocarbons in shales: Nature, v. 331, p. 63–65.
- Oremland, R. S., M. J. Whiticar, F. E. Strohmaier, and R. P. Kiene, 1988, Bacterial ethane formation from reduced, ethylated sulfur compounds in anoxic sediments: Geochimica et Cosmochimica Acta, v. 52, p. 1895–1904.
- Rice, D. D., and G. E. Claypool, 1981, Generation, accumulation, and resource potential of biogenic gas: AAPG Bulletin, v. 65, p. 5–25.
- Schoell, M., 1983, Genetic characterization of natural gases: AAPG Bulletin, v. 67, p. 2225–2238.
- Stahl, W. J., 1977, Carbon and nitrogen isotopes in hydrocarbon research and exploration: Chemical Geology, v. 20, p. 121–149.
- Taylor, S. W., B. S. Lollar, and L. I. Wassenaar, 2000, Bacteriogenic ethane in near-surface aquifers: Implications for leaking hydrocarbon well bores: Environmental Science and Technology, v. 34, p. 4727–4732.