Advances in Organic Geochemistry 1987
Org. Geochem. Vol. 13, Nos 1–3, pp. 537–547, 1988
Printed in Great Britain

0146-6380/88 $3.00 + 0.00
Pergamon Press plc

Generation and migration of oil in the Maturin Subbasin, Eastern Venezuelan Basin

SUHAS TALUKDAR, OSWALDO GALLANGO and ARMANDO RUGGIERO
INTEVEP, S. A., Apartado 76343, Caracas 1070-A, Venezuela

Abstract—Regional geochemical evaluation of the possible Cretaceous and Tertiary source rocks and oil–oil and oil–source rock correlation studies, have identified the calcareous shales and limestones of the Upper Cretaceous, Querecual and San Antonio Formations of the Guayuta Group, with amorphous marine type II organic matter, as the source rocks for oil in the Maturin Subbasin. The deposition of the source rocks took place on a passive continental margin whilst the generation and migration of oil occurred in a foreland basin during Miocene–Recent times.

The oils found in the northern part of the subbasin in different reservoirs (Cretaceous, Eocene, Oligocene, Miocene and Pliocene formations) are of mature, marine type with or without bacterial alteration. Geochemical data indicate that some of these oils were mixed with the highly altered residue of a previously accumulated oil. Based on maturity and migration modelling, it appears that the oils essentially migrated from active, Upper Miocene–Recent, kitchens in the Cretaceous source rocks below the main thrusts. The highly altered residue was formed during the Upper Miocene by the biodegradation of oil migrating during the Middle and Upper Miocene.

Large areas of mature to overmature Cretaceous source rocks (now exposed in the Interior Mountain Front) were in active oil kitchens during the Lower and Middle Miocene before being involved in thrusting around 12 Myr BP. Long distance (150–300 km) southward lateral migration of oils during the Middle Miocene gave rise to the altered moderately mature marine oils in the shallow Miocene stratigraphic reservoirs of Cerro Negro (Orinoco Oil Belt) in the southern fringe of the subbasin.

Key words: generation and migration of oil, Maturin Subbasin, Eastern Venezuelan Basin, North Monagas oil fields, source rocks, oil–oil and oil–source rock correlations, thermal maturity modelling, secondary migration

INTRODUCTION

The Maturin Subbasin occupies a large part of the east–west trending Eastern Venezuelan Basin (Fig. 1). The subbasin, as defined in this study, covers an area of approximately 60,000 km^2. The northern and southern boundaries are limited by the El Pilar Fault and the Guayana Shield, respectively.

Oil accumulations in the subbasin occur in two separate, east–northeasterly trending belts, one to the north and the other to the south. The northern belt includes light to medium gravity as well as heavy biodegraded oils of the Maturin area (North Monagas oil fields), whilst the southern belt includes heavy and extra heavy oils of the Cerro Negro area (within the Orinoco Oil Belt) and heavy and medium gravity oils of the areas to the north of Cerro Negro.

The sediments of the subbasin are of Mesozoic and Cenozoic ages. The pre-Upper Miocene sediments in the northern part were deformed into an east–northeast trending fold-thrust belt which is partly exposed in the Interior Mountain Front. Repetitions by thrusting gave rise to considerable thicknesses of the sediment in areas immediately to the north of Maturin where the pre-Mesozoic basement reaches depths close to 30,000 ft (9150 m).

This paper represents an integrated geochemical study of the Maturin Subbasin which includes evaluation of source rocks, geochemistry of oils and their correlation with source rocks, reconstruction of hydrocarbon generating areas and establishment of the hydrocarbon generation and migration history through time. Emphasis has been given to understanding the origin, migration and evolution of oils accumulated in the reservoirs of widely varying depths and stratigraphic intervals, in the North Monagas oil fields.

GEOLOGICAL SETTING

The stratigraphic and structural development pertinent to hydrocarbon generation and migration in the Maturin Subbasin are given below based on the authors' critical review of the published work (Hedberg, 1950; Renz *et al.*, 1958; Salvador, 1958; Rosales and Claxton, 1969; Gonzales de Juana *et al.* 1980) and some recent unpublished data. Figure 2 shows generalized stratigraphic sections across the Maturin Subbasin.

The Lower Cretaceous to Middle Eocene sediments, deposited in a passive continental margin setting, exhibit increasing thickness and more marine facies from south to north. The marine, pelagic limestones and shales of the Guayuta Group (source rock facies) were deposited in the northern part of the

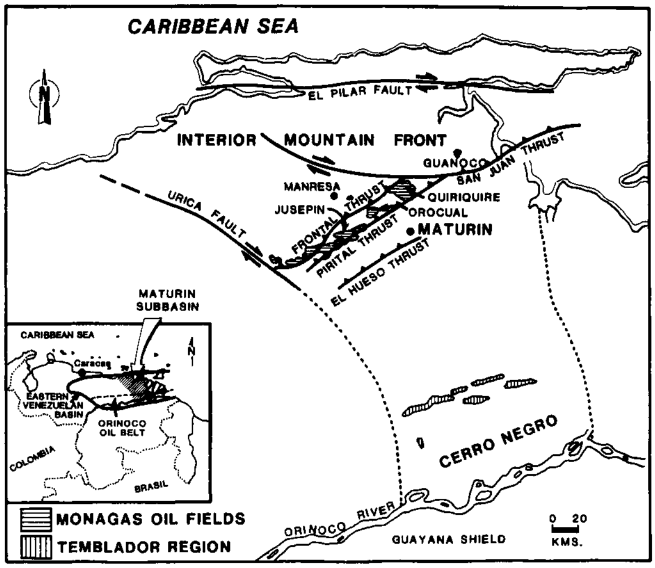

Fig. 1. Location of the Maturin Subbasin showing principal structures and oil fields.

subbasin in anoxic or near anoxic conditions during the maximum marine transgression of the Upper Cretaceous (Cenomanian–Campanian). Northward regression began in the uppermost Cretaceous (Maestrichtian) and continued through the Paleocene and Eocene depositing in marine environments, the predominantly sandy San Juan Formation (reservoir facies) the shaly Vidoño Formation (seal facies) and the sandy Caratas Formation (additional reservoir facies), respectively.

The Upper Oligocene–early Upper Miocene sediments constitute the deposits in a southwardly migrating foreland basin. In the northern part, the Los Jabillos sandstones (reservoir facies) deposited in shallow marine environments overlie unconformably, from north to south, the successively older formations of the earlier cycle. The overlying, thick, predominantly shaly Carapita Formation (with the thin basal Areo shales) deposited in marine conditions grades, in the southern part, into the partly equivalent Merecure and Oficina Formations that unconformably overlie the continental Cretaceous and the Precambrian basement. The Carapita Formation in the Maturin area contains both reservoir and seal facies, whereas the Oficina sandstones in the south deposited in fluvio-deltaic environments show good reservoir facies.

The foreland basin stabilized by the late Upper Miocene. The Upper Miocene–Pliocene, continental deposits (Morichito and Quiriquire Formations) and shallow marine to fluvio-deltaic deposits (La Pica and Las Piedras Formations) overlie discordantly the eroded surface of the strongly deformed Carapita and older formations, in the northern part. The erosion of the pre-La Pica sediments is highly variable (3500 ft to more than 20,000 ft) and is very important to evaluate for the hydrocarbon generation modelling. The La Pica, Las Piedras and Quiriquire Formations contain sandstone reservoirs.

As regards the structural development, compressional tectonics during the Miocene deformed the Carapita and older sediments into an east-northeast trending fold-thrust belt in the northern part of the Maturin Subbasin. The main thrusts are successively younger southward. The Frontal and San Juan Thrusts bordering the Interior Mountain Front (Fig. 1), are emplaced at about 12 m.y. before present (BP.). The Pirital and El Hueso Thrusts (Fig. 1) encountered progressively southward are emplaced at about 8 and 6 Myr BP, respectively. Structural configuration in the pre-La Pica sediments developed during these periods remained practically unchanged until Recent times.

A generalized north–south geological cross-section of the northern part of the subbasin, depicting the structures, is shown in Fig. 3. Subsurface seismic interpretations are restricted to relatively shallow depths, and interpretations of deeper parts are speculative. The authors have modified the original interpretation of Lagoven, S.A. (1987) in the deeper sections of the Maturin area.

SOURCE ROCK CHARACTERISTICS

The organic richness, type of organic matter, thermal maturity and the oil–source rock correlation studies have identified the fine grained calcareous shales, argillaceous limestones and shales of the marine Querecual and San Antonio Formations of the Guayuta Group as the source rocks for the oils in the Maturin Subbasin. Table 1 summarizes the general source rock characteristics of the formations and the group as a whole.

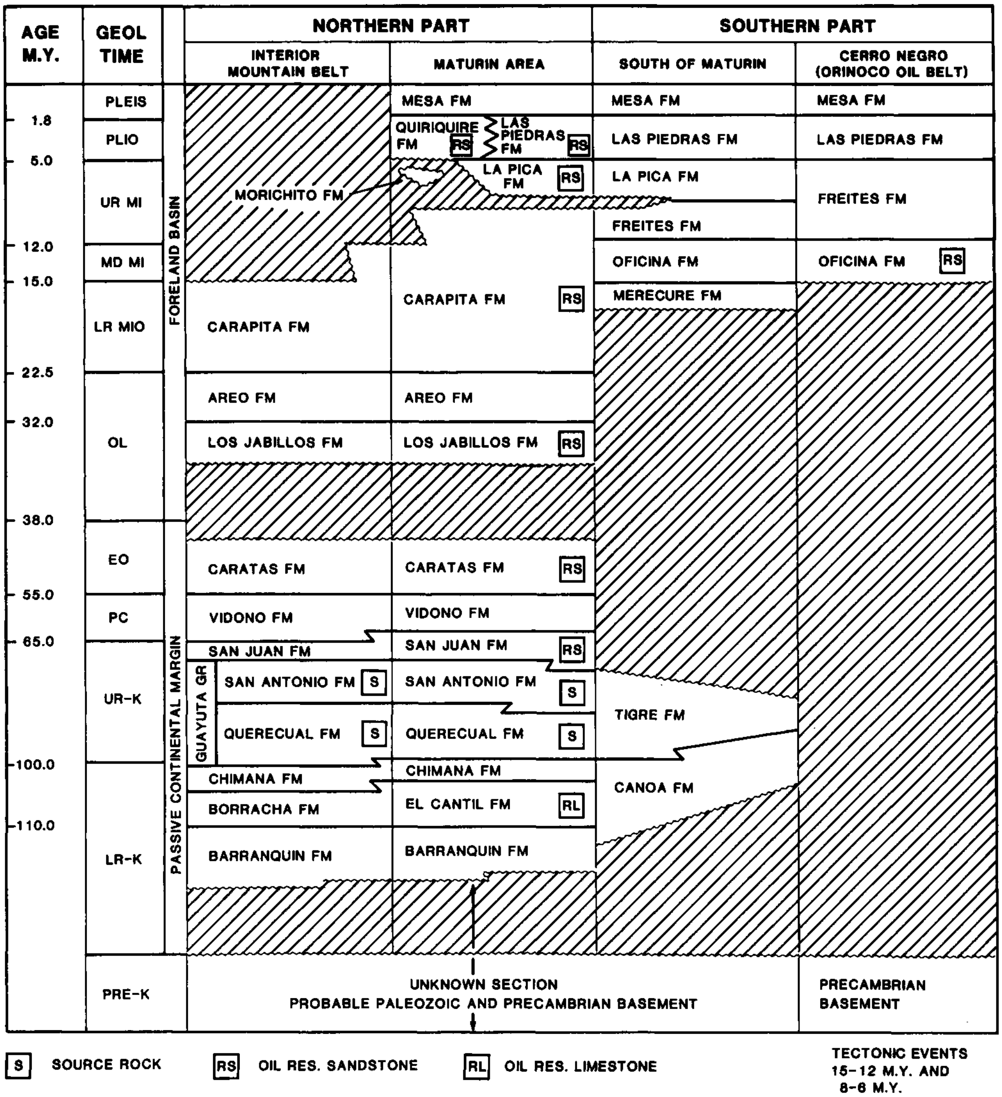

Fig. 2. Generalized stratigraphy across the Maturin Subbassin, showing Basin types, main tectonic events, source rocks and oil reservoirs.

The total organic carbon (TOC) of the source rocks varies between 0.25 and 6.60% wt. Two organic facies, namely Facies A and Facies B, have been distinguished in each formation and the group as a whole on the basis of visual kerogen analysis (Table 1), which also differ from each other in their oil generating capacity. Facies A contains on average more than 85% amorphous marine organic matter,

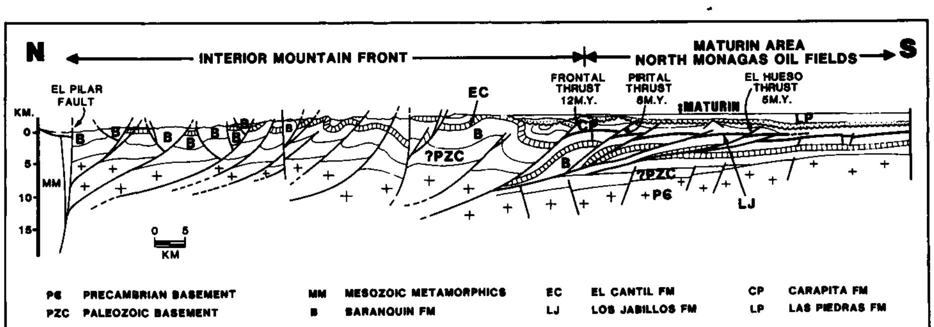

Fig. 3. Generalized North–South cross-section across the Interior Mountain Front and Maturin area, Northern part of the Maturin Subbasin [Section from Lagoven S.A. (1987), partly modified by the authors].

Table 1. Source rock characteristics of Querecual and San Antonio Formations and of the Guayuta Group in general

Formation group	Lith	Organic facies (No. of samples)	TOC range (% wt)	TOC average (% wt)	Average org. matter constituents (% vol) Am.	Herb.	Woody	Coaly	Org. matter type	Maturity
San Antonio Formation	Calc. sh., Sh., Arg. lst.	A (19)	0.67–4.52	2.38	86	2	10	2	II	Low mature to overmature
		B (9)	0.60–2.80	2.02	40	12	45	3	II + III	Low mature
Querecual Formation	Calc. sh., Arg. lst.	A (44)	0.85–6.60	3.06	89	2	6	3	II	Highly mature to overmature
		B (11)	0.80–2.10	1.64	56	9	31	4	II + III	Low mature
Guayuta Group	Calc. sh., Arg. sh., Sh.	A (84)	0.25–6.60	2.54	88	2	7	3	II	Low mature to overmature
		B (20)	0.60–2.80	1.82	49	10	37	4	II + III	Low mature

Calc. sh. = calcareous shale; Arg. lst. = argillaceous limestone; Sh. = shale.
Am. = amorphous Herb. = herbaceous.

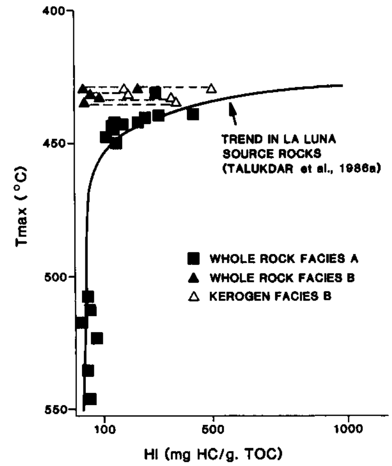

Fig. 4. Variation in hydrogen indices with maturity (T_{max}) in the Organic Facies A and B of the Guayuta Group.

whilst Facies B includes less than 60% amorphous marine organic matter and a significant proportion of woody material (> 30%). The amorphous material is usually distributed in very thin laminae parallel to the bedding and is characterized by high fluorescence in ultraviolet light.

The distribution of C_{15+} saturated hydrocarbons obtained from 9 rock extracts of both facies, show a predominance of *n*-alkanes in the C_{20}–C_{24} range, pristane/phytane values less than 1.0 and pristane/*n*-C_{17} less than 0.5 which are characteristic of algal organic matter deposited under anoxic marine conditions (Hunt, 1979; Talukdar *et al.*, 1986a).

The distributions of biomarkers (terpanes and steranes) have been determined in 8 rock extracts by GC–MS (see oil source correlations). In the tricyclic terpanes, C_{23} is the most abundant whilst amongst the pentacyclic triterpanes the C_{29} norhopane and the C_{30} hopane are the most abundant, also suggesting a marine source (Simoneit, 1977). In the sterane fragmentograms, the stereoisomers of the C_{29} sterane are slightly more abundant than those of the C_{27} sterane. This is somewhat uncommon in a marine source as the C_{29} sterane is considered to be largely derived from the higher plants. The C_{29} sterane in the marine source may however be derived from brown algae and certain species of green algae that live in marine environments (Moldowan *et al.*, 1985).

The source rocks of Facies A, having equivalent vitrinite maturities between 0.6 and more than 1.3%R_o (T_{max} between 440°C and more than 550°C), show hydrogen indices (HI) between 30 and 454 mgHC/gTOC which decrease with maturity (Fig. 4). The trend of variations in HI with maturity in the source rocks of Facies A falls along the general trend of Type II, oil prone, marine La Luna source rocks of the Maracaibo Basin (Talukdar *et al.*, 1986a). The analyzed source rocks of Facies B show low HI values (15–295 mgHC/gTOC) in spite of their low thermal maturities (T_{max} between 431 and 433°C,

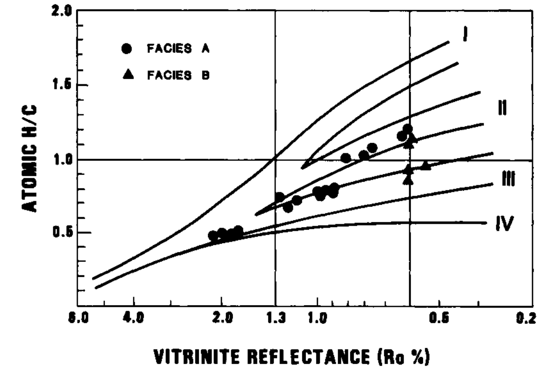

Fig. 5. Variation of atomic H/C ratios with R_0 in the Organic Facies A and B of The Guayuta Group (Based on Demaison, 1983).

equivalent R_0 close to 0.5%). Isolated kerogens of 5 rock samples of Facies B (with HI values between 21 and 295 mgHC/gTOC) show higher HI values between 193 and 507 mgHC/gTOC (Fig. 4), probably indicating the effect of mineral matrix in the shaly rocks (0–11% carbonate content) with relatively low TOC contents (1.2–2.7%), as suggested by Orr (1983).

Figure 5 shows the variation of atomic H/C ratio with vitrinite reflectance, R_0 in the source rocks of Facies A and Facies B. The trends fall along oil prone Type II and between Type II and Type III respectively. The H/C ratio extrapolated for the immature rocks of Facies A and Facies B are 1.3 and 1.1 respectively.

Thermal maturity of the top of the Guayuta Group, based on measured vitrinite reflectance (R_0) data and reconstructed vitrinite gradients in different areas, varies greatly over the subbasin increasing from low maturity in the south to high maturity in the north (Fig. 6). Maturity at the base of the Guayuta Group is about 0.12–0.26% R_0 higher than at the top of the Group. The maturity distribution shown in Fig. 6 is in the upper slabs of different thrusts and was acquired prior to their tectonic emplacement. Hence, these maturity values correspond to pre-emplacement hydrocarbon generation. However, active hydrocarbon kitchens at deeper levels are most likely to be present below the important thrusts and have been modelled in this study (see generation and migration of oil).

In summary, Guayuta source rocks are considered highly oil prone. Organic Facies A has a better capability of oil generation than Facies B. The average values of TOC are 2.54 and 1.82% wt (Table 1). The average HI of immature source rocks of Facies A is considered to be 700 mgHC/gTOC based on their similarity with the La Luna trend (Fig. 4) and the average HI of the immature La Luna source rocks (Talukdar *et al.*, 1986a). The average HI of immature source rocks of Facies B is much lower and has been taken as 400 mgHC/gTOC. Taking these averages, the approximate oil volume generated at the end of the oil window in the source rocks of Facies A and B, (assuming 50% convertibility of kerogen into oil), have been calculated roughly as 166×10^6 and 68×10^6 bbl/km^3 rock, respectively. Estimated thickness of the Guayuta Group as a whole varies between 2000 ft (610 m) in the subsurface in areas south of Maturin and 3350 ft (1021 m) in the Interior Mountain Front. Based on the Gamma-ray and SP logs, about 50–55% of the total thickness are considered as source rock facies. Facies A is found in the Interior Mountain Front while both the Facies A and Facies B are present towards its south. Both source rock facies apparently disappear south of Maturin.

OIL TYPES AND OIL-SOURCE CORRELATIONS

The oils in the northern part of the Maturin Subbasin (North Monagas oil fields) accumulated in

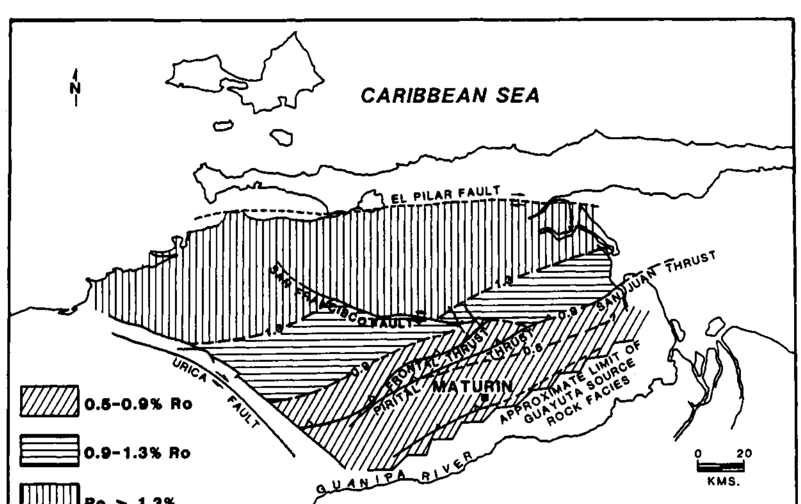

Fig. 6. Regional variations in thermal maturity (R_0) of the top of the Guayuta Group.

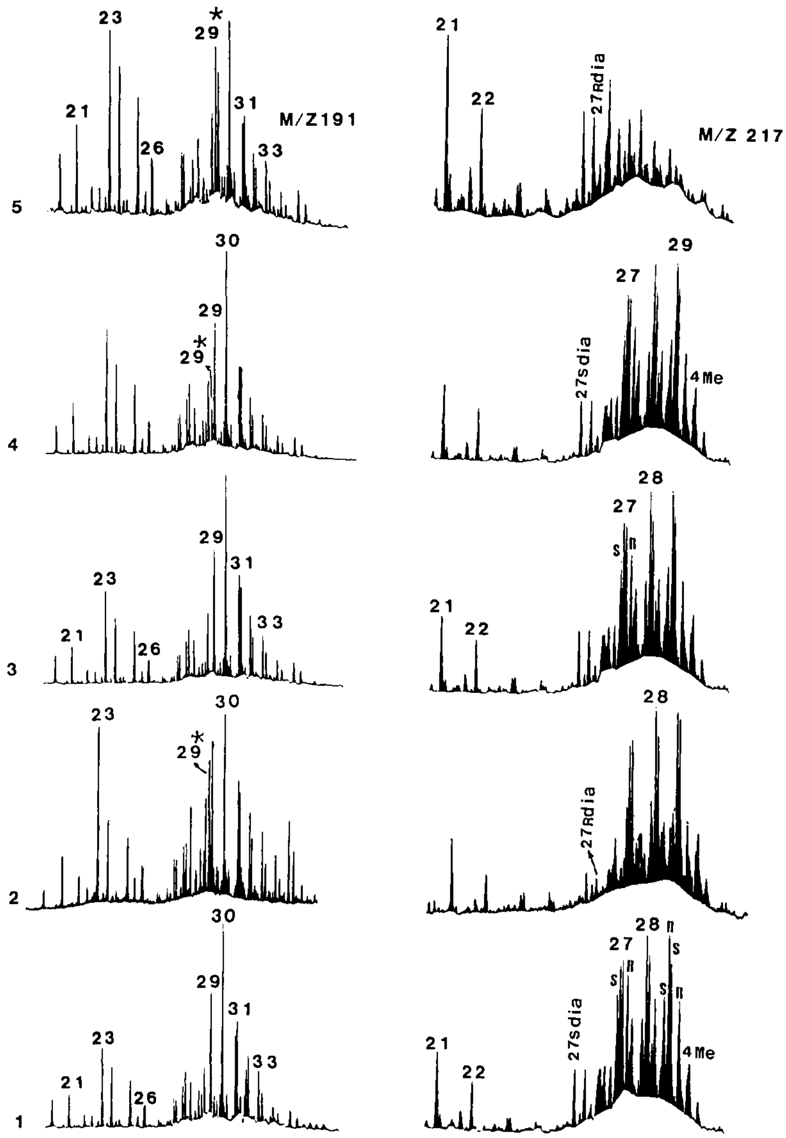

Fig. 7. Triterpane (m/z 191) and sterane (m/z 217) distribution patterns of (1) a rock extract from the marine Querecual Formation, (2) a biodegraded marine oil from the Cerro Negro area (Orinoco Oil Belt), (3) a marine oil from the North Monagas oil fields area, (4) a marine oil mixed with an extremely biodegraded oil residue from the North Monagas oil fields area, and (5) a biodegraded marine oil from the North Monagas oil fields area. 29* = C_{29} demethylated hopane.

structural and stratigraphic traps at different stratigraphic levels ranging in age from the Cretaceous to Pliocene (Figs 1 and 2). They include light to medium gravity as well as heavy (biodegraded) oils. The biodegraded oils are obtained from reservoirs at relatively shallow depths (1180–4544 ft).

The oils in the southern part of the subbasin (Cerro Negro area of the Orinoco Oil Belt and the Temblador region) accumulated in stratigraphic traps of the Oficina Formation of Miocene age (Figs 1 and 2). The Cerro Negro area includes heavy and extra heavy biodegraded oils having API gravities between 6 and 13°. The Temblador region includes biodegraded heavy oils and some medium gravity oils.

This section briefly summarizes the results of a detailed geochemical study of the Monagas oils which has established their origin and source rocks. A correlation of these oils with the Cerro Negro oils (Cassani, 1985) has also been undertaken.

Twenty four unaltered oils, 30 biodegraded oils and 6 oil seeps from the North Monagas area have been studied. The unaltered oils show a complete range of n-alkanes in their GC traces, and have API gravities between 23 and 41° and sulfur contents between 0.5 and 1.5% wt. The distributions of C_{15+} saturated hydrocarbons show a predominance of n-alkanes in the C_{20}–C_{24} range and pristane/phytane ratios close to 1.0, suggesting an algal marine organic matter source. The biodegraded oils and oil seeps are characterized by a complete absence of n-alkanes, low API gravities ($< 20°$) and sulfur contents between 0.9 and 2.3% wt.

Fifteen of these oils (8 unaltered, 7 biodegraded) and four oil seeps were selected for analysis by GC–MS to determine the biomarker compounds terpanes, steranes and aromatic steroids, and by HPLC to determine porphyrins in order to establish the origin and maturity of these oils and to correlate them with their potential source rocks and the Cerro Negro oils. Biodegradation had not affected the terpane distributions but had changed the sterane distributions considerably in some oils. Both the sterane and terpane distributions of the oil seeps, however, have been changed by biodegradation. Figure 7 shows some examples of the triterpane and sterane distribution patterns of the oil types and their source rocks.

With respect to the distribution of terpanes and steranes, both the unaltered and biodegraded oils of the North Monagas oil fields show very similar patterns to those of Guayuta Group source rocks as well as to those of the biodegraded oils of the Cerro Negro area. The terpane and sterane distribution patterns (as discussed earlier in the section on source rock characteristics) indicate a marine algal organic matter source. Amongst the tricyclic terpanes, C_{23} is the most abundant, whilst in the pentacyclic triterpanes the C_{29} norhopane and C_{30} hopane are the most abundant components in all the oils and the Guayuta source rock extracts. In the sterane distributions, C_{29} steranes are slightly more abundant than C_{27} sterane stereoisomers, and the concentrations of 20S and 20R component pairs of the stereoisomers 5α(H), 14α(H) and 17α(H) are similar in both oils and the source rock extracts.

Some of the unaltered oils and all of the biodegraded oils and oil seeps of the Monagas area as well most of the oils from Cerro Negro area show the presence of a C_{29} demethylated hopane in their terpane fragmentograms in varying concentrations (Fig. 7). Demethylated hopanes have been observed in strongly biodegraded oils from California and Australia (Seifert and Moldowan, 1978; Volkman *et al.*, 1983) and from the Bolivar Coastal fields of the Maracaibo Basin, Venezuela (Talukdar *et al.* 1986a). Volkman *et al.* (1983) suggested that demethylated hopanes are the ultimate product of the biotransformations of hopanes at a very advanced stage of biodegradation. If this opinion is correct, their presence in some of the unaltered oils of the Monagas area would imply mixing of the unaltered oils with the highly altered residues of earlier generated oils. Similar explanations have been given for the presence of demethylated hopanes in the apparently unaltered crude oils of other basins (Talukdar *et al.*, 1986a; Sofer *et al.*, 1986).

GENERATION AND MIGRATION OF OIL

In order to determine the timing of oil generation and migration from the Guayuta source rocks, thermal maturity assessments using the TTI-maturity calculations (Waples, 1980) have been made. The calculated TTI values have been calibrated against measured vitrinite reflectance data in the subbasin (Fig. 8). R_o values of 0.5, 0.9 and 1.3% have been tentatively considered to represent the beginning, main phase, and the end of oil generation based on comparisons with similar La Luna source rocks from the Maracaibo Basin (Talukdar *et al.*, 1986a, 1987). Significant expulsion has been considered to take place during the main phase of oil generation. The calculated TTI values corresponding to 0.5, 0.9 and 1.3% R_o are 11, 165, and 950 respectively. The TTI-R_o calibration obtained for the Maturin Subbasin is different from that of other basins (Waples, 1980; Issler, 1984) and could be due to a number of factors such as estimations of eroded sequences, change of heat flow through time, changes in thermal conductivity with lithology and subsidence rate, the effect of compaction on subsidence, and the effect of fluid flow on temperature. These factors are difficult to evaluate correctly, as well as their variation from one basin to another. However, it is considered more appropriate to use these TTI values to indicate hydrocarbon generation as they are calibrated against measured R_o data in the subbasin.

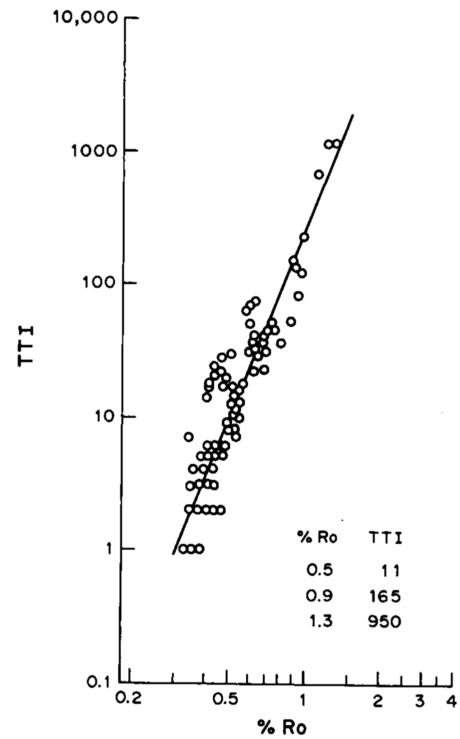

Fig. 8. TTI-R_o calibration in the Maturin Subbassin.

The areas that should be considered in evaluating the hydrocarbon generation in the Maturin Subbasin include: (1) the overthrust slab of the Frontal Thrust and (2) the areas beneath the three principal thrusts, namely the Frontal Thrust (and the equivalent San Juan Thrust), the Pirital Thrust and the El Hueso Thrust (Figs 1 and 3).

The thermal maturity of the Guayuta source rocks on the uplifted upper slabs of the Pirital and El Hueso thrusts (Fig. 6) was acquired prior to thrusting, but was not high enough for oil expulsion. Likewise, the areas to the south of the El Hueso Thrust, even though they have the Cretaceous at its maximum depth of burial at the present time, apparently lack the Guayuta source facies and adequate maturity for oil expulsion.

Maturity modelling of the overthrust slab of the Frontal Thrust: Oil generation and migration

The entire Interior Mountain Front represents the overthrust slab of the Frontal Thrust. The Guayuta source rocks in this area show maturities corresponding to both oil and gas generation stages (Fig. 6). This maturity was acquired prior to tectonic emplacement in the Middle Miocene.

To reconstruct the thermal maturity diagrams for the area, three parameters are critical: viz, (1) the age of thrusting; (2) an estimation of the eroded sedimentary column; and (3) the thermal history.

The timing of tectonic emplacement has been considered as instantaneous, and the age of the Frontal Thrust is taken as 12 Myr BP. The thickness of the eroded sedimentary column was estimated from vitrinite reflectance values and calculated vitrinite reflectance gradients. A constant temperature gradient of 1.4°F/100 ft was used for the maturity calculations. This is slightly higher than the measured present day average of 1.3°F/100 ft in the area. Temperature gradients calculated from the theoretical considerations (Talukdar *et al.*, 1986b) decreased from 1.9 to 1.4°F/100 ft from the beginning of deposition of the Guayuta Group until the end of deposition of the Los Jabillos Formation. A temperature gradient of 1.3°F/100 ft remained from the time of deposition of the Carapita Formation until the present time. Since the maturation level for oil generation was attained during the Carapita deposition, a constant gradient of 1.4°F/100 ft has been considered a good approximation. In addition, the

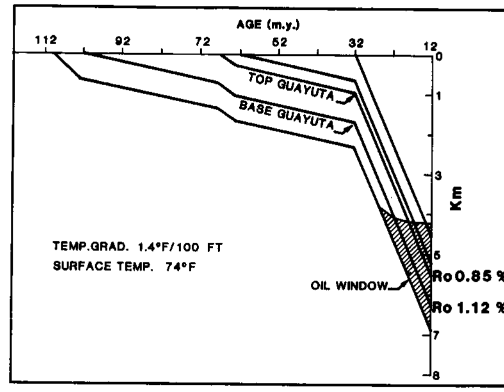

Fig. 9. Thermal maturity diagram for the Guayuta source rocks of the Guanoco area of the Interior Mountain Front, prior to thrusting at 12 Myr BP.

calculated R_o values using this gradient closely agree with measured R_o values.

Figure 9 shows an example, for the Guanoco area, of the thermal maturity modelling for the Interior Mountain Front prior to thrusting at 12 Myr BP. Based on this and other examples it is suggested that the oil generation began in the Guayuta source rocks in the Lower Miocene, or slightly earlier, whilst expulsion and migration of oil took place at the end of the Lower Miocene to Middle MiLocene. The hydrocarbon generation and migration were suspended following the thrusting episode at 12 Myr BP.

Figure 10 is a schematic N–S cross-section drawn to show oil migration in the subbasin prior to 12 Myr BP. The foreland basin configuration was still tectonically undisturbed. An updip southward lateral migration of oil for long distances can be envisaged. Oil expelled from the active Guayuta oil kitchen migrated first through the overlying San Juan sandstones (that underlie the Vidoño shales) and then progressively southward through Los Jabillos sandstones and the basal Merecure-Oficina sandstones representing the Oligocene and Miocene discontinuities. Migration continued mainly updip along a

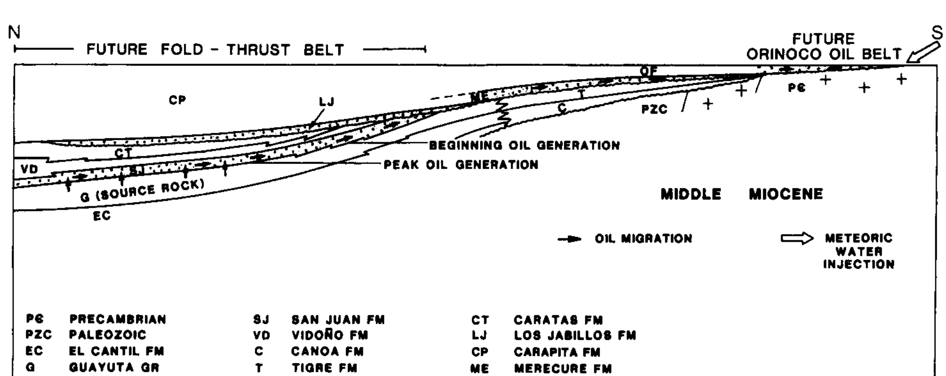

Fig. 10. Schematic North–South cross-section showing oil migration in the Maturin Subbasin, prior to 12 Myr BP.

monoclinal surface towards the south as far as the Orinoco Oil belt where the Oficina Formation gradually pinched out. Some oil accumulated in areas of the Temblador region along uplifted northern sides of east–northeast trending faults before reaching the Cerro Negro area. The migrated oils were moderately mature, marine type, of probably medium to light gravity, which were biodegraded in the reservoirs into heavy and extra heavy oils during Middle Miocene–Recent times.

The fold-thrust belt involves a north–south crustal shortening of the order of 40% or more. Accordingly, lateral migration distances could be as great as 150–300 km.

Maturity modelling beneath principal thrusts: Oil generation and migration

Oil accumulations in the Upper Miocene and Pliocene reservoirs of the Monagas oil fields suggest expulsion and secondary migration during Upper Miocene–Recent times. Structural traps in pre-Upper Miocene sediments formed during the Middle and early Upper Miocene (12–6 Myr BP). The oils in these traps are genetically related and must have migrated after the structures developed.

Guayuta source rocks on the uplifted upper slabs of the principal thrusts are not undergoing active hydrocarbon generation. However there is a strong possibility that hydrocarbon (oil and gas) generation has been actively taking place beneath the main thrusts following their emplacements. In this section, conclusions regarding the timing of oil generation and migration beneath the Frontal, Pirital and El Hueso Thrusts (Fig. 3) are summarized.

Parameters which are critical for the reconstruction of thermal maturity diagrams beneath thrusts are: (1) the stratigraphic section before being overridden by the thrust; (2) the age of the thrust; (3) the depth configuration of the thrust (tectonic load); (4) the stratigraphic section present in the subthrust position; and (5) the thermal history.

In the thermal maturity modelling of sediments underlying the thrust sheets the model of Angevine and Turcotte (1983) which calculates the temperature distribution as a function of depth and time computed since the time of thrusting, has been used. The effect of erosion of parts of the thrust sheet has been neglected.

A complete stratigraphic section before thrusting has been reconstructed from estimation of the eroded sequence on the basis of vitrinite reflectance data. The stratigraphic section present in the subthrust position is approximate and is obtained from the original (pre-thrust) column and the assumed structural section (Fig. 3). The average present day equilibrium temperature gradient of 1.3°F/100 ft was used in the modelling.

Figure 11 (a and b) gives an example of the reconstructed thermal maturity of the Guayuta source rocks which are supposed to be present below the Pirital thrust. The thermal maturity is modelled for a tectonic load (thickness of the overthrust slab) of 6000 m. Figure 11(a) models the thermal maturity in the source rocks before being overidden at 8 Myr BP. Figure 11(b) shows the change in the maturity of the source rocks with time since thrusting. According to these diagrams, the Guayuta source rocks at this depth are in the main phase of oil generation at the present time.

Based on the reconstruction of a series of thermal maturity diagrams, the timing of oil generation and migration beneath each thrust has been obtained. The timing of oil migration below the Frontal, Pirital and El Hueso Thrusts are approximately 12 Myr to Present, 5 Myr to Present and 3 Myr to Present, respectively. The sub-surface structural traps in the pre-La Pica reservoirs in the Monagas oil fields were formed during 8–6 Myr BP. These traps could, there-

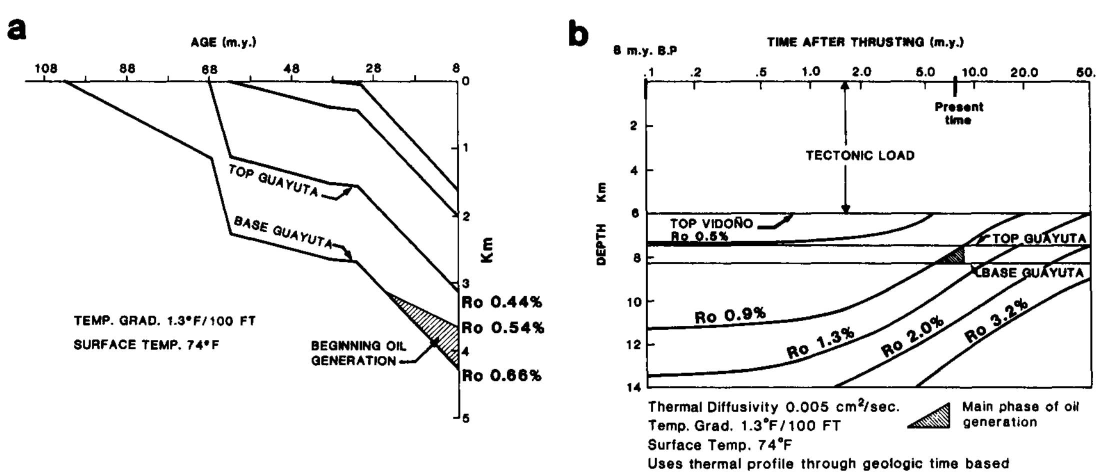

Fig. 11. Thermal maturity of the Guayuta source rocks below the Pirital Thrust (assumed thickness of the thrust slab 6000 m). (a) Maturity in the source rocks at 8 Myr BP prior to thrusting; (b) Change in maturity of the source rocks with time since thrusting.

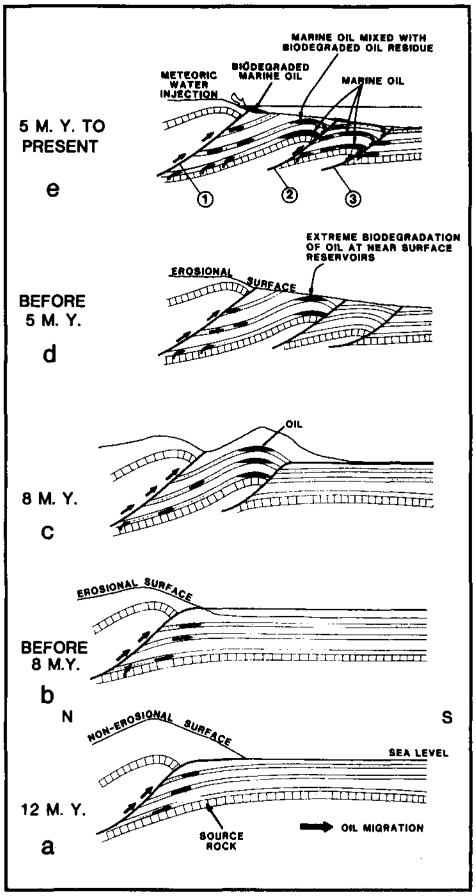

Fig. 12. Conceptual model for the origin, migration and evolution of the oil types of the North Monagas oil fields area through time. (1) Frontal Thrust, (2) Pirital Thrust, (3) El Hueso Thrust.

fore, have been filled by the oils migrating since that time.

Figure 12 gives a conceptual model of the origin, migration and evolution of the oil types in the North Monagas oil fields through time. From 12 Myr up to 8 Myr BP, oils were generated from marine Guayuta source rocks beneath the Frontal Thrust [Figs 12(a) and 12(b)]. The marine oils which migrated during this time were probably not accumulated significantly in the area because of lack of structural traps at this time. At 8 Myr BP, structural traps developed on the upper slab of the subsequent Pirital Thrust [Fig. 12(c)]. Marine oils migrating from the kitchen beneath the Frontal Thrust since 8 Myr, then accumulated in the structural traps to the south. Until 5 Myr BP, the marine oils continued to migrate into the same reservoirs. However, some of the reservoirs were completely eroded, whilst in others that were very close to the surface the oils were extremely biodegradated forming an oil residue [Fig. 12(d)]. Between 5 Myr to Present, marine oils migrated from the kitchens beneath the three thrusts. Oil migration during this period gave rise to the accumulation of: (1) mature marine oils; (2) mature marine oils mixed with the biodegraded oil residues in the reservoirs (formed prior to 5 Myr BP); and (3) biodegraded, mature marine oils, in the North Monagas oil fields area. The movement of oil from the active kitchens occurred primarily by vertical migration along thrusts and fractures and, secondarily by short distance lateral migration along the pre-La Pica (San Juan, Caratas, Carapita) sandstones encountered along the vertical migration paths as well as along the unconformity at the base of La Pica and Las Piedras Formations.

CONCLUSIONS

Geochemical data, thermal maturity reconstructions and the proposed models for oil generation and migration lead to the following conclusions:

(1) All the oils accumulated in the northern and southern parts of the Maturin Subbasin are genetically related to the Type II, marine source rocks of the Guayuta Group (Querecual and San Antonio Formations).

(2) The Guayuta source rocks now largely exposed in the Interior Mountain Front are the source for the oils in the Cerro Negro area of the Orinoco Oil Belt in the southern part of the subbassin. Migration took place during Lower to Middle Miocene times (prior to the thrusting event at 12 Myr BP) and involved long distance (150–300 km), updip lateral migration to the south in an undisturbed foreland basinal setting. The oils were biodegraded during the Upper Miocene–Recent times.

(3) Oils in the North Monagas oil fields in the northern part of the subbasin migrated from active hydrocarbon generating areas of the Guayuta source rocks present beneath the principal thrusts in the area. Timing of oil migration from the source area beneath the Frontal, Pirital and El Hueso Thrusts were probably 12 Myr to Present, 5 Myr to Present and 3 Myr to Present, respectively. Oil accumulations in the area formed mainly during 5 Myr to Present. A highly altered oil residue in some apparently unaltered oils, shown by the presence of C_{29} demethylated hopanes, suggested mixing of oils. The oil residue was probably formed by the biodegradation of oils which migrated earlier during 8–6 Myr BP.

(4) Based on the deduction that active hydrocarbon generating areas exist beneath the principal thrusts, deep potential structural traps in the Maturin area appear prospective.

Acknowledgements—The paper includes the results of a work financially supported by Lagoven S.A. and S.A. Meneven. The authors are grateful to PDVSA and INTEVEP S.A. for authorizing the presentation and publication of this paper. Special thanks are due to Dr John M. Hunt of Woods Hole Oceanographic Institution, U.S.A.

and Mr Fernando Marcano of INTEVEP S.A. for critical reading and suggesting improvements. The authors also thank Dr G. C. Speers of Geological Survey of Denmark for reviewing it.

REFERENCES

Angevine C. and Turcotte D. L. (1983) Oil generation in overthrust belts. *Bull. Am. Assoc. Pet. Geol.* **67,** 235–241.

Cassani F. (1985) Organic geochemistry of extra-heavy crude oils from the Eastern Venezuelan basin. *Ph.D. thesis*, University of Bristol, U.K.

Demaison G. (1983) Lectures on petroleum formation and occurrence. *Am. Assoc. Pet. Geol.*, Petroleum Formation and Occurrence School, 17 pp.

Gonzalez de Juana C., Arozena J. and Picard X. C. (1980) *Geologia de Venezuela y de su cuencas petroliferas*, 1031 pp. Ediciones FONINVES, Caracas.

Hedberg H. D. (1950) Geology of the Eastern Venezuelan Basin. *Bull. Geol. Soc. Am.* **61,** 1173–1216.

Hunt J. M. (1979) *Petroleum Geochemistry and Geology*, 617 pp. W. H. Freeman, San Francisco.

Issler D. R. (1984) Calculation of organic maturation levels for offshore Eastern Canada—Publication of general application of Lopatin's method. *Can. J. Earth Sci.* **21,** 477–488.

Lagoven S.A.—An affiliating company of Petroleo de Venezuela, S.A. (1987) Generalized North-South crosssection across Interior Mountain Front and Maturin area. Unpublished data.

Moldowan J. M., Seifert W. and Gallegos J. (1985) Relationship between petroleum composition and depostional environment of petroleum source rocks. *Bull. Am. Assoc. Pet. Geol.* **69,** 1255–1268.

Orr W. L. (1983) Comments on pyrolytic hydrocarbon yields in source-rock evaluation. In *Advances in Organic Geochemistry 1981* (Edited by Bjorøy M. *et al.*), pp. 775–787. Wiley, Chichester.

Renz H. H. Alberding H., Dallmus K. F., Patterson J. M., Robie R. M., Wiesbord N. E. and Mass Val J. (1958) The Eastern Venezuelan Basin. In *Habitat of Oil—a Symposium, Am. Assoc. Pet. Geol.* (Edited by Weeks L. G.) pp, 551–600.

Rosales H. and Claxton C. D. (1969) The Lower Tertiary–Cretaceous of Northeastern Venezuela. *Creole Petroleum Corporation Internal Report No. 3300-228-11*, Caracas, 242 pp.

Salvador A. (1958) Northern Monagas oil prospects. *Creole Petroleum Corporation Unpublished Report*, Caracas, 57 pp.

Seifert W. K. and Moldowan J. M. (1978) Applications of steranes, terpanes and monoaromatic steroids to the maturation, migration and source of crude oils. *Geochim. Cosmochim. Acta.* **42,** 77–92.

Simoneit R. T. (1977) Diterpenoid compounds and other lipids in deep-sea sediments and their geochemical significance. *Geochim. Cosmochim. Acta* **41,** 463–476.

Sofer Z., Zumberge J. E. and Lay V. (1986) Stable carbon isotopes and biomarkers as tools in understanding genetic relationship, maturation, biodegradation and migration of crude oils in the Northern Peruvian Oriente (Marañon) Basin. In *Advances in Organic Geochemistry 1985*, Part I: *Petroleum Geochemistry* (Edited by Leythauser D. and Rullkötter J.). *Org. Geochem.* **10,** 377–389. Pergamon Press, Oxford.

Talukdar S., Gallango O. and Chin-A-Lien M. (1986a) Generation and migration of hydrocarbons in the Maracaibo Basin, Venezuela: An integrated basin study. In *Advances in Organic Geochemistry 1985.* Part 1; *Petroleum Geochemistry* (Edited by Leythaeuser D. and Rullkötter J.). *Org. Geochem.* **10,** 261–279. Pergamon Press, Oxford.

Talukdar S., Gallango O. and Ruggiero A. (1986b) Estudio geoquimico regional de la Subcuenca de Maturin. *Internal Report No. INT 01543,86, Intevep S.A.*, Caracas.

Talukdar S., Gallango O., Vallejos C. and Ruggiero A. (1987) Observations on the primary migration of oil in the La Luna source rocks of the Maracaibo Basin, Venezuela. In *Migration of Hydrocarbons in Sedimentary Basins*, pp. 59–78. Editions Technip, Paris.

Volkman J. K., Alexander R., Kagi R. L. and Rullkötter J. (1983) GC-MS characterization of C_{27} and C_{28} triterpanes in sediments and petroleum. *Geochim. Cosmochim. Acta* **47,** 1033–1040.

Waples D. W. (1980) Time and temperature in petroleum formation: Application of Lopatin's method to petroleum exploration. *Bull. Am. Assoc. Pet. Geol.* **64,** 916–926.