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Petroleum System of the Cuban Northwest Offshore Zone

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ABSTRACT

In order to quantify the petroleum potential of the northwest offshore zone of Cuba, the source-rock potential has been estimated as well as the maturation level and the possible migration pathways. An interpretation of new seismic lines acquired by Compagnie Générale de Géophysique (CGG) has been coupled with field work and well data synthesis. To better characterize the source rocks, Institut Français du Pétrole's (IFP) Rock-Eval 6 apparatus was run on about 300 samples, and the analyses have been added to the existing IFP and Cuba Petroleo's (CUPET) databases. Specific kinetic parameters have been computed and modeling has been performed using both 1-D and 2-D models of maturation and migration processes.

Several source-rock intervals could be defined in the area: (1) synrift clastic Jurassic, (2) deep-basin Upper Jurassic and Lower Cretaceous carbonate formations, and (3) Middle Cretaceous facies, also carbonates. One of the main results of this study is evidence of the potential of a deep petroleum system in the siliciclastic rift sequence. Shales from a Middle Jurassic synrift section initially appear to have good potential, depending on the maturity of the offshore zone, sufficient depth of the initial synrift half grabens, and the postrift carbonates being several

kilometers thick. Upper Jurassic/Lower Cretaceous source rocks associated with deep-water carbonates are largely immature in the deep offshore (Northwest Cuba) except near the coast, where maturity level is high mainly because of thrusting and/or thickness of the foreland deposits. The third source rock is middle Cretaceous (Aptian/Cenomanian), recognized in onshore Cuba as well as in an Ocean Drilling Project (ODP) well; it appears to be an excellent source rock. In the offshore zone, these source rocks are mature only when buried under the flexural basin. The migration pathway under Jurassic evaporites and the middle Cretaceous unconformity (MCU) may lead to long northward as well as lateral migration from the kitchens. In the vicinity of the island of Cuba, in the first 100–150 km northward from the coast, various petroleum systems are active, and the high quality of numerous Cretaceous source-rock intervals show promise for hydrocarbon exploration in the area.

INTRODUCTION

Oil exploration in Cuba mainly has been active onshore, where key problems for exploration have been focused on trap geometries. The traps are all situated in the highly thrusted area, some of them below an ophiolitic sheet. In this context, the source-rock potential of the full lithostratigraphic column has been incompletely evaluated, although numerous producing fields and oil seeps on the island suggest the existence of various source rocks in the oil windows. The aim of this study, a collaboration between CUPET, IFP, and CGG, has been to evaluate the petroleum potential of the northwest offshore zone of Cuba. First, a reevaluation of the various facies from both syn- and postrift as well as from Tertiary foreland deposits has been performed. Then, maturation/migration modeling has been carried out. In parallel, a complete reconstruction of the paleo-environment during the Jurassic and Cretaceous has been done at a more regional level, including the full northern coast of Cuba as well as the southern Florida and eastern Yucatán Peninsulas (Figure 1). This stratigraphic synthesis is presented in detail in Gaumet, 2002, personal communication. Within the northwest Cuba thrust belt, the existence of more than 15 oil fields demonstrates that a petroleum system is indeed active. The traps are associated with drag-fold staking as duplexes in the belt during the last phase of the orogen (lower–middle Eocene). Onshore, the reservoirs are deep-sea carbonates from the Kimmeridgian to Lower Cretaceous and clastics from the uppermost Maastrichtian. The seals are represented mainly by synorogenic clays involved in the stacking of the sheets (see Perez and Blickwede, 2000, for a synthesis of the petroleum system of Cuba).

Hydrocarbons, both oil and gas, from the wells also have been sampled and analyzed. Details of the geochemical oil and gas characterization can be found in Magnier et al., 2004. The principal conclusions are summarized herein.

GEOLOGICAL SETTING

The southeastern Gulf of Mexico (Figure 2), which connects the Yucatán Straits with the Straits of Florida, is a seaway linking the Central Gulf with the Caribbean domain since the Upper Jurassic (Marton and Buffler, 1999). It has recorded a Jurassic through Early Cretaceous passive-margin evolution directly connected to the break-up of the western Pangea. To the north, the southeastern Gulf of Mexico, which is underlain mostly by Mesozoic oceanic crust (Marton, 1995), consists of the flat, deep-marine turbidite Florida plain, where water depth exceeds 3000 m. It is positioned between the steep Campeche and Florida escarpments. To the south, the southeastern Gulf of Mexico is a higher-standing broad area cut by several erosional channels and underlain by thinned continental crust (Schlager et al., 1984; Marton, 1995). Several knolls (such as Pinar del Rio and Jordan) exist in the area and represent basement highs on which were superimposed stacked platforms and which were presumably Lower Cretaceous in age (Bryant et al., 1969; Schlager et al., 1984; Marton and Buffler, 1994, 1999). The modern Florida-Bahamas domain is dissected by several troughs where deep-marine currents flow (for instance, the Gulf Stream) are canalized. The Strait of Florida was previously a shallow-water depositional setting during the Upper Jurassic/ Lower Cretaceous. It was thought that the Strait of
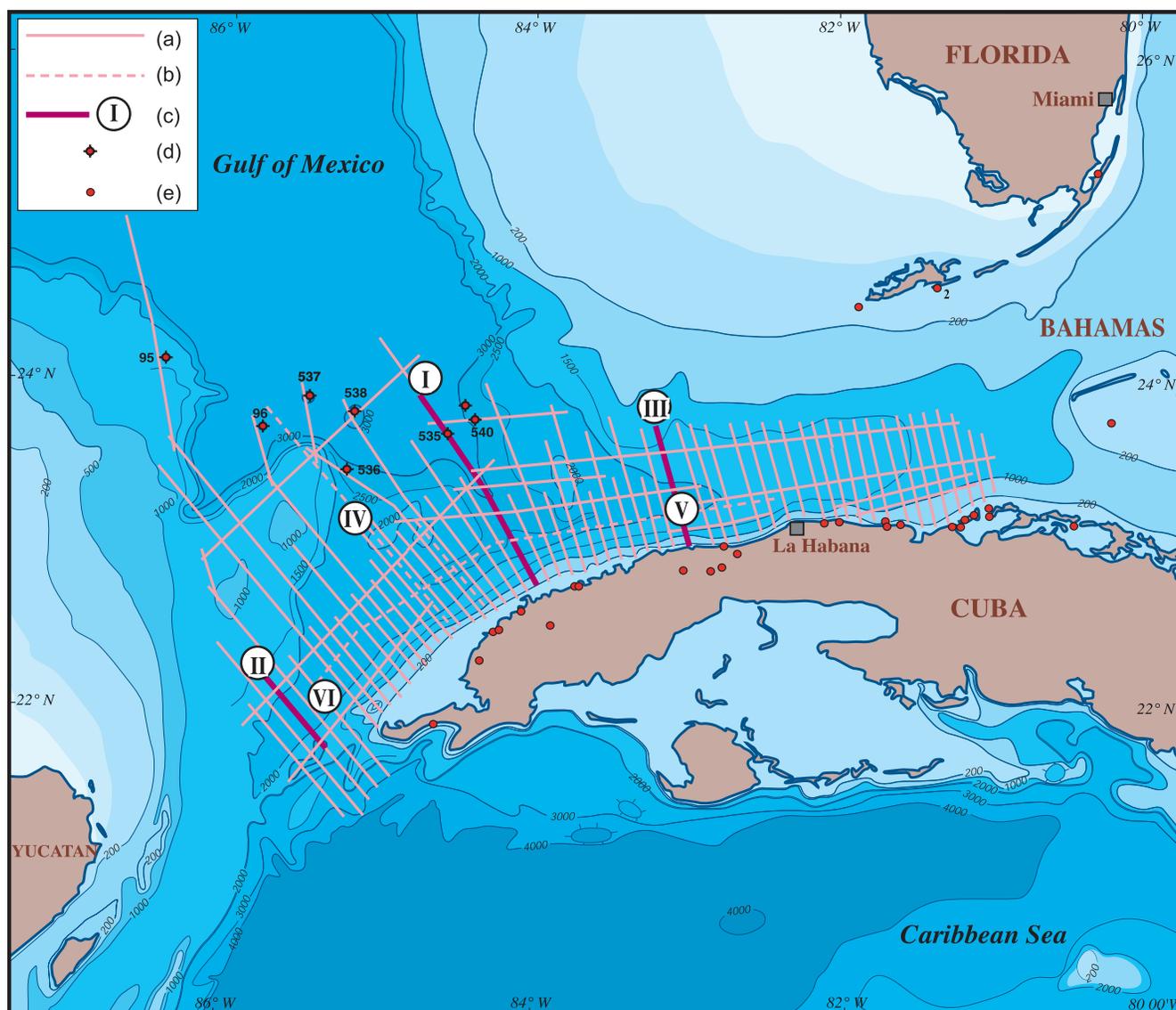
Figure 1. Schematic map showing sampled wells and outcrops, as well as seismic section locations. a = 2001 CGG nonexclusive seismic survey offshore northwest Cuba; b = 1984 seismic survey; c = seismic examples (I, II, and III shown in Figure 3; IV, V, and VI shown in Figure 12); d = ODP boreholes; e = industry wells used in this study.

Florida had become a deep-water trough in the Middle Cretaceous (Denny et al., 1994).

From a geological point of view, the island of Cuba is the result of orogenic interaction between a Cretaceous volcanic arc and the extensional continental margin of North America. The collisionnal phase has been studied by various authors who have defined several tectonostratigraphic units. Details of compressive events in the inland Cuba are not in the scope of this paper and may be found in Iturralde-Vinent, 1994; Tenreyro et al., 1994; Sanchez and Tenreyro, 1996; and Pszczolkowski, 1999.

The Gulf of Mexico began to form during two rifting episodes of Late Triassic/Early Jurassic (?) and Middle Jurassic ages (Marton, 1995), represented by

the half graben morphology in the northern Cuba provinces (Sequence A, Figure 2). To date no offshore well is deep enough to enable collection of date from the bottom of the half graben on seismic lines. Our interpretation is based on on-land dates and the seismic facies analyses. An important geological event is the deposition of a salt layer across the Gulf of Mexico. This salt is rather thick and continuous in both west and east sides of the Gulf of Mexico, but it is more ''restrained'' in the eastern part (Sequence B). Formations containing halite, gypsum, and white anhydrite have been found in a few wells in onshore Cuba (Punta Alegre Formation, Wells: Collazo-1 and Tina-1 and -3). The seismic facies analyses of these series is specific (high amplitude–low frequency) and
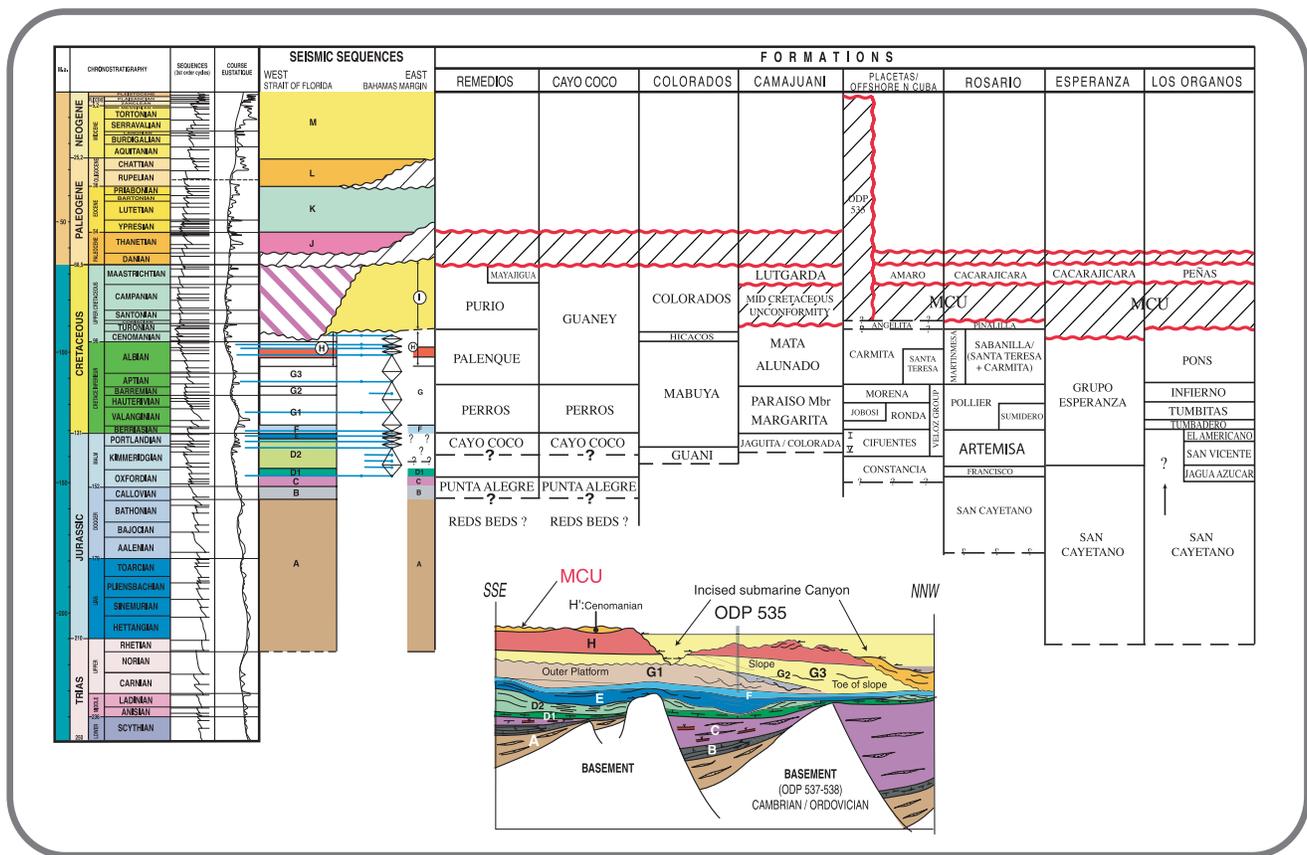
Figure 2. Schematic cross section showing correlation of the seismic sequences with lithostratigraphic charts (north-central and western Cuba).

may be extended to the off-shore area without much doubt. This seismic sequence could be extended to the Strait of Florida domain, where well data are available. The rifting led to the creation of a Late Jurassic oceanic crust during the Malm. Southward, the Proto-Caribbean rifted at more or less the same time, but structures in horsts and grabens are dominant. The early post-rift sedimentation during thermal subsidence consisted of shallow-marine platform that developed along the northern Proto-Caribbean margins. This first carbonate build-up phase took place from the Oxfordian to the lower Tithonian. The end of the normal fault activity is still debatable and may not be synchronous over all the area. Nonetheless, the Berriasian flooding event has sealed most of the tilted blocks (Sequence F). Rapid thermal subsidence then led to the deposition of stacked, shallow-water platforms (Sequences G1, G2, G3, and H). Total thickness of this second carbonate build-up phase reaches approximately 1.5 km (Figure 3).

The central basin deepened from the Aptian after a phase of relative starving. Current intensification and sediment starvation determine a major unconformity generally called the middle Cretaceous unconformity (MCU), which started after the late Cenomanian and continued to the Maastrichian or later. The great Antilles Arc then collided with the Bahamas margin in the late Paleocene (Gordon et al., 1997). Since then, clastis and flysch were deposited in the flexural basin (Sequences J and K), whereas platforms persisted in Yucatán and south Florida. Note that the thrusting ceased in the Eocene, whereas infilling of the basin continued to the Quaternary because of sediment influx resulting from the mountain belt erosion. Few minor reactivations occurred during the Tertiary (Masaferro, 1997). This evolution is synthesized in Figure 4.

The structural position of these different sequences has been summarized in a schematic cross section in Figure 2, which also shows the position and depth of the deepest ODP well in the area.

SOURCE-ROCK EVALUATION

Considering the existing source-rock information, we focused on new acquisitions of rock samples mainly from the Jurassic sediments of western Cuba and particularly from the synrift stage. New analyses
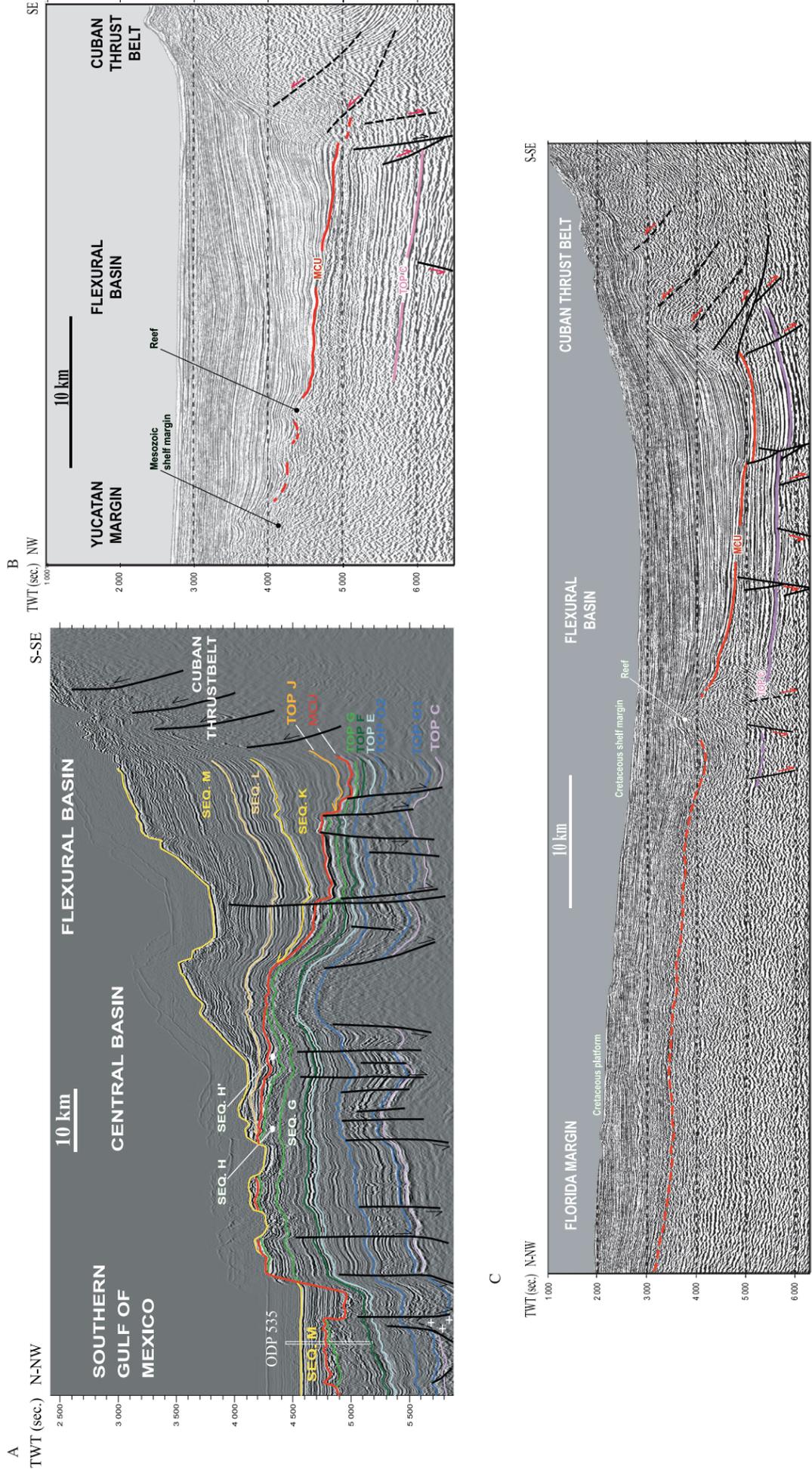
Figure 3. Seismic sections (see location in Figure 1). A = line III; B = line I; C = line II.

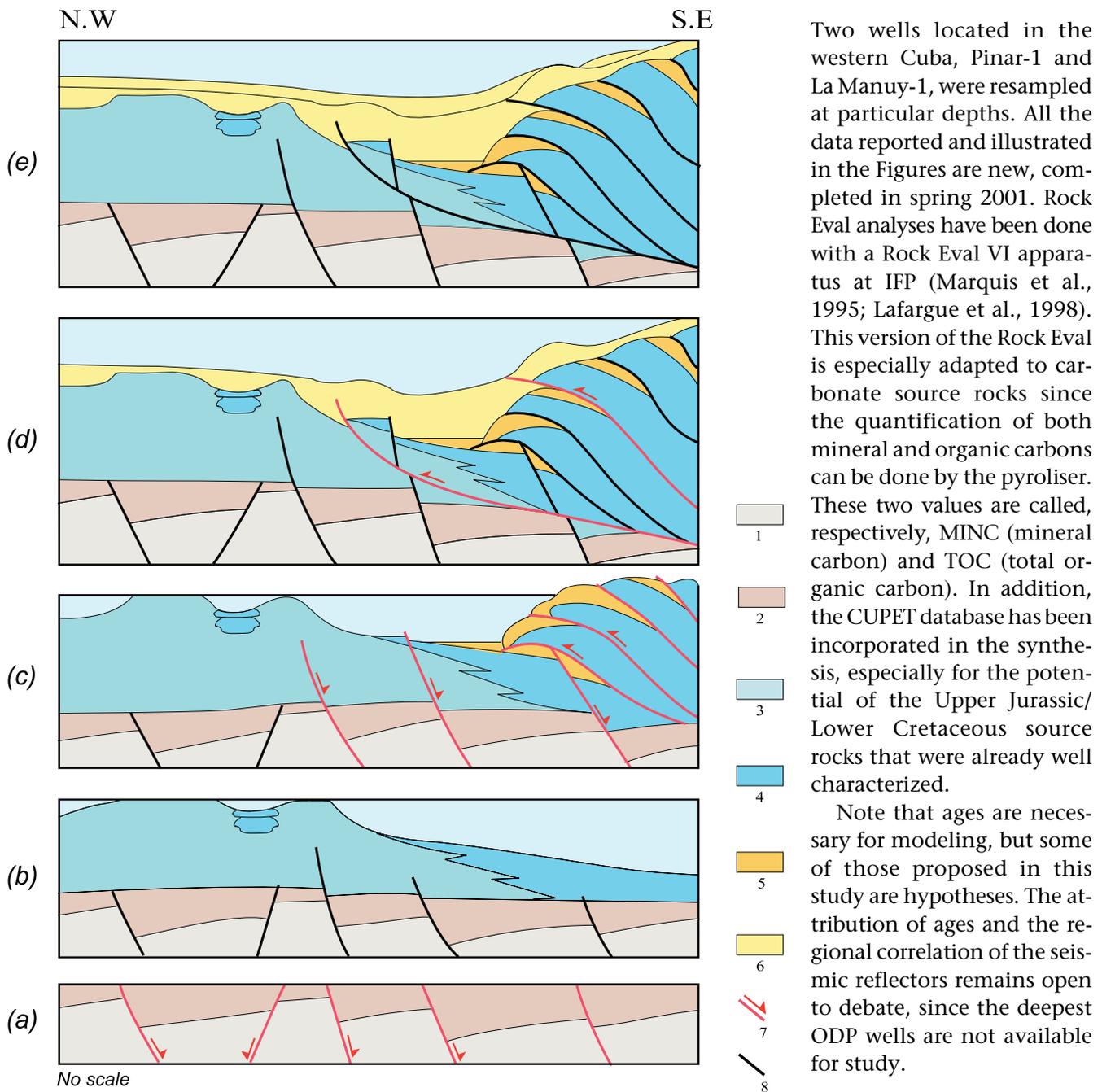N.W   S.E

No scale

Figure 4. Schematic evolution of the northwest offshore area of Cuba. (a) Proto-Caribbean synrift period (Early to Middle Jurassic). (b) Postrift subsidence. (c) End of Cuban orogen in the early Eocene; the collision started in the Maastrichian, caused by northeastward migration of the Cuban island arc. (d) Infilling of the basin, which started as foreland during the previous phase. A slight Neogene compressive reactivation induced the formation of a few new inverse faults. (e) Passive subsidence caused by the sedimentary influx from the Cuban island. 1 = continental basement; 2 = synrift; 3 = postrift carbonate platform (end Jurassic to Cretaceous); 4 = postrift deep-water facies (Late Jurassic to Cretaceous); 5 = Tertiary syntectonic deposit; and 6 = Tertiary posttectonic deposits. Active faults are in red.

Two wells located in the western Cuba, Pinar-1 and La Manuy-1, were resampled at particular depths. All the data reported and illustrated in the Figures are new, completed in spring 2001. Rock Eval analyses have been done with a Rock Eval VI apparatus at IFP (Marquis et al., 1995; Lafargue et al., 1998). This version of the Rock Eval is especially adapted to carbonate source rocks since the quantification of both mineral and organic carbons can be done by the pyroliser. These two values are called, respectively, MINC (mineral carbon) and TOC (total organic carbon). In addition, the CUPET database has been incorporated in the synthesis, especially for the potential of the Upper Jurassic/Lower Cretaceous source rocks that were already well characterized.

Note that ages are necessary for modeling, but some of those proposed in this study are hypotheses. The attribution of ages and the regional correlation of the seismic reflectors remains open to debate, since the deepest ODP wells are not available for study.

The Synrift Clastic Deposits

This facies was thought to be deposited in small basins and half grabens found at the bottom of the seismic sections. In the schematically interpreted cross sections, it is identified as groups A, B, and C (Figure 2).

of sampled potential source rocks, both in central and in western Cuba, were done to improve the understanding of the petroleum system processes.

Group A has been deposited between the base Jurassic to the Bathonian (approximately 210–160 Ma). It is represented by the San Cayetano Formation

in western Cuba. It is a siliciclastic sequence with thin intercalations of black shales and sandstones (Haczewski, 1976) that outcrops largely in the Pinar del Rio province but also southward on the island of Juventus and in the eastern part of the island of Cuba. The San Cayetano Formation has been dated on land in outcrops as well as in various wells (Arroyos-1 and -2 and Esperanza-2).

The Rock Eval VI data from this formation are presented in Figure 5, and they show that it is difficult to estimate the initial potential because all the samples are in the mature-to-overmature range. Nevertheless, at the three sites where samples are numerous, the results are rather homogeneous, with a remnant TOC between 0.7 and 1.5%. The average TOC, omitting the samples from one site where the

facies was very silty, is 1.1% for a production index (PI) of more than 0.98. (The production index measures the quantity of already generated hydrocarbon versus the original quantity; i.e., an immature sample may have a low PI, one in the oil window may have a PI of around 0.5, and an overmature sample may have a PI between 0.9 and 1). It means that the initial TOC of the San Cayetano Formation was about 3%. It is thus impossible with the current data to have a precise idea of the hydrogen index (HI), the best value being 170 for a sample with a PI of 0.85 (remnant S2 = 3.1 mgHC/g). In the modeling, we have used 600 as a conservative value. Eventually, it could be more.

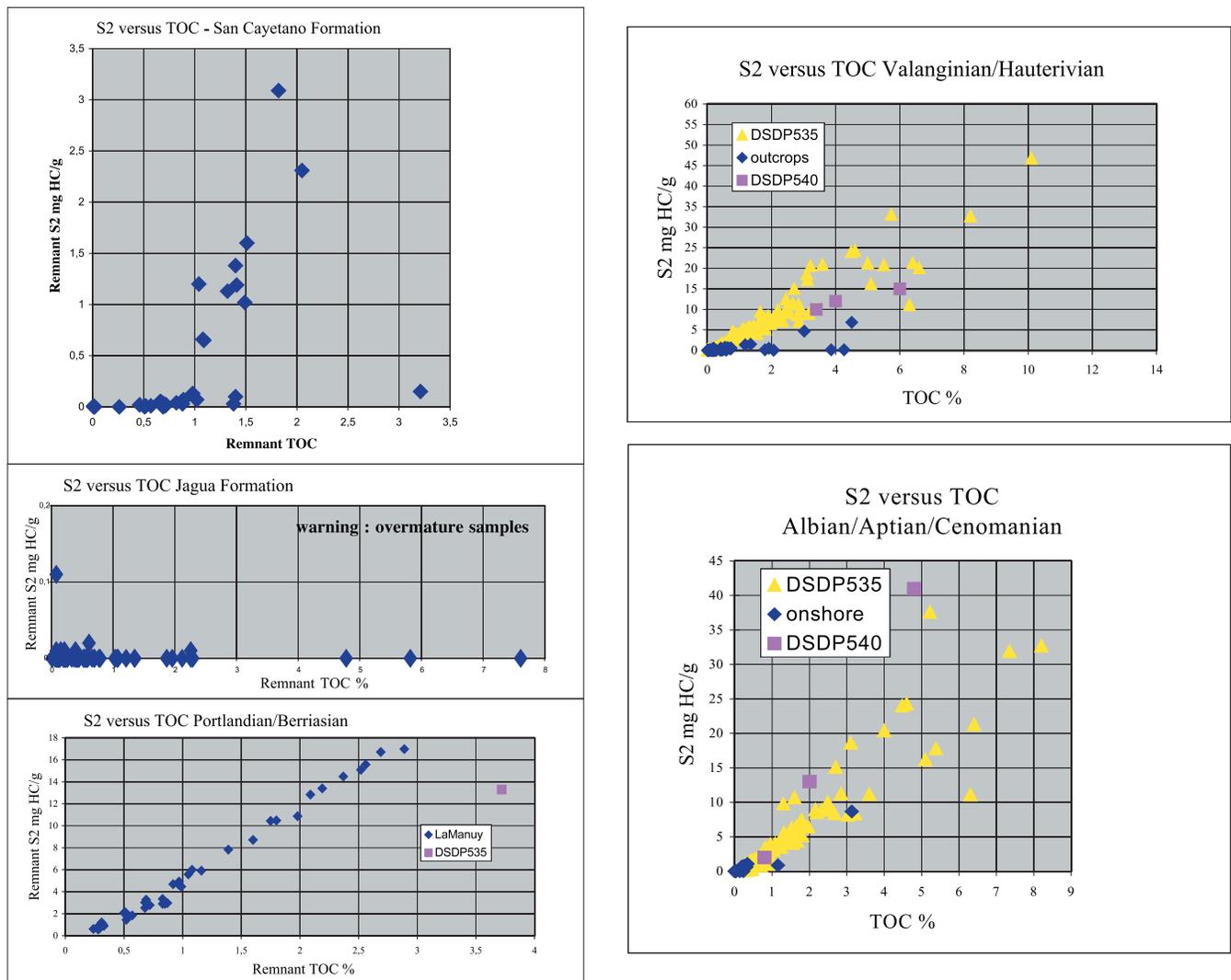Group B corresponds to the Callovian (160–152 Ma) and consists of carbonate layers of the synrift

Figure 5. Rock Eval data from outcrops and wells. Onland, the La Manuy- and Pinar-1 wells have been resampled and analyzed in the Cretaceous sequence. All these data have been measured with Rock Eval 6 in this study except the ODP data, which was measured in 1984 with Rock Eval 2 and published by Herbin et al. (1984).

deposits, with evaporites and some salty intercalations. It includes the upper part of the San Cayetano Formation and the Francisco Formation. Dating has been done on the equivalent Punta Alegre Formation in central, Cuba which has been encountered in several wells.

Group C (Oxfordian) consists of shaly layers from the synrift period. These source- rock potential characteristics seem to be the same as those of the San Cayetano Formation. The thickness of this facies is variable, from a few meters to more than 2 km.

In general, because of tilting of the blocks during extension, these synrift facies are missing on the crest of the tilted blocks, caused by pinch-out in case of continuous tilting and/or erosion during the emergence of the crests.

Postrift Regional Carbonate Platform (from Middle Oxfordian to Hauterivian)

Figure 5 presents the new Rock Eval data from both outcrops and wells that have been measured. In general, all the samples have good potential. We will comment on the results using classical names designated by geologists who have studied the Cuban onshore; but for the modeling purpose, later we shall consider this platform as one thick source rock.

Group D1: Jagua Formation (Upper Oxfordian)

The base of the carbonate series is known as the Jagua Formation in Western Cuba. The Rock Eval data are presented in Figure 5. All the samples are overmature; therefore, the S2 is 0 and the Tmax, HI and OI, cannot be analyzed in terms of initial potential. Nevertheless, the remnant TOC reaches 7.61%. On average, the TOC is 0.9% for the PI of 0.99. As a range of values, the remnant TOC of a completely overmature sample is more or less than one-third of the initial value. It means that this series, which had been disregarded previously, may also be considered as a source rock (initial TOC of about 3%) and is incorporated in the source-rock potential of the area.

The Jagua Formation is analogous in time to the Smackover Formation, which is considered to be an important source-rock level in the Gulf of Mexico megabasin. In Central Cuba, the isochronic section is known as the Constancia Formation and is considered to have a certain oil potential.

Group D2: San Vicente Formation (Kimmeridgian)

The Group D2 seismic package corresponds to the San Vicente Formation in western Cuba. It is identified as a shallow-water carbonate section. In central Cuba, it corresponds to the lower part of Cifuentes Formation. None of the collected (April 2001) samples from this formation contain any organic carbon values (TOC less than 0.05%, which is extremely poor). The San Vicente Formation represents the shallow-water facies and thus cannot be considered as a potential source-rock level.

Group E: El Americano, Artemisa, and Cifuentes Formations (Upper Kimmeridgian – Tithonian)

Historically, the best results of Rock Eval analyses have been reported in this part of the section. It is necessary to note, however, that a large amount of work was performed in central Cuba (Cifuentes and Trocha Formations). Our new analyses of these formations confirm the high potential of the synchronous facies, which is also present in western Cuba.

For the Cifuentes and Trocha Formations, our best values average 17 mgHC/g for the S2, 621 for the HI, and 2.9% for the TOC. These values are from the wells La Manuy-1 and Pinar-1. The source rock is rather homogeneous (average S2 = 5.5 mgHC/g, average HI = 437), which is not surprising since the cutting has been collected every 2 m, whereas bed thickness on outcrops is about 5 cm. The rock has a high mineral content of around 12%.

Westward, for the El Americano and Artemisa Formations, the average values on our data are lower (S2 = ~1 mg HC/g and HI = 151), but one should take into consideration that most of the analyses were done using overmature source rocks sampled in this westernmost part. The best values are S2 = 11 mg HC/g and HI = 640. The rock consists of thin-bedded black carbonates (bed from 5- to 10-cm thick) interbedded with a few millimeters of more shaly facies. Data indicate that these thin beds have a carbonate base (MINC ~10%). Generally, these thin beds should be richer in organic matter, but results did not emphasize such differences.

Group F: Tumbadero, Sumidero, and Ronda Formations (Berriasian to Hauterivian)

This section has been studied extensively in Central Cuba. Extremely poor and scarce data existed previously in western Cuba. As observed in the Artemisa Formation, the sampling has been done in both outcrops and cuttings. Data shows that the Neocomian section in western Cuba is as rich as in central Cuba; the best S2 values reach 26 mgHC/g, HI = 608, and TOC exceeds 6% for immature samples (PI = ~ 0.1). Some of the samples were mature source rocks;

therefore, the average data is not representative of the initial potential of the formations.

Middle Cretaceous Bahamas Channel Deposit

Group G2-G3: Pons and Carmita Formations (Aptian–Albian–Early Cenomanian)

The lower Aptian–Cenomanian section in western Cuba has been known mainly offshore because of the ODP well, while onshore data has been scarce prior to this study. The new results show the existence in onshore Cuba of an additional Lower Cretaceous source-rock level that is synchronous with the source rocks in the ODP wells, and therefore suggests a possible regional extension of these source rocks.

From the outcrops, the best values are S2 = 9 mg HC/g, HI = 280, and TOC = 3.1% for a mature sample (PI = 0.8), which means an initial S2 of more than 30 mgHC/g. There are three ODP wells in this area; two have been sampled for Rock Eval analyses and show an excellent potential for the Cretaceous sequence. The highest S2 are found in the Valanginian and Hauterivian (S2 as much as 50 mg HC/g and HI as much as 700) in the well DSDP 535. In these wells, the Middle Cretaceous does not show good values (S2 < 2 mgHC/g), but the top of the Lower Cretaceous (upper Albian) contains a few thin, excellent levels (S2 as much as 40 mg HC/g, HI as much as 800). Figure 6 shows the geochemical log of well 535.

Group H (Cenomanian)

The Upper Cretaceous section is considered to be a source-rock level both in central Cuba and in the ODP wells, although the thickness of the organically rich beds is very small in ODP 535 (see Figure 6). In western Cuba, data was very scarce with the exception of good sampling in the synchronous upper part of the Sabanilla and Carmita Formations in the Sierra del Rosario (Pinar-2 well, core 5 at 704-m deep). From the new data, TOC values may reach 3% and the HI may exceed 610 for immature samples. In the well La Manuy-1, the thickness of the source rock (Cenomanian/Turonian Angelica Formation) exceeds 70 m, with a constant potential of about 6–8 mg HC/g for the S2, and 550/600 for the HI (immature samples, between 726- and 800-m deep). The Upper Cretaceous sequence is partially eroded or missing because of lack of sedimentation during the middle Cretaceous unconformity (MCU). A second unconformity exists at the end of the Maastrichian, as shown in Figure 2.

Group J (Paleocene)

Analyses in Paleocene sediments, known as the seals in a number of the onshore fields, have sporadically shown relatively high levels of TOC in Central Cuba; e.g., the wells Marbella Mar-2 and LPC-1. The present study confirms this tendency (S2 as much as 10.5 mg HC/g, HI as much as 600 in the La Manuy-1 well at 1762-m deep). Nevertheless, the section is generally immature onshore.

The Paleogene deposits are related to the foreland, and there is no regional stability in the sedimentary environment and lithology.

Regional Extension of the Source Rocks

In conclusion, the source rocks in Cuba are numerous and the source-rock potential is never a weak parameter in this area. Formations with source-rock potential may be grouped in four "source rock" categories.

1) **Synrift clastics** (mainly the San Cayetano Formation in western Cuba): New seismic data from offshore of northwest Cuba show that Jurassic half grabens caused by the rifting phase are present in a large part of the northwest Cuban deep offshore. Figure 7 shows the possible extension of the source rock associated with these grabens.

2) **Upper Jurassic/Lower Cretaceous carbonate facies**, where numerous formations have good potential. These are found in most basinal facies in onshore Cuba. The Jurassic and Early Cretaceous section in the offshore Cuban sector of the Gulf of Mexico remains undrilled; nevertheless, the Oxfordian and Tithonian are source rocks in the Mexican part of the Gulf of Mexico (Guzman and Mello, 1999), as is the area along the Florida shelf slope (Gohrbandt, 2001). In these different cases, a marine source rock is associated with carbonate basinal facies. Figure 7 shows the possible extension of this facies in the studied area.

3) **Upper Cretaceous sections**, which is also a carbonate source rock associated with marl and mudstones deposited in marine-restricted environments (Guäney Formation, Bahamas Channels).

4) **The Paleogene**, which is related to the foreland deposit and is often involved in the Cuban thrust belt.

In the northern part of the Gulf of Mexico, similar potential has been published in the Perdido fold belt (Fiduk et al., 1999), where the best source rocks are
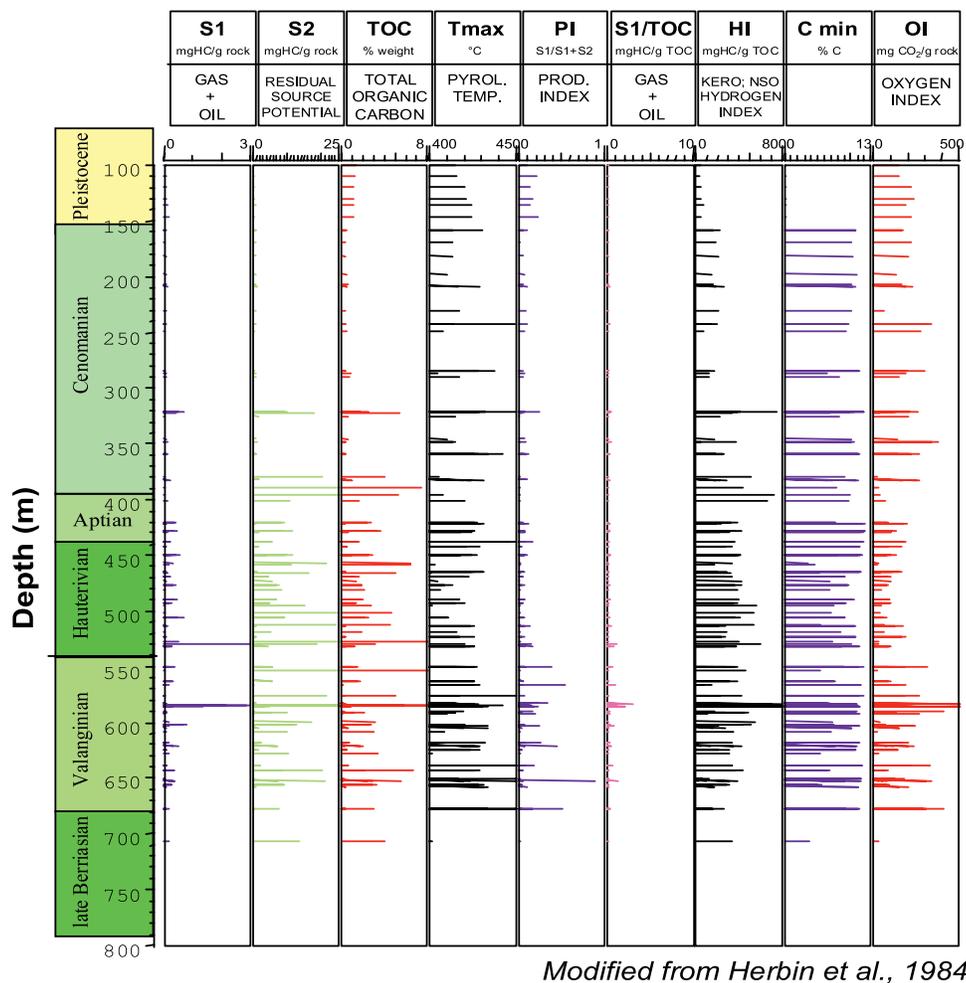
Geochemical data - well ODP 535

Modified from Herbin et al., 1984

Figure 6. ODP 535 geochemical profile, data from Herbin et al. (1984).

(west of Havana) and in serpentinite reservoirs in Cantel (east). Oil and gas samples were compared to the Jurassic and Cretaceous reservoired fluids.

Bulk

The bulk properties of the Upper Jurassic and Lower Cretaceous crude oils highlighted rather homogeneous viscous (°API 8–20) and sulfurous (2–9%) fluids, with high proportions of polar compounds and metal content such as vanadium and nickel (Table 1).

The sampled Tertiary reservoired fluids had higher °API gravities, and lower sulfur and metal content.

Depositional Environments of Parent Source Rocks

Molecular analyses of most Upper Jurassic and Lower and middle Cretaceous crude oils showed that they clearly were linked to organic matter deposited in limestones and in restricted anoxic/hypersaline conditions. Oil/oil and oil/source-rock correlations were straightforward and in agreement with carbonate environments and reflected Type II-Type IIS organic matter. As an example, predominant hypersaline marine markers such as gammacerane, high phytane/pristane ratios, high C_{35}/C_{34} hopane ratios, and strong C_{24} tetracyclics were clearly detected by gas chromatography–mass spectrometry analyses. Little if no biodegradation was detected in these reservoired fluids.

Accumulated fluids in Tertiary and serpentinite reservoirs in shallower depths were more conventional oils with distinct features, which associated them more readily to siliciclastic depositional environments. Reservoired Tertiary oils at low depths (<800 m) showed minor to strong occurrence of bacterial degradation. More terrigenous influence was noted in the biomarkers, highlighting a significant

upper Valanginian (average TOC of 4.8%) and Turonian/Coniacian (average TOC of 4%), but the full sequence, from the Kimmeridgian to the Santonian, is a source rock.

CURRENT HYDROCARBON DATA IN CUBA

Oils and gases were collected for the most part from Upper Jurassic and Lower and middle Cretaceous carbonate reservoirs. The sampling made with CUPET allowed us to collect samples at representative wells in the northern onshore area: Via Blanca, Yumuri, and Boca Jaruco fields, and farther northeast of Havana at Varadero, Marbella Mar, and Cantel fields.

Few Tertiary reservoirs in the melange of the Manacas Formation were sampled at Martin Mesa

differences in the carbonate samples and perhaps suggesting some other source rocks for these accumulations.

Thermal Maturity

Thermal maturity levels of both Upper Jurassic and Lower Cretaceous reservoired oils converged to an overall low thermal degree of hydrocarbon cracking (detailed by Magnier et al., 2004. The shallow, serpentinite, reservoired Tertiary crude oils, on the other hand, were clearly more thermally evolved.

Associated gases provided useful information relevant to maturity and hydrocarbon distances of migration from kitchen to reservoirs as supported by molar and isotopic compositions of C1-C5 fractions. Geochemical gas data pointed to thermogenic, and not biogenic, generated hydrocarbons, with a lower thermal maturity in Upper Jurassic reservoired gases (vitrinite reflectance of 0.8–0.9) as compared to gases in Lower Cretaceous reservoirs (vitrinite reflectance of 0.9–1.0). However, both have gases in the beginning of the hydrocarbon cracking window. A dry gas with a very evolved thermogenic carbon isotopic signature was observed in one Martin Mesa well (3A).

Figure 7. Schematic map showing the potential offshore extension of three of the source rocks present in onshore Cuba. (a) Shaly Jurassic synrift. (b) Late Jurassic deep-water carbonates (1 - Oxfordian, 2 - Thithonian). (c) Early Cretaceous deep-water carbonates (1- early Neocomian, 2 - late Neocomian).

Migration and Secondary Processes

The northern Cuban fields produce a majority of oils of low API gravity and high sulfur content. However, these bulk properties were not found to be synonymous with biodegraded fluids, but rather reflected reservoired fluids of low thermal cracking levels of Type IIS–Type II-derived organic matter. Moreover, the oils correlated well to the underlying sediments corresponding to the source rocks, and also to an offshore ODP-535 site corresponding to a Lower Cretaceous stained limestone.

Little if no biodegradation is occurring in the Upper Jurassic and Lower and middle Cretaceous res-

ervoirs, although the temperatures are not above 80°C in most reservoirs. Mild to severe biodegradation was observed only in the Tertiary serpentinites, Cantel crude oils, and in Martin Mesa field.

Low to middle thermal maturities were observed in Upper Jurassic and Lower and middle Cretaceous crude oils and gases, while Tertiary reservoirs had fluids with higher maturation levels, and sometimes complex signatures resulting from secondary effects like mixing/hydrocarbon recharging and early biodegradation (enhanced by the low temperatures in reservoirs today).

The isotopic and molar compositions of gases indicate that Jurassic and Cretaceous reservoirs have hydrocarbons that have undergone short migration distances.

Based on these results, we propose that these onshore northern reservoirs are acting both as reservoirs and source rocks. In these low bulk-porosity carbonate rocks, the porosity and, therefore, the encountered reserves are mainly a result of the fractures.
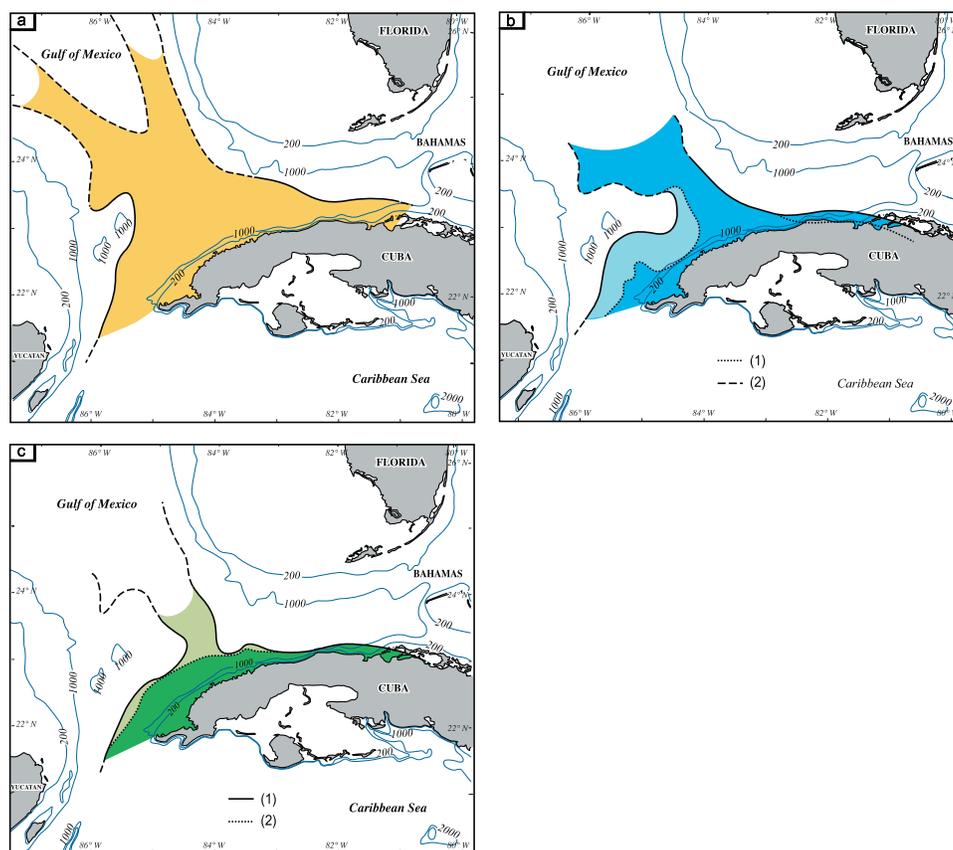
Table 1. Onshore cuban oils.

WELL	Depth Top	Depth Bottom	Cord.X UTM	Cord.Y UTM	Geological formation	Age	*API	Sulfur (%)	Nickel (ppm)	Vanadium (ppm)	% ASPH*	% RES*	% ARO*	% SAT*
MARTIN MESA 1	824	807	328377	351639	Manacas	Lower Eocene	23,2	1,38	24	12	6	30.6	25.3	34.1
MARTIN MESA 24	733	773	328377	351639	Manacas	Lower Eocene	18,6	0,69	13	5	1.4	21.5	31.9	40.8
YUMURI 37	1280	1350	380000	368739	Cifuentes	Upper Jurassic	6,3	5,96	70	111	10.9	43.4	25.0	13.3
YUMURI X	2321	3600	380000	368739	Cifuentes	Upper Jurassic	na	7,64	54	102	16	45.0	20.2	13.2
YUMURI 31	1487	1467	380000	368739	Ronda	Lower Cretaceous	10,4	4,6	na	na	24.8	35.9	21.4	10.1
VIA BLANCA 101	1380	1410	390671	372560	Carmita	Lower Cretaceous	33,7	2,9	9	14	2.3	28.1	23.7	38.9
VIA BLANCA 103	1989	2054	390671	372560	Cifuentes	Upper Jurassic	21,1	6,2	30	50	11.3	34.3	22.1	26.4
BOCA JARUCO 359	1826	1857	394448	373227	Cifuentes	Upper Jurassic	na	6,76	28	47	9	42.7	23.4	19.3
BOCA JARUCO 370	1306	1356	394448	373227	Carmita	Lower Cretaceous	na	3,53	23	23	1.2	31.8	30.1	31.2
MARBELLA MAR 1	2550	2565	474196	367108	Paraiso	Lower Cretaceous	11,0	5,69	45	76	19	38.6	20.6	15.6
MARBELLA MAR 2	1898	1912	474186	367106	Vega	Paleocene	26,6	na	na	na	10.35	45.4	23.8	15.8
VARADERO 103	1690	1720	470647	365772	Cifuentes	Upper Jurassic	9,6	8,9	68	109	19.6	46.8	18.0	11.0
VARADERO 306	1613	1645	470671	366214	Cifuentes	Upper Jurassic	10,4	8,9	66	105	20.2	46.4	17.7	10.7
CANTEL 30	477	683	466078	363988	Serpentinite	Paleocene	12,0	1,17	na	na	3.7	38.9	27.3	27.4
CANTEL 33	1140	1172	465130	362800	Carmita	Upper Cretaceous	na	na	na	na	5	30.1	27.1	34.2
CANTEL 229	424	488	468572	362575	Serpentinite	Paleocene	14,1	na	49	41	3.6	38.8	28.1	27.0

%ASPH* Asphaltenes.
%RES* Resins.
%ARO* Aromatics.
%SAT* Saturates.

MATURATION/MIGRATION

In the Pinar del Rio province, where our field work was made extensively, oil seeps and oil shows in the source rocks are numerous. In most of the outcrops of the Upper Jurassic and Cretaceous limestones, oil is present in the fractures. This is coherent with the source-rock potential evaluation; the main exploration risk in the area is not the source-rock potential. In the current productive area of central Cuba, the maturity and the trap formation is caused mainly by the Tertiary burial during the thrusting. The chief questions about offshore would then be:

Is the postrift (Upper Jurassic and Cretaceous) mature under the foreland northward as well as westward, where there are no Tertiary deposits?

If the maturity and traps are pre-MCU, have we preserved the infilling?

Do synrift traps exist?

What is the accumulation timing of these eventual deep prospects?

Do synrift source rocks participate in the sourcing of the carbonate Cretaceous or older prospects?

In the next pages, we shall attempt to answer these questions with a modeling approach.

Maturation of the Northwest Offshore Area

Hypotheses

Two-dimensional TEMISPACK modeling has been done on the depth-converted seismic Line 123 which joins the north Cuban coastline to ODP well 535. This software has been designed for basin modeling purpose and allows study of sedimentation, erosion, compaction, heat-flow evolution, maturation, and migration of both water and hydrocarbons at basin scale. Because of the lack of deep well data and precise value of the permeability of the offshore Cuba series, the migration pathway proposed in this paper is very qualitative. Moreover, no specific prospect has been defined for the studied section. TEMISPACK software allows the user to describe the hydrocarbon (GOR, chemical contents), but it will not be used here since exploration is very immature in the area. Horizontal displacement is not allowed on this version of the software. The physics used to describe the various phenomena in the program can be found in Doligez et al. (1987), Ungerer (1990), and Vandenbrouke et al. (1998).

Data from DSDP well 535 have been used for the thermal calibration.

Stratigraphy and lithology: The geometry of the section is shown in Figure 8; the values used for the ages are the ones proposed in the first part of this paper. The Jurassic stratigraphic section onshore consists of siliciclastic rocks deposited in half grabens and interbedded with evaporites and hypersaline facies. Some carbonates also are present in Group C (see Figure 2).

Source rock potential: There are no data on the deep offshore source-rock potential of the synrift half graben of the northern Jurassic margin. Nonetheless, the presence of Type II marine source rocks should be accepted, because it may be extrapolated from the onshore data (San Cayetano Formation). The large extension of clastic source rocks is also suggested by regional synthesis in the Gulf of Mexico (Cole et al., 2001). As detailed previously, the postrift section composed mainly of carbonates could be divided into two facies: (1) basinal starved carbonate sediments and (2) shallow-water carbonate platforms and ramps. The deep-water facies are predominantly rich in organic matter; the shallow-water carbonates have a poor source-rock potential. A third source rock is modeled in the middle Cretaceous section, to take our data into account, as well as data from the DSDP well, where the best source rock is Lower Cretaceous (Valanginian to Albian) in age. The Paleogene source rocks have not been included in the models since their extension is unknown, and the burial on this section is too low to allow for any maturation possiblity. The source-rock location in the section is displayed in Figure 8.

Kinetic parameters: Kinetic parameters were studied in two samples from the La Manuy-1 well at 1740 and 2545 m in depth, which correspond to the Cifuentes Formation (Tithonian) and Trocha Formation (Tithonian), respectively. Initial Rock-Eval data on the two samples gave S2 = 12 mg HC/g, IH = 600, and S2 = 15 mg HC/g, IH = 614. The kinetic parameters have been done on the extracts (TOC = 40% and 52%, respectively). For the shales of the synrift formations, a classical Type-II marine source-rock profile has been chosen.

The evolution versus temperature and depth of these source rocks therefore is very close to a Type-II source rock, with a requested depth for the 10% transformation ratio (TR) the same as for the Cifuentes sample and the Type-II source rock, and only 200 m deeper for the La Trocha Formation sample. For the peak of the oil window, at TR = 50%, the difference is still minor.

Permeability: The basinal limestones are thinly bedded and fractured. The permeability measured in the wells shows high values. Therefore, no regional

a: Current geometry and stratigraphy

STRATIGRAPHY

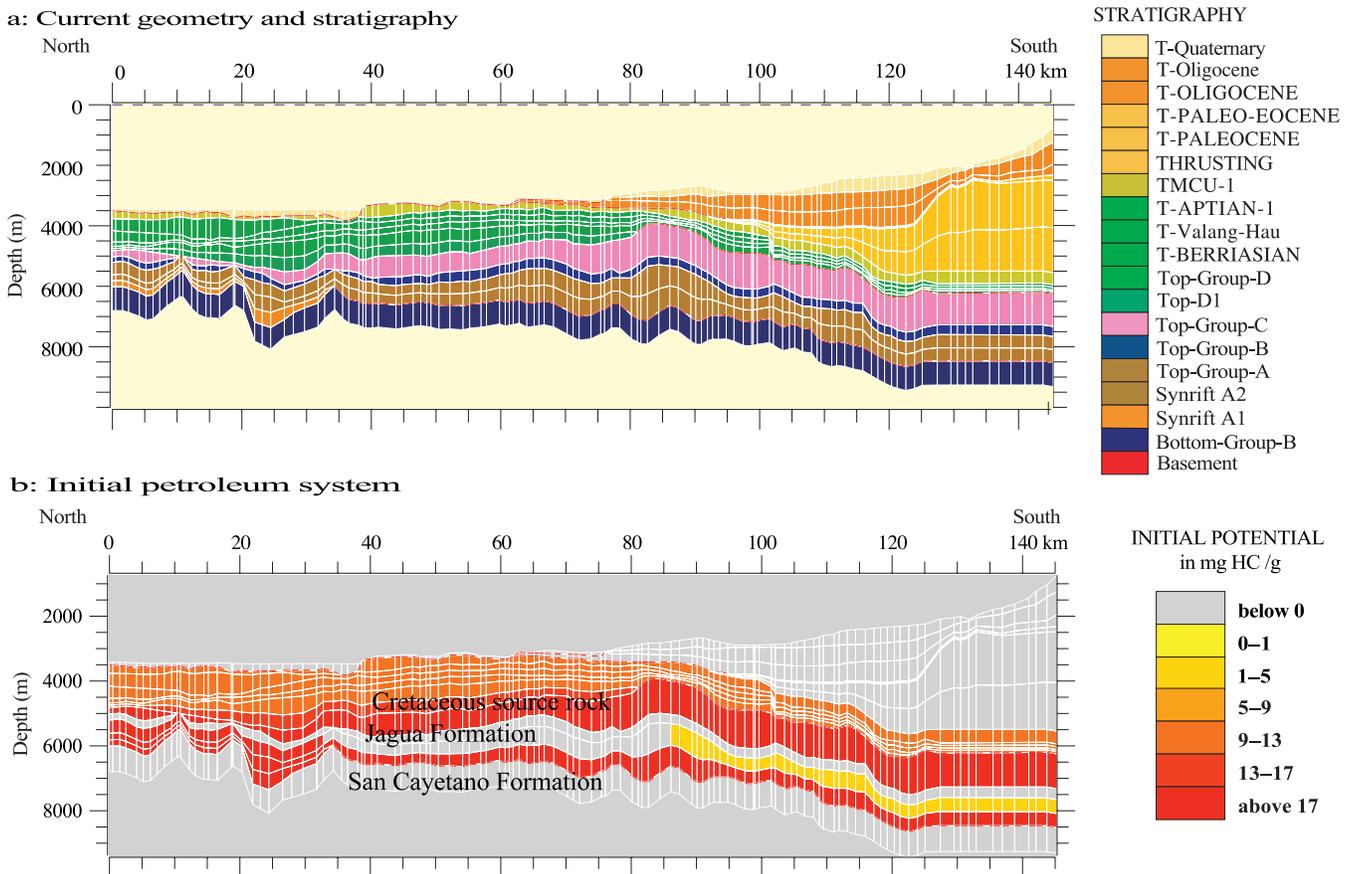b: Initial petroleum system

INITIAL POTENTIAL
in mg HC /g

Figure 8. TEMISPACK section based on the interpretation of Line 123 (see Figure 3). (a) stratigraphy; (b) initial source-rock potential (mg HC/g of rock).

seal can be defined in the Upper Jurassic/Lower Cretaceous sequence. In the complete sequence, the main potential seals are (1) the evaporitic sequence of the Middle and Upper Jurassic, (2) the MCU, (3) the condensed series of the upper Cretaceous, and (4) the thrusts, especially the basal décollement level of the thrust pile.

The hydraulic fault behavior is debatable. Nevertheless, in the case of large thrusts, the problem is easier than for normal faults. The field data generally show that the thrusts are good transversal seal—fluids above and below are different. However, because of the damaged zone of high-fracture density, or just because it is a transversal seal, longitudinal migration took place below the thrust, and sometimes above, but the two migration avenues are independent. Such behavior has been described, for instance, in the sub-Andean Zone of Bolivia (Moretti et al., 2002) and in the southern Pyrenean thrusts (Travé et al., 1998). As a result of the basal thrust seal behavior, the hydrocarbons generated below the thrusts migrate below the basal décollement to the foreland.

On the northwest deep-offshore Cuban domain, seismic lines show that some of the normal faults associated with the rifting remained active as late as the Berriasian and were reactivated in the early Tertiary in the flexural domain (see seismic data, Figure 3).

However, the sealing characteristics of the eventual evaporite horizons (Group B) have not been determined. In our model, permeability of the evaporite layers is considered to be ~0.01 μD. It could have been eroded at the level of the nose of the tilted block.

Boundary Conditions

Temperatures: A constant bottom-heat flow of 48 mW/m^2 has been used for the last 80 m.y.; the resulting heat flow in the sediments is ~60 mW/m^2. At the level of the DSDP-540 well, the gradient at the present time is 29°C/km. During the rifting phase, an increase of the heat flow of 25 mW/m^2 has been used, followed by a slow decrease. These values are compatible with known current heat flow in active or recently active rift systems such as the Gulfs of

Suez and Aqaba (Moretti and Chénet, 1987; Ben Avraham and Von Herzen, 1987). Nevertheless, at the level of seismic Line 123, the thickness of the synrift is too small (less than 2 km), and the Jurassic synrift heat-flow increase will not be sufficient to reach the beginning of the oil window.

The sea bottom temperature is taken at 5°C, since water depth exceeds 1000 m. The left and right sides of the model are adiabatic.

Since we are using TEMISPACK, the thrusting in the south has to be assimilated in a fast sedimentation. Although it is a sharp simplification, it is relevant for our present aim: to quantify the potential of the deep offshore. The modeling of the petroleum system of onshore Cuba is beyond the scope of this study. The compressive events, active mainly during the early Eocene in this area, led to the overthrust of several thousand meters of thrust sheet. The sediments corresponding to the thrusts in the runs have been heated to the correct temperatures.

Paleo Sea Level

The current sea level is ~2500 m in the deepest (northern) part of the studied cross section. One may consider the current value as a maximum on this line; a progressive decrease versus time has been imposed, as well as an increase from south to north. This paleo sea-bottom geometry is only a rough approximation but will have no influence on the conclusions of this study, since we do not try to define the geometric evolution of a particular trap. The main feature is the south-north evolution that would induce the south-to-north hydrocarbon migration and which is caused by the thrusts that increase the depth of the Cretaceous to the south.

Results

Maturation History

The current transformation ratio is given in Figure 9 and its evolution versus time in Figure 10. The synrift Jurassic sequence is overmature below the thrusts and the foreland. This sequence is in the oil windows at km 70 that correspond to the northern extremity of the foreland. In the deep offshore, unaffected by the Tertiary phase, the bottom of the synrift is buried at only 2500–3000 m; therefore, it is at the beginning of the oil window. Figure 10c shows the evolution versus time of the San Cayetano Formation at various positions. The red line (km 4.6) corresponds to the deep part of the first half graben to the north of the section, which is immature here.

Any deeper grabens would be as mature as the one at km 23.

Along this section, the Upper Jurassic/Cretaceous source rocks are not deeply buried, and they may only mature below the foreland and in the compressive zone. Therefore, if we consider that two petroleum systems exist, only the deepest one (Jurassic synrift deposit) may be active in the deep offshore (Figure 11). The upper one, with carbonate source rocks from the upper Oxfordian to Albian, is immature offshore northward from the foreland.

Northward, because of low sedimentation rate after the MCU, the current transformation ratio is the one obtained before the Upper Cretaceous and at the end of the Cretaceous, and only the southern part of the section contains some mature source rocks, which are represented by shales of the San Cayetano Formation synrift. They are mature in the area where the Oxfordian is thick, as shown in the other models (Figure 12).

Migration Pathway

On Line 123, all source rocks, from the synrift to the middle Cretaceous, matured and expelled hydrocarbons below the foreland and the thrusts. These hydrocarbons then may migrate northward and may be trapped in the structures. In such a flexural context, lateral migration may occur over long distance. In several other forelands, lateral migration has been proved to have taken place over hundreds of kilometers (Nesbitt and Muehlenbachs, 1995; Moretti et al., 2002). In the Cuban case, the MCU and Jurassic evaporites both favor this northward migration. Oil and gas seeps may be expected at the emerging point of the basal thrust and/or the bottom of the flexural basin; i.e., roughly, the MCU in the studied area. This 2-D view gives a partial idea of the migration pathway. Indeed, the lateral thickness variation of sediments is large (for synrift, as for the carbonates) and, therefore, local kitchens may occur and prospects may be laterally filled.

PETROLEUM POTENTIAL OF THE NORTHWEST OFFSHORE OF CUBA

It is beyond the scope of this paper to estimate all the potential kitchens and traps of the northwest offshore zone of Cuba. Nonetheless, some specific geometries have been modeled in 1-D to explore the various possibilities. Two cases are presented here; both are located in the northwestern part of offshore Cuba. In the first one, the synrift half graben is very
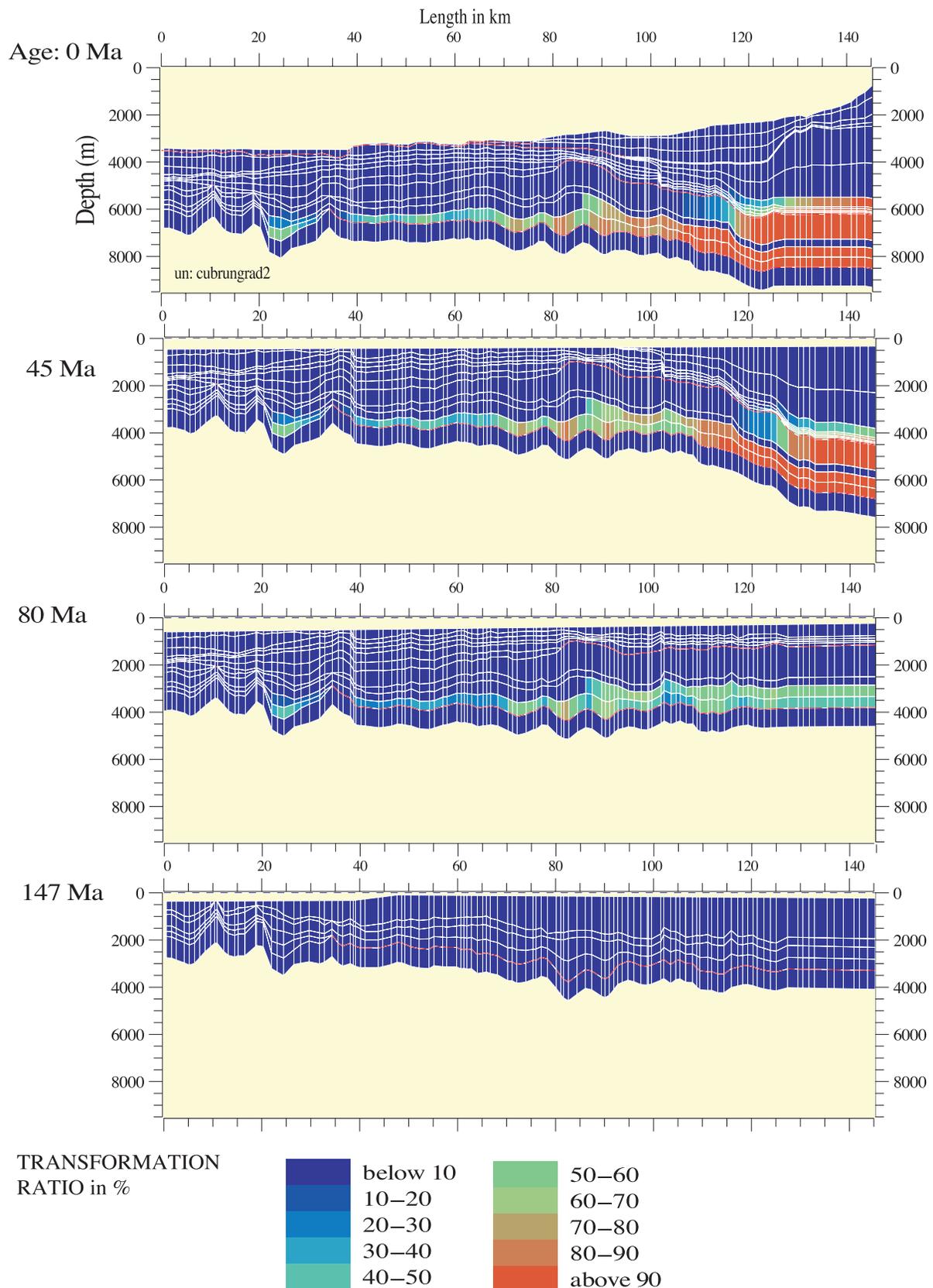
Figure 9. Transformation ratio versus time of the studied cross section (see Figure 8).
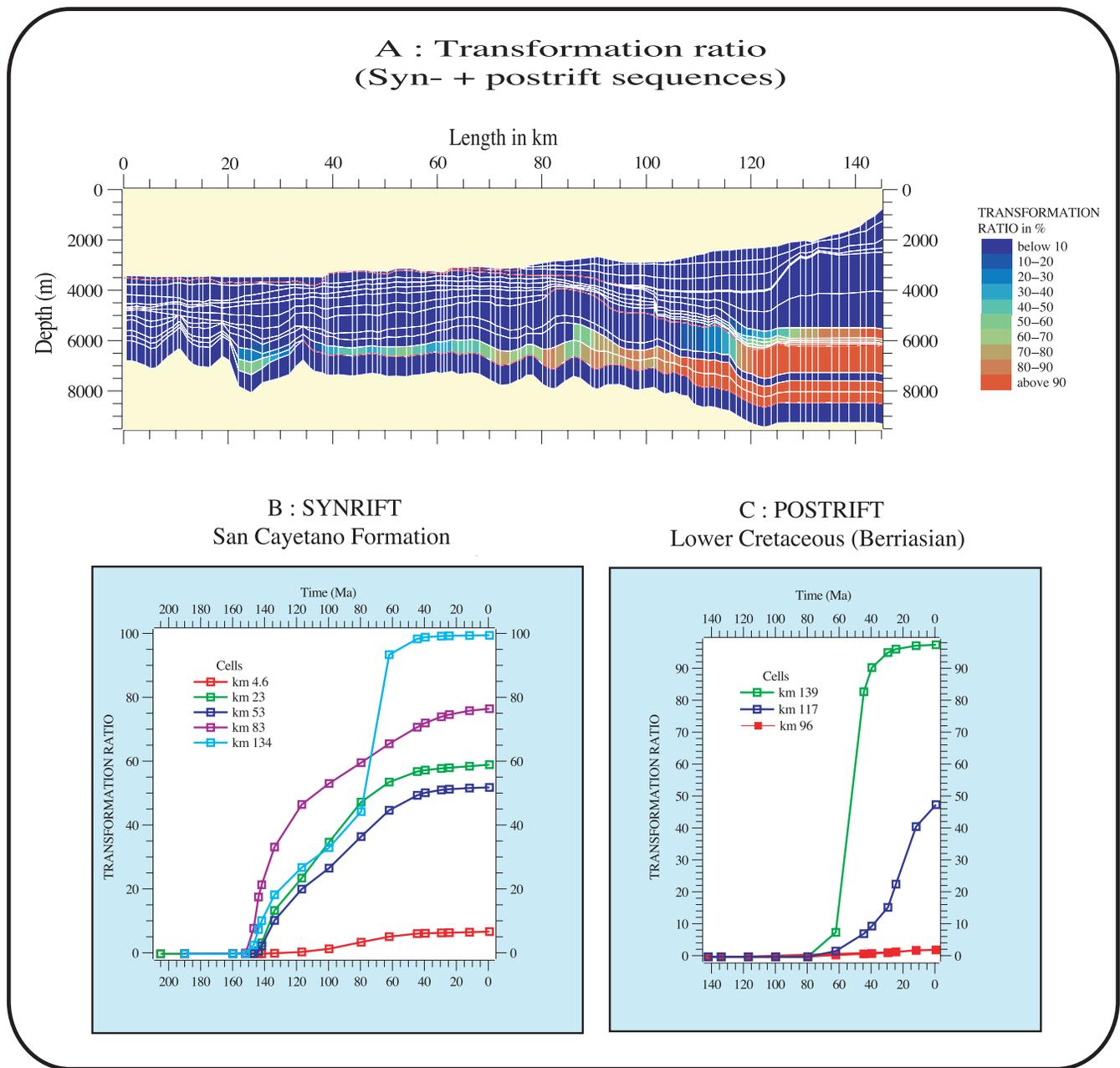
Figure 10. Transformation ratio versus time of the bottom of the synrift and of the Cretaceous source rock at various points (distances are from the northern extremity of the studied cross section [see Figure 8]).

deep, as much as 5 km, and the postrift is thin. In the second case, both have a thickness of ~3 km. The last shown 1-D model is located in the foreland where the Paleocene to Miocene series are thick.

Maturation in a Thick Synrift Half Graben

A synrift graben may have variable thicknesses, from a few hundred meters to more than 5.5 km. On Line 123, none of the half grabens are very thick; therefore, another example is shown here on an older seismic line also located off the northwest coast of

Cuba. One of the examples of the deep half grabens is visible on Russian line 8404, which has a 60°N orientation and is located in western Cuba, about 50 km from the coast (see location in Figure 1).

As shown in the transformation ratios versus time and depth (Figure 12A), the synrift sediments in this case are mature during the Middle and Upper Jurassic. The expulsion also took place at this time. Note that the values shown in the TR-versus-time graph are the TR at the middle of the interval of the concerned formation (San Cayetano Formation and

Lower Cretaceous, respectively). In this case, the upper part of the synrift series also is overmature before the end of the Lower Cretaceous. Thus, only an early structure related to the tilted block and sealed before the carbonate platform development may be charged by these source rocks.

Maturation in a Thick Carbonate Platform

At the level of Line 123, the carbonates are not very thick, although in a few other places, the development of the Upper Jurassic/Lower Cretaceous carbonate platform led to a 4-km thickness of limestones, which drastically increased the maturity of the syn- and early postrift sediments. This is the case in the example shown in Figure 12B along an offshore north-south seismic line between Pinar del Rio and Havana (for location, see Figure 1).

In this case, the synrift sediments also were mature during the Jurassic, but all levels of maturity are found in the postrift series before the Middle Cretaceous erosion (Figure 12B). The increase of maturation of the postrift source rocks during the Tertiary deposits allowed the eventual traps to be charged.

Maturation in the Foreland

The synrift sediments in this line (IV in Figure 1) are also also thicker than in Line 123 and therefore enter the oil window during carbonate platform development (Upper Jurassic/Lower Cretaceous). These source rocks may have charged traps that were formed previously but where hydrocarbons also may have migrated elsewhere and been lost during the middle Cretaceous erosion. The postrift carbonate source rocks show a continuous level of maturity between the peak of the oil window (TR >50%) and early maturation (TR = 10%) before the foreland deposits. For all of these Upper Jurassic/Lower Cretaceous source rocks, the increase in maturity during the Miocene and the expulsion was active. In this area the source rock potential and the timing of their maturities are positive for the infill of the potential traps, either carbonate build-up or tectonic traps.

CONCLUSION

We may consider two petroleum systems to exist in northwest offshore Cuba:

1) The ''classical'' system, which also is active onshore, consists of Upper Jurassic/Cretaceous carbonate-dominated source rocks and reservoirs; we call it the postrift system.

2) The second system revealed by this study consists of shaly Jurassic synrift source rocks and any of the upper reservoirs (sandy Jurassic sequence and/or limestones from the post rift sequence).

Depending on the continuity of the Jurassic evaporite sequence, the deepest system may or may not be connected to the upper one.

On the Line 123 seismic document, modeled here as the postrift system with carbonate source rocks from the upper Oxfordian to the Albian, is immature offshore. Only the southern part of the section, where the burial has been increased by the stack of the thrusts and the foredeep deposits, may generate hydrocarbon. Lateral migration took place below the MCU discontinuity and/or the basal décollement level of the thrusts; therefore, accumulations are expected if traps exist below the flexural basin and near its northern limit (km 60 in the section). Numerous oil seeps are expected at the emerging point of the MCU and, should that be the case, below the thrusts.
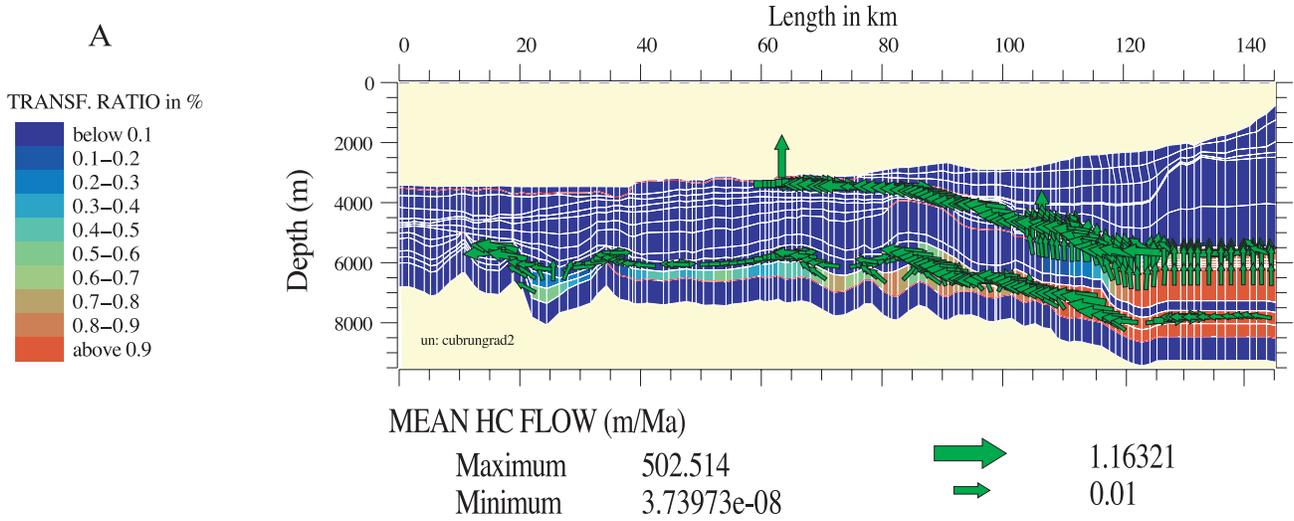
We have no evidence of other regional seals in the Lower Jurassic/Cretaceous platform; therefore, we cannot prove very long northward lateral migration in the carbonate platform.

On the contrary, the deepest synrift petroleum system may be active in the deep offshore northward. In this area, because of the low sedimentation rate after the MCU, the current transformation ratio is the one obtained before the Upper Cretaceous. The old traps, e.g., the tilted blocks, may have been filled and preserved from this time.
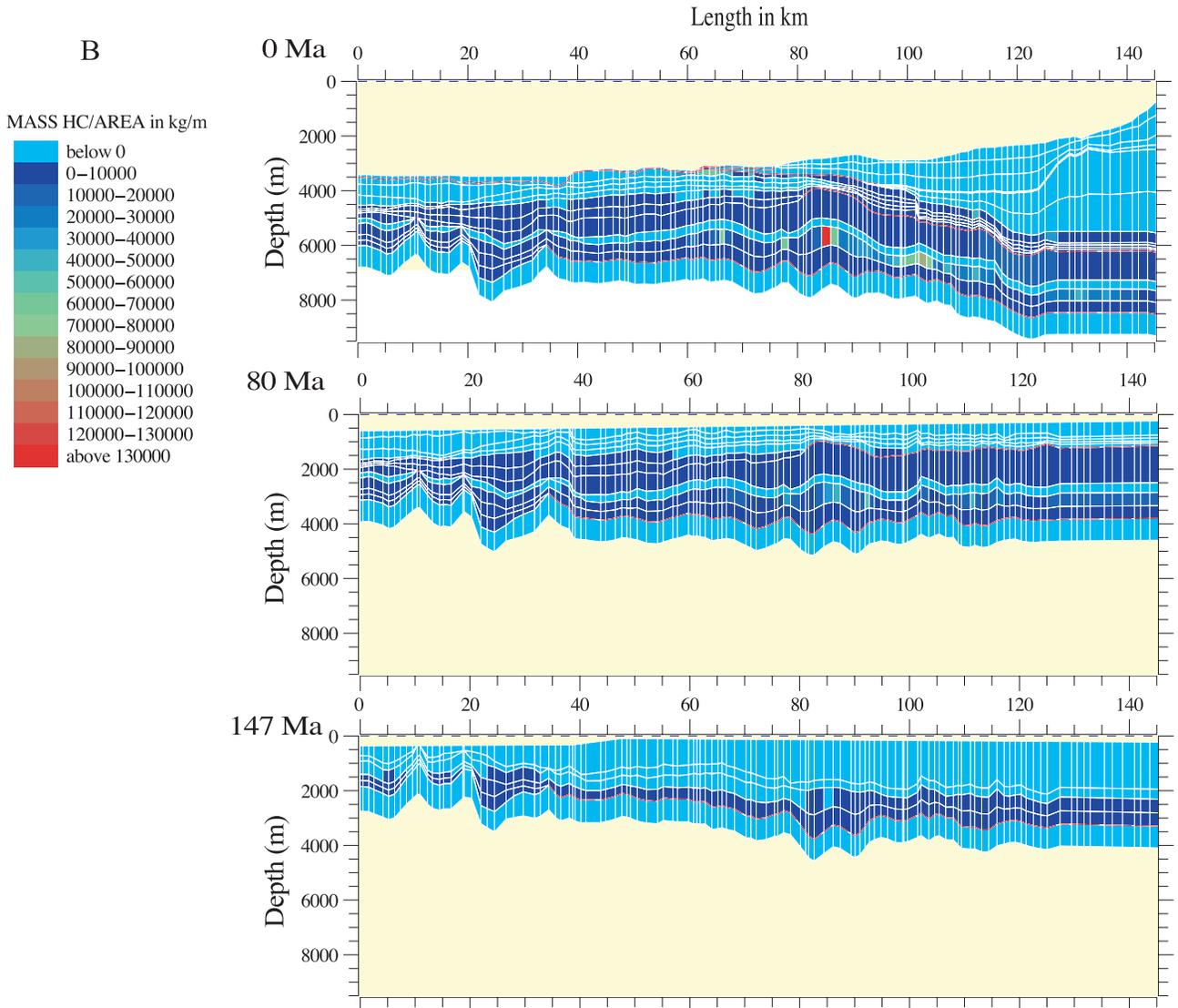
More recently, the maturation increase in the southern part below the foreland has provided new generations of hydrocarbons. If the evaporite seal is continuous, long-distance migration may have taken place and hydrocarbons may have reached traps from the synrift sequence. If the Jurassic evaporite seal is not continuous, the hydrocarbons will reach the postrift carbonate platforms and follow the same migration pathways. In this case, they are expected to be found below the MCU and/or the basal thrust décollement level.

Figure 13 shows the various plays near the coast; the anticlines related to the thrust constitute structural traps as they do onshore. Offshore they are deeper and are related to deeper-buried kitchens; therefore, they are likely to contain mature oil and gas, unlike the onshore shallow traps that contain early mature heavy oil. The most prospective area appears to be below or just north of the foreland, where the increase of Tertiary burial led to post-Cretaceous maturation
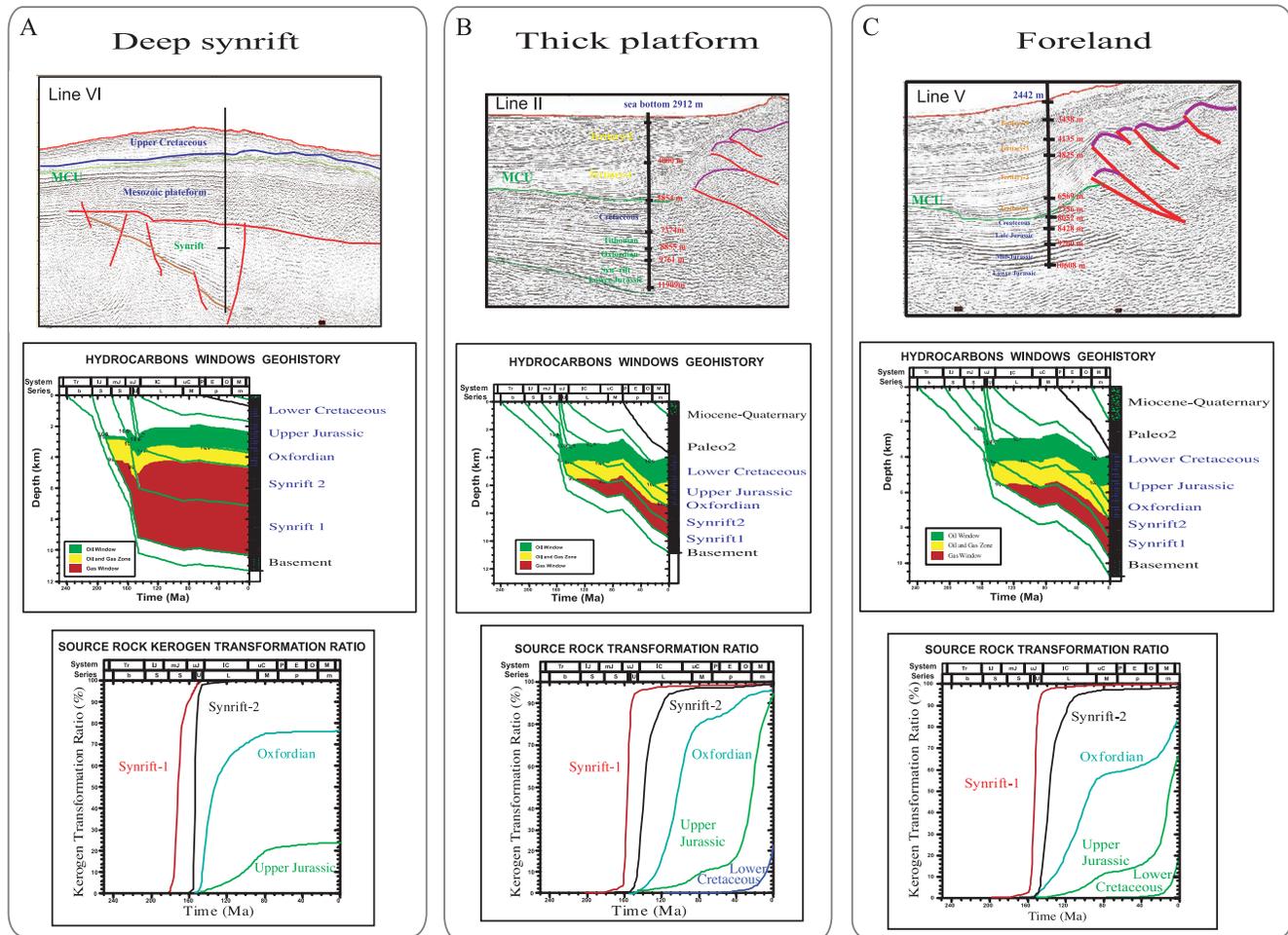
MIGRATION PATHWAY AND ACCUMULATIONS

A

TRANSF. RATIO in %

	below 0.1
	0.1–0.2
	0.2–0.3
	0.3–0.4
	0.4–0.5
	0.5–0.6
	0.6–0.7
	0.7–0.8
	0.8–0.9
	above 0.9

Length in km

un: cubrungrad2

MEAN HC FLOW (m/Ma)

Maximum	502.514		1.16321
Minimum	3.73973e-08		0.01

ACCUMULATION

B

MASS HC/AREA in kg/m

	below 0
	0–10000
	10000–20000
	20000–30000
	30000–40000
	40000–50000
	50000–60000
	60000–70000
	70000–80000
	80000–90000
	90000–100000
	100000–110000
	110000–120000
	120000–130000
	above 130000

Length in km

0 Ma

80 Ma

147 Ma

Figure 12. Maturation modeling on three representative cases based on seismic lines IV, V, and VI (for location, see Figure 1). The models have been done using GENEX (IFP software trade marketed by BEICIP-FRANLAB; Ungerer, 1990; Forbes et al., 1991). A. Deep synrift half graben. In this case, the synrift shaly source rocks have been mature since the Middle Jurassic in the depot centers, and the crest of the tilted block may have been charged at this time. This section is located north of the deep foreland, and there is no increase of maturation after the middle Cretaceous. B. Thick Lower Cretaceous platform. Maturation started at the end of the Jurassic for the synrift source rocks and during the Lower Cretaceous for the carbonates. Maturation was still increasing during the Tertiary for the Late Jurassic and youngest source rocks. C. Below the foreland. In some places, the foreland is as much as 7-km deep. In this line, the Upper Jurassic–Lower Cretaceous platform is thin; therefore, the maturity of the carbonate source rocks increased drastically during the Tertiary. The upper petroleum system is currently active.

of the hydrocarbons. However, a deep synrift petroleum system, completely sealed from the Cretaceous, also may exist over all the northwest offshore Cuban domain.

Figure 11. Accumulations and migration pathway in the current geometry below the foreland and/or northward. Note that no source rocks have been included or modeled in the thrustsheets. A. Transformation ratio and migration from the source rocks. The arrows indicate the migration pathways (lengths are proportional to the flow). Note the two petroleum systems caused by the two seals. The deeper one is restricted below the Jurassic evaporites, the source rock being the Jurassic synrift shales. The upper one is carbonate, with source rock from the Upper Jurassic to middle Cretaceous and reservoirs in the carbonates themselves. The bottom of the foreland, which corresponds roughly to the middle Cretaceous unconformity (MCU) acts as a seal and favors northward migration of the hydrocarbons. B. Accumulation versus time. The potential prospects are: the highest part of the Jurassic tilted blocks, the reefs and the carbonated platform wedge facies below the Tertiary, and structural traps of the Cretaceous limestones (because of the late compressive phases).
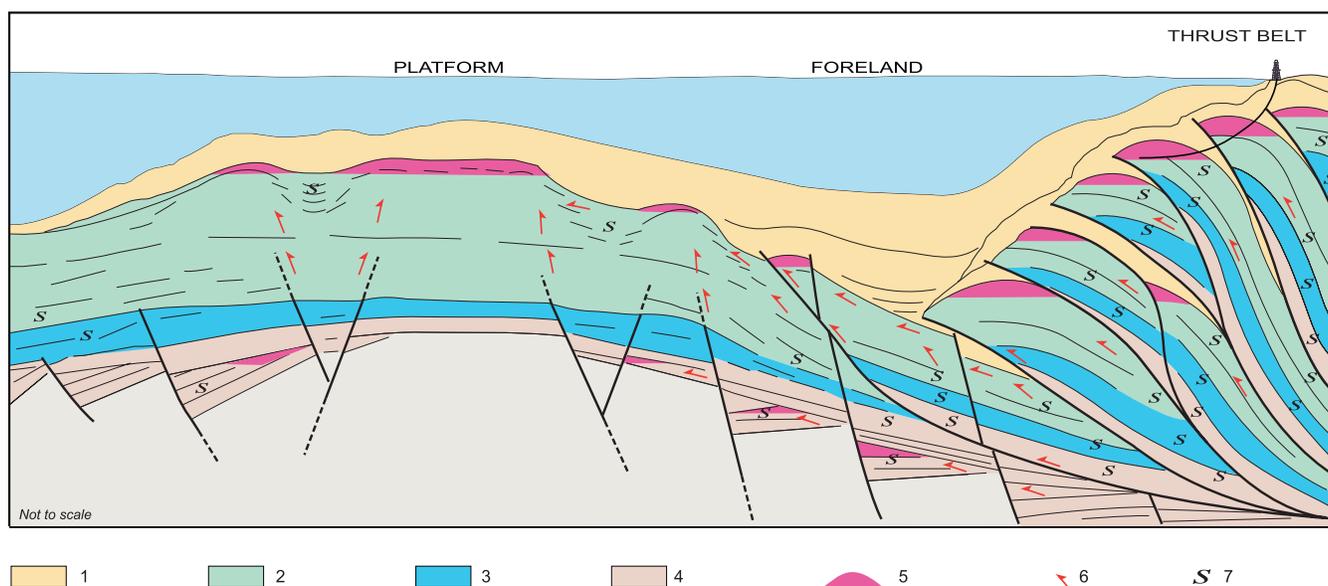
Figure 13. Synthesis of the play concept of the northwest offshore Cuba petroleum system. 1 = Tertiary; 2 = Cretaceous; 3 = Jurassic, mainly carbonates; 4 = Jurassic, mainly clastics; 5 = potential accumulation; 6 = hydrocarbon pathway; and 7 = main source rocks.

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