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Generation and migration of hydrocarbons in the Maracaibo Basin, Venezuela: An integrated basin study

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Abstract—The history of hydrocarbon generation and migration in the Maracaibo Basin, Venezuela, is closely related to its stratigraphic, structural and tectonic evolution during the Cretaceous and Cenozoic times. Geochemical evaluation of the possible source rocks within the Cretaceous and the Tertiary sequences indicates that the argillaceous limestones and calcareous shales of the La Luna Formation (Cenomanian–Coniacian) are the most important source rocks in the basin. These rocks contain organic carbon ranging from 1.5 to 9.6% (*c.* original TOC 2.5–10.8%), have fluorescent amorphous marine, type II organic matter (oil prone) and have in the immature stage a H-index of 700 mg HC/g TOC and a H/C ratio of 1.5. The beginning of the oil window in these rocks occurs at a relatively low thermal maturity (Lopatin TTI about 10) and the peak of oil generation corresponds to a TTI value of 35.

Geochemistry of oils from the different reservoirs (Cretaceous, Paleocene, Eocene and Miocene beds), and oil–oil and oil–source rock correlation studies based on biomarkers have identified three genetic types of oil in the basin: a marine type essentially derived from the the La Luna source, a terrestrial type possibly originating either from the Cretaceous Lisure shales or the Paleocene shales, and a third type derived from the mixing of the first two types. The marine type oil is distributed extensively throughout the basin whereas the terrestrial as well as the mixed marine and terrestrial types are found only in the southwestern part of the basin. The marine type oils have been further subdivided based on their alteration and maturity.

Reconstruction of the hydrocarbon generating areas at different geological times using TTI-maturity diagrams indicates that the generation of oil and gas in the basin took place during two periods; the first phase occurred during the Middle to Upper Eocene times in the northeastern part of the basin, while the second phase occurred during the Upper Miocene to Recent times in the central, western and southern parts of the basin.

Based on organic geochemical and sedimentological characteristics, it is proposed that primary migration of oil from the La Luna source rocks took place by expulsion of hydrocarbons through abundant microfractures developed by the pore fluid overpressure during hydrocarbon generation. Mass balance considerations suggest that the expulsion probably occurred as a hydrocarbon single phase and the expulsion efficiency for oil in La Luna source rocks should have been very high (30–50%).

Taking into consideration the development of oil and gas kitchens through time, the paleostructures at the time of hydrocarbon generation, and the characteristics of oils, the migration history of the oil and gas generated from the La Luna source has been outlined. Mixing of oils, derived at different times (Eocene and Miocene–Recent) from the La Luna source of different areas, appeared to have taken place in Block IV, Block 11, Lago–Lamar, Motatan and Bolivar Coastal fields.

Key words: generation of petroleum, migration of petroleum, integrated basin study, Maracaibo Basin, La Luna source rocks, oil–oil and oil–source rock correlation, TTI maturity modelling, expulsion of hydrocarbons, expulsion efficiency

INTRODUCTION

The Maracaibo Basin of western Venezuela is one of the excellent examples of sedimentary basins in the world where the total volume of hydrocarbons (oil and gas) accumulated was essentially derived from source rocks within the area of the basin. The total drainage area of the basin covers an area of approximately 50,000 km^2 and is limited to the north by the Oca Fault, to the northeast by an imaginary north-northwest trending line which marks the maximum thickness of the Eocene deltaic sediments, to the south and southeast by the Venezuelan Andes, to the southwest by the Santander massif and to the west and northwest by the Perija Range (Fig. 1). The present work represents an integrated regional geochemical study of the Maracaibo Basin which includes evaluation of source rocks, geochemistry of oils and their correlation with the source rocks, reconstruction of the hydrocarbon generating areas and outlining the hydrocarbon generation and migration history through time.

Earlier geochemical studies on the characterization and origin of oil were done by Brenneman (1960), Bond (1967), Barker *et al.* (1979), Core Lab. (1982) and Bockmeulen *et al.* (1983). On the other hand, only Blaser (1979), Stauffer and Betoret (1979), Core Lab. (1982) and Blaser and White (1984) made partial studies on the generation, migration and accumulation of hydrocarbons in the basin. However, it still remains an important question whether all the oils accumulated in the basin are essentially of the same genetic type and were derived from the La Luna source rocks or if there also exist other source rocks which contributed significantly to the oil generation in the basin. The present paper also attempts to answer this question.

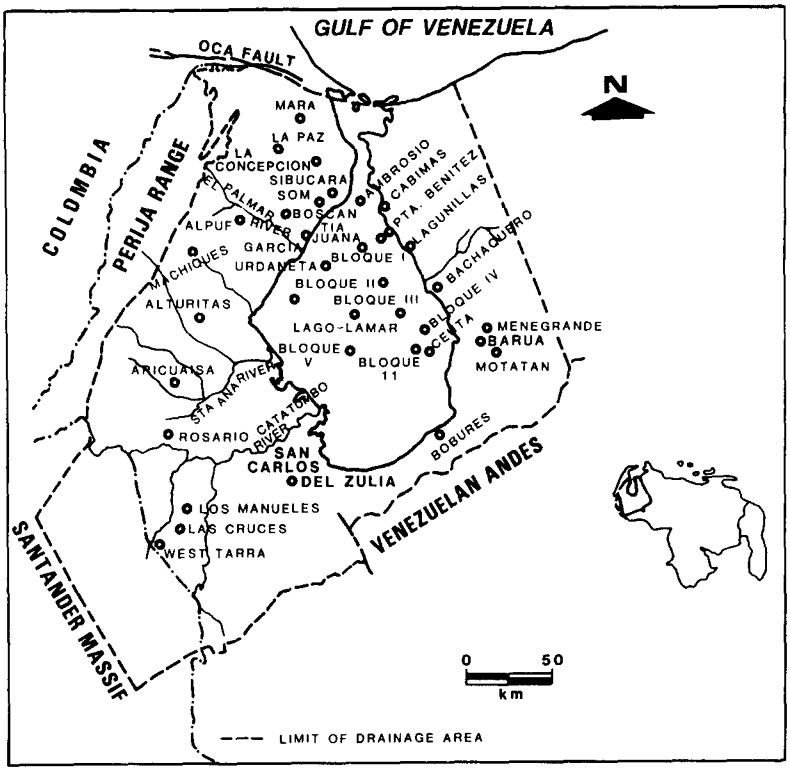

Fig. 1. Location of the Maracaibo Basin with names of oil fields.

GEOLOGICAL TIME	WEST	EAST		DEPOSITIONAL ENVIRONMENT	
PLEISTOCENE	ONIA	EL MILAGRO		CONTINENTAL	
PLIOCENE	▨	BETI-JOQUE	LA PUERTA	CONTINENTAL	
		ISNOTU		FLUVIAL (WEST)	
	LA VILLA LOS RANCHOS	LAGUNILLAS			
MIOCENE				FLUVIO-DELTAIC (EAST)	
	EL FAUSTO	LA ROSA		FLUVIAL (WEST) MARINE (EAST)	
OLIGOCENE		ICOTEA		FLUVIAL	
EOCENE	LA SIERRA	PAUJI		FLUVIAL (WEST) MARINE (EAST)	
	MIRADOR	MISOA		FLUVIO-DELTAIC	
		TRUJILLO		FLUVIAL (WEST) MARINE (EAST)	
PALEOCENE	OROCUE	MARCELINA	GUASARE	FLUVIO-DELTAIC (WEST) MARINE (EAST)	
CRETACEOUS	MITO JUAN			MARINE	MARINE OXIC
	COLON				
	CAPACHO	LA LUNA			OPEN MARINE ANOXIC (EAST)
	COGOLLO				CARBONATE PLATFORM
	RIO NEGRO			FLUVIAL	
PRE-CRETACEOUS	BASEMENT				

Fig. 2. General stratigraphy of the Maracaibo Basin.

GEOLOGICAL HISTORY AND STRATIGRAPHY

The actual structural configuration of the Maracaibo Basin probably began to develop only since the Miocene. During the Miocene–Recent period it may be compared to an intermontane basin in a foredeep position in relation to the ranges surrounding it (Perrodon, 1983). However, the tectonic setting of the basin, relevant to hydrocarbon habitat, changed through time and includes the evolutionary history of the basin during the Mesozoic (Cretaceous) and Cenozoic periods.

Figure 2 shows a generalized stratigraphy of the Maracaibo Basin. An outline on the geology of the basin has been given by Zambrano *et al.* (1969) and Gonzalez de Juana *et al.* (1980). From their work some information about the deposition of the main source rock formations of the Maracaibo Basin (Table 1) is briefly summarized in the following. In Aptian–Albian times, a marine transgression led to the deposition of thick shallow water platform carbonates and associated sediments which include, the Apon, Lisure and Maraca Formations (or their equivalents) of the Cogollo Group. During maximum marine transgression between the Cenomanian and the Coniacian, the sedimentation was typically of pelagic and euxinic facies, represented predominantly by limestones and calcareous shales of the La Luna Formation (200–700 ft thick) or locally by the Capacho Formation in the southwestern part of the basin. During the Paleocene in the southwestern and western part of the basin, nonmarine shales, sandstones and coals of the Catatumbo, Barco and Los Cuervos Formations of the Orocue Group were deposited. In the central part, the sedimentation occurred in a shallow marine platform, represented by the Guasare Formation. In the Perija area and Alturitas, the sedimentation, however, took place in shallow marine to deltaic conditions, characterized by limestones, sandstones, shales and coals of the overlying Marcelina Formation. During the lower to middle Eocene time, a great delta system was developed in the Maracaibo Basin; the sedimentation was mainly fluvial in the southwestern part (Mirador Formation), fluvio-deltaic to deltaic on the platform until the hinge line (Mirador and Miosa Formations), and turbidite and flysch in the Barquisimeto trough to the east of the hinge line (Trujillo Formation).

ORGANIC MATTER AND SOURCE ROCKS

All the possible source rocks from the Cretaceous and Tertiary sequences in the Maracaibo Basin have been evaluated for organic richness, type of organic matter and thermal maturity. Table 1 summarizes the general source rock characteristics for these formations. In the present study, core and cuttings material from 151 wells distributed throughout the basin were analyzed (Fig. 3). In this discussion, the source rocks are defined as those which have generated and expelled hydrocarbons (oil and/or gas) in sufficient quantity to form commercial accumulations. Thus the source rocks must have three fundamental requisites: sufficient organic carbon content (TOC), appropriate type of organic matter and thermal maturity.

As can be seen from the Table 1 the important oil prone source rocks (type II of Tissot and Welte, 1978) are the La Luna, Capacho and Apon Formations of the Cretaceous. The La Luna Formation which is the most important source rock in the basin is being discussed in detail separately. The Capacho Formation which is mainly mature to overmature, is only present in the southwestern part of the basin; it is characterized by a high average TOC content (3.1%), high concentrations of extractable organic matter in some rocks (3180–8010 ppm) and high hydrogen index (HI) values at low thermal maturity levels (up to 650 mg HC/g TOC). The Apon Formation, though regionally distributed, varies in carbonate facies, organic matter content and thermal maturity, and can be considered as a oil-prone source rock in certain areas (Alturitas, Rosario, Sol, Ambrosio and Urdaneta). Among the other Cretaceous sequences, the Lisure Formation might have generated some oil only

Table 1. Source rock characteristics of the stratigraphic sequences in the Maracaibo Basin

Age	Formation	Source rock types	TOC range (%)	TOC average (%)	Organic matter type	Maturity
Eocene	Trujillo	Shales	0.5–0.3	1.20	III	Overmature
Eocene	Misoa	Shales	0.6–3.0	1.47	III	Mature to overmature in the east and northeast
Eocene	Mirador	Shales	0.3–2.3	0.97	III	Mature locally in the south
Paleocene	Marcelina	Shales	0.6–1.7	0.90	III	Mature locally in the west
Paleocene	Guasare	Shales	0.8–1.7	1.18	III	Mature only in the south and Ambrosio area
Cretaceous	Colon	Shales	0.5–1.1	0.80	III	Immature to overmature
Cretaceous	Capacho	Limestones, calc. shales	0.6–8.3	3.10	II	Mature to overmature
Cretaceous	La Luna	Limestones, Calc. shales	1.5–9.6	3.80	II	Mainly mature to overmature
Cretaceous	Lisure*	Shales	0.1–2.6	0.97	II and III	Mainly mature to overmature
Cretaceous	Apon*	Limestones	0.1–2.8	1.14	II	Mainly mature to overmature

*Formations belong to Cogollo Group.

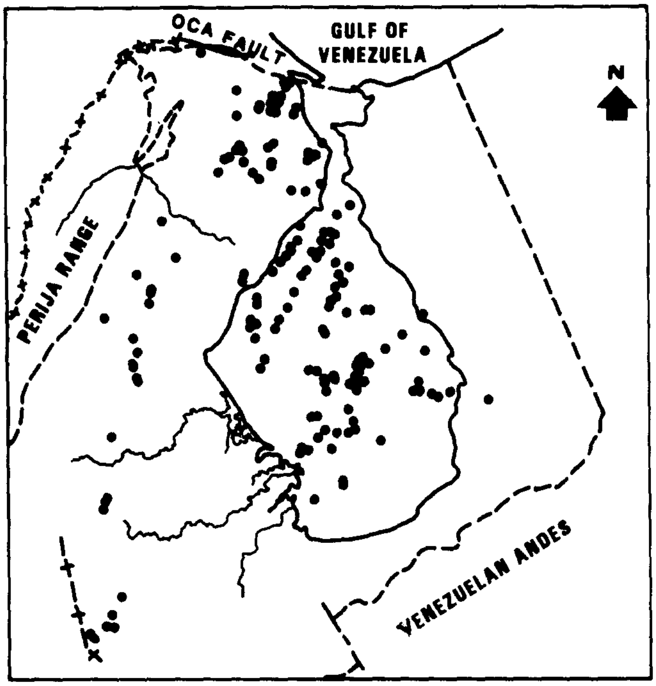

Fig. 3. Location of wells studied for source rock evaluation.

in the western and southwestern parts where TOC is high in some intervals.

The other sequences in the basin, namely the Colon Formation of the Cretaceous and the Paleocene and Eocene formations (Table 1), show mainly gas prone type III organic matter with low hydrocarbon potentials (<2 kg HC/Trock); these are not considered as source rocks for oil in the basin.

La Luna Formation

Limestones and calcareous shales of the La Luna Formation, analyzed in 21 wells and the type section in Perija, contains organic carbon (TOC) between 1.5 and 9.6% with an average of 3.8% (Table 1). In a total of 59 samples, about 80% show TOC between 2 and 6%. The samples present high concentration of extractable organic matter (>2000 ppm) and hydrocarbons (>1000 ppm). Figure 4 shows the regional variation of TOC in the La Luna Formation. The original TOC calculated range between 2.5 and 10.8%.

The organic matter indicated by pyrolysis data is mainly type II (Tissot and Welte, 1978). Visual kerogen analysis in samples from 6 wells in Urdaneta, Alpuf, Alturitas, Sol and La Paz as well as in surface samples from the type section, indicates the predominance of amorphous marine and algal organic matter with rare particles of vitrinite. The amorphous organic matter is usually distributed in very thin laminae parallel to stratification and is characterized by high fluorescence in ultraviolet light (see primary migration).

About 27 rock extracts were characterized by GC. The distribution of C_{15+} saturated hydrocarbons showing the predominance of *n*-alkanes in the C_{20}–C_{24} range, the pristane/phytane values less than 1.0 and the pristane/*n*-C_{17} less than 0.5 are also characteristic of marine organic matter deposited in anoxic conditions (Hunt, 1979).

The distributions of the biomarkers (steranes and terpanes) were obtained in 12 rock extracts by GC–MS. The stereoisomers of C_{27} sterane are more abundant than those of C_{29} sterane which imply a major contribution of predominantly marine microorganisms relative to land plants. Among the tricyclic terpanes, the C_{23} is the most abundant while the C_{19} and C_{20} diterpanes are present in very low concentration, also suggesting a marine source (Simoneit, 1977). The pentacyclic triterpanes consist principally of the hopane series, of which the C_{29} norhopane and the C_{30} hopane are the most abundant (see oil source rock correlations). According to Van Dorsselaer *et al.* (1977) the hopanes are derived mainly from bacteria.

Thermal maturity of the La Luna Formation varies greatly over the basin, ranging from immature to overmature. The regional organic maturity trends of the La Luna Formation based on the TTI-maturity of Waples (1980) are discussed later in generation of hydrocarbons. The TTI-maturity values were compared with other measured maturity parameters (e.g. T_{max}, % R_0, % extractable organic matter, and distribution of biomarkers by GC–MS).

In the diagram TTI vs extractibility (Fig. 5) which defines the oil window with maturity, it can be observed that the beginning, peak and end of oil

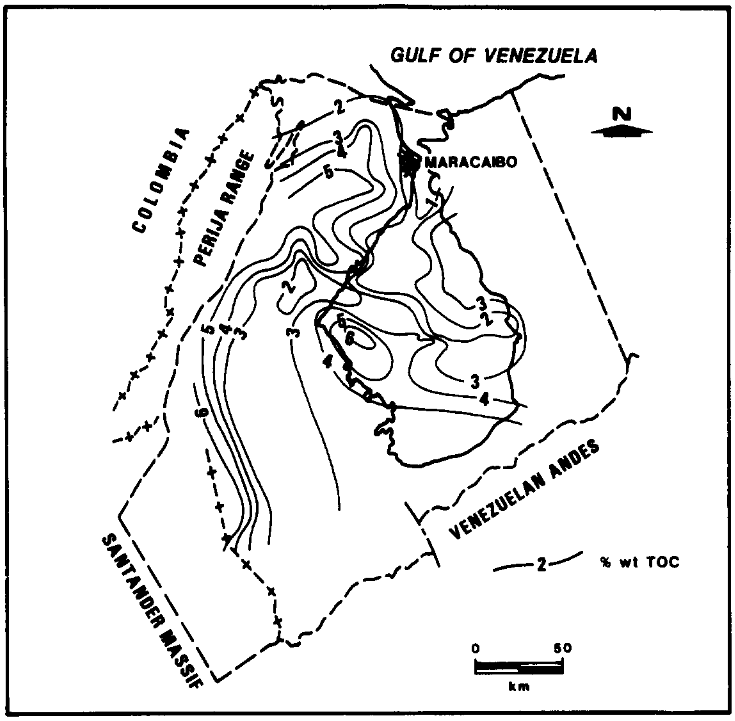

Fig. 4. Variation in total organic carbon content (TOC) in La Luna Formation.

window correspond to TTI values of less than 15, 35 and 160, respectively. These TTI values in the La Luna Formation correspond approximately to T_{max} 429°, 435° and 450°C, or to R_0 0.5, 0.8 and 1.3%, respectively. The hydrogen index (HI) of the samples analyzed corresponding to the beginning and end of oil window are 700 and 200 mg HC/g TOC, respectively (Fig. 6). The H/C ratio varies between 0.6 and 1.5, the latter being characteristic of the immature korogen.

In summary, based on organic richness, organic matter type and maturity, the La Luna Formation is considered as a strongly oil prone source rock having a very high oil potential. Using the average calculated original TOC (5.56%), the HI of the immature samples (700 mg HC/g TOC) and assuming 40% convertibility of TOC into hydrocarbons at full maturity, it has been estimated that on the average 290 x 10^6 barrels of oil were generated by 1 km^3 of the La Luna source rocks at the end of oil window.

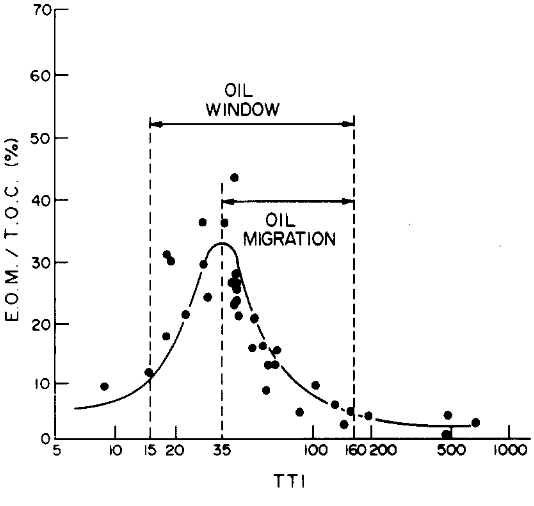

Fig. 5. TTI versus extractable organic matter/total organic carbon in La Luna Formation.

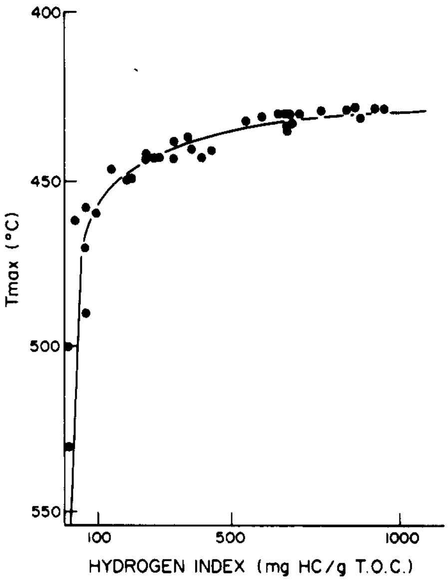

Fig. 6. Variation in hydrogen index with maturity (T_{max}) in La Luna Formation.

OIL TYPES AND OIL–SOURCE ROCK CORRELATIONS

In this chapter, it is intended to describe the types of oil present in the basin and to identify their source rocks. The oils were accumulated in different stratigraphic levels, namely Cretaceous, Paleocene, Eocene and Miocene reservoirs. The study of oils is based on conventional analyses (API gravity; vanadium, nickel and sulphur contents; proportion of saturated and aromatic hydrocarbons, resins and asphaltenes; distribution of saturated and aromatic hydrocarbons, pristane/phytane, pristane/n-C_{17} and phytane/n-C_{18} ratios), and special analyses by computerized GC–MS (distribution of biomarkers such as steranes, terpanes and aromatic steroids). Oil–source rock correlations are based on conventional geochemical data by GC and molecular distribution of steranes and terpanes in oils and rock extracts.

Oil Types

Based on the conventional analysis of 130 samples (27 from Cretaceous, 5 from Paleocene, 58 from Eocene and 40 from Miocene reservoirs) and special analysis of 57 selected oil samples (17 from Cretaceous, 2 from Paleocene, 25 from Eocene and 13 from Miocene reservoirs) distributed throughout the basin, three genetic types of oil, namely marine oil, terrestrial oil and mixed marine and terrestrial oil, have been recognized in the Maracaibo Basin.

Marine oil

The marine oils are distributed all over the Maracaibo Basin and have been differentiated into two main groups, namely unaltered and altered oils (Fig. 7). The unaltered marine oils show a complete range of n-alkanes and have variable API gravity between 11 and 55°, vanadium content between 20

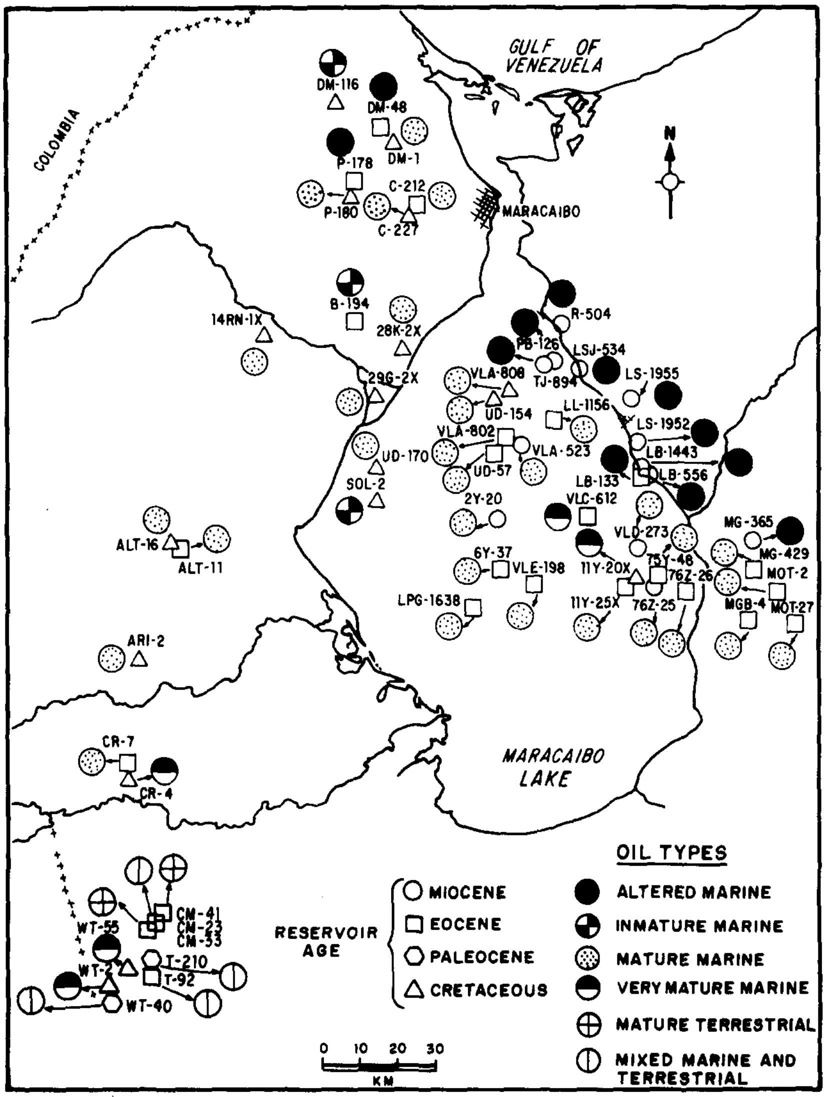

Fig. 7. Oil types and their distribution in the Maracaibo Basin.

and 1100 ppm, sulphur content between 0.5 and 5.2%, and saturated hydrocarbons/aromatic hydrocarbons ratio between 0.6 and 14. The origin of these oils from the marine organic matter source has been indicated in their chromatographic characteristics by (1) abundant *n*-alkanes in the C_{20}–C_{24} range, pristane/phytane ratio less than 1 and pristane/*n*-C_{17} less than 0.5; (2) slightly higher abundance of C_{27} sterane stereoisomers compared to C_{29} sterane stereoisomers (Fig. 8A); and very low concentration of C_{19} and C_{20} diterpanes and absence of triterpane 18α(H) oleanane (Fig. 9A).

The unaltered marine oils have been further subdivided according to maturity into early generated (or immature) oil, mature oil and highly mature oil (Fig. 7). The early generated oils are only known in relatively shallow reservoirs (<8700 ft) of Mara (Cretaceous reservoirs) and Boscan (Eocene reservoirs) and are characterized by low API gravity (<16°), high vanadium (>900 ppm), high sulphur (>4%), low saturated hydrocarbons content (<25%) and high resins + asphaltene contents (>33%). They are clearly distinguished from the altered oils by the presence of complete range of *n*-alkanes and steranes. The oils also have low values (51% or less) for the ratio triaromatic steroids/(triaromatic steroids + monoaromatic steroids) which are indicative of the lower level of thermal evolution of the oils (Mackenzie *et al.*, 1982).

The mature oils, on the other hand, are widely distributed in the basin and were accumulated in Cretaceous, Eocene and Miocene reservoirs (Fig. 7). The oils have sulphur contents in the range 0.7–1.3%, vanadium 20–500 ppm and saturated hydrocarbons 50–70%. The values for the ratio triaromatic steroids/(triaromatic steroids + monoaromatic steroids) are greater than 70% which indicate their maturity (Mackenzie *et al.*, 1982).

The highly mature oils which are restricted to Cretaceous and Lower Eocene reservoirs of the southwestern, central, southeastern, and northeastern parts of the basin (Fig. 7) have high API gravity (37–55°), high concentrations of saturated hydrocarbons (>70%), low vanadium (<8 ppm) and low sulphur contents (<0.5%). The monoaromatic as well as triaromatic steroids are present in very low concentration probably due to their high level of thermal evolution.

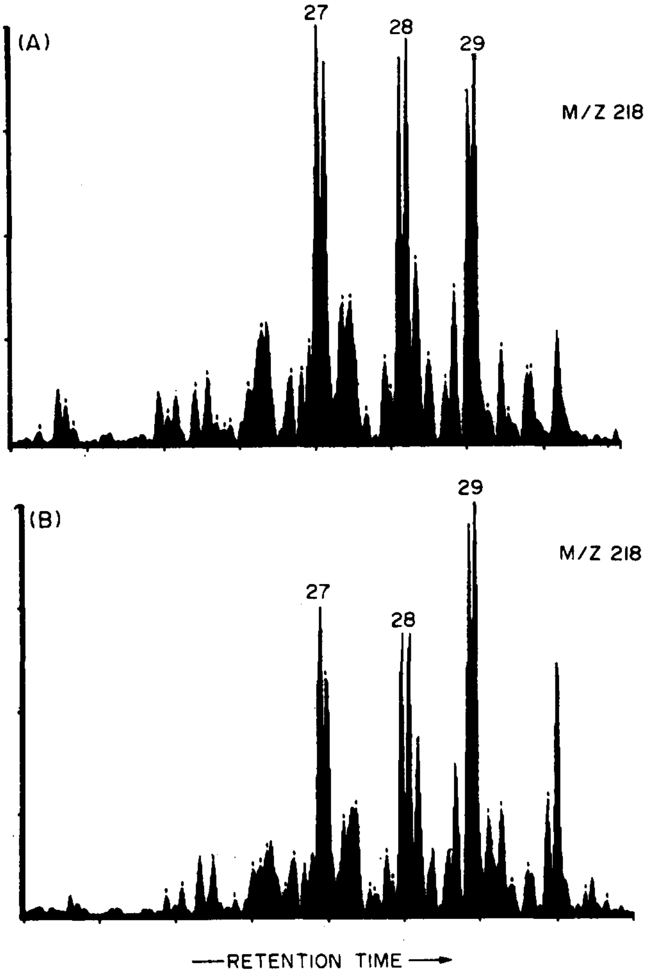

Fig. 8. Mass fragmentograms of steranes (*m*/*z* 218) in (A) marine La Luna type oil and (B) terrestrial oil.

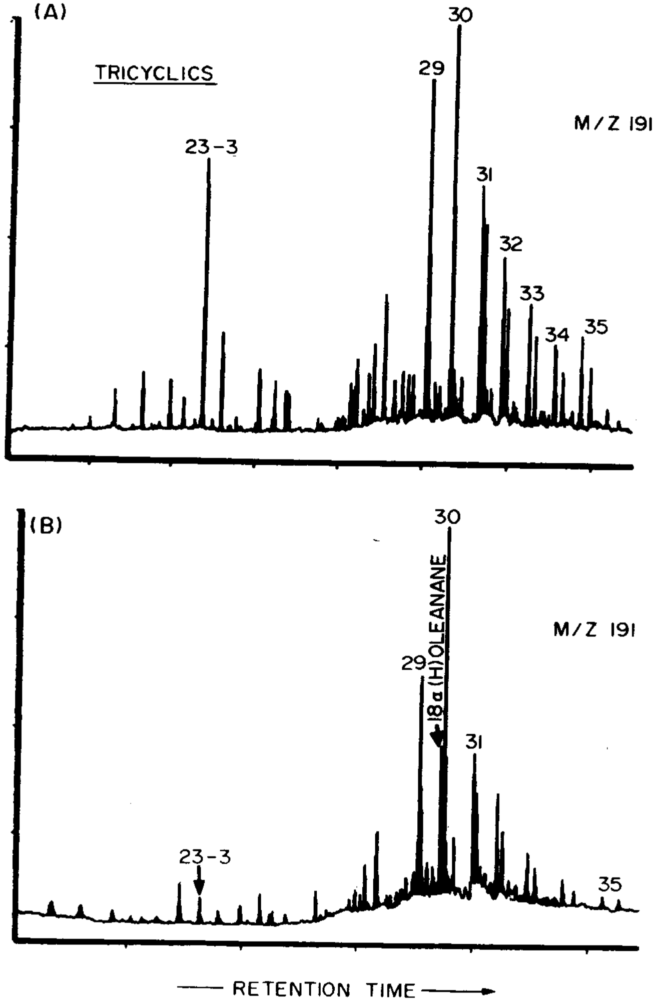

Fig. 9. Mass fragmentograms of terpanes (m/z 191) in (A) marine La Luna type oil and (B) terrestrial oil. Note the presence of 18α(H) oleanane in the terrestrial oil.

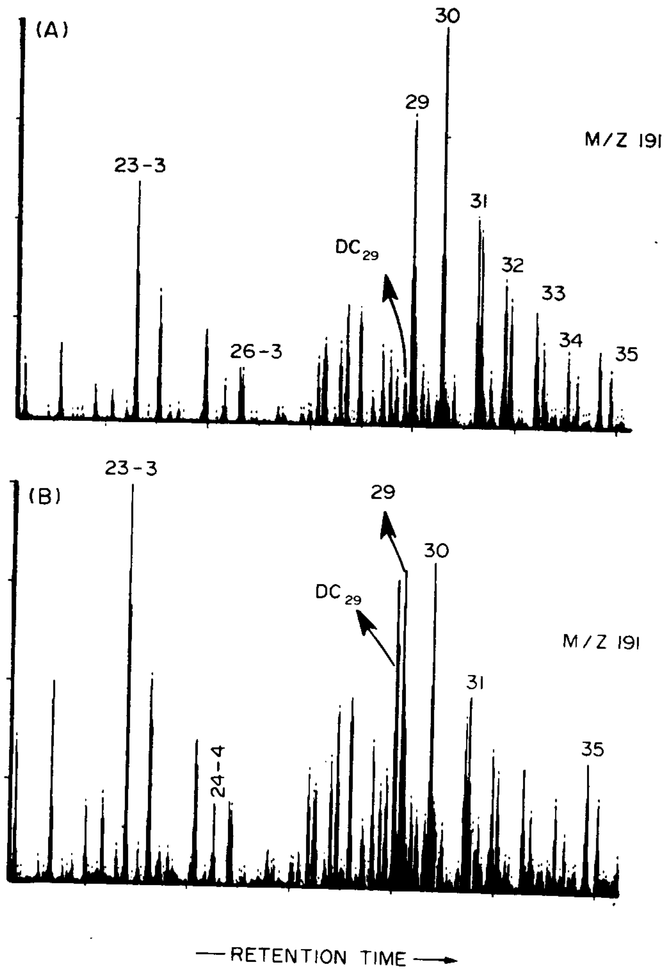

Fig. 10. Mass fragmentograms of terpanes (m/z 191) in (A) unaltered marine, La Luna type oil, Motatan field and (B) altered marine, La Luna type oil, Lagunillas field. Note the presence of C_{29} demethylated hopane (DC_{29}) in the terpane fragmentograms of both the oils.

The altered marine oils occur only in the shallow reservoirs (<5000 ft) of Miocene and upper Eocene ages in the eastern and northwestern parts of the Maracaibo Basin (Fig. 7). They are characterized by the absence or almost complete absence of *n*-alkanes, and have high sulphur ($>1.3\%$) and vanadium contents (200–500 ppm), low API gravity ($<25°$) and low saturated hydrocarbons/aromatic hydrocarbons ratios (<2). The steranes and terpanes data indicate their derivation from the marine organic matter source and their maturity. The oils have been correlated with the unaltered marine oils based on the similarity in the distribution of steranes and terpanes fragmentograms. Figure 10, shows an example of correlation between an unaltered oil from Motatan and an altered oil from Lagunillas; both the oils show very similar distribution of tricyclic terpanes and pentacyclic triterpanes in the terpanes fragmentograms.

It is important to note that the highly altered oils from the Bolivar Coastal fields (Ambrosio, Cabimas, Tia Juana, Pta. Benitez, Lagunillas and Bachaquero) present variable concentration of demethylated hopane C_{29} in their terpane fragmentograms (Fig. 10B). The demethylated hopane series has also been observed in some strongly biodegraded oils from California and Australia (Seifert and Moldowan, 1978; Volkman *et al.*, 1983), which according to Volkman *et al.* (1983) is the ultimate product of biotransformations of hopanes at a very advanced stage of biodegradation. In the Maracaibo Basin, the demethylated hopane C_{29} has also been found in trace amounts in the apparently unaltered oils from Block IV, Block V, Block 11, Motatan, Ceuta and Lago–Lamar. If the hypothesis of Volkman *et al.* (1983) is applied, the presence of demethylated hopane C_{29} in the unaltered oils would imply mixing of unaltered oils with the highly altered residues of earlier generated oils. This conclusion is later discussed in relation to the migration models.

Terrestrial oil

The oils of this type have an API gravity of 36° and are located only in the southwestern part of the Maracaibo Basin (Los Manueles field; Fig. 7). In contrast to the marine oils, these are characterized by low sulphur (less than 0.5%), low vanadium (4 ppm), abundant *n*-alkanes in the C_{23}–C_{35} range, high pristane/phytane (>3) and pristane/*n*-C_{17} ratios (>0.6), relatively high concentration of C_{29} sterane stereoisomers compared to C_{27} sterane stereoisomers (Fig. 8B), low concentration of tricyclic terpanes and presence of triterpane 18α(H) oleanane (Fig. 9B), and high hopanes/steranes ratio (>10). The values for the ratio triaromatic steroids/(triaromatic steroids + monoaromatic steroids) are between 77 and 100 which indicate their maturity.

Mixed marine and terrestrial oil

These mixed oils, like the terrestrial oils, are also located only in the southwestern part of the basin (Eocene reservoirs, Los Manueles; Paleocene reservoirs, West Tarra; Eocene and Paleocene reservoirs, Las Cruces).

They are characterized on the one hand by their distribution of *n*-alkanes, steranes and terpanes typical of the marine oils while also showing high hopanes/steranes ratio (7–9) and presence of triterpane 18α(H) oleanane typical of the terrestrial oils. These characteristics can be explained either by the generation of oil from source rocks with mixed marine and terrestrial organic matter or by the mixing of oils originating independently from marine and terrestrial sources. The occurrence of both the marine and terrestrial oils in the area might suggest the latter possibility.

Oil–Source Rock Correlations

Attempt has been made to identify the source rocks for the marine and terrestrial oils of the Maracaibo Basin based on the comparison of chromatographic characteristics of the oils with the rock extracts of the different formations (GC in 66 rock extracts and GC–MS in 23 rock extracts).

On the basis of these results, the La Luna source rock has been identified as the principal source for the marine oils in the basin. The unaltered marine oils show *n*-alkanes distribution very similar to that of the La Luna extracts. With respect to the distribution of terpanes and steranes both the unaltered and altered marine oils show very similar patterns to those of the La Luna extracts. The C_{27} sterane are more abundant than the C_{29} sterane stereoisomers and the concentration of 20S and 20R component pairs of the stereoisomers 5α(H), 14α(H) and 17α(H) are similar in both the oils and the rock extracts. Among the tricyclic terpanes the C_{23} is the most abundant while among the pentacyclic triterpanes the C_{29} norhopane and C_{30} hopane are the most abundant in both the oil and the rock extract (Fig. 11).

The rock extracts of the Capacho and Apon limestones also indicate very similar distributions of *n*-alkanes, steranes and terpanes to those of the La Luna extracts. This suggests that these formations might have also contributed to the generation of the marine oils in the basin; however their geochemical characteristics, effective thickness and geographic distribution indicate that the contribution would not be very significant.

The distribution of terpanes and steranes of the La Luna extracts have also been compared to those of the Lisure, Colon and Misoa shale extracts. The patterns of the La Luna extracts are different from those of the others. Besides, none of the marine oils show distributions of steranes and terpanes similar to those of the extracts of Lisure, Colon and Misoa samples.

The present work could not identify the source rock for the terrestrial oils. The Lisure shale extracts analyzed from Alturitas show very similar distribu-

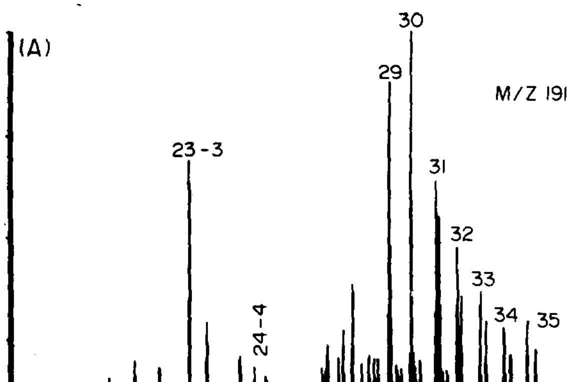

Fig. 11. *M/z* 191 mass fragmentograms showing the terpanes distribution in (A) marine oil, Eocene reservoir and (B) rock extract from the La Luna Formation.

tion of *n*-alkanes to that of the terrestrial oils; however, in the terpanes fragmentograms, the triterpane 18α(H) oleanane present in the oils is not found in the rock extracts. The Lisure shales from other areas or the Paleocene shales and coals in the southeastern and eastern areas could be the possible candidates. More work is needed to verify this correlation.

GENERATION OF HYDROCARBONS

The geochemical source rock evaluation, identification of oil types, and oil–oil and oil–source rock correlations have indicated that most of the oil in the Maracaibo Basin originated mainly from the marine organic matter of the La Luna Formation and in minor amount from the marine organic matter of the Capacho and Apon Formations. Estimations based on source rock characteristics and rock volumes, have indicated that more than 90% of the total volume of oil generated in the basin was derived from the La Luna source while about 7% derived from the Capacho and Apon sources (not discussed in this work). The La Luna type source rocks also produced abundant gas as indicated by their thermal maturity in the gas zone.

In this paper, we have reconstructed the hydrocarbon generating areas (oil and gas kitchens) in the La Luna Formation through geologic time. The TTI index of maturity described by Waples (1980) which is based on the concept of Lopatin (1971) has been calculated for 81 wells located in different parts of the basin; the calculated maturity has been calibrated with the measured maturity if available.

The TTI-maturity evaluates the integrated effect of time and temperature on the maturation of organic matter in sediments and therefore needs data on the history of subsidence and uplift, and the temperature gradients in the present and the past.

The main uncertainty in the reconstruction of geohistory diagrams in the wells of the Maracaibo Basin lies on the correct estimation of eroded Eocene thickness and the timing of this uplift/erosion. In this work, estimation of the eroded Eocene thickness made by Banks (1978) have been used. The time of uplift/erosion was assumed to be continuous occurring between 38 and 22.5 Ma. The geohistory curves have been drawn without the compaction correction; the error introduced is insignificant compared to the uncertainties related to the estimation of the thickness of eroded sediments.

The present day temperature gradients obtained from calculated equilibrium temperatures vary between 0.9°F/100 ft and 1.2°F/100 ft within the Tertiary sequence, and between 1.5°F/100 ft and 2.4°F/100 ft within the Cretaceous sequence, in different parts of the Maracaibo Basin. The average gradients are 1.2°F/100 ft and 1.8°F/100 ft, in the Tertiary and the Cretaceous sequences respectively. The higher gradient in the Cretaceous sequence appears to coincide approximately with the top of the Colon–Mito Juan Formations and was probably caused by the generation of overpressure in the thick Colon shales. This introduces the necessity of knowing the absolute time when overpressure in the Colon shales (so also the higher temperature gradient) began, which has been obtained for each well using the calculated post-Colon–Mito Juan sedimentation rates in Magara's (1978) diagram on depth of overpressure zone vs sedimentation rate, and the subsidence diagrams of the top of the Colon–Mito Juan Formations.

In the Maracaibo Basin as can be visualized from the tectonic setting, the regional heat flow since the deposition of the La Luna Formation probably did not change significantly. Hence the variation in thermal gradient in time was possibly related only to the generation of overpressure in the Colon shales. The thermal history used in the reconstruction of TTI-maturity diagrams of each well therefore takes into consideration a low temperature gradient (similar to that within the Teritary sequence) for the entire sedimentary section until the overpressure in the

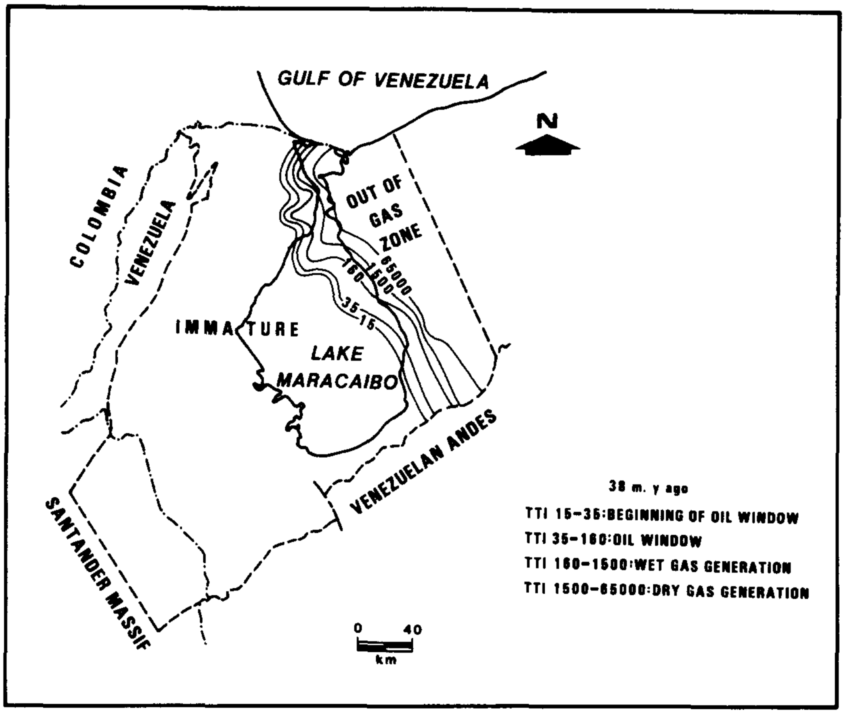

Fig. 12. Hydrocarbon generating areas in La Luna Formation at the end of Eocene (38 Ma ago).

Colon shales began; thereafter the temperature gradients higher within the Cretaceous sequence and lower within the Tertiary sequences, are used.

The regional distribution of TTI maturity trends in the La Luna Formation has been reconstructed for 4 different geological times namely the end of Eocene (38 Ma), end of Middle Miocene (12 Ma), end of Miocene (5 Ma) and at the present time (Figs 12, 13, 14 and 15). As discussed earlier, the beginning, peak and end of oil generation in the La Luna Formation correspond to TTI values of approximately 15, 35 and 160. The limits of wet gas and dry gas zones in

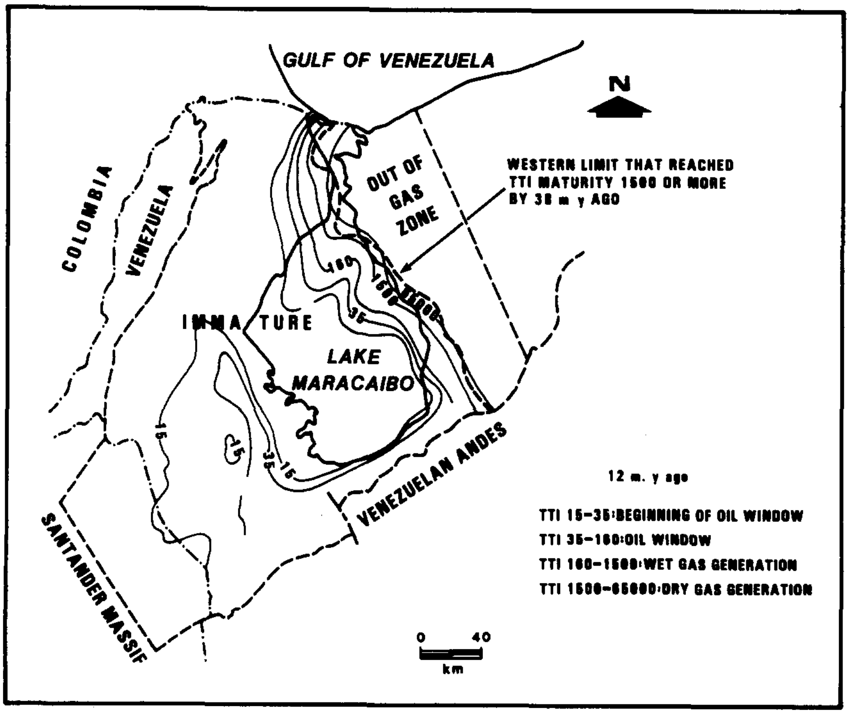

Fig. 13. Hydrocarbon generating areas in La Luna Formation at the end of middle Miocene (12 Ma ago).

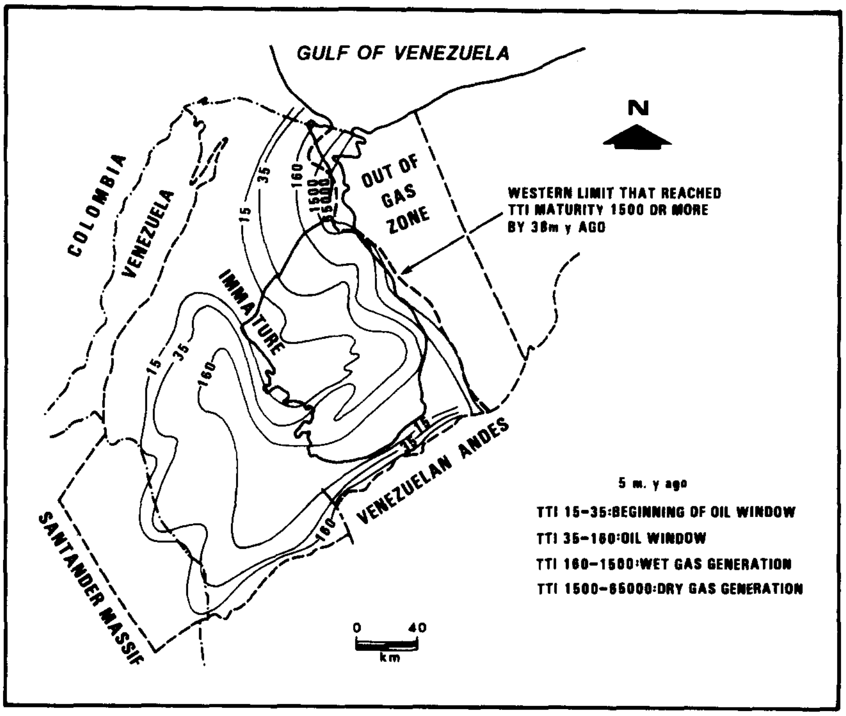

Fig. 14. Hydrocarbon generating areas in La Luna Formation at the end of Miocene (5 Ma ago).

the La Luna source have been taken as 1500 and 65,000 respectively, as given by Waples (1980). The TTI value of 65,000 for the limit of dry gas preservation should however be considered as very approximate because of the uncertainty in correlation between R_0 and TTI at high maturity levels (Katz *et al.*, 1982; Waples, 1983).

The TTI-maturity calculations of the Cretaceous rocks of the Maracaibo Basin in the areas to the east of Perija Range, to the northeast of Santander massif

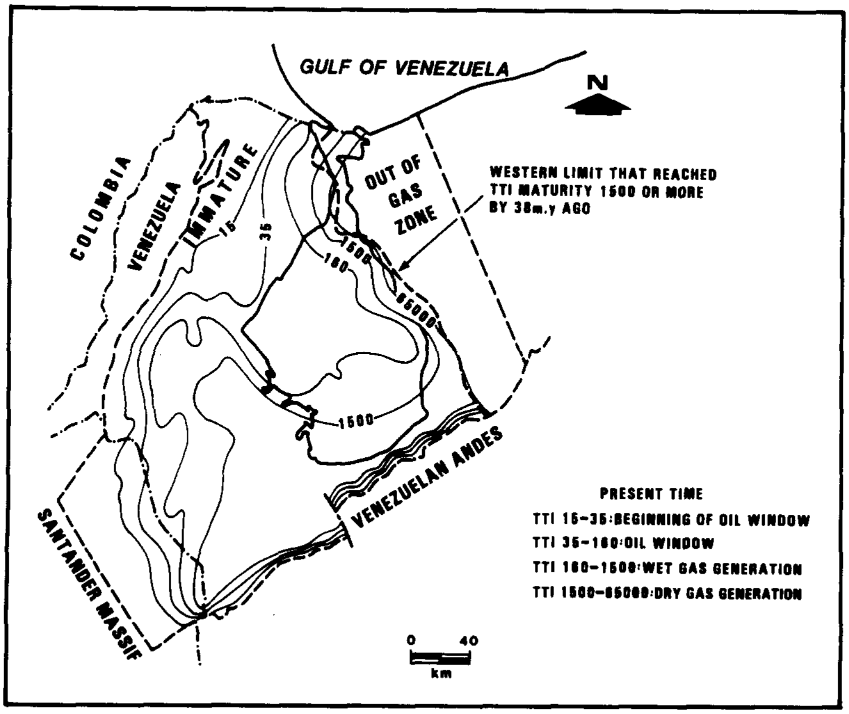

Fig. 15. Hydrocarbon generating areas in La Luna Formation at present time.

and to the north of Venezuelan Andes, indicate that these rocks hardly reached sufficient maturity to generate oil by 12 Ma. Besides the La Luna Formation is still immature both in the Perija Range and the Andes. This implies that since the Middle Miocene, oil generated in the western and southern parts of the Maracaibo Basin could not migrate to the west, south and southeast, out of the basin beyond the structural highs, nor any oil could migrate into the basin from adjacent areas. The northeastern limit of the basin as defined by the northnorthwesterly trending axis of the maximum thickness of Eocene deltaic sediments was a hydrocarbon drainage divide and has also similar significance. The northern limit of the basin defined by the Oca Fault may not be truely the northern limit of the drainage area of the basin. If the dextral movement on the Oca Fault began since the Miocene, some oil migration might have taken place to the northwest (the area of Dibujo syncline) during the late Eocene.

Generation of hydrocarbons at the end of Eocene

The oil window (TTI 15–160) in the La Luna Formation by 38 Ma covered the zone presently occupied by Sibucara, Som, Urdaneta East, Blocks I, II, III and the areas directly to the east of Ceuta (Fig. 12). In general terms the major part of the La Luna Formation which is encountered to the northeast of the actual eastern limit of the lake went through the oil and gas windows, and only a narrow northwest trending belt to the west, fringing the gas zone, remained in the oil window. In the areas further west and southwest, the Formation was still immature.

During the Eocene, the oil kitchen in the La Luna source was first formed in the axial part of the Eocene basin during 52–50 Ma, which during the later Eocene was progressively displaced to the southwest concomitant with the progressive accumulation of sediments of the Misoa delta. In Barua-Motatan, the beginning of oil window was reached during 48–44 Ma, and in about 2 to 4 Ma the formation in these areas passed through the oil window to wet gas zone and then to dry gas due to the rapid subsidence.

Generation of hydrocarbons at the end of middle Miocene

During the Oligocene, the previously formed oil and gas kitchens in the La Luna Formation became inactive because of significant uplift and consequent lowering of temperature.

As shown in Fig. 13 a very narrow zone with TTI range 35–160 was formed by the end of Middle Miocene (12 Ma) bordering the western limit of the inactive Eocene kitchens. In the western and southwestern parts of the basin, in the areas south of Machiques, Rosario, West Tarra and Rio Santa Ana, the formation was possibly in the early phase of oil window (TTI 15–35); in the small area to the southwest (Santa Ana area), the formation was in the phase of oil expulsion while in the areas of La Concepción, Som, Urdaneta East, Blocks I, II, III and Ceuta, it is encountered in the main phase of oil window and/or in the wet gas zone. Much of the oil generated in the La Luna source rocks during this time was probably not expelled out of the source rocks because of their low thermal maturity (TTI 15–35). However, in the TTI maturity zones 35–160 and 160–1500 light oil, condensate and wet gas were generated and expelled. The Capacho source rocks in the areas of Rio Catatumbo and Santa Ana reached low thermal maturity (TTI 15–35) by 12 Ma.

Generation of hydrocarbons at the end of Miocene

The hydrocarbon generating areas of the La Luna Formation which had begun to appear in the south, southwest and northeast by Middle Miocene times, extended further to the north and west by the end of Miocene (5 Ma, Fig. 14). By this time, extensive areas of the formation reached the main phase of oil window (TTI 35–160) in the south and southwest (Alturitas, Rosario, West Tarra, La Concepción, part of the southern area of the Maracaibo lake and part of Urdaneta). In the areas around San Carlos de Zulia and Bobures, the formation reached a TTI maturity greater than 160 and was generating condensate and wet gas. In the bordering areas to the north of the Venezuelan Andes, the La Luna source rock was immature or just entering the oil window. Only in a small area on the western part of the basin and in zones bordering the Perija Range the rocks of the La Luna were still immature.

Generation of hydrocarbons in present time

Figure 15 represents the TTI-maturity trends of the La Luna Formation at the present time. The formation in the south and west of the basin is actually encountered in the active dry gas zone. This dry gas zone is accompanied and bordered by large oil and wet gas zones. At the present time, within the drainage area of the basin, the major part of the La Luna Formation reached sufficient maturity to generate hydrocarbons (oil and gas). The only immature part of the La Luna source is in the narrow belt bordering the eastern limit of the Perija range.

PRIMARY MIGRATION IN LA LUNA FORMATION

To understand the mechanism of primary migration of oil in the La Luna source rocks it is important to evaluate the geological conditions under which the generation of oil in these rocks took place in the basin. The important organic sedimentological characteristics of the La Luna Formation are (1) the rhythmic alternations of thin beds of limestones, calcareous shales and shales with occasional intercalations of thin cherty and phosphatic beds; (2) the millimeter to submillimeter scale lamminations in the rocks defined by variable proportion of planktonic foraminifera, matrix material and organic matter; (3) high organic matter content; and (4) the presence of highly oil prone organic matter.

Petrographic study of thin sections and polished slabs of the La Luna source rocks with maturity corresponding to oil window, have shown parallel laminae consisting of fluorescent kerogen matrix, which are the productive part of the source rock, alternating with dark nonfluorescent matrix (Fig. 16). The bitumen present in these rocks occurs in different forms: (1) as irregular, very thin layers parallel to stratification and associated with kerogen; (2) in both parallel and oblique fractures (Figs 16A and B); (3) in the cavities of foraminifera; and (4) distributed throughout the rock matrix in diffuse condition.

Referring to matrix porosity, petrographic examination of the La Luna rocks with maturity corresponding to the oil window has not shown any visible porosity. In the Maracaibo Basin, the La Luna source rocks reached maturity within the oil window at depths between 12,000 and 15,000 ft (data from the TTI-maturity diagrams). In the northeastern part these depths were reached at the end of Eocene while in the areas further west and south they were reached in the Miocene–Recent period. Scholle's (1977, 1978) studies suggest that the primary porosity of pelagic limestones diminishes practically to zero at depths of about 3000 m (9842 ft) under conditions of normal pore fluid pressure. At these depths, permeability of the pelagic limestones are also extremely low (<0.1 md.).

The organic rich highly oil prone character of the La Luna source rocks, the existence of extremely low primary porosity (0–5%) at the time of oil generation and the occurrence of bitumen in fractures suggest that the expulsion of oil probably took place through abundant microfractures caused by the increase in pore fluid pressure during oil generation. Before the oil generation began both the solid organic matter and the mineral grains had essentially supported the whole weight of the overlying sediments. When the rocks reached maturity within the oil window, a part of the solid organic mater became converted into liquid hydrocarbons. Because of the volume increase of the fluid resulting from the partial transformation of organic matter into liquid hydrocarbons, the pore fluid pressure continued to increase and at a certain stage almost the entire weight of the overlying sedimentary column would have been supported by the pore fluids. It is important to mention that the La Luna rocks did not have much water at this stage. As the volume of liquid hydrocarbons generated by the high quantity of organic matter possibly was greater than the existing porosity, the expulsion probably took place as a single oil phase through the generation of fractures. Mass balance considerations suggest that if the oil was transported in aqueous solution, it would require a solubility of 18,000 ppm of oil in water which appears unlikely from the experimental data (Price, 1976, 1977). The fractures through which the oil escaped probably were both parallel and oblique to the stratification. As the kerogen is mainly distributed in parallel layers, it is expected that the initial expulsion of oil was predominantly through fractures parallel to the stratification. According to Foster (1975), the effective permeability in fractured limestones could be 50 to 500 times higher than in nonfractured limestones. After the oil had escaped through fractures the solid rock (minerals and organic matter) again supported the weight of the overlying sedimentary column until the process was repeated. Similar mechanism of primary migration was suggested earlier by Momper (1978) and Meissner (1978).

The importance of the generation of gas in the migration of oil has been emphasized by different authors (Hedberg, 1980; Nogaret, 1983). If one examines the distribution of oil and gas kitchens in the La Luna Formation by 38 Ma ago and the present time (Figs 12 and 15) it is possible to visualize that great quantities of gas (while migrating updip) could dissolve a good quantity of oil and migrate as a single phase under the expected fluid pressure conditions. If the mechanism for the primary migration of oil as suggested above is feasible the expulsion efficiency could be very high (30–50%).

HISTORY OF MIGRATION

The history of migration of hydrocarbons (oil and gas) can be traced by utilizing the simple concept which states that the hydrocarbons originating in an active kitchen migrate updip towards zones of lower pressure. In this work, the history of migration in the Maracaibo Basin has been described considering the TTI-maturity maps of the La Luna Formation at different times, paleostructural maps at different times, the nature of the carrier paths, and the distribution of oil types. It has been assumed that significant migration of oil commenced at the peak of oil generation stage (TTI 35).

Migration in Eocene–Oligocene times

Figures 17A and B show schematically the pattern of migration of oil and gas in the Maracaibo Basin during the late Eocene–Oligocene period. As indicated earlier, the oil kitchen in the La Luna Formation was first formed in the northeast in the axial part of the Eocene basin during 52–50 Ma, which by the end of Eocene (38 Ma) moved towards west and southwest with the development of gas kitchens in the adjacent eastern areas. Hydrocarbons (oil, oil dissolved in gas and gas) from the active oil and gas kitchens migrated laterally undip towards soutwest

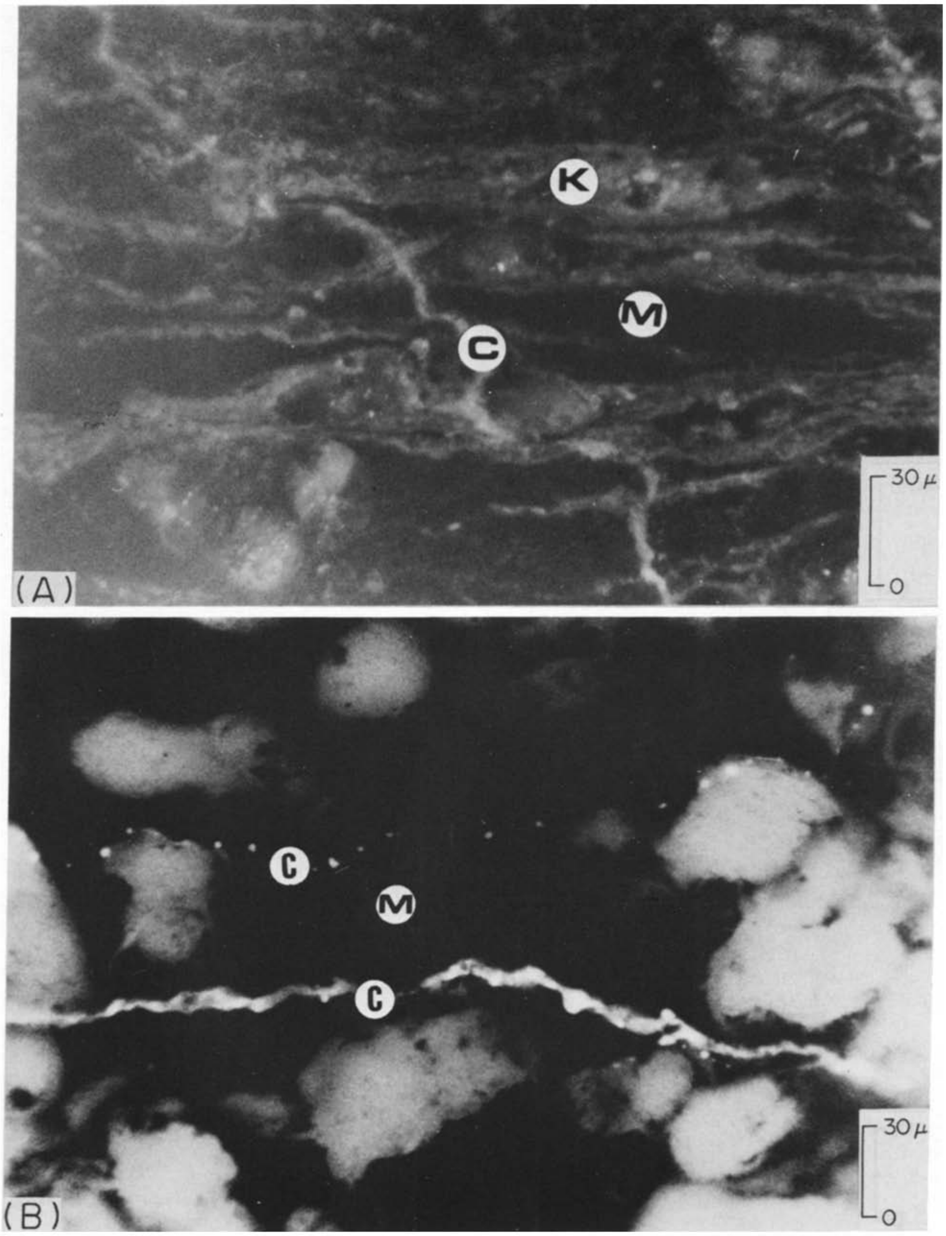

Fig. 16. Photomicrographs of La Luna thin sections showing: (A), a fracture filled with fluorescent bitumen (C) crosscutting the fluorescent organic matter arranged parallel to stratification (K) and the matrix mineral (M); (B), a fracture filled with fluorescent bitumen (C) arranged subparallel to stratification.

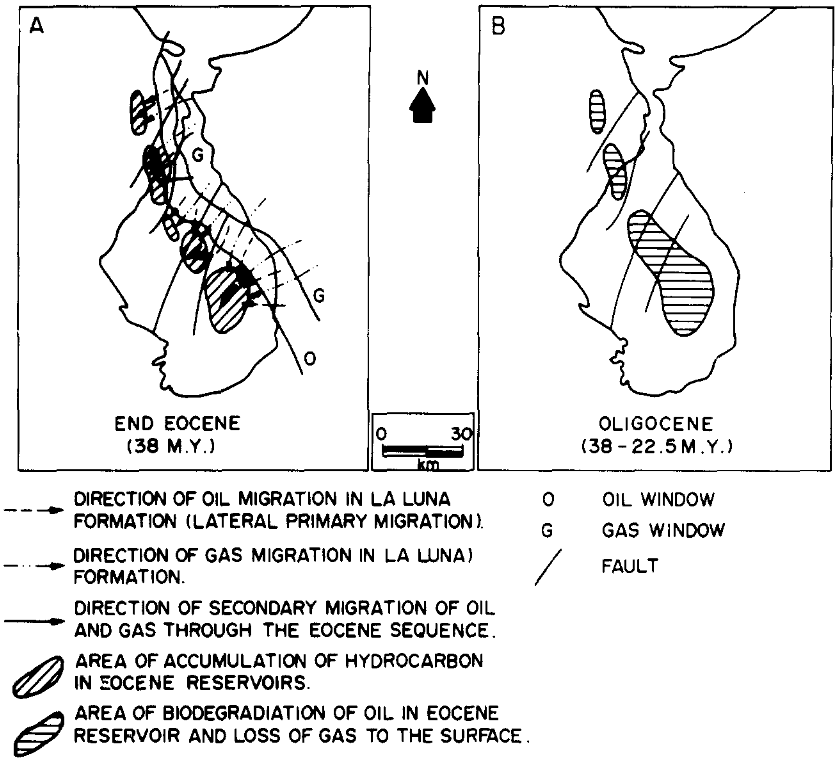

Fig. 17. Sketch of hydrocarbon migration in the Maracaibo Basin during end Eocene–Oligocene times.

through the La Luna source rock system which was sealed on top by the thick Colon shales. The hydrocarbons preferentially migrated towards the north-northeasterly trending structural highs developed within the Cretaceous sequence (Fig. 17A). The Colon shales which were then overpressured (suggested by our calculations on the depth of beginning of overpressure) probably hydrofractured in their shallowest parts. As a result the hydrocarbons which migrated through the La Luna source into these structural highs mostly broke through the seals and migrated vertically into the Eocene sandstones. The hydrocarbons reaching the Eocene sandstones probably migrated further west into stratigraphic traps. Most of the oils generated and trapped at the end of Eocene were probably light oil and condensate.

Towards the end of Eocene and during the Oligocene, the basin was subjected to strong uplift and erosion. This gave rise to: (1) suspension of further hydrocarbon generation and (2) erosion of the upper part of the Eocene (B-sands) exposing the underlying Eocene sequence at shallow levels. As a consequence, it is likely that the oil accumulated in the part of eroded Eocene sediments was lost while the rest of the oil in the remaining Eocene sands was subjected in many parts of the structural highs, to conditions favorable to extreme biodegradation. The TTI-maturity diagrams of different wells from the structural highs of Punta Benitez–Tia Juana, Block III–Block IV–Ceuta–Block II and Sibucara–Som indicate that the lower Eocene sediments in these areas were at depths less than 8500 ft and temperatures less than 80°C (where biodegradation is effective), during 30–15 Ma. Even though the relict of highly altered Eocene oil is not commonly found as a separate phase, the occurrence of demethylated hopane C_{29} in the terpane fragmentograms of most of the altered and unaltered oils of Bolivar Coastal fields, Block IV, Block 11 and Lago–Lamar probably indicate the presence of such altered residues of the Eocene oil within the oil generated and accumulated in Miocene–Recent times (discussed later).

Migration in Miocene–Recent times

The history of migration of hydrocarbons in the Maracaibo Basin during Miocene–Recent times was limited to the area defined within the Trujillo Range, the Venezuelan Andes and the Perija Range.

At the end of Middle Miocene (12 Ma), active hydrocarbon generating areas in the La Luna source bordered the suspended kitchens of the Eocene time (Figs 13 and 18A). Hydrocarbons (oil and gas) from the generating areas migrated in a westerly direction towards the structural highs defined at the Cretaceous level (Fig. 18A). These structural highs were also exhibited on a minor scale at the Eocene level; so the oil and gas which had migrated vertically (through faults and fractures within the Colon Formation) into the Eocene sandstones possibly accumulated in the Eocene reservoirs at these highs. A certain quantity of oil and gas migrating vertically further up probably reached the post-Eocene unconformity and

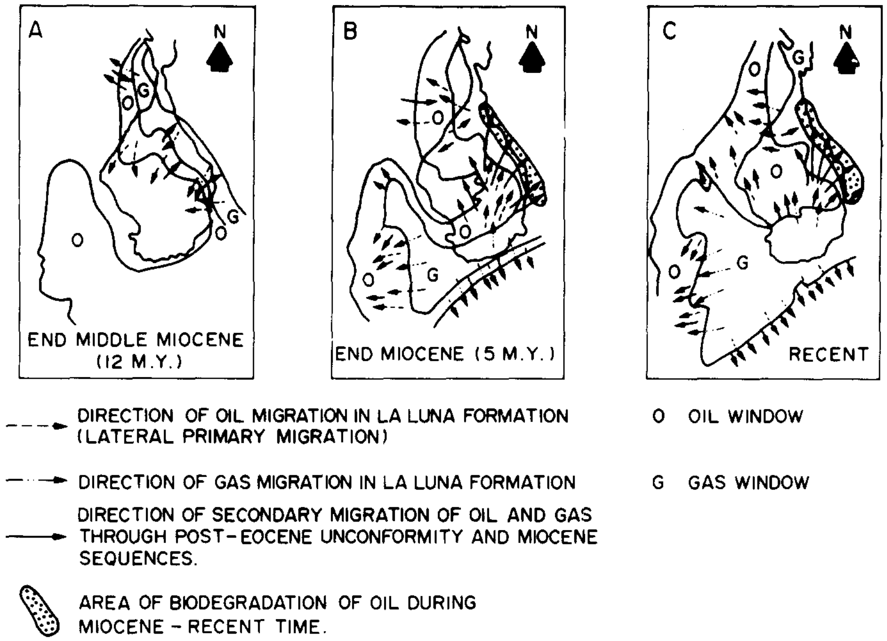

Fig. 18. Sketch of hydrocarbon migration in the Maracaibo Basin during end middle Miocene–Recent times.

the Miocene sands, when updip lateral migration continued towards east and northeast being controlled by their low southwest dipping homoclinal structure. By 12 Ma, the La Luna source rocks in the southwestern and southern parts of the basin did not acquire enough maturity to expell significant quantity of oil.

By the end of Miocene (5 Ma), the oil and gas generating areas in the La Luna Formation extended considerably and covered a large part of the basin (Figs 14 and 18B). During this period, active oil and gas kitchens were developed in the south (Andean foredeep) and southwest from where light oil and wet gas migrated to the south towards the northern flank of the Venezuelan Andes, mainly light oil to the west and westnorthwest towards the structures of the southwestern and western parts of the basin (Los Manueles, West Tarra, Tarra, Rosario, Alturitas and Machiques), and light oil to the north towards the structures of Barua–Motatan, Mene Grande, Block 11 and South Lake. Besides, the structures of Urdaneta area received light oil and gas from the surrounding kitchens and the Mara–La Paz and Conception highs received light oil from the surrounding oil kitchen and wet gas from the areas further to the east and southeast.

It is important to mention that by the end of Miocene lateral migration of hydrocarbons at the Cretaceous level was considerably hindered by faults reactivated in the Miocene. The faults served in many cases as vertical migration paths to allow migration of hydrocarbons into the Eocene and Miocene sequences. At the Eocene and Miocene levels, the migration was towards north and northeast in the direction of Bolivar Coastal fields. The shallow Miocene and Eocene reservoirs in the northeastern limit of the lake was subjected to conditions favorable to biodegradation.

In the present time, the major part of the La Luna Formation in the basin reached maturity corresponding to oil window or to zones of wet or dry gas generation; only a small band bordering the eastern limit of the Perija range is found immature (Fig. 15). The hydrocarbon migration pattern in the basin practically remained similar since the end of Miocene, even though there was further extension of oil and gas kitchens (Figs 18B and C).

In the Maracaibo Basin, mixing of marine oils, derived at different times (Eocene and Miocene–Recent) from the La Luna source of different areas appears to have taken place in Bolivar Coastal fields, Motatan, Mene Grande, Block IV, Block 11 and Lago–Lamar. In the Bolivar Coastal fields, most of the oils in the Miocene reservoirs (depths 947–4345 ft) are altered, mature marine oils. These altered oils contain either high concentrations or trace amounts of demethylated hopane C_{29} in their terpane fragmentograms. It has been suggested earlier in chapter on oil types and oil–source rock correlations that this compound forms under conditions of severe biodegradation of oils. However, the oils of the Bolivar Coastal fields contain the demethylated hopane C_{29} compound together with abundant steranes and terpanes. This leads to a contradiction in the interpretation of the grade of alteration of the oils; the demethylated hopane on the one hand suggests extreme alteration while the abuandance of steranes and terpanes indicates less severe conditions. This apparent discrepancy can be explained by assuming that the demethylated hopane formed by extreme biodegradation of the oils generated in the Eocene, which later became mixed with a new generation of oil formed in Miocene–Recent times. The mixed oil finally accumulated in the Miocene and Eocene reservoirs where it was again subjected to biodegradation. The history of migration since the last 12 Ma indicates that the major part of the oil of Bolivar Coastal fields was derived from the oil kitchens to the south and central parts of the lake which might have dissolved the highly altered residues of the Eocene oil during their migration or in the final reservoirs.

The demethylated hopane C_{29} is also found in trace in the apparently unaltered oils of Motatan, Block IV, Block 11 and Lago–Lamar, which can be similarly interpretated as due to the mixing of the oil generated in Miocene–Recent times with the highly altered residues of the Eocene oils.

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