GEOLOGIC RATIONALE FOR HYDROCARBON EXPLORATION IN THE CARIBBEAN AND ADJACENT REGIONS

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Sedimentary basins in the Caribbean and adjacent areas are assessed in terms of the plate-tectonic and paleogeographic history of the regions. Primary phases of development were rifting and passive margin development during Jurassic-Cretaceous drift of North from South America; and the Late Cretaceous to Recent relative eastwards migration of the Caribbean Plate from the eastern Pacific area to its present position between North and South America.

Two primary stratigraphic suites of rock occur in the Caribbean region: (1) autochthonous Jurassic, Cretaceous and Cenozoic passive margin sediments deposited along the rifted margins of North and South American basement; and (2) allochthonous oceanic crustal and magmatic arc rocks and overlying sedimentary units of the migrating Caribbean Plate. The tectonic boundary between these suites coincides roughly with the limit of circum-Caribbean thrusted metamorphic/mafic rocks above the formerly passive Proto-Caribbean shelf rocks (episutural foredeep basins), and juxtaposition youngs from west (latest Cretaceous in southern Yucatan) to east (late Neogene in Trinidad). Although Jurassic rift/early drift-related source rocks occur in some areas, such as in Cuba—Bahamas, the primary source rocks in both suites were deposited well after rifting in the “medial” Cretaceous. Basin development during the Late Cretaceous to Recent tectonic juxtaposition of the two suites (i.e. Caribbean migration) directly controlled both clastic reservoir facies deposition and hydrocarbon maturation in many areas around the Caribbean. Basin development, source and reservoir rock deposition, and maturation of source rocks in all basins in the region can be directly related to plate-tectonic evolution. A satisfactory understanding of the hydrocarbon potential of the Caribbean/northern South America province therefore requires a full appreciation of the region's plate-tectonic evolution.

INTRODUCTION

Petroleum exploration to-date in the Caribbean area has had only limited success (Morris et al., 1990), compared to that in the Gulf of Mexico and onshore northern South America. Due to past and present tectonic complexity, the diversity of rock and crustal characteristics in and underlying the Caribbean region complicates assessments of petroleum potential.

However, this diversity can be used to help guide exploration. For example, crust in the region varies from pre-Mesozoic continental, to magmatic arc, to oceanic of various ages, depending on location (Banks, 1975). Continental and some arc areas, relative to old oceanic areas, have higher heat flow, are more deformable and therefore more capable of

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developing small, deep basins, and usually possess quartzose lithologies, the erosion of which can enhance sandstone reservoir quality. Areas of young oceanic crust or rift zones with lithospheric attenuation have very high initial heat-flow, which decreases through time. Reservoir potential in oceanic and magmatic-volcanic arc complexes of the region is relatively poor, because derived sands are highly feldspathic (weathering to clays which inhibit porosity). Arcs with tonalite intrusions may provide some free quartz, but sands derived from such intrusions will be local and only partially composed of quartz. Porous reefs/carbonates are potential reservoirs throughout the Caribbean, but, except for the Bahamas bank, these are usually small and irregular, due to Cenozoic tectonic instability and limited platformal foundations. Fracture porosity may exist in deformed limestones, chert units, or other brittle formations, and can be of significance, especially when fracturing is contemporaneous with maturation of source units nearby. For these reasons, areas proximal to continental crust, such as nuclear Central America, Yucatan, and northern South America, are of lower exploration risk than arc and oceanic areas.

Plate-tectonic and paleogeographic assessments of the region provide a genetic understanding of Caribbean and adjacent basins, critical to understanding petroleum systems. Such evolutionary analyses help to explain why certain areas within the region are productive, and suggest additional areas where petroleum exploration may be viable.

This paper begins with a discussion of regional geology and evolution, focusing on stratigraphic and basin aspects, in order to show the importance of plate tectonics to the region's hydrocarbon potential, and to set the stage for assessments of individual areas and basins. The analysis leads to (1) a genetic classification of Caribbean basins; (2) an understanding of why petroleum has been found where it has; and (3) identification of areas that may deserve additional examination.

CARIBBEAN REGIONAL GEOLOGY AND PLATE-TECTONIC EVOLUTION

This section identifies those geological elements required to outline regional evolution, and to derive relationships between plate-tectonic evolution and basin parameters that are essential for petroleum accumulation. Numerous in-depth reviews of Caribbean geology, geophysics, and neo- and paleo-tectonics have been compiled by Dengo and Case (1990).

Many of the Caribbean region's major tectonic features, basins, oilfields, and locations mentioned in the text are shown in Fig. 1 (basins are keyed to Table 1). The mainly oceanic, arc-bearing Caribbean Plate is held approximately in the mantle reference frame by opposing subduction zones (consuming Atlantic and Cocos oceanic crust at the eastern and western trench margins, respectively), while continental portions of the North and South American Plates migrate relatively westwards along the northern and southern Caribbean plate boundary zones. Northern zone deformation is mainly left-lateral strike slip, with strong transpression at Hispaniola and Guatemala; while southern zone deformation is generally right-laterally transpressive, but is complicated by the independent motion of the Maracaibo Block being forced northwards from the highly-compressive Eastern Cordillera thrust belt of Colombia (Mann and Burke, 1984a). Such motion has produced the compressive South Caribbean Foldbelt and the Santa Marta and Merida strike-slip systems since the early Neogene (Dewey and Pindell, 1986).

Plate-kinematic framework for assessing Caribbean evolution

Using marine magnetics and Seasat gravity data to constrain fracture zones in the Atlantic oceans, Pindell et al. (1988) measured the relative motion history between continental areas of North and South America since the Triassic (Fig. 1, inset). Continental rifting, followed by nearly 3,000 kms of plate separation, occurred from Late
Triassic to “medial” Cretaceous* time in a NW-SE (present co-ordinates) relative direction.

The “Proto-Caribbean Seaway” between Yucatan, the Bahamas, and northern South America was created during this phase by plate separation (Pindell, 1985). “Medial” Cretaceous-middle Eocene relative motion was absent or very minor. Since the middle Eocene, slow north-south relative convergence has occurred, with the magnitude increasing westwards away from a stage pole of rotation east of the Lesser Antilles (200-400 kms along northern South America). Caribbean regional evolution must have occurred within this quantitative kinematic framework.

Many workers have argued for large-scale, east-west, Late Cretaceous to Present Caribbean-American relative motion. Pindell (1990) summarized arguments suggesting a Pacific origin for the bulk of the Caribbean Plate, collectively indicating a total migration of at least 1,500 kms. since probably Albian time. These arguments include:

1. dredges and exposures of rock from the Aves Ridge and Lesser Antilles arcs indicate a 90 MM* year history of Atlantic subduction beneath the Caribbean Plate;
2. assessments of strike-slip basins in the northern Caribbean, the opening history of the Cayman Trough, and seismic-tomographic images (Hilst, 1990) of the sub-Caribbean mantle, together suggest at least 1,100 km of relative displacement since the mid-Eocene;
3. lithostratigraphies of two distinct suites of rock — the tuff/volcanism-dominated “Caribbean” suite (maggmatic arc/oceanic terranes), and the tuff-deficient “Proto-Caribbean” suite (Mesozoic passive margins of North and South America, discussed later) — now tectonically juxtaposed along the circum-Caribbean episutural ophiolite belt (Pindell and Barrett, 1990); significant spatial separation during Cretaceous deposition of the distinct suites seems necessary, because the Proto-Caribbean suite contains no record of Caribbean volcanism;
4. geometrical incompatibility between the pre-Aptian Caribbean crust and the Aptian size of the widening Proto-Caribbean Seaway — the Caribbean Plate could not have fitted between the Americas until the Late Cretaceous;
5. Paleogene magmatic-arc truncation and uplift history of the SW margin of Mexico, which suggests 1,000-1,500 kms of eastwards migration of the Chortis Block (continental fragment of Nuclear Central America) along Mexico to its present position, at rates similar to the Caribbean Plate since the Paleogene;

These arguments indicate that the Caribbean Plate and Chortis Block were situated west of the Cretaceous shelf margins of Yucatan, Bahamas, and northern South America for most of the Cretaceous. The actual position of the Caribbean Plate is not fully manifest until the Campanian, when an arc terrain, presumably part of the Caribbean Plate, overthrust the southern margin of the Yucatan Block, creating the Sepur foredeep basin (see below). However, NE migration of the plate above SW-dipping Atlantic crust probably began in the Albian, as marked by the onset of the “Antillean cycle” of magmatism in the Greater Antilles (Albian-Eocene), and the Albian metamorphic event on several of the Caribbean Islands (e.g. Tobago: Sноke et al., 1990). Caribbean-American relative motion since the Late Cretaceous has allowed the Caribbean Plate to reach its present position between the Americas.

*The term “medial Cretaceous” is used herein to denote the economically-significant Albian to Santonian interval, for which biostratigraphy is relatively poorly-known, eustatic sea-level was very high, and magnetic reversals did not occur.

+ Million (10^9) years.
Table 1. Genetic associations of Caribbean basins (numbers keyed to Fig. 1).

A. \textit{Proto-Caribbean/Caribbean episutural foredeep basins:}
1. Sepur foredeep basin (and Chiapas Foldbelt), Guatemala and Belize.
2. North Cuba-Southern Bahamas foredeep basin.
3. Maracaibo foredeep basin, Colombia and Venezuela.
4. Eastern Venezuela/Trinidad foredeep basin.

B. \textit{Larger rift/pull-apart basins:}
5. Yucatan Basin (lithospheric rift).
8. Cayman Trough (western end) basin (lithospheric rift).
10. Falcon Basin (lithospheric rift).
12. South America borderlands basins (Baja Guajira, Triste, Cariaco, Bonaire, La Vela, Carupano, Leeward Antilles inter-island basins (probably upper crustal grabens, but Bonaire Basin probably had Oligocene lithospheric extension similar to the Falcon).

C. \textit{Accretionary prisms/forearc basins:}
13. Barbados Ridge (Proto-Caribbean suite) and Tobago Trough basin.
14. South Caribbean/Panama/San-San Jacinto foldbelts and Lower Magdalena Basin.
15. San Juan-Azua-San Pedro-Enriquillo Basin, Dominican Republic.

D. \textit{Arc-flank and other basins:}
18. North Puerto Rican basin.
19. South Cuban shelf.
20. Cibao Basin (fault-assisted).
21. Cesar Basin, Colombia (Sierra Perija overthrust).
22. Saba Bank platform.

\textbf{Proto-Caribbean Seaway and regional source-rock deposition}

Sea-floor spreading between North and South America had ceased during "medial" Cretaceous time, at the onset of or during NE Caribbean Plate migration, leaving the Proto-Caribbean oceanic arm of the Atlantic to subside thermally in the absence of active plate boundaries for most of the Late Cretaceous. Acknowledgement of the existence of a "Proto-Caribbean Seaway", with the Caribbean Plate situated to the west, is critical to the hydrocarbon history of the Caribbean region, because it was along this seaway's passive margins that the region's best source rocks were deposited (Fig. 2). Fig. 3 shows Proto-Caribbean paleogeography and the minimum westwards displacement for the Caribbean Plate during pre-Campanian time, with the Greater Antilles/Aves Ridge arc connecting the Cretaceous arcs of Mexico/Chortis and Colombia.

Excellent source rocks were deposited primarily at two intervals along the margins of, and possibly within, the Proto-Caribbean Seaway (Figs. 2 and 3). The first group are Jurassic in age, and are well-known in western and central Cuba (e.g. San Cayetano and equivalents), where early Paleogene northwards-overthrusting by the Cuban island-arc has brought the early Proto-Caribbean shelf-and-slope sections of NE Yucatan and the southern Bahamas to shallow levels (Pardo, 1975; see also Rodriguez \textit{et al.}, pp. 259-274, \textit{this volume}). These sediments represent the post-rift, early-drift stage of sedimentation along the northern Proto-Caribbean (Fig. 3, inset), when conditions may have been restricted due to the closed geometry of the early Proto-Caribbean Basin. Along the South American margin, Upper Jurassic marine shales and limestones in Venezuela's Caracas Group and Paria Peninsula (Gonzalez de Juana \textit{et al.}, 1980) and Trinidad's Northern Ranges (Algar and Pindell, 1991a) are black and graphitic, but these passive margin slope
Fig. 1. The Caribbean region, showing important plate boundaries, basins (dashed outlines: keyed to Table 1), oilfields, and locations mentioned in the text A. Gulf of Venezuela; B. Paria Peninsula; C. El Pilar Fault; D. Santa Cruz Ophiolite Body; E. Newmarket — Montpelier/Wagwater Troughs. Inset: Triassic-recent displacement history of a point in Colombia relative to North America defining Proto-Caribbean paleogeography (after Pindell et al., 1988).
and rise sediments, for which there are no clearly-defined Jurassic shelfal equivalents, were metamorphosed in the Eocene-Miocene interval, and their original source potential is unclear. Most true rift-related Proto-Caribbean units, such as the Todos Santos of Yucatan and La Quinta of Venezuela, are terrestrial redbeds of little-known source potential.

The second primary group of Proto-Caribbean source rocks was deposited in the "medial" Cretaceous (Figs. 2 and 3). This interval was marked globally by above-normal bottom-water temperatures and high eustatic sea levels, such that strand lines are recorded well inland on all Proto-Caribbean margins, with seas inundating large continental areas. These warm-water, high-nutrient conditions probably contributed to enhanced source-rock accumulation within the Proto-Caribbean and its margins. In addition, bathymetric elevation of the developing Greater Antilles arc may have restricted Proto-Caribbean circulation. Further, upwelling and high bioproducivity may also have contributed to source quality along northern South America, due to that margin's north-facing, east-west orientation within the easterly trade winds of the northern hemisphere.

The effects of upwelling may have been enhanced at the end of the Albian, at the same time as initial deposition of the richest source rocks in Venezuela/Trinidad, due to the late Albian onset of deep-water circulation to/from the South Atlantic, through the juvenile Equatorial Atlantic. The South American margin has the best petroleum source rocks (Type II: La Luna, Querecul, and Naparima Hill Formations) of the region, but "medial" Cretaceous shelf sections of the Coban Formation on Yucatan (Lopez Ramos, 1975) and in Honduras on the Chortis Block (Horne, 1989) are also source-prone.

The Cretaceous deep-water oceanic anoxic "events" documented by DSDP cores (Tissot et al., 1980) in the Atlantic probably extended across the basin and shelves of the Proto-Caribbean, judging from the similar kerogens. One could also postulate the deposition of equivalent deposits along the northern flank of the Greater Antilles arc, as the Antilles presumably formed a westward morphologic extension of northern Venezuela, trending towards Central America (Fig. 3). Although recrystallized and locally cleaved due to tectonism, the limestones of the "medial" Cretaceous Los Ranchos, Hatillo and Las Canas Formations of eastern Dominican Republic (Bowin and Lewis, 1980) are black-to-grey locally, with black, cherty nodules (personal observation), similar in field appearance to the La Luna, which was only a few hundred km to the east at that time. Upwelling in the south may be one reason why this margin's source rocks are richer than the contemporary Bahamian section to the north.

The Caribbean lithostratigraphic suite also has "medial" Cretaceous source rocks, deposited in the Pacific realm prior to relative eastward migration. Edgar et al. (1973) reported TOC concentrations of up to 4.2% from black, anoxic shales among limestones and tuffs of this age. Similarly, the Nicoya area of Costa Rica, which represents either basement or a zone of Pacific oceanic rocks accreted to the Central American arc, also has "medial" Cretaceous sections of organic-rich pelagic sediments.

It appears that "medial" Cretaceous deposition in the eastern Pacific (and Caribbean crust) was affected by oceanic anoxic events similar to roughly contemporaneous events in the Atlantic and Proto-Caribbean. These shales have entered the Caribbean region with the Caribbean Plate, and should not be correlated directly with the formations defined for the Proto-Caribbean margins. However, in areas of sufficient sediment accumulation or structural repetition and thickening (such as accretionary prisms), these Caribbean/Pacific source rocks could provide mobile hydrocarbons to reservoir rocks or overthrusts higher in the section.

**Basins of the Caribbean region**

The Proto-Caribbean ocean basin has been progressively consumed by subduction beneath the Caribbean Plate during Caribbean-American relative motion. Accordingly, the once-passive margins of the Proto-Caribbean Seaway were tectonically loaded over a
Fig. 2. Simplified Proto-Caribbean and Caribbean suite stratigraphic columns. The timing of allochthon emplacement in foredeep basins of arc-continent collision zones is shown by black wedges above basal thrusts.
distance of approx. 200 km ahead of the leading edge of the Caribbean Plate, so that the site of load subsidence appears to have migrated eastwards over time, with the Caribbean Plate, along the Proto-Caribbean margins.

This subsidence diachronously produced four distinct, large, asymmetric episutural foredeep basins, with synorogenic flysch, above the previously-passive Proto-Caribbean shelf sections. The basins record the Campanian-Recent Caribbean relative motion history (Fig. 4). Flysch in each basin is overlain by, and interthrust with, the obducted, often serpentinite-bearing Caribbean allochthons, with olistostromes and melange (Fig. 2), thereby dating the obduction or arrival of the Caribbean rock suite upon the Proto-Caribbean rock suite at each basin. The onset of such foredeep sedimentation and collision progressed eastwards (Figs. 2 and 4), beginning along southern Yucatan during the Campanian (Sepur Formation); in the Bahamas/northern coastal Cuba in the early Paleogene (Pica Pica, Universidad Formations, and offshore seismic units 1, 2 of Fig. 4); in the Maracaibo Basin of Venezuela in the Eocene (Misoa/Trujillo delta/flysch); and in the Eastern Venezuelan or Maturin Basin in the Miocene (Oficina/Carapita Formations). The foredeep fill in Trinidad is Upper Miocene-Lower Pliocene (Cruse Formation), as it lies even further east. Shales of these foredeep basins, especially those of South America, have some source-rock potential, but the kerogen is mixed to gas-prone owing to the terrestrial influence. Sands in the deltaic and flysch sections of the basins (e.g. Misoa Formation, Lake Maracaibo) form primary reservoir facies, especially where they are craton-derived. The absence of older orogenic foredeep deposits along the Proto-Caribbean margins (Fig. 2) precludes interaction with the Caribbean Plate at times earlier than suggested in Fig. 4. Local orogenic flysch of Late Cretaceous age in Cuba (Pardo, 1975) is allochthonous, and was transported northwards with the arc during migration toward the Bahamas. This flysch probably originated from the Late Cretaceous collision zone of southern Yucatan, and was transported eastwards into the trench, there to be accreted and carried northwards to the Bahamas.
Fig. 4. Cross-sections of episutural foredeep basins, compiled from Wilson (1974), Rosenfield (1980, 1981), Angstadt et al. (1985), Bockmeulen et al. (1983), Lamb and Sulec (1968), and Case and Holcombe (1980). Caribbean-American relative motion shown by heavy lines through Proto-Caribbean Seaway. North and South America are plotted in Maestrictian relative positions, and the blocks of NW South America are restored to their pre-Neogene positions (modified after Pindell, 1991).

From Fig. 4, gross Caribbean motion relative to the Americas occurred at the rate of 15 (Neogene) to 30 (Paleogene/Cretaceous) mm/yr back to Campanian time (a total migration of about 1,500 km over 75 MM yrs). These rates are slower than Late Cretaceous-Cenozoic convergence rates for Farallon/North America; the difference can be accounted for by subduction of Farallon crust beneath the Chortis and Costa Rica-Panama arcs, which probably formed the western boundary of the Caribbean Plate since about Santonian-Campanian time (Pindell and Barrett, 1990).

Figs. 5a-d summarize Caribbean relative-motion history, and the following three aspects of Caribbean evolution may be particularly important for hydrocarbon potential:

The first is the Paleocene-Eocene opening of the Yucatan (Rosencrantz, 1990), Grenada (Speed and Westbrook, 1984), and the early Cayman Trough (Eocene, Rosencrantz et al., 1988) basins. The Yucatan and Grenada Basins were probably formed by intra-arc rifting and expansion of the Greater Antillean/Aves Ridge Arc, after the arc passed between the Yucatan-Colombia “bottleneck” (Pindell and Barrett, 1990). Development of the Cayman Trough allowed the onset of eastwards Caribbean migration after or during the “docking” of Cuba and the Yucatan Basin with the Bahamas. Early deposition in these three basins may have occurred in restricted conditions above stretched-arc or juvenile oceanic basement with high initial heat-flow, and portions of these basins may therefore be prospective.

A second important aspect of Fig. 5 is the probable onset of underthrusting of Proto-Caribbean crust beneath northern South America in the Eocene, which Pindell et al.
Fig. 5. Four-stage depiction of the evolution of the Caribbean region (after Pindell et al., 1988).
Fig. 5 (cont). (see caption, p. 246).
(1991) interpreted as having: (1) accounted for North and South American relative convergence since that time (Fig. 1, inset); (2) caused moderate regional uplift, local erosional shoaling, and widespread deposition of shallow-water sandstones along the Eocene shelf section of eastern Venezuela and Trinidad; and (3) produced middle Cenozoic D3 compressive deformation, with northwards vergence (Potter, 1973), in northern Trinidad’s passive-margin slope and rise sediments, which were previously interpreted as Cretaceous in age (Algar and Pindell, 1991b).

The third notable aspect of Fig. 5 is the recognition of progressive, transpressional, eastwards-younging orogenesis between the Caribbean and northern South America, involving the oblique emplacement of the previously-metamorphosed Villa de Cura Klippe and the underlying Lara Nappes onto the shelf margin (Dewey and Pindell, 1986; Burke, 1988). This model certainly explains Mesozoic-Cenozoic subsidence curves for the shelf sections of northern South America, and it also appears to have resolved a longstanding debate about the “allowable” magnitude of strike-slip offset along the southern Caribbean (Pindell et al., 1991). In earlier interpretations of Venezuelan orogenesis, arc-continent collision in central Venezuela was considered to be Cretaceous in age, with some emphasis placed on age of metamorphism (Beets et al., 1984; Maresch, 1974). In this view, large magnitudes of Eocene-Recent offset, which had been suggested from other regional Caribbean studies, were viewed as unacceptable for Venezuela, because such offsets were not superposed upon the supposedly pre-existing orogenic zone. However, in the interpretation of Fig. 5, orogenesis in South America is viewed as being due to the oblique emplacement of previously-metamorphosed allochthons (e.g. Villa de Cura Klippe) along basal thrusts, as a direct consequence of Tertiary Caribbean Plate migration. Emphasis in this interpretation is attached to the Oligocene Roblecito Formation (Gonzalez de Juana et al., 1980), representing the foredeep facies of the Guarico area, rather than the thrusted Paleocene-Lower Eocene Guarico Formation. Therefore, only relatively small, post-emplacement offsets should exist within the transpressional orogenic zone that record Neogene displacements, with most Caribbean-South American offset (>1,000 km) having occurred upon the basal thrusts of the allochthons before and during their oblique emplacement. Only the autochthonous, overthrust passive-margin sediments (e.g. Caracas Group of Venezuela and Northern Range sediments of Trinidad) have a Tertiary age of metamorphism.

Numerous notable basins have been produced at the Caribbean Plate boundaries during Caribbean migration. The Barbados accretionary prism is a >20-km thick pile of accreted Proto-Caribbean basinal sediments and Tertiary marginal clastics derived from South America (Fig. 5 b, c, d). Both the Muertos and North Panama offshore foldbelts are mainly Neogene accretionary wedges (Fig. 5d) above the actively-underthrusting Caribbean crust and its “medial” Cretaceous source-rock section (Lu and McMillen, 1983; Ladd et al., 1990). The onshore Chiapas foldbelt of southern Mexico and Guatemala has been shortened and thickened during Neogene time (Fig. 5 c, d), with sinistral transpressional displacements related to the motion of the Chortis Block along Mexico/Yucatan (Guzman-Speziale et al., 1989). This foldbelt may have ties to productive areas of the southern Gulf of Mexico, and also has source rocks of the “medial” Cretaceous Coban and Late Paleozoic Chochal limestone at depth (Roberts and Irving, 1957; Sanchez-Montes and Sanchez-Ortis, 1989).

In Hispaniola, the Cibao, San Juan-Azua, and Enriquillo valleys have pre-Neogene sections, but are now sinistrally-transpressional ramp basins, which have undergone significant Neogene elastic infilling amid the intervening uplifted ranges (Fig. 5d), as a result of Miocene closure of the two halves of Hispaniola and the subsequent Neogene oblique convergence with the Bahamas. The Neogene Arroyo Blanco Formation (McLaughlin and Sen Gupta, 1991) of the San Juan-Azua Basin is an example of a quartz-bearing sand derived from a tonalite pluton.
In the latest Cretaceous and early Tertiary, the western portion of Cuba's arc-terrane migrated NNW along the eastern Belize margin (Rosencrantz, 1990), creating several fault-bounded basins (Fig. 5b), which have received Tertiary sediments above a variety of older rocks, including Late Paleozoic clastics and Jurassic shelf-margin facies. Along the Nicaragua Rise, a small amount of Tertiary east-west extension (sinistral shear couple?; Mann and Burke, 1984b) has created several small basins (Fig. 5b, c and d), at least one of which contains Eocene source rocks of an undisclosed nature (Williams, 1989).

The Miocene-Recent Cariaco Basin of the SE Caribbean (Erlich and Barrett, 1990; Schubert, 1982) is a fault-bounded basin between active strike-slip faults of the transcurrent portion of the southern PBZ (Fig. 5d), with deep-water stagnant deposition. The Falcon Basin onshore NW Venezuela accumulated mid-Cenozoic marine shales (e.g. Pecaya Formation) during Oligocene-Early Miocene extension (Fig. 5c), within the previously-emplaced central Venezuelan Lara Nappes and metamorphic shelf section (Muessig, 1984; Pindell, et al., 1991). Basinal areas at La Vela Bay, Golfo de Triste, and the Carupano Shelf are similar in many characteristics: Tertiary source rocks are mixed or gas-prone, owing to their terrestrial affinity (Kiser, 1981). Like the Cretaceous section beneath the Falcon, the Gulf of Venezuela's original shelf section was metamorphosed during early Tertiary orogenesis. Colombia's Lower Magdalena Basin has both a continental (east) and oceanic (west, like Western Cordillera) basement foundation, but lacks the Cretaceous shelf-section of the Maracaibo Basin, because it was always situated...
west rather than east of the Andean arc. Shales of Lower Tertiary turbidites derived from the Santa Marta-Central Cordillera arc-complex probably possess source potential, but may be gas-prone. Neogene sands and carbonates (Middle and Upper Carmen Formation) serve as reservoirs, and were deposited after regional uplift pertaining to Andean orogenesis.

This Caribbean Plate migration history, with “America-ward” vergent overthrusting along all Proto-Caribbean margins, has been overprinted in NW South America by Miocene-Recent northwards extrusion of the Maracaibo Block from an intense zone of convergence in Colombia’s Eastern Cordillera (Fig. 6), which is itself a consequence of Caribbean relative migration. The escape of the block has caused northwards obduction of previously-accreted terranes of the Colombian-Venezuelan borderlands onto the Caribbean Plate, thereby creating the South Caribbean Foldbelt, an accretionary prism of marginal clastic rocks thrust and folded with the Caribbean Plate’s cover. In addition, this is a potentially-important phase of deformation for South America’s offshore borderlands, in that it produced many small basins there and led to variable but rapid accumulations of Neogene clastics and shales (Silver et al., 1975). Intervening tectonic highs of the deforming Borderlands were locally the site of reef/high-energy sandstone development with reservoir potential, such as the Uitpa Formation of western Guajira Peninsula. However, the most dramatic development of this phase is the rapid uplift of the various Cordilleras and the associated deposition of Neogene flanking sediments, which in southern Lake Maracaibo reach a thickness of 6-8 km (Bockmeulen et al., 1983). Likewise, several km of Neogene clastics were deposited in the Barinas Basin to the SE of the Merida Andes.

CARIBBEAN HYDROCARBON POTENTIAL

Timing of maturation

From the above discussion, the Cenozoic clearly was an important period for basin development and subsidence in and around the Caribbean. Important sedimentary sections in many basins, and the genesis of other basins, are direct consequences of, and can be easily tied to, the region’s plate-tectonic evolution. The relatively youthful Cenozoic age of basin subsidence and formation is critical to hydrocarbon exploration, because it implies that the maturation and migration of large volumes of oil and gas did not occur until that time. Assuming typical paleo-geothermal gradients for Jurassic passive margins, sediment accumulation in most areas along the Cretaceous Proto-Caribbean Seaway was insufficient to drive maturation of the “medial” Cretaceous source rocks until the onset of Caribbean migration and associated basin developments. Thus, maturation of Proto-Caribbean marginal units was a function mainly of sediment burial and/or tectonic overthrusting during Caribbean evolution. Only in southern Yucatan (Sepur Foredeep, Fig. 3), or at unknown but possible deltaic depocentres along northern South America, or at isolated locations of anomalously high heat-flow (e.g. near intrusions), did maturation probably precede the Cenozoic.

Thus, Cenozoic sediment-accumulation curves (and those of Late Cretaceous age for southern Yucatan) can be used to model the timing of hydrocarbons generation from specific older source-rock units. Discrete episodes of enhanced sedimentation due to orogenesis are well-defined and very conspicuous: high rates of sedimentation allow fairly straightforward assessments of the timing of petroleum maturation, that can easily be related to specific tectonic events.

Krause and James (1990), James (1990), Sweeney et al. (1990), Talukdar et al. (1988), and Rodrigues (1986) have modelled maturation timing and oil “kitchens” of various Cenozoic ages along the basins of northern South America, showing that Cenozoic burial is, in fact, the driving mechanism of maturation. Their collective results show that:
(1) maturation in the northern Maracaibo Basin is Eocene, due to Misoa/Trujillo deposition and southwards overthrusting; (2) maturation in the southern Maracaibo Basin is Miocene to Recent, due to Neogene deposition derived from the uplifting Cordillera; (3) maturation in the Maturin Basin is Miocene to Recent, due to Oficina/Carapita foredeep infilling and southward overthrusting; and (4) maturation in the southern Trinidad Basin is Neogene-Recent, due to Upper Cruse and younger foredeep/deltaic infilling and southwards overthrusting. Clearly, foredeep infilling and southwards thrusting is the driving cause of maturation in northern South America.

This principle can be extended to other Caribbean basins to predict the timing of maturation in areas where detailed studies are lacking. Onset of maturation in the other episutural foredeep basins is therefore predicted as latest Cretaceous and earliest Tertiary in southern Yucatan (beneath the Sepur foredeep), and as Paleogene in the northern Cuba/southern Bahamas Basin. Most other Caribbean basins, such as the “ramp” basins of Hispaniola, the small rift or pull-apart basins of the northern and southern plate boundary zones, or the Neogene to Recent Muertos, South Caribbean, and North Panama accretionary prisms, should have Neogene to Recent maturation histories. The Barbados prism has been forming throughout the Cenozoic, and may have a correspondingly complicated maturation history.

The collective youth in maturation times in basins across the Caribbean is conducive to the accumulation of hydrocarbons at the present time. Areas shown to have Neogene to Recent maturation, as opposed to Late Cretaceous to Paleogene, are more productive and appear to have greater remaining potential.

Finally, it should be noted that any hydrocarbons in the region that were matured early on, under the high heat-flow conditions during Jurassic rifting in the Proto-Caribbean, have probably been lost, due to the extreme Cenozoic tectonic structuring of virtually the entire Caribbean province, rendering less-prospective the search for such early oil.

**GEOLOGICAL RATIONALE FOR HYDROCARBON EXPLORATION**

From the region’s evolution, Caribbean basins may be classified by genetic association (Table 1), which specifies basin type and the mechanism of formation. Commonly, basins of the same association have formed at the same time, and are related to a specific tectonic event or period of Caribbean development. Basins of the same genetic association are similar, but may possess important predictable differences concerning prospectivity, such as the quartz content of sands or the timing of maturation. Knowledge of one basin in an association can be applied to others, and the basins can then be ranked by consideration of predictable differences.

Factors that help define petroleum prospectivity in the Caribbean region include: (1) proximity to continental crust, for sandstone reservoir quality, basement deformability, and fair heat-flow; (2) youth of basin genesis or enhanced sedimentation (lithospheric-scale rifts, foredeeps, deltas), leading to enhanced heat-flow and relatively recent maturation and migration; (3) areas that possess unmetamorphosed sections of the Proto-Caribbean stratigraphic sequence, especially the Jurassic San Cayetano Formation (Figs. 2 and 3); (4) structurally-thickened areas of Caribbean suite sediment that incorporate the “medial” Cretaceous black shale horizons (intra-Caribbean accretionary prisms).

In the following discussion, basins in the genetic associations of Table 1 are considered in the light of the above factors for prospectivity. The discussion highlights the most prospective areas, suggesting why petroleum has been found where it has, and identifies areas deserving additional examination. (Numbers after basin names (1-22) refer to Fig. 1.)

**A. Proto-Caribbean/Caribbean episutural foredeep basins**

These basins developed by arc-continent collision above Proto-Caribbean shallow-water shelf sequences possessing good-to-excellent Jurassic and “medial” Cretaceous
source rocks, with thrusting and folding extending well into the Proto-Caribbean autochthon. In each, the degree of maturation increases towards the line of suturing and underneath the overthrust allochthons. For example, in the Maracaibo region, the Cretaceous shelf rocks are overmature (dry gas) in the Guajira Peninsula, Gulf of Venezuela, and NE Lake areas, which lie very close to the southern boundary of obducted oceanic-arc rocks. Eocene migration of oils in the Maracaibo region was towards the SW, away from the overthrust belt, and probably most of it was lost to the surface: the equivalent of an Orinoco "Tar Belt" (Eastern Venezuelan Basin) is missing. The Neogene phase of deposition in the southern and central parts of the basin, where Cretaceous strata were not matured in the Eocene, provided a second period of maturation. The same deposition in the south induced a southwards tilt upon the entire basin, such that Miocene to Recent updip migration was generally northwards. The Miocene-Recent phase is largely responsible for the Maracaibo productivity.

Of the four foredeeps, the Maracaibo (3) and Eastern Venezuelan/Trinidad (4) basins have the best reservoir rocks — mainly Cenozoic quartzose clastics derived from the Guyana Shield and Andean Cordillera. The Sepur foredeep (1) contains abundant volcanioclastic detritus from the arc system that collided with Yucatan, but quartz content increases westwards towards more continental areas, thereby improving porosity (S. Barrett, 1984, pers. comm.). In the Bahamas foredeep (2), relatively little quartz is involved, as the Bahamian carbonate section and Cuban volcanic arc mainly provided the detritus. In both the Sepur and Cuban foredeeps, pre-foredeep shelf-carbonate sections may be the best reservoir strata.

Cenozoic deformation of the Sepur foredeep and the underlying shelf, associated with transpression between Mexico-Yucatan and Chortis, may have disrupted originally-efficient structural and stratigraphic traps. On the other hand, the Neogene structural shortening in the Chiapas foldbelt of southern Mexico and Guatemala may have been sufficient to have quite recently depressed previously-immature source rocks to maturation depths.

As each of these basins owes its genesis to arc-continent collision, tectonic shortening is considerable, and Proto-Caribbean shelf source-rock sections were overthrust several tens to possibly hundreds of kilometres by the Caribbean allochthons. This factor raises two points: first, that abyssal Proto-Caribbean accretionary prism lithologies should and do occur at the suture zones; and second, that the total volume of liquid hydrocarbons preserved basinwards of the suture lines may exceed that predicted from known mature source-rock sections within the basins (Krause and James, 1990).

In summary, the combination of Proto-Caribbean source rocks, youthful maturation, and craton-derived sandstone reservoir rocks, makes the Eastern Venezuela Basin the most prospective of the four episutural foredeeps. The Maracaibo Basin is second only because it has lost so much oil during the Eocene and possibly Oligocene. The Cuban and southern Yucatan foredeeps/foldbelts have older times of maturation, poorer reservoirs, and less-rich source rocks, and are therefore less favourable. Inadequate seals in Bahamian carbonates may also be a drawback for the Cuban basin.

B. Rift and pull-apart basins

The Yucatan (5) and Grenada (6) Basins probably formed by intra-arc extension and sea-floor spreading within the Greater Antillean arc foundation during the Paleogene entrance of the Caribbean Plate into the Proto-Caribbean realm. Heat flow in both should have been initially high, and restricted circulation and euxinic sedimentation was likely during basin development, as both were bounded by arc platforms. Quartzose reservoirs may be lacking, although the Maya Mountains and the relatively migrating northern South American margin could have provided detritus to the western Yucatan Basin and the southern Grenada Basin, respectively. Along the eastern Belize margin (7), strike-slip basins formed contemporaneously with the Yucatan Basin by the migration of
the Cuban arc NNE to its present position (Fig. 5b and c; Rosencrantz, 1990). Paleogene clastics and shales from the Yucatan Peninsula and/or Cuba filled these troughs (Toledo Formation), which may have hindered early transportation of continental detritus into the Yucatan Basin. Although within reach of the drill, no wells have yet penetrated deeper sections of these fault-bounded basins which may have their own potential or, possibly, migration pathways to deep sections of the Yucatan Basin (personal review of Belize well-data).

The Cayman Trough (8) began to form in the Eocene, with an initial phase of lithospheric extension followed by sea-floor spreading at the mid-Cayman Spreading Center (Rosencrantz et al., 1988). Although now over 1,000-km long, only the western portion has received significant volumes of Cenozoic sediments, due to the progradation of deltaic sequences from the linear fault-zones of Central America. These sediments should be fairly quartz-prone, judging from source areas in Guatemala. Cenozoic strike-slip faulting has continued along the southern wall of the Trough and may have produced compressional structures in the depocenter which is located on the rifted margin of the basin. Initial extension in the Eocene must have created a deep, possibly anoxic basin with an arc foundation with high heat flow (onset of sea-floor spreading in basin), although the kerogen may be mixed due to the influence of Central America. Eocene source rocks occur in the Mosquitia Basin onshore Honduras and along the western Nicaragua Rise (9), which was nearby at the time (Williams, 1989). Increased compression and uplift during the Miocene within Guatemala probably enhanced clastic input in the Trough. Early Paleogene extension in basins along Jamaica/western Nicaragua Rise may have been related to the onset of transform motion along the Motagua-Cayman Fault zone.

The Falcon Basin (10) of Venezuela is an Oligo-Miocene pull-apart basin with a small number of alkaline intrusions. The basin developed above and after the emplacement of thrust sheets and flysch of the allochthonous belt of coastal Venezuela. Thus, the Proto-Caribbean shelf section, although present to the south, has been metamorphosed during the Eocene and is not therefore a viable source-rock section for the Falcon, where Oligo-Miocene marine shales (Pecaya Formation) are source rocks of poor quality. The Falcon has less potential than other onshore Venezuelan basins with unmetamorphosed Proto-Caribbean stratigraphy.

The Gulf of San Miguel (or Sambu) Basin (11) within the Panama arc is probably a pull-apart type basin of Miocene and younger age, related to NNW-trending left-lateral strike-slip faulting that crosses Panama (Mann and Corrigan, 1990). Arc-related volcanism may have occurred in the area as recently as Late Miocene, in which case heat flow could be quite high, but it is unlikely that extension of the entire lithosphere was involved with development. In a pull-apart interpretation of this basin, anoxic sediments may have been deposited near the basin floor. Bioproductivity in the area may have been enhanced by upwelling and early basinal conditions. A highly folded and faulted thick Miocene to Recent fill is indicated on existing seismic sections, but reservoir quality is questionable, judging from known source areas for clastic detritus (oceanic/arc crust). Current drilling in the area has apparently been encouraging, with shows reportedly occurring at three levels in the section (G. Lichtman, 1990, pers. comm.).

C. Accretionary prisms/forearc basins

The Barbados Ridge (13) represents a prism of Proto-Caribbean basinal sediment and voluminous quartzose, reservoir-quality Cenozoic clastics, shed from South America (e.g. the Scotland Formation) interfaulted and accreted to the leading edge of the Caribbean Plate. The Cenozoic Tobago forearc basin overlies the prism. Accreted proto-Caribbean pelagic rocks may constitute large sections of the submarine fold-and-thrust belt. Cenozoic source rocks may be mixed or gas-prone. Structure is chaotic however, and
large intact reservoirs may be lacking at the surface (see Speed et al., pp. 323-342, this volume).

The South Caribbean and North Panama foldbelts (14) are north-facing accretionary wedges, composed of sedimentary sections of the deep-marine Caribbean suite, and clastic sediments derived mainly from South America/Panama, folded and faulted into structures of variable sizes. Although mostly in deep water, updip migration could fill shallower reservoirs. Locally, large-scale gravity-faulting cuts the section where it has become overthickened and therefore unstable. Other evidence for recent structural activity is the wide occurrence of mud-volcanism in these prisms. Neogene-Recent structural and depositional thickening of the section may have caused recent maturation of older Caribbean-suite source rocks.

Between these two young accretionary belts lie the partially onshore Sinu and San Jacinto (14) accretionary belts, whose collective history of underthrusting (Caribbean crust beneath Western and Central Cordillera and Santa Marta Massif) goes back to the Late Cretaceous (Figs 5 and 6: Duque-Caro, 1984). The mainly Cenozoic Lower Magdalena forearc basin, with its terrestrial clastics and carbonates, lies behind and east of the San Jacinto Belt, and differs fundamentally from the Middle Magdalena, because of its permanent position west, rather than east, of the Colombian arc.

The San Juan-Azua-San Pedro Basin (15) of Hispaniola can be considered as an accretionary belt between the island’s northern arc-complex and its southern oceanic terrane (mainly Tertiary pelagic carbonate on a Cretaceous basaltic foundation), which became merged by sinistral transpression during the Eocene to Early Miocene interval (Fig. 5b, c; Biju-Duval et al., 1982). Oil seeps and shows in the Azua portion of the basin may have been sourced from overthrust Tertiary limestones of the southern terrane, which, at least in the Dominican Republic, appears not to include the Cretaceous section of the Caribbean suite. Reservoir rocks are limited, but reefs and quartz-bearing sandstones are locally developed in Neogene sections, the latter derived from Cretaceous-Eocene tonalite intrusions. The Muertos Trough accretionary prism of Neogene age bounds the southern San Pedro Basin, and may be similar to the South Caribbean Foldbelt. Mann and Lawrence (this volume, pp. 291-308) discuss Hispaniola’s petroleum potential in detail.

D. Arc-flank and other basins

Because of limitations on reservoir quality, the potential for large oil accumulations in Caribbean arc-flank basins is low. Local carbonate sections may offer the best chances for reserves. Of the arc-flank basins listed in Table 1, the south Cuban shelf (19) and Cayman Ridge will have carbonate sections updip from Yucatan Basin sections, which have experienced high early-Cenozoic heat flow. The carbonates of the Cayman Ridge have the same setting. The Cibao Basin (20) of the Dominican Republic has a favourable loading history, with up to 6 km of Late Miocene and Pliocene sediments (gravimetric interpretation: G. Karner, E. Fuller and L. Dent, pers. commun. 1991). The Limon Basin (17) of Costa Rica and northern Panama (Winslow et al., 1988), also has a favourable loading history, with an 11-km thick Late Cretaceous — Cenozoic section that has been thrust eastwards since the Neogene.

The Cesar Basin (21) of Colombia includes the Proto-Caribbean suite, but predictions of maturation history relative to the timing of structural development are difficult to make, because of the basin’s proximity to the Caribbean suture zone (Maestrichtian-Paleocene suturing here), and intense Neogene disruption associated with uplift of the Perijá and Santa Marta ranges.
CONCLUSIONS

The bulk of the hydrocarbons in the Caribbean region were sourced from Cretaceous and possibly Jurassic strata of the Proto-Caribbean suite. In most areas, maturation was driven by sedimentary overburden, which was insufficient for oil generation until the occurrence of specific tectonic events such as rifting, foredeep basin formation, or deposition of orogen-derived sediments at deltas. These tectonic events occurred during the Cenozoic, except along the southern Yucatan block (Late Cretaceous), so most Caribbean oil generation is Cenozoic in age.

The tectonic events that drove local maturation can be directly tied to the plate-tectonic evolution of the Caribbean region. This involved the progressive relative migration of the plate from the Pacific to its present position between the Americas. Therefore, the satisfactory understanding of the hydrocarbon potential across this province cannot be achieved without a full appreciation of the region’s plate-tectonic evolution.

From the above analysis, areas which may deserve additional exploration include the western end of the Cayman Trough, the flanks of the Yucatan and Grenada Basins, the Barbados and intra-Caribbean accretionary prisms, the north Cuban-Bahamas foredeep basin, the Chiapas fold-belt, and the eastern Belize margin.

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