Bol., Soc. Venezolana de Geól. , Vol. 22, N° 2, 17 - 28, 1997

Geochemical Modelling of the Principal Source Rocks of the Barinas and Maracaibo Basins, Western Venezuela

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Presented at the II AAPG/SVG International Congress and Exhibition in Caracas, Venezuela

Abstract

This study presents a geochemical review of the principal source rocks in the western Venezuelan basins. The area covers more than 100,000 km^2, and includes the Lake Maracaibo and the Barinas-Apure basins. The geochemical modelling recognizes three source rocks: 1) the main one, corresponding to the K3-K4-K5 Cretaceous sequences and represented by the La Luna, Capacho and Navay formations, 2) a secondary one, corresponding to the T4 Oligocene sequence, represented by the Carbonera Formation, and 3) an accessory source rock, K7-K8 Paleocene sequences, represented by the carbonaceous shales and coals of the Orocué Group and Marcelina Formation. Three periods of hydrocarbon expulsion were defined for La Luna Formation (Early Eocene-Middle Eocene, Late Eocene-Early Miocene and Early Miocene-Holocene), and one principal period of hydrocarbon expulsion for the Orocué Group and the Carbonera Formation (Plio-Pleistocene and Middle Miocene-Plio-Pleistocene).
Key words: Geochemical modelling, Lake Maracaibo, Barinas, La Luna Formation, Orocué Group, Carbonera Formation.

Resumen

En el presente trabajo se presentan los resultados del modelo geoquímico realizado en las cuencas occidentales de Venezuela. El área de estudio cubre una extensión de más de 100.000 km^2 , e incluye las cuencas del Lago de Maracaibo y de Barinas-Apure.

Del modelo geoquímico se reconocieron tres rocas madre principales: 1) Una principal, perteneciente a las secuencias K3-K4-K5 del Cretácico, representada por las formaciones La Luna, Capacho y Navay, 2) una secundaria, correspondiente a la secuencia T4 del Oligoceno, representada por la Formación Carbonera, y 3) una roca madre accesoria, perteneciente a las secuencias K7-K8 del Paleoceno, representada por las lutitas carbonosas y carbones del Grupo Orocué y la Formación Marcelina.

Igualmente, se definieron tres períodos principales de expulsión de hidrocarburos para la Formación La Luna (Eoceno Temprano-Eoceno Medio, Eoceno Tardío-Mioceno Temprano y Mioceno Temprano-Holoceno), y un período principal de expulsión de hidrocarburos para el Grupo Orocué y la Formación Carbonera (Plio-Pleistoceno y Mioceno Medio-Plio-Pleistoceno, respectivamente).
Palabras claves: Modelaje geoquímico, Lago de Maracaibo, Barinas, Formación La Luna, Grupo Orocué, Formación Carbonera.

Introduction

Previous works (Talukdar et al. 1986; Cassani et al. 1989; Tocco 1990; Gallango and Tocco 1994; Talukdar and Marcano 1994; Tocco et al. 1995) refer to the La Luna Formation (Late Cretaceous) as the principal source rock of marine crude oils in the western Venezuelan basins. Equally, these works indicate that the Orocué Group (Paleocene) and the Carbonera Formation (Late Eocene-Oligocene) are the source rocks of seeps and crude oils with significant contributions of terrestrial organic matter. The sedimentary basins of western Venezuela contain large volumes of oil, however, most of the large structures have already been produced. Exploration for new reserves of light and medium oil now depends on integrated studies that will lead to a more comprehensive basin evaluation.

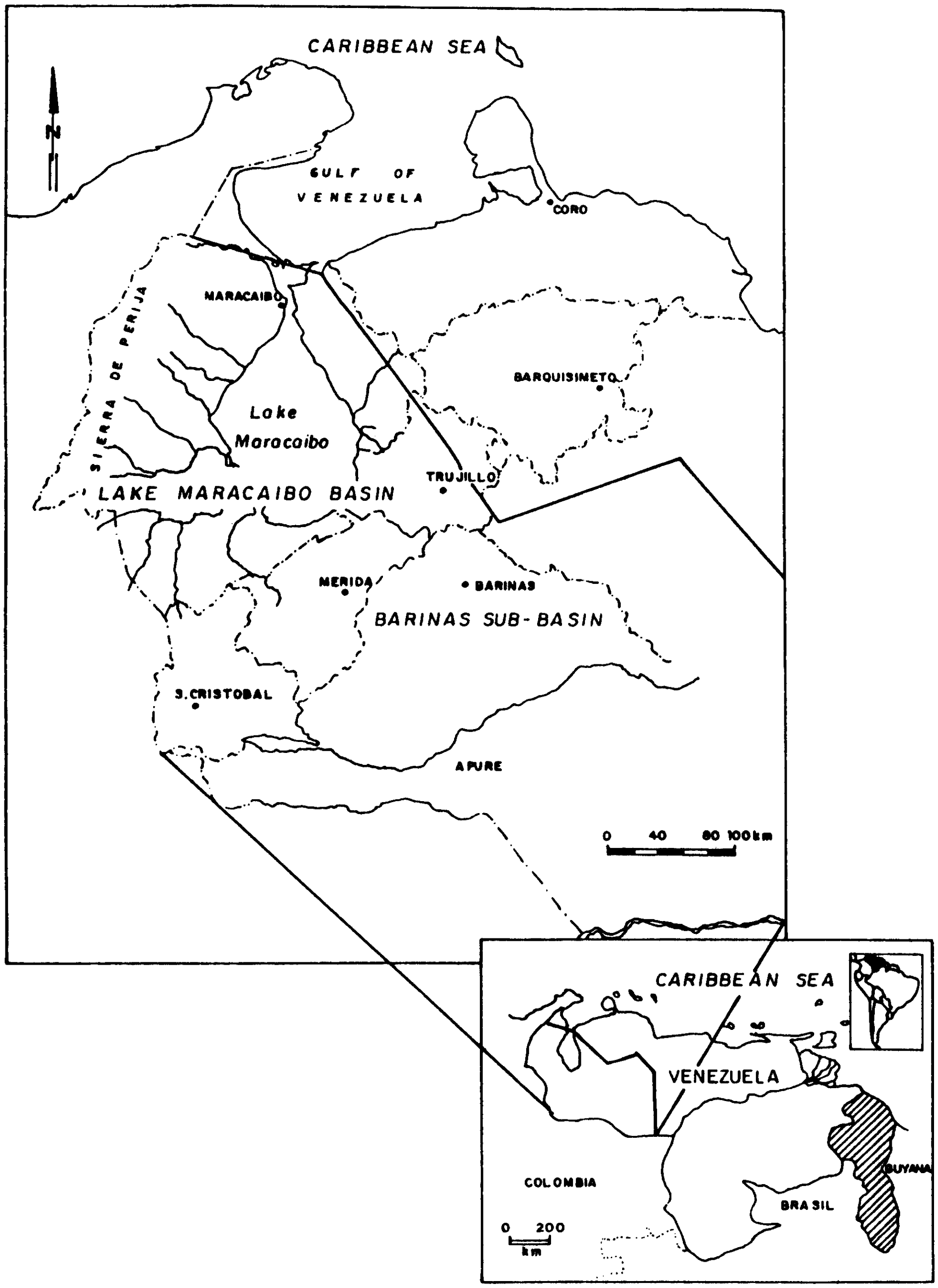

Figure 1
Location of the study area.

Western Venezuela is structurally divided into several units (Zambrano et al. 1970, 1971). These are: 1) The Guyana shield or Cuchivero granitic province (Menendez 1968); 2) the Mérida Andes mountain range, separating the Barinas-Apure Basin to the southeast from the Lake Maracaibo Basin to the northwest; 3) the Serrania de Perijá in the west, separating the Lake Maracaibo Basin (east) from the Colombian Cesar-Rancheria Basin (west); and the 4) Serrania de Trujillo separating Lake Maracaibo Basin from the Lara nappes (Stephan, 1977). Sedimentologically, the Cretaceous and Paleocene consist of a heterogeneous carbonate-siliciclastic association (Parnaud et al. 1995).

A foreland downwarping following deposition of Early Cretaceous sequences resulted in episodic Late Cenomanian-Early Campanian transgression and three back-stepping depositional sequences: K3, K4 and K5 (Parnaud et al. 1995). These sequences correspond in the Serranía de Perijá and Lake Maracaibo Basin to the La Luna Formation and the Tres Esquinas Member of the Colón Formation, in the Mérida Andes to the Capacho (upper Seboruco and Guayacán members) and La Luna formations, and finally in the Barinas-Apure Basin to the Escandalosa (P and O members) and Navay (La Morita and Quevedo members) formations (Parnaud et al. 1995). This succession has substantial hydrocarbon potential, especially because it includes the exceptional La Luna source rock (Alberdi et al. 1994).

Toward the end of the Cretaceous, the Perijá foredeep was filled by highstand sediments of the

Mito Juan sequence sourced from the west. The entire area was affected by erosion above a shallowing basement. A new transgressive episode from the northeast deposited two subordinate Paleocene sequences, K7 and K8. The lower sequence covered the entire shelf and displays marine characteristics, while the upper sequence is essentially deltaic (Parnaud et al. 1995). The shelf terrace wedge (K7) comprises several formations. The Guasare Formation consists of shallow marine deposits in the Lake Maracaibo Basin. The overlying deltaic suite (K8) comprises three formations: the Barco and Los Cuervos formations (Orocué Group) to the south and the Marcelina Formation to the north. The overlying T4 sequence, Late Eocene and Early Oligocene in age corresponds in the western part of the studied area to a deltaic domain fed from Colombia and includes the Carbonera and the La Sierra formations (Parnaud et al. 1995).

This study presents a geochemical review of the principal terrestrial and marine source rocks of the Barinas and Maracaibo basins (Fig.1). The fundamental objetive of our 1-D geochemical modelling was to give information on the hydrocarbon generation and expulsion processes of the studied source rocks, as well as the evolution of these processes through time in relationship to the basin history.

This review pays a special attention on La Morita Member within Navay Formation as a possible source rock of Barinas-Apure sub-basins, and incorporates the geochemical characteristics (and kinetics parameters) of Carbonera Formation in the northern flank of the Andes which is postulated as the principal Tertiary oil-prone source rock in the area.

Methods

The GENEX program, developed by the Institut Français du Pétrole, helps researchers integrate (in one dimension) the physical-chemical parameters associated with the evolution of the sedimentary basin, in particular the stratigraphy, the thermal history and the geochemistry of the rocks. This program is most useful in a simple structural context such as a platform. In the case of the studied zone and where the source rock is present, two structural domains exist, one with a simple structural history where the program will be used and another with a complex history (Lara nappes zone and the extensive zone of the Late Eocene-Early Oligocene of eastern Zulia) where the use of the program is limited.

The methodology used to corroborate or discard the thermal data is as follows: GENEX program worked with the temperature gradients obtained from well data, known stratigraphic sequences and geochemical data. From our first mathematical modelling, simulated values of the vitrinite reflectance index and Tmax were obtained. These were then compared with the maturity data obtained from laboratory experiments. Depending on the agreement observed between the simulated maturity values and the laboratory data, the global geological model was accepted or rejected. In the latter case a refined geological model must be constructed; for example along the Andes, where strong erosionn occurred, the original model had to be modified. In the studied area, a hypothesis that would involve big variations is concern to the stratigraphic model in the tectonic flakes zone where erosion has removed an important part of the geological information.

In order to calibrate the geochemical model, 199 %Ro values and 622 Tmax values were used, as follows:

- 498 Tmax values and 137 %Ro values were used in La Luna Formation.
- 41 Tmax values and 16%Ro values were used in Carbonera Formation.
- 83 Tmax and 46 %Ro values were used in Orocué Group and Marcelina Formation.

A constant gradient in time was considered, equivalent to actual gradient since La Luna Formation was sedimented.

Results and Discussion

Geochemical review of the principal source rocks and crude oils of the Barinas and Maracaibo basins

<u>Source rocks geochemistry</u>

Six sedimentary sequences exhibit characteristics of potential source rock:

- The K3-K4-K5 sequences, with a principal source rock containing marine organic matter (La Luna Formation), located in the Lake Maracaibo Basin. Toward the Barinas-Apure basins, this sequence contains mixed organic matter (marine with contributions of terrestrial organic material: Navay Formation, La Morita Member, Fig.2).
- The K7-K8 sequences in the south of the Lake Maracaibo Basin (Fig.2), contain terrestrial organic matter in the carbonaceous shales and coals of Orocué Group and Marcelina Formation.
- The T4 sequence in the west of Lake Maracaibo Basin (Fig.2), contains large amounts of terrestrial

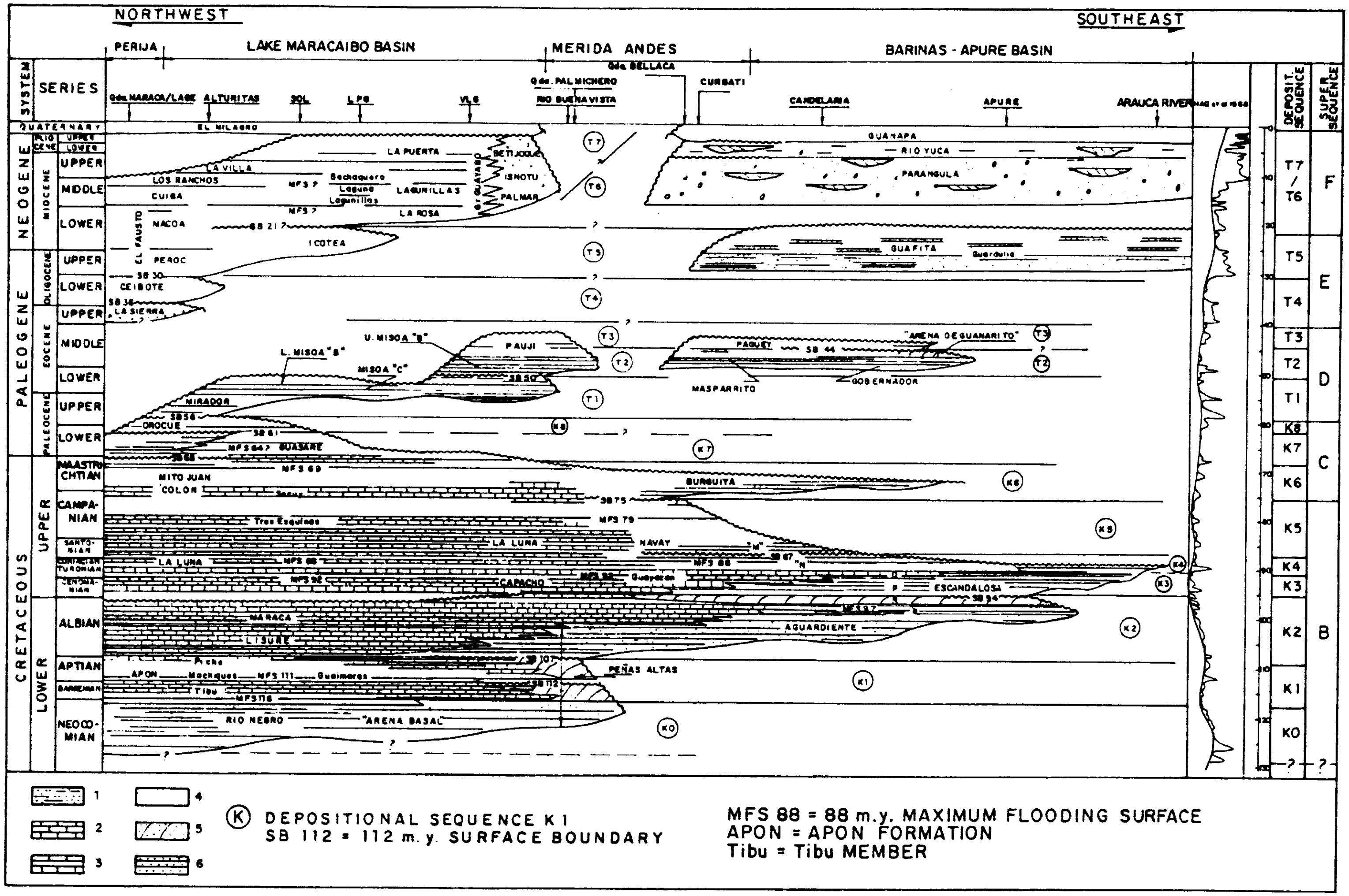

Figure 2

Stratigraphic chart. 1) Continental, sandstones and shales; 2) Inner to mid-shelf, carbonates; 3) Middle to outer-shelf, carbonates and shales; 4) Outer-shelf to bathyal, shales; 5) Nearshore, regressive sandstones; 6) Nearshore, transgressive sandstones (Parnaud et al. 1995).

organic matter associated with the carbonaceous shales and coals of Carbonera Formation.

K3-K4-K5 sequences (La Luna-Capacho-Navay formations)

These sequences present exceptional potential as source rock, especially in the Lake Maracaibo Basin. In this area, the sequences reach a thickness that varies between 300 and 1000 feet and are composed of limestones and bituminous calcareous shales with fetid scent, characterized by ellipsoidal concretions of bioclastic limestones. The age of these sequences range from Late Cenomanian/Early Turonian-Campanian (Fig.2, Parnaud et al. 1995). The net thickness of source rock is from 60 to 85% of the total thickness (Alberdi et al. 1994). The geochemical data indicates that the organic matter is marine (type II) with a very low content (< 12%) of terrestrial organic matter (Type III). The average TOC varies between 3% in the Táchira State (0.5% -10%) and 4% in Machiques zone. In the north of the Lake Maracaibo the low observed TOC values (< 1%) are due to the higher maturity of the organic matter (Tmax > 550 °C and % Ro > 1.3%, Alberdi et al. 1994).

In the Barinas-Apure Basin, the K3-K4-K5 sequences have thicknesses that range from 500 to more than 2000 feet to the south. In the south of the Mérida Andes these sequences are more than 2000 feet thick. Towards the north of the Andes thicknesses are less than 1000 feet. In this sector these sequences are made of two different lithologic types. The P Member and the Escandalosa Formation at the base are essentially sandy, whereas the upper part is more shaly: calcareous-shaly (La Morita Member of the Navay Formation) and sandy-shaly (Quevedo Member of the Navay Formation). Geochemical data show that the organic matter is marine in origin with an important contribution of terrestrial material. Towards the Mérida Andes a high percentage of marine organic matter is observed, while towards the southeast of the Barinas-Apure Basin the contribution of terrestrial material increases. The TOC in the south of the Andes is approximately 2% and the maturity level is low (Alberdi et al. 1994).

The Navay Formation in Escandalosa River (Táchira State) shows the best characteristics for oil generation between the localities geochemically analized (Alberdi et al. 1994). The kerogen isolated from the inter-stratified shales between the chert-beds of Quevedo Member is amorphous with a high fluorescence under reflected light. The samples have high HI values (>500 mgHc/g TOC) and good content of organic matter. The estimated net thickness of source rock is about 25% of total section (Alberdi et al. 1994). The best sample of Morita Member in La Escandalosa River was selected for further analysis of kinetic parameters.

Two rock samples were analyzed with the purpose of determining the kinetic parameters associated with the kerogen, one sample of La Luna Formation and another of La Morita Member (Navay Formation). Figure 3 shows the compositional cracking parameters of the La Luna Formation. The geochemical characteristics are: TOC= 8%, Tmax= 432 °C, HI= 619

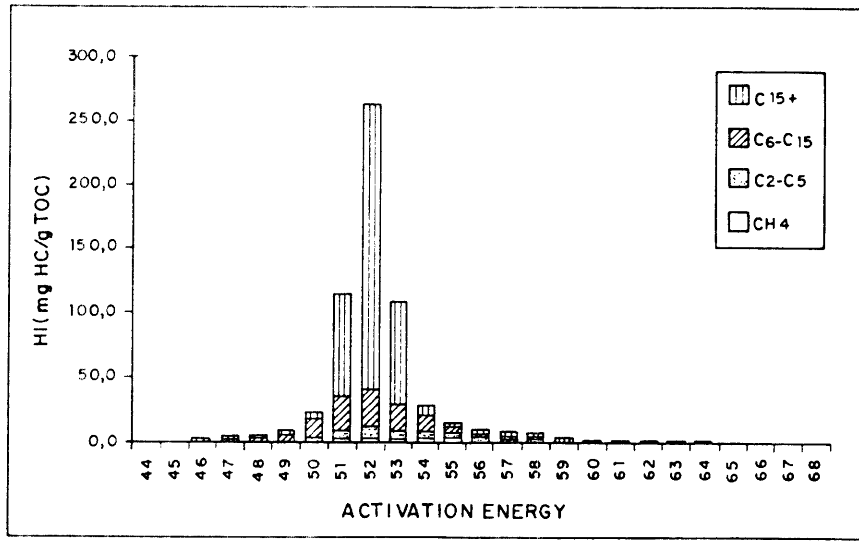

Figure 3
Distribution of the hydrocarbon classes in relation with the energy of activation (Arrhenius constant: 3.33x1013/sec), La Luna source rock.

mg HC /g TOC, OI= 8-13 mg CO2/g TOC, S_2= 50 mg HC /g rock, and Arrhenius constant = $3.33x10^{13}$/sec. The geochemical characteristics of La Morita Member are: TOC= 2.9%, Tmax= 425 °C, HI= 543 mg HC /g TOC, OI= not determined , S_2= 50 mg HC/g rock, and Arrhenius constant= $3.18x10^{14}$/sec.

K7-K8 sequences (Orocué Group, Guasare and Marcelina formations)

These sequences have a Late Maastrichtian-Early Paleocene age. The K7-K8 sequences correspond to deltaic sedimentation towards the south of the Lake Maracaibo Basin (Orocué Group) and marine platform towards the northwest (Guasare Formation). The Orocué Group is divided in three formations: Catatumbo, Barco and Los Cuervos. Only the Catatumbo and Los Cuervos formations contain carbonaceous shales. Los Cuervos Formation shows coals whose rank oscillates between lignitic and bituminous. Coals contain type III kerogen in agreement with the dominance of vitrinite in the maceral distribution (Alberdi et al. 1994; Tocco et al. 1995).

The geochemical data shows that Orocué Group shales don't present good potential as hydrocarbon source (Tocco et al. 1995). However, their coals present good characteristics as source rock. Coals, except for very unusual ones, typically are gas-prone. These coals have high TOC values (46-48%) and a variable thickness between 2 and 131 feet, with an average of 50 feet (Alberdi et al. 1994).

<u>T4 sequence (Carbonera Formation)</u>

This sequence is of Late Eocene-Early Oligocene age. In the western Venezuelan basins, the sequence reaches thicknesses that range from zero to more than 900 feet in the northern flank of the Andes and Machiques area. The Carbonera Formation is mainly composed of gray shales, sandy shales and sands. The shales contain plant debris. The top and the bottom of the Carbonera Formation consist of coals and bioclastic limestones. A stratigraphic section in Oro River (Táchira State) shows a net thickness of these coals about 5-10% of the total section (Alberdi et al. 1994).

Geochemical analysis has identified a terrestrial origin for the organic matter. The coals present fundamentally terrestrial organic matter with high HI values that suggest the presence of significant quantities of exinite, rich in hydrogen, that allows to classify them as sapropelic coals. The total thickness of these coals

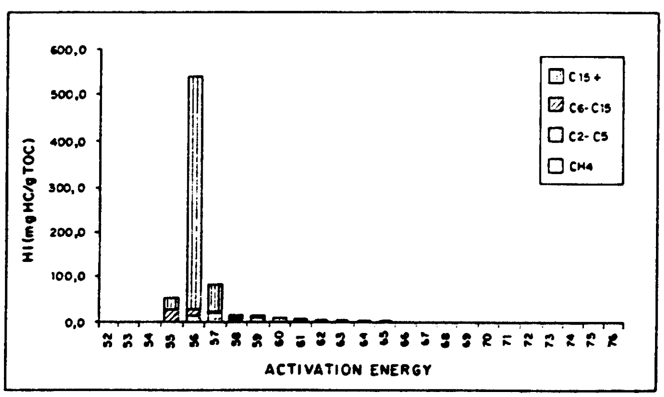

Figure 4
Distribution of the hydrocarbon classes in relation to the energy of activation (Arrhenius constant: 3.35x1014/sec), Carbonera source rock.

with very elevated HI is around 15 feet. Figure 4 shows the compositional cracking parameters. The geochemical characteristics of exinitic coals of the Carbonera source rock are: TOC= 78%, Tmax= 448 °C, HI= 721 mg HC/g TOC, OI= 5 mg CO_2/g TOC, S_2= 564 mg HC/g rock, and Arrhenius constant= 3.35×10^{14}/sec. These characteristics typify a mature coal with abundant exinite. The TOC average of the carbonaceous shales is 2%, while the TOC average of the coals is 40%. In conclusion, this sequence presents good characteristics as source rock, more oil-prone than Orocué Group, previously studied.

<u>Source rock-crude oil correlation</u>

Talukdar et al. (1986), Talukdar and De Toni (1989), Tocco (1990), Gallango and Tocco (1994), and Tocco et al. (1995), identified the source rocks of these crude oils and seep oils accumulated in several reservoirs of the western Venezuela basins.

The marine crude oils and seep oils of the Barinas and Lake Maracaibo basins were generated mainly from the K3-K4-K5 sequences (La Luna Formation). Additionally, the marine seep oils located in the northern flank of the Andes correlate very well with the K3-K4-K5 sequences (Talukdar et al. 1986; Cassani et al. 1989; Tocco 1990; Gallango and Tocco 1994; Tocco et al. 1995).

The terrestrial seep oils of the northern flank of the Andes correlate satisfactorily with Tertiary rocks. The carbonaceous shales and coals of the K7-K8 sequences (Orocué Group, Paleocene), and the coals of the T4 sequence (Carbonera Formation, Late Eocene-Oligocene) are the possible source rocks. Nevertheless, the coals of the T4 sequence present better geochemical characteristics to be considered as source rock (Cassani et al. 1989; Tocco 1990; Tocco et al. 1990; Alberdi et al. 1994; Gallango and Tocco 1994; Tocco et al. 1995).

The crude oils (southwest of the Lake Maracaibo Basin) and seep oils (Las Virtudes, Mérida State) that present mixed origin (marine and terrestrial) possibly are the product of a mixture of crude oils generated independently from marine and terrestrial organic matter (Tocco et al. 1995).

Geochemical Modelling

Thermal Calibration

The temperature measurements came from well profiles (BHT) and temperature tests in 103 wells of the Barinas-Apure Basin (166 measurements) and 114 wells

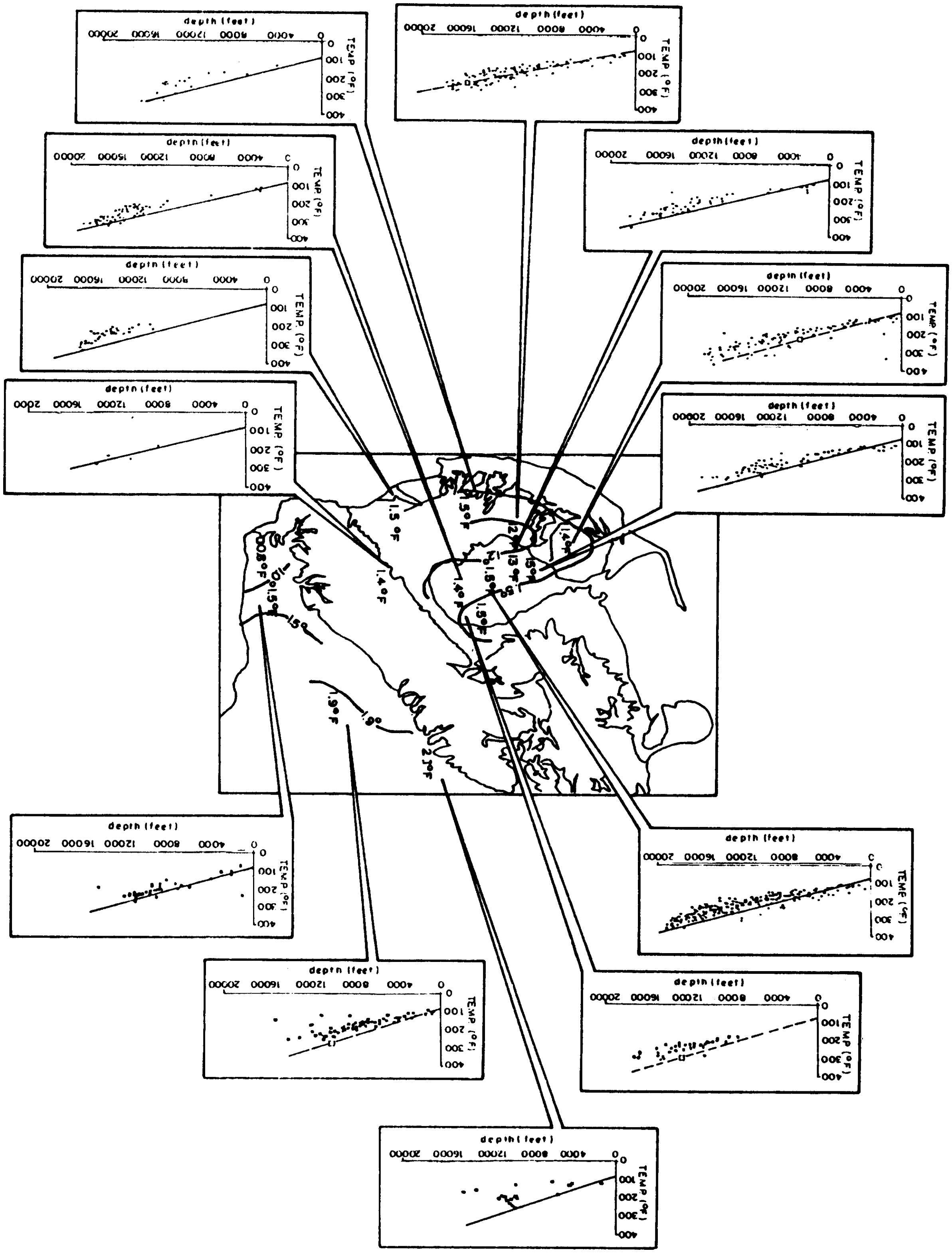

Figure 5
Temperature/depth graphics that include BHT and formation test data, where the variations of the geothermic gradient are shown.

in the Lake Maracaibo Basin (855 measurements). A surface temperature of 74 °F for the Lake Maracaibo Basin and 85 °F for the Barinas-Apure Basin was assumed in order to calculate the temperature gradient. The cross-plots of temperature versus depth show geothermal gradient variations (Fig.5). The results indicate a minimal gradient of 1.2 °F/ 100 feet in the central-west part (Soledad Field) and west (Alturitas Field) of the Lake Maracaibo. The maximum gradient value, 1.5 °F/ 100 feet, meet to the east (La Ceiba and Mene Grande fields), northwest (La Paz Field), west (Aricuaisá Field) and southwest (Distrito Colón) of the lake. In the west of the northern flank of the Andes the geothermic gradient is 1.4 °F/ 100 feet (Guaruries-1S well). The Barinas-Apure Basin shows a gradient that increases toward the north. For example, in the Cutufito-1X well, the temperature gradient is 0.8 °F/100 feet, in the Guafita Field is 1.5 °F/100 feet, in the Barinas fields is 1.9 °F/100 feet and, in the Guanarito Field is 2.1 °F/100 feet.

For the thermal calibration it is necessary to determine and analyze the temperature gradient variations with time. From the stratigraphic model (Parnaud et al. 1995), the history of the studied basin can be subdivided in several geological episodes:

- Pre-rifting
- Rifting in the Jurassic.
- Passive margin in the Cretaceous.
- Intermediate period during the Cretaceous-Paleocene.
- Compression during the Early Eocene-Middle Eocene due to the collision of the Caribbean Plate against the South American Plate and the emplacement of the Lara nappes.
- Two last compressive periods. During these periods the Lake Maracaibo and Barinas-Apure basins (Oligo-Mio-Pleistocene) were separated.

The principal source rock (La Luna Formation) was deposited in the Cretaceous during the passive margin period, and the secondary source rocks were laid down in the Tertiary. These source rocks matured during the active margin period. The heat flow increases during a rifting phase whereas it disminishes in a foreland basin because of high sedimentation rates. Thus, the actual gradient range found along the basins (1.2 to 2.1 °F/ 100 feet) could be considered as minimal values. In consequence, if the model has been calibrated against these values, we consider the gradient to be constant through time and equivalent to the actual gradient. This condition is taken at the time of deposition of the main source rock (La Luna Formation). However, from the available data, a very high heat flow is obtained (50 to 60 mW/ m^2) for this foreland basin. This could be explained by a long period of low sedimentation (Cretaceous-Early Miocene), to exception of the slope zone of Eocene age to the northeastern of the Lake Maracaibo (Parnaud et al. 1995). During the Miocene-Pleistocene a decrease of the heat flow of 70 to 60 mW/m^2 is observed and is coeval to a high sedimentation rate of more than 300m/Ma.

The vitrinite reflectance (%Ro) and Tmax (°C), permit evaluate the actual maturity of the source rocks, and are used for calibrate the thermic history. The %Ro and Tmax, present an excellent geographic distribution, which allows to carry out a good thermic calibration. According to the correlation observed between the values of simulated maturity and the laboratory results, either the global geological model is accepted or others hypothesis must be considered.

Geochemical modelling of the principal source rock: La Luna Formation

The quantities of fluids expelled have been calculated considering a crude oil expulsion with conditions of maturity reaching a Ro percentage equivalent to 0.75%. This value corresponds approximately to a Tmax of 440 °C.

The Lake Maracaibo Basin shows four kitchens of crude oil generation (Fig.6). 1) An Eocene kitchen, corresponding to the subsidence associated to the Paleocene-Middle Eocene slope located to the northeastern of the Lake Maracaibo; 2) a Miocene kitchen, corresponding to the Andean foredeep; 3) the

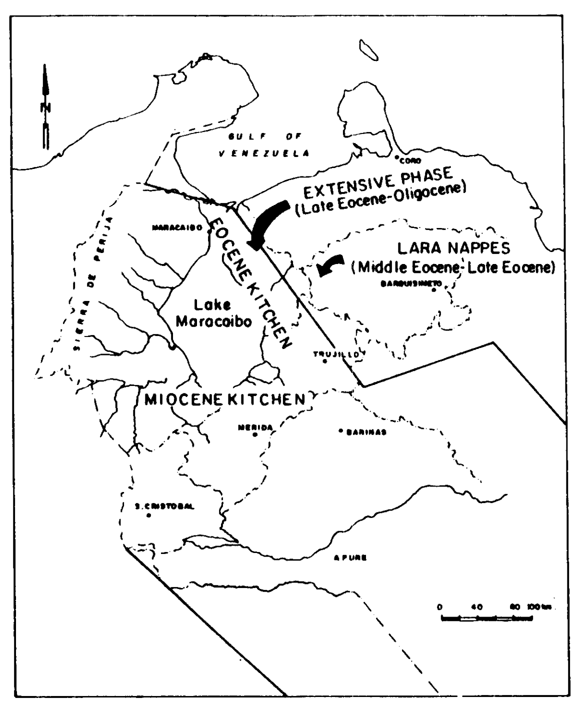

Figure 6
Kitchens for crude oil generation in the Lake Maracaibo Basin

kitchen associated with the emplacement of the Lara nappes during the Middle Eocene-Late Eocene and 4) the kitchen associated to a phase of extension during the Late Eocene-Oligocene that is responsible for grabens located in the northeastern part of the Lake Maracaibo.

Considering the geodynamic history, three generation and expulsion periods are important: 1) Early Eocene-Middle Eocene period, characterized by a rapid sedimentation in the slope zone in the northeastern part of the Lake Maracaibo, 2) Late Eocene-Early Miocene period characterized by the emplacement of the Lara nappes (Middle-Late Eocene), the rifting of the extensive basins in eastern Zulia and the Oligocene sedimentation in the west, southwest and south of the basin, and 3) the andean tectonic period with the uplifting of the Andes and the foredeep formation (northern flank of the Andes).

The geochemical modelling was carried out in 55 fictitious wells (with a regular distance of 50 km and 25 km) along three domains: Lake Maracaibo and Barinas platform, Lara nappes, and eastern Zulia. Along eastern Zulia and Lara nappes the mathematical simulations were very limited. However, the one fictitious well was modeled. The results of this modelling, assuming an original TOC average of 4% for La Luna Formation, shows that this formation generated and expelled crude oils at the end of the Middle Eocene (45 Ma) and gas during the emplacement of the nappes. Part of these hydrocarbons possibly migrated towards the Barinas Subbasin, while another part probably has been trapped in the structures associated with the emplacement of the nappes or in the eastern Zulia grabens.

In the Maracaibo and Barinas platform became the mathematical simulation with a TOC average of 4% in most of the studied sector and 3% toward the south zone (Táchira State). The geochemical modelling in this sector permits recognition of three principal periods of expulsion: Early Eocene-Middle Eocene (52-40 Ma), Late Eocene-Early Miocene (40-21 Ma) and Early Miocene-Holocene (21-0 Ma).

During the first period (Early Eocene-Middle Eocene) the kitchen was located in the northeastern part of Lake Maracaibo and corresponds to the slope zone where the Late Paleocene-Middle Eocene sequences were deposited (Trujillo, Misoa and Paují formations). In this period crude oil was expelled and migrated toward the southwest, south and southeast in the Maracaibo Basin. With a hypothesis of secondary migration rate of 1cm/ year, these crude oils reached the Barinas fields (Fig.7). During this period small quantities of condensate were also expelled in the deepest part of the basin.

The second period (Late Eocene-Early Miocene) is characterized by little hydrocarbon generation and expulsion but by important events of migration, remigration, entrapment, escape and crude oil biodegradation. In the Lake Maracaibo platform the kitchen was located along the northeastern border of the lake (Fig.8) and the quantities of hydrocarbons expelled were not important. These crude oils migrated southwards. However, during this time the Oligocene sequences were deposited in the west, south and southeast of the basin, causing a local inversion of the northeast-southwest structural inclination to southwest-northeast. This sedimentation and the structural inclination associated with the Lara nappes caused remigration of fluids, in particular towards the center of the lake. Similarly, it is expected that some reservoirs were eroded during this period. The erosions caused loss of hydrocarbons and a strong biodegradation.

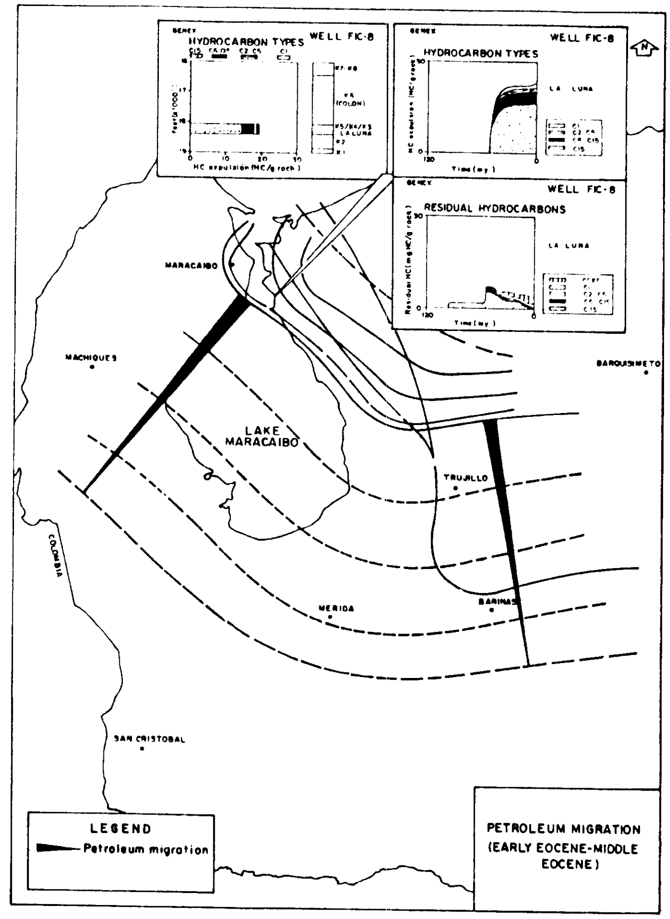

Figure 7
Petroleum expulsion and migration directions at the end of Middle Eocene (40 Ma).

The third period (Early Miocene-Holocene) is characterized by a migration of the kitchens. The new kitchen appeared in the northern flank of the Andes while the kitchen located in the southeast of the lake moved towards the central part of the lake. These new kitchens are associated with the molasse sedimentation and are due to the emplacement of the Serrania de

Perijá, the Macizo de Santander and Mérida Andes range. During this period crude oils are generated and expelled, and in the deepest part of the basin, condensates and gas are also generated. These fluids migrated towards the northern flank of the Andes, the

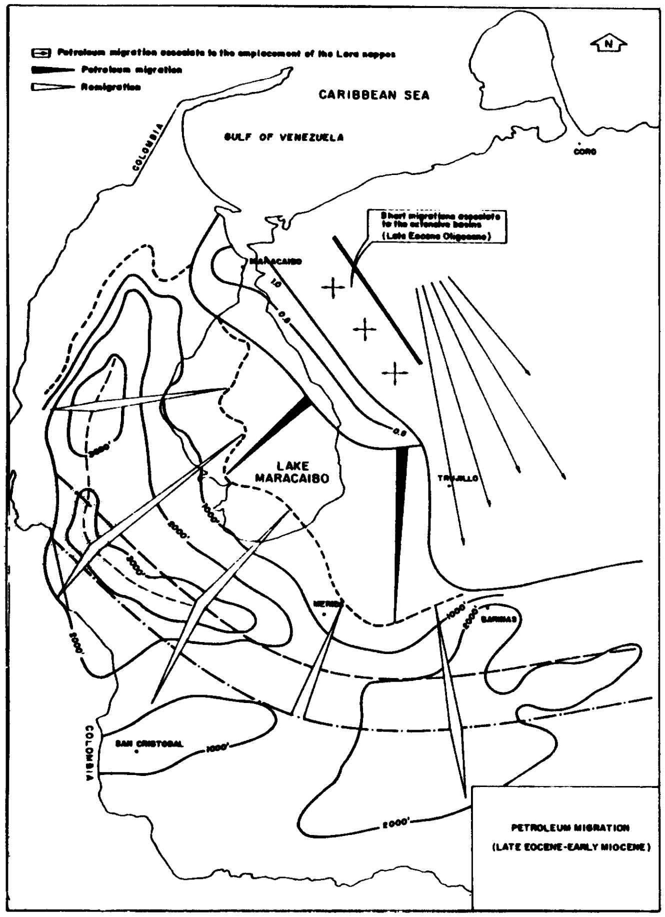

Figure 8
Migration directions of petroleum expelled from the Late Eocene until Early Miocene (40-21 Ma).

Tarra area and south of Perijá, La Ceiba-Betijoque, the southeast of the Lake Maracaibo and Boscán. During this period, the on-going inversion of the structural inclination that started in the Oligocene continued, causing remigrations from the southeast towards the northeast, in particular, towards the zones located along the northeastern border of the Lake Maracaibo and towards the Miocene reservoirs.

The actual window of crude oil and gas expulsion shows three domains: 1) in the west, a domain corresponding to the actual expulsion window of crude oil that includes light hydrocarbons (5 Ma, during the Pliocene). In this sector the window of crude oil expulsion meet around 14000 feet; 2) in the northeast and southeast, a domain corresponding to the actual expulsion window of condensate and gas. This process began in the northeastern sector during the Middle Eocene and continued until the present, and in the southeastern sector during the Pliocene. In these sectors the window of crude oil expulsion varies between 13000 feet in the north and 16000 feet in the south. The window of gas expulsion varies between 17500 and 19000 feet in the same direction, and 3) in the southeast,

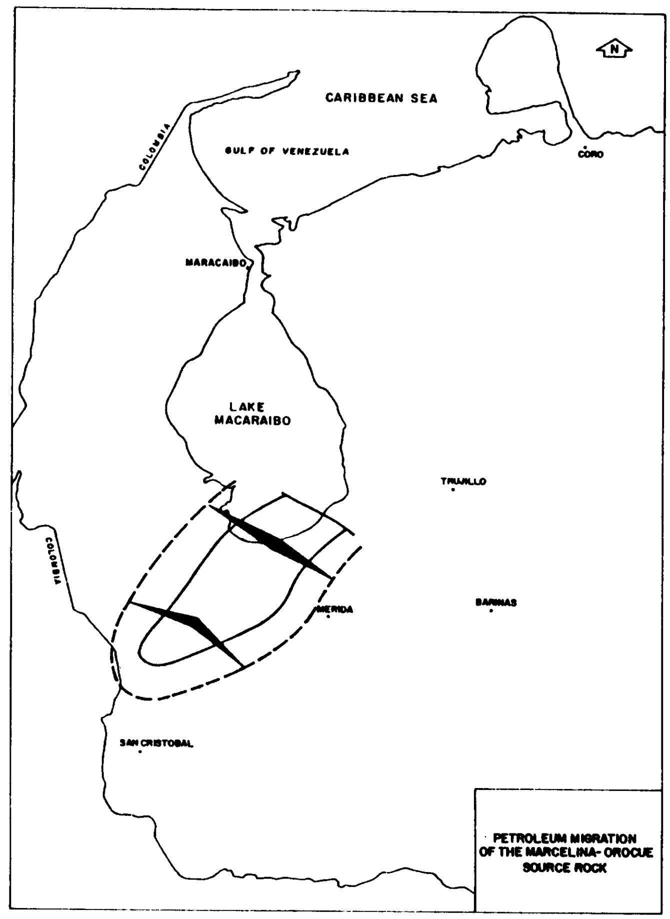

Figure 9
Migration directions of petroleum expelled from the Marcelina-Grupo Orocué source rock.

a domain located in the Andes sector. This is a zone of remnant crude oil expulsion during the Pliocene (5-2 Ma) where the expulsion window was reached to 14500 feet.

Geochemical modelling of the secondary and accessory source rocks: Marcelina Formation and Orocué Group (Paleocene) and Carbonera Formation (Late Eocene-Oligocene)

Considering the exposed previously for the La Luna Formation the modelling in 31 fictitious wells was carried out with a regular distance of 50 km and 25 km.

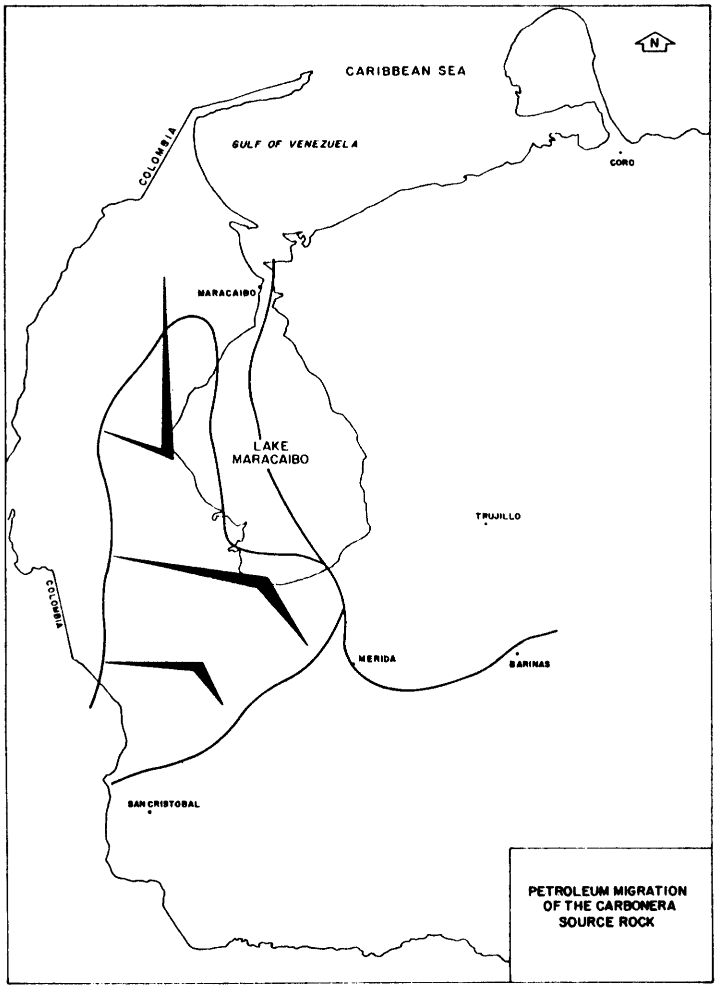

Figure 10
Migration directions of petroleum expelled from the Carbonera source rock.

Marcelina Formation and Orocué Group

Only one main period of expulsion during the Plio-Pleistocene is observed (2.0-0.0 Ma, Fig.9). The actual window of crude oil expulsion shows a single domain located along the andean foredeep. The petroleum window is confined between 16000 and 19500 feet. With a migration hypothesis of 1cm/ year the crude oil generated and expelled doesn't reach the Tarra-Los Manueles zone (toward the west), while it could have contributed partly to the seep oils of the south of Mérida Andes

Carbonera Formation

A single period of expulsion from Middle Miocene to Plio-Pleistocene is observed (13.0-0.0 Ma, Fig.10). The actual window of crude oil expulsion shows two principal events. One along the andean foredeep and another to the west of the Lake Maracaibo limited by the Serranía de Perijá. The window of petroleum expulsion is located between 9500 and 11700 feet. Considering a migration hypothesis of 1 cm/ year the crude oil generated and expelled could have reached all the sectors where the presence of crude oil with contributions of terrestrial organic matter had been identified, in particular, in the south of the Andes and the Distrito Colón reservoirs. Similarly there may be seep or crude oils of terrestrial origin along a zone located between the Lake Maracaibo and the Perijá Range.

Conclusions

Three source rocks were recognized: the main one, represented by La Luna Formation; a secondary one, represented by the Carbonera Formation; and an accessory one that corresponds to the Orocué Group and to the Marcelina Formation.

Three periods of generation and expulsion for La Luna Formation were identified: Early Eocene-Middle Eocene (52-40 Ma), Late Eocene-Early Miocene (40-21 Ma) and Early Miocene-Holocene (21 Ma- to the present).

One period of generation and expulsion for the Orocué Group and the Marcelina Formation is observed (Plio-Pleistocene, 2.0-0.0 Ma); and a single period of generation and expulsion for the Carbonera Formation was identified (Middle Miocene to Plio-Pleistocene, 13.0-0.0 Ma). Considering a migration hypothesis of 1cm/year, the crude oil generated and expelled by Carbonera Formation would have reached all the sectors where the presence of crude oil contributions of terrestrial organic matter had been identified.

Acknowledgements

The authors are grateful to Corpoven, S.A.; Lagoven, S.A.; Maraven, S.A. and Intevep, S.A. for authorizing the publication of this paper. Special thanks are extended to Andrés Pilloud, Bruno De Toni, Jean Claude Pascal, Armando Ruggiero, Jean Chatellier, Carmen Toro, Carmen Rodríguez and Irenio Berrios for technical assistance.

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