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Petroleum Source Rock Analysis in the Western Caribbean Region: An Overview

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ABSTRACT

Compilation, analysis, integration, and interpretation of geochemical data from oil and gas fields, exploratory and scientific wells, oil and gas seeps, and outcrop samples allows the identification of effective and potential Cretaceous and Tertiary source rocks throughout the western Caribbean. In this vast region, seven source rocks of different ages are proven to be considered source rocks: (1) lower–middle Eocene Punta Gorda and Touche Formations along the Nicaraguan Rise (SR1), (2) middle Eocene, Yellow Limestone Group in Jamaica Island (SR2), (3) late Cretaceous (Cenomanian–Campanian) Loma Chumico Formation present mainly in northwestern Costa Rica (SR3), (4) middle Miocene Gatun Formation in Panama and Costa Rica (SR4), (5) late Cretaceous (Coniacian–Campanian) Cansona Formation in the Sinu and San Jacinto basins (SR5), (6) Oligocene to early Miocene Cienaga de Oro and lower Porquero Formations and age-equivalent units in the Lower Magdalena Valley basins (SR6), and (7) late Cretaceous (Coniacian–Santonian) rocks in the Colombian and Venezuelan basins (SR7).

Although the Cretaceous section sequence is generally considered the most likely source rock in the northern part of the South American plate, data from the Venezuela and Colombian basins suggest that the petroleum generative potential of the Campanian–Maastrichtian rocks is a non-source rock, normally with total organic carbon values < 0.5%. Also, in the Mosquitia Basin offshore Honduras and Jamaica Island, the middle and upper Cretaceous contain low organic matter, suggesting the absence of source rock.

The identification of several source rocks in the western Caribbean region is quite encouraging; however, future geologic research and petroleum exploration will allow to constrain the geographic distribution of the source rocks already identified and to refine in more detail their geochemical characteristics and petroleum generative potential.

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INTRODUCTION

We call the "western caribbean region" an area where source rocks and petroleum systems are only partially understood, and where previously known studies are mainly confined to local areas. Recently, petroleum exploratory activities have increased in this region, so we decided to conduct a regional integration and preliminary assessment of source rocks that may yield new insights into the petroleum system framework. The study area (Figure 1) comprises the western Caribbean region, including the following regions: southern Central America Chorotega and Choco Blocks; Lower Magdalena Valley Basins (San Jacinto, Sinu, Plato, and San Jorge basins); offshore Honduras and Nicaragua and Jamaica Island in the Nicaraguan Rise; the Chortis Block; Siuna terrane; and the Colombian Basin. Figure 1 shows the location of the area, the regions that were screened, and main tectonic and structural features. Figure 2 depicts the wells and seeps that have geologic and geochemical information and were used in this analysis. Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) scientific wells that have been drilled in the area are also integrated.

The existence and geographic distribution, thickness, and organic richness of Cretaceous and Tertiary source rocks throughout the western Caribbean region is poorly understood because of the complex geologic and tectonic evolution of the Caribbean plate through time (Erlich et al., 2003). In this scenario, the original depocenters could have been developed in a variety of geologic settings ranging from rifted, transtensional, transpressional, collisional foredeeps, and passive margin settings. Basement rocks, on the other hand, could have included oceanic, transitional, and continental crustal types (Mann and Burke, 1984; Mann et al., 1990; Pindell, 1993), which is crucial for the development of sedimentary basins with good source rock potential. In this complex scenario, the paleogeographic framework was not only controlled by the existing tectonic-structural setting but influenced also by global sea-level changes and long periods of volcanic activity (Kerr et al., 2002, 2009).

Traditionally, the presence of source rocks in the western Caribbean Margin basins has been always a concern during petroleum exploration activities, because there is a general perception that source rocks are mainly Tertiary gas-prone, with only minor potential to generate important volumes of liquid hydrocarbons, and that their geographic distribution is limited.

The Cretaceous has long been debated as a potential source rock in the western Caribbean, particularly the middle–late Cretaceous sequences associated with the global Cretaceous anoxic events (Erlich et al., 1996, 2003). Unfortunately, the Cretaceous source rocks in this region have limited geographic distribution, their thicknesses are insignificant, organic facies are poorly known, and thermal maturity is a serious concern because of thin overburden. Given the known complex tectonic setting in which sedimentary basins evolved throughout geologic time within the Caribbean plate, it is difficult to determine what controls the Cretaceous source rock geographic distribution, their aerial extent and thickness, and organic matter quality and content. In terms of source rock, petroleum exploration efforts in the Caribbean will be largely dependent on a better understanding of basin geologic evolution and architecture, source rock depositional facies, source rock quality, content, and preservation. To conduct this study, the following datasets were utilized: (1) geologic and geochemical information available to constrain the existence of source rock in the western Caribbean region; (2) geochemical data (total organic carbon [TOC], Rock Eval, and vitrinite analysis, etc.) from outcrops and from exploratory and scientific wells (ODP, DSDP); and (3) gas and crude oil geochemical information (bulk geochemical, GC, and GC-MS).

The existence of several source rocks capable of generating hydrocarbons along the western Caribbean region is supported by developed hydrocarbon fields, oil and gas seeps and oil slicks, bottom-simulating reflectors (BSRs) (Silver et al., 1995) BSRs, noncommercial discoveries, well production tests (DSTs), and oil and gas shows. Nevertheless, Cretaceous and Tertiary source rocks identified so far throughout the region are confined to local sedimentary depocenters associated with a specific paleogeographic setting and structural grain. A notorious example of this confinement is the Nicaraguan Rise platform, where 26 wells penetrated the organic-bearing middle–lower Eocene section; however, only five wells encountered source rock intervals with distinctive organic facies and thickness. The spotty nature of source rock intervals is a challenge to petroleum exploration, as thickness, organic facies (kerogen type), and organic carbon content are all extremely variable and, to a great extent, unpredictable. In addition, thermal maturity of these source rocks apparently is confined to the continental margin where sedimentation rates are higher (deeper overburden), whereas the abyssal plains of the basins are commonly immature because of thin overburden.

From a regional perspective, we will attempt to integrate geologic and geochemical information on source rocks throughout the western Caribbean region, including the Chortis Block, the Nicaraguan Rise

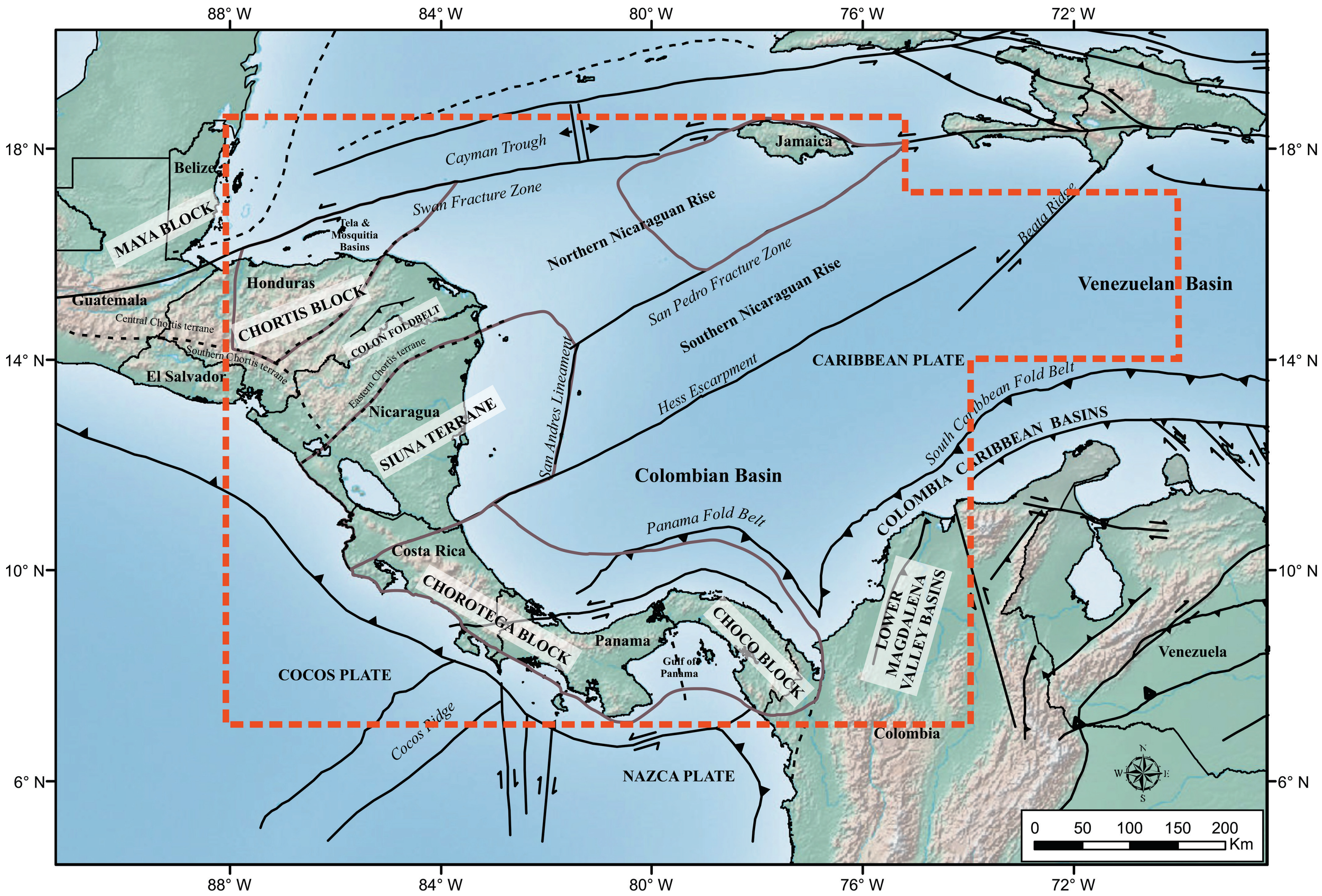


Figure 1. Location map of the study area. The map shows the main tectonic and geologic features of the western Caribbean region. The red, dashed line encloses the study area. 50 km (31.1 mi)

(including Jamaica), the Chorotega Block (Costa Rica and Panama), the Colombian Basin, and the Lower Magdalena Valley basins (San Jacinto, Sinu, Plato, and San Jorge Basins). Given the fact that only a very limited number of exploratory wells have been drilled offshore of the western Caribbean, a regional analysis and interpretation of petroleum source rocks in this large province is hindered by the availability of geologic data. Our most realistic approach to better understand, in a very broad way, the distribution of petroleum source rocks along the western Caribbean involves the integration of outcrops, exploratory wells, and DSDP and ODP boreholes. Using a limited database compiled recently, we attempt to define the following objectives: (1) integrated overview of the occurrence of petroleum source rocks, (2) source rock geographic distribution, and (3) ages and lithology of source rocks throughout the western Caribbean region.

SEDIMENTARY BASIN FRAMEWORK

This regional overview attempts to document the presence and distribution of source rocks throughout the western Caribbean region (Figure 1). A geologic synthesis of the Chortis Block, the northern Nicaraguan Rise (includes Jamaica), the Siuna terrane, the Chorotega and Choco Blocks, the Colombian Basin, and the Colombia's Caribbean Margin basins is included in the following subsections.

Chortis Block

Central America is divided into several tectonic blocks (Dengo, 1985): (1) the Maya Block, (2) the Chortis Block, (3) the Chorotega and Choco Blocks, and (4) the Siuna terrane (Figure 1). The Maya Block in the north is formed by southern Mexico and the Yucatan Peninsula and most part of Guatemala. The Chortis Block comprises El Salvador, Honduras, southernmost Guatemala, and the northern portion of Nicaragua. The Siuna terrane occupies the central region of Nicaragua (Venable, 1994; Rogers et al., 2007a), and the Chorotega and Choco Blocks comprise Costa Rica, Panama, and the northwest corner of Colombia (Figure 1). The northern boundary between the Chortis and Maya Blocks is the Polochic–Motagua transform fault system, whereas the southern boundary with the Siuna terrane has been proposed to be a strike-slip fault, which apparently extends offshore Honduras (Rogers et al., 2007a). The Chortis Block, originally regarded as the Precambrian–Paleozoic continental core of northern Central America, and whose area exceeds 500,000 km^2, has long been proposed to have detached from its original late Cretaceous position in southern Mexico (Pindell and Dewey, 1982) and displaced eastward approximately 1100 km (683.50 mi) of left-lateral strike-slip movement and 30–40° counterclockwise rotation (Gose and Swartz, 1977; Pindell and Dewey, 1982; Case et al., 1984, 1990; Dengo, 1985; Gose, 1985; Rosencrantz et al., 1988; Pindell and Barrett, 1990; Mann, 2007). This magnitude of lateral displacement is apparently recorded by the Cayman trough to the east. Thus, in this geodynamic context, the Chortis Block records a pre-Eocene geologic history (Karig et al., 1978) associated with the geologic and tectonic evolution in southern Mexico. Fairly recently, and to better explain the tectonic origin of the Chortis Block, Rogers et al. (2007b) subdivided it into (1) the central Chortis terrane, (2) the eastern Chortis terrane, and (3) the southern Chortis terrane based on regional aeromagnetic data, field studies, isotopic dates, and lead isotope data. According to these subdivisions, the central Chortis terrane is underlain by Precambrian and Paleozoic continental crust from southern Mexico; the eastern Chortis Block is made up of Mesozoic meta-sediments originally formed in rifted basins along the margin of the Chortis Block; and the southern Chortis terrane is underlain by late Cretaceous island arc suites (Guerrero terrane, Mexico) accreted to the Chortis Block sometime in late Cretaceous time (Rogers et al., 2007c).

Nicaraguan Rise and Jamaica

The Nicaraguan Rise is a giant submarine crustal province that extends northeast across the Caribbean Sea from the coast of Honduras and Nicaragua to Jamaica (Figure 1). It includes the prominent Rosalind and Pedro banks, the Colon fold belt, and Jamaica Island, covering approximately 420,000 km^2 (Nnameka, 1980). Ewing et al. (1960) and Edgar et al. (1971) examined numerous regional seismic refraction profiles and concluded that the depth of the mantle lies approximately 20–25 km (12.42–15.53 mi) under the Nicaraguan Rise and that, in general, the rise consisted of a four-layer crustal structure comparable with those found in deep-oceanic basins. Dengo and Bohnenberger (1969), Dengo (1973, 1985), and Meyerhoff (1966) concluded that the submarine shelf area of the northern Nicaraguan Rise is an extension of the Precambrian–Paleozoic basement of the Chortis Block, whereas Arden (1975) proposed that the western Nicaraguan Rise was a continuation of the older crustal rocks in Central America. Years later, the Nicaraguan Rise was divided into the northern (upper) and southern (lower) Nicaraguan Rise (Holcombe et al., 1990), in which the northern Nicaraguan Rise includes the well-preserved, huge shelf area that extends to Jamaica. Its southern limit is the Pedro fracture zone (or Pedro fault), while the southern Nicaraguan Rise separates the northern Nicaraguan Rise from the Colombian Basin (oceanic plateau) to the south (Figure 1). The boundary of the southern Nicaraguan Rise and the Colombian Basin is the 1200 km (745.64 mi)- long Saint–Elena Hess escarpment (Arden, 1975; Holcombe et al., 1990; Meyerhoff, 1996; Mauffret and Leroy, 1997). Case et al. (1990) suggested the presence of diverse crustal types under the Nicaraguan Rise, such as accretionary terranes, oceanic and continental crustal blocks, and indeterminate crust. Based on multichannel seismic data, they proposed that the southern Nicaraguan Rise was composed of oceanic crust, as it was the southern part of Central America. Most recently, several authors have attempted to interpret and subdivide the Chortis Block and the Nicaraguan Rise into different tectonic provinces and terranes (Figure 1), utilizing aeromagnetic surveys and field geology studies (Mann et al., 2006; Rogers and Mann, 2007; Rogers et al., 2007a, b; Baumgartner et al., 2008). It is obvious that the most controversial issue about the Nicaraguan Rise is its composition, structure, and age(s), as the deepest exploratory wells have not yet penetrated rocks older than middle Cretaceous. The older rocks encountered by these wells are the mid-upper Cretaceous sedimentary and meta-sedimentary rocks offshore Honduras (Tela and Mosquitia Basins) and a suite of granitoids that range in age from late Cretaceous to Paleocene (Lewis et al., 2011).

In general, the shelf of the Nicaraguan platform is an Eocene–Recent carbonate-type platform formed unconformably on the crystalline basement of poorly known age. The platform is made up of Eocene sequences, commonly known as the Punta Gorda and Touche Formations characterized by a lower Eocene basal volcanic, volcaniclastic, and occasional limestone succession. The basal part of the Eocene increases to more detrital and volcanic–volcaniclastic facies toward the southwest. The Eocene section is unconformably overlain by the Oligocene–lower Miocene Mosquitia Formation, which in turn is unconformably overlain by the Miocene to Recent Martinez Reef Formation. The two regional unconformities developed extensively during Oligocene and middle Miocene times along the Nicaraguan platform, play a key role in the evolution of the petroleum system along the offshore area. Exploratory wells Perlas-2 and Perlas-3, and Coco marina-1 (Figure 3) depict in general the stratigraphy, ages, and predominant lithologies of the Nicaraguan Tertiary platform successions.

Jamaica Island is considered to be part of the Nicaraguan Rise (Lewis et al., 2011). The geologic evolution of the island is related to the following: (1) formation of a Cretaceous oceanic island arc from Hauterivian to Maastrichtian, (2) Paleocene to early-Eocene rifting stage, (3) middle Eocene to Miocene deposition of carbonate platform successions, and (4) late Cenozoic uplift and mountain building (Mitchel, 2002). The pre-Cretaceous geology of Jamaica in relation to the basement of the Nicaraguan Rise is unknown.

Siuna Terrane

The Siuna terrane was first defined by Venable (1994) for a suite of thrusted ultramafic cumulates, serpentinites, and intermediate volcanic and sedimentary rocks of early Cretaceous age that are widely exposed in Siuna, northern and central Nicaragua (Figure 1). The magmatic rocks record isotopic signatures characteristic of an oceanic crust, which most likely were formed along the Caribbean arc system at the edge of the Caribbean large igneous province (Kesler et al., 1990; Venable, 1994; Rogers et al., 2007a). This allochthonous terrane crops out in northern Nicaragua and apparently extends east into the Nicaraguan Rise, and it was accreted to the eastern Chortis Block sometime in the late Cretaceous (Venable, 1994; Rogers et al., 2007a, b). A previously unknown, thin-skinned fold-and-thrust belt of Cretaceous age was defined by Rogers et al. (2007a) near the Honduras–Nicaragua border (Figure 1). The Colon Belt consists of imbricate, southeast-dipping reverse faults and open folds, which indicate a broad foreland zone of convergent deformation. Rogers et al. (2007a) concluded that the Colon fold-and-thrust belt in eastern Honduras and in the northern Nicaraguan Rise, which trends for 350 km (217.47 mi), developed in response to the tectonic suturing of the oceanic Siuna terrane to the eastern Chortis Block in the late Cretaceous. The Colon fold belt apparently continues offshore Honduras, in the Mosquitia Basin. The southern boundary of the Siuna terrane lies somewhere in southern Nicaragua, but is not well defined because of the lack of good surface exposures near the limit with the Chorotega Block. Over the years, the Siuna terrane has been modified somewhat to reflect the advances on the tectonic evolution of the Caribbean region and the southern Cordillera (Pindell and Barrett, 1990; Tardy et al., 1994; Moores, 1998; Mann, 1999; Rogers et al., 2007a).

Chorotega and Choco Blocks

The Chorotega Block (Figure 1) as defined by Dengo (1985) is constituted by Costa Rica and Panama

(Duque-Caro, 1990a; Coates et al., 1992). Apparently during the Pliocene, the Choco (Dengo, 1985) and part of the Chorotega Block separated from the Caribbean plate to form the so-called Costa Rica–Panama microplate (Kellogg and Bonini, 1982; Kellogg and Vega, 1995; Kellogg and Mohriak, 2001; Trenkamp et al., 2002). In this scenario, the autochthonous part of the Chorotega Block formed a narrow oceanic island arc on the Caribbean plate, between the southern margin of the Chortis Block and the detached Costa Rica–Panama microplate (Fisher and Gardner, 1991; Gardner et al., 1993; Fisher et al., 1994). The complex geologic setting of the Chorotega and Choco Blocks record the interaction of the South American, Caribbean, Cocos, and Nazca plates as shown originally from Molnar and Sykes (1969), Mann and Burke (1984), Dengo (1985), Silver et al. (1990), Kellogg and Vega (1995), Mann and Kolarsky (1995), Reed and Silver (1995), DeMets et al., (1995), and Mann (2007). The southern Central America arc occupied the westernmost margin of the Caribbean plate since late Cretaceous time and moved eastward to collide with NW South America in the Neogene (Coates and Stallard, 2013). The timing of initial collision has been proposed to have occurred between 10 Ma and 20 Ma (Wadge and Burke, 1983; Trenkamp et al., 2002), but total closure of the Pacific–Caribbean seaway was approximately at 3 Ma, interrupting the circulation of water between the Pacific and Atlantic oceans (Schmittner et al., 2004) and permitting terrestrial American biotic interchange between North and South America (Marshall et al., 1979; Marshall et al., 1982; Marshall, 1985). This tectonic collision triggered a major stage of uplift and deformation in the Colombian Andes in the late Miocene (Keller et al., 1989; Duque-Caro, 1990a, b; Mann and Corrigan, 1990; Coates et al., 1992; Kellogg and Vega, 1995; Mann and Kolarsky, 1995; Moore and Sender, 1995; Westbrook et al., 1995; Trenkamp et al., 2002). Plate tectonic interactions at the northwest corner of South America between the Nazca, oceanic Caribbean, and South American plates define a triple junction where the Choco Block and the northern Andes coexist (Figure 1). The western limit of the Choco Block is the Gatun fault zone, whereas the eastern margin of the Panama Arc (Choco Block) is defined by the Uraba-Atrato fault, which is long considered the collisional suture with the South America plate (Trenkamp et al., 2002).

The Colombian Basin

The Colombian Basin is located in the westernmost part of the Caribbean plate (Figure 1). The basin is bounded to the north by the Hess escarpment and to the south by the Southern Caribbean fold belt. The western limit is with Costa Rica and Panama, and to the east, the Colombian Basin is partly separated from the Venezuelan Basin by the Beata ridge (Figure 1). The basin abyssal plain is the flattest and the deepest part of the basin, with water depths between 2.8 km (1.739 mi) and 4 km (2.485 mi). The Colombian Basin is 350 km (217.47 mi) wide in the south, about 100 km (62.137 mi) in the north, and approximately 900 km (559.23 mi) long. The age of the basin ranges from the Cretaceous to the Neogene, and its sediment fill varies from 2.5 km (1.553 mi) to 3 km (2.485 mi), being the Nicaraguan Rise and the Magdalena delta the main sediment sources. The thickness of the lower crustal layer varies from 6 km (3.728 mi) to 7 km (4.349 mi), but commonly exceeds 10 km (6.213 mi) (Ewing et al., 1960; Edgar et al., 1971). Analysis of magnetic anomalies and linear patterns suggests that the anomalies are compatible with seafloor spreading during the early Cretaceous (Hall et al., 1995). Burke et al. (1984), Pindell and Barrett (1990), Mann (1995), and Pindell et al. (1988) have conducted extensive analyses, reviews, and tectonic interpretations of the Caribbean plate geologic history and evolution since the Mesozoic.

Ocean drilling project Leg 165 Site 1001 sampled 38 m (124.67 ft) of basaltic basement of the Caribbean plate on the Hess escarpment. The section recovered consists of 12 basaltic flow units with a weighted mean Ar/Ar age of 80.9 ± 0.9 Ma (Kerr et al., 2009). The basalts are overlain by Campanian limestones with nannofossils corresponding to biozone CC21, which indicate a minimum age of 77 Ma (Sigurdsson et al., 1977). DSDP 153, located between the Beata ridge and the Venezuela northern margin, encountered an upper Eocene and Neogene sequence (“A”) consisting of pelagic, fossiliferous chalk, ooze, marl, claystone, zeolite, and volcanic ash layers. Stratigraphically below is a transitional sequence of lower Eocene to middle late Cretaceous (Turonian–Maastrichtian) age, characterized by pelagic, siliceous limestone, claystone, bedded chert, silicified claystone, carbonaceous, phospathic, and volcanic clays. The borehole bottomed in 17 m (55.774 ft) of aphanitic basalts (“B”) of possible Cretaceous age (Edgar et al., 1971). Near the central part of the Colombian Basin, ODP Site 999 was drilled down to 1066.4 m (3498.68 mi) below seafloor. A description of the sequence from younger to older is as follows: Pleistocene–upper Miocene clayey mixed sediment with scattered interbedded ash layers containing nannofossil, foraminifera, and siliceous fossils; lower Miocene–upper Oligocene clayey calcareous limestone with common thin ash layers;

lower Oligocene–middle Eocene clayey calcareous limestone but contains thicker and more frequent ash layers; middle Eocene–upper Paleocene consisting of a clayey calcareous mixed sedimentary rock with some interbedded ash layers; and a basal sequence consisting of basal Paleocene hard, light gray limestone and upper Maastrichtian limestone with clay (Sigurdsson et al., 1996, 1997).

Lower Magdalena Valley Basins

Plato, San Jorge, Sinu, and San Jacinto Basins

The northwest corner of South America is occupied by three main tectonic plates: the South American plate, the Caribbean plate, and the Nazca plate (Figure 1). The interaction of these three major lithospheric plates has triggered a large-scale critical tectonic process, such as subduction, collision, transpression, and accretion of allochthonous oceanic terranes through geologic time. These evolving complex tectonic settings have given rise to the dominant and highly complex tectonic domains present in northwest Colombia (Burke et al., 1984; Duque-Caro, 1984, 1990b; McCourt et al., 1984; Bourgois et al., 1987; Pindell et al., 1988; Coates et al., 1992; Restrepo-Pace, 1995; Cediel et al., 2003; Cortes, 2004; Cortes et al., 2006). Since Cretaceous time, tectonic and structural events have generated at least four basins (Plato, San Jorge, San Jacinto, and Sinu), each one with a very distinctive stratigraphic history. The Romeral, a N–NE-trending lineament, is a large-scale structure that divides the region into eastern and western areas. The eastern area is formed by the Plato and San Jorge Basins, which are depressions separated by structural highs developed by wrench faulting within the basement consisting of continental crust. Sedimentation in the eastern areas of the Lower Magdalena Valley Basin began in the Oligocene during which sediments transported from the proto-Magdalena were deposited in deltaic, littoral to platform, and bathyal environments. The Cienaga de Oro and Porquero Formations were deposited during this geologic period. The western area is thought to be part of the San Jacinto accretionary wedge, which is associated with an oceanic crust fragment that was tectonically sutured to the South American plate in the late Cretaceous (Duque-Caro, 1984, 1990a). According to Caro and Spratt (2007), the San Jacinto fold belt is an inverted rift or graben on the northwest continental margin of South America, whose structural inversion began in middle Eocene time because of lateral compressional stresses. The San Jacinto fold belt lies mainly onshore and its northern part is offshore, and it is limited by the Romeral fault (lineament) to the east and by the Sinu lineament to the west. The late Miocene collision of the Panama microplate in northwestern Colombia has been linked to the main Andean orogenic stage (Duque-Caro, 1990b).

PETROLEUM SYSTEM FRAMEWORK

The first attempt to understand the paleoceanography, geographic distribution, and hydrocarbon generative of Cretaceous and Tertiary source rocks in the Caribbean region was conducted by Erlich et al. (1993, 2003). This time, we integrate all geochemical data available to provide a better understanding of the hydrocarbon-generative sequences throughout the different basins of the study area. The samples studied include outcrop samples, well data, and gas and oil seep samples (SR1–SR7; Figure 2). The tentative position and age of source rock intervals are depicted in Figure 3. This figure shows the predominantly carbonate and shale Tertiary successions along the Nicaraguan Rise and Jamaica and the more clastic nature of the Tertiary strata along Costa Rica, Panama, and the Colombian Margin. Cretaceous sequences have been penetrated by wells offshore Honduras, Jamaica, and Costa Rica onshore, and they also crop out in Jamaica, Costa Rica, and Sinu–San Jacinto areas. The Tierraalta-2XP in the Sinu Basin is the only well that penetrated the upper Cretaceous section in the Colombia Caribbean Margin. To better understand the quantity, quality, and types of organic facies and the thermal maturity of Tertiary and Cretaceous source rocks in the western Caribbean region, we compiled, analyzed, and evaluated the following geochemical parameters: (1) TOC, to estimate the quantity of the organic matter, (2) Pyrolysis RockEval data to comprehend the quality of the organic matter (HI, OI, S2/S3, and PP) as well as the thermal maturity of kerogen ($T_{\max}$ and PI), (3) Elemental analysis composition, and (4) Maceral distribution to estimate the quality of organic matter and Vitrinite Reflectance (R_o) and thermal alteration index (TAI) to disclose the thermal evolution of the Cretaceous and Tertiary successions. Table 1 is a summary of the main geochemical parameters of samples in each main region. Only the sequences that have the potential to be considered a source rock and the strata that have been proposed source rocks in previous publications are included. Geochemical and compositional data from gas and oil samples were also evaluated to determine, to the best possible extent, the source rocks that could have generated them, applying geochemical inversion analysis. Bulk geochemical composition, carbon isotopic ratios, and biomarker distribution of the saturated and aromatic fractions are also integrated.

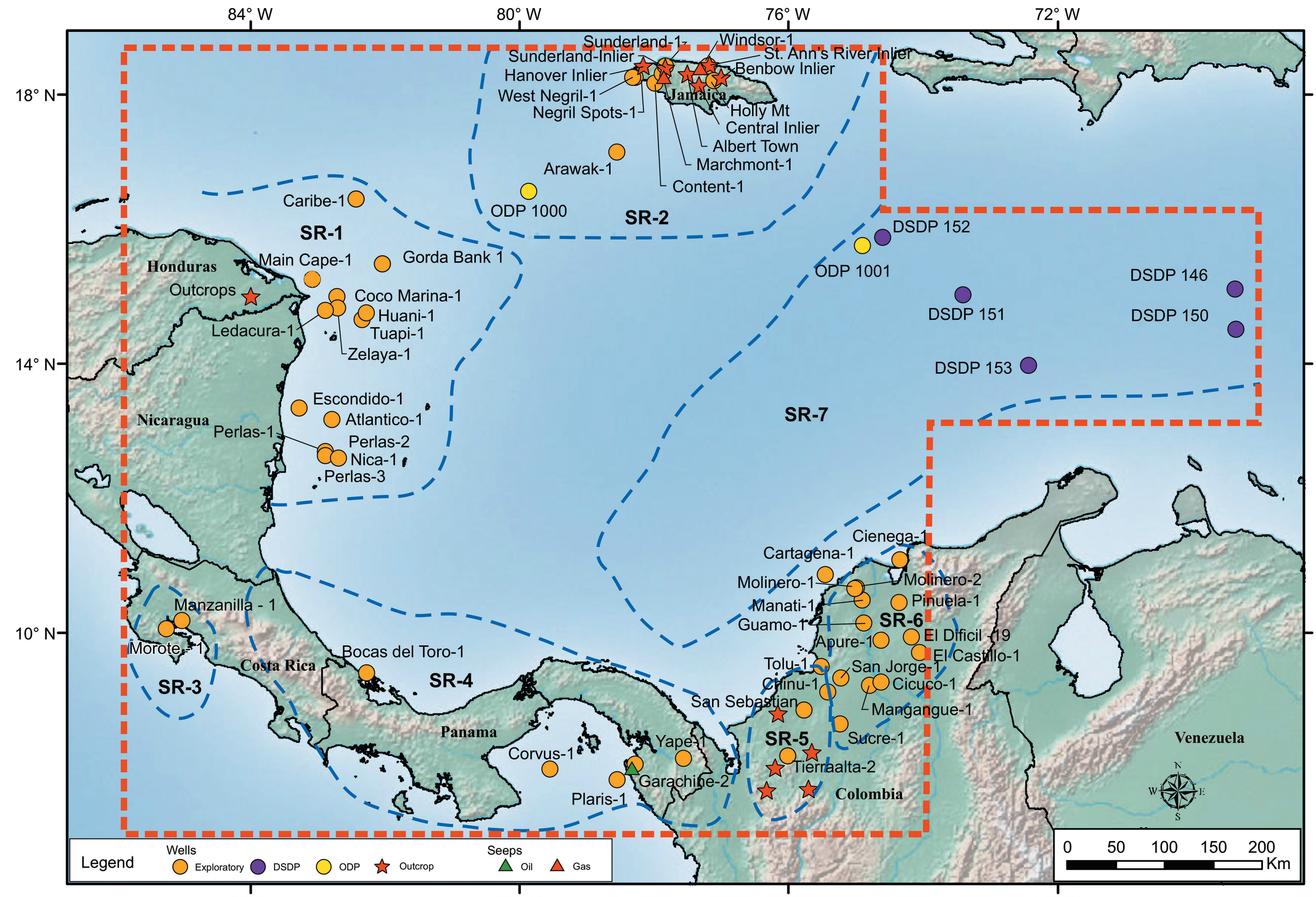


Figure 2. Map of the western Caribbean region showing wells, outcrops, and seeps that were utilized, analyzed, and interpreted in this study. The map depicts all exploratory and scientific (ODP/DSDP) wells drilled throughout the western Caribbean region (IHS, 2014). The map also shows the areas where specific source rocks are present, and they are labeled SR1 to SR7. It is important noting that the area outlines are tentatively defined by the availability of wells, but they do not indicate geologic control. 50 km (31.1 mi)

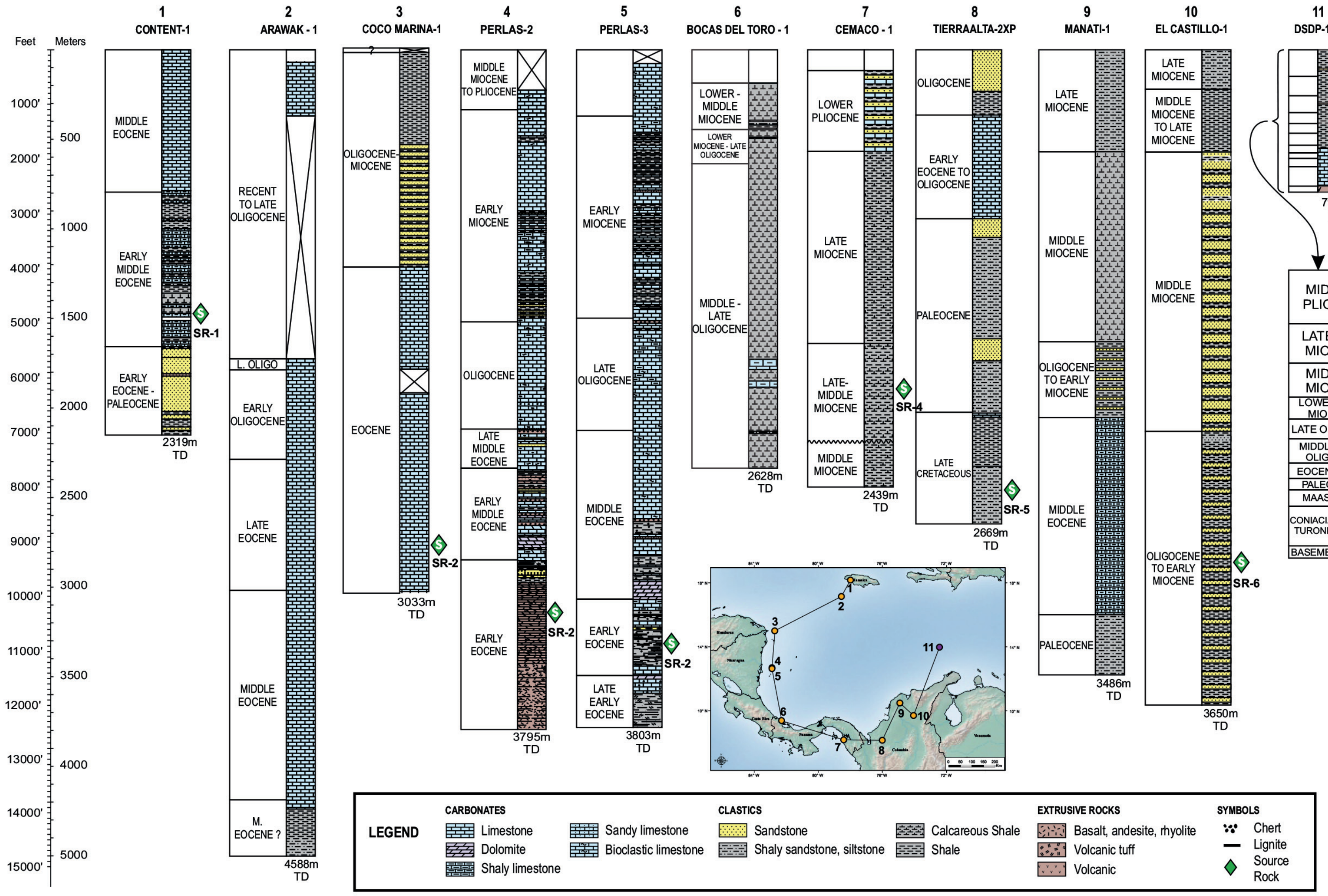


Figure 3. Stratigraphy and age of the sequences penetrated by exploratory and scientific (ODP/DSDP) wells. Approximate position and age of source rock intervals are shown by green diamonds. Based on the location of the well, source rock intervals are assigned a SR1 to SR7 nomenclature.

Table 1. Geochemical data summary from source rocks along the western Caribbean region.

Geological Region	Geological Unit and Age	Number of Samples	TOC%			HI (mgHC/gTOC)			OI (mgCO/gTOC)			PP (mgHC/grock)			S2/S3			$T_{max°}$			PI			Vitrinite Reflectance Ro%			H/C			O/C			Thickness (m)
			Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	
Nicaraguan Rise	Neogene Kanamon/ Martinez formations.	152	0.39	0.04	1.30	86	19	319	254	64	693	0.40	0.04	1.78	0.39	0.06	1.54	424	413	435	0.24	0.05	0.50	0.29	0.17	0.35							
Nicaraguan Rise	Eocene Punta Gorda/Touche formations. whole samples	551	1.21	0.07	16.40	159	2	902	163	0	800	3.82	0.04	56.4	3.71	0.1	51.4	430	402	454	0.21	0.01	1.00	0.47	0.25	0.80							
Nicaraguan Rise	Organic Rich Eocene Punta Gorda/Touche formations.	155	2.27	0.50	16.40	204	31	902	87	5	433	7.31	0.23	56.42	7.43	0.24	51.41	429	409	446	0.13	0.01	0.52	0.46	0.25	0.80							100–500
Nicaraguan Rise	Cretaceous Yojoa Group and Valle de Angeles Fm.	93	0.59	0.18	1.33	56	15	243	242	113	528	0.45	0.11	3.40	0.24	0.07	1.46	432	321	444	0.37	0.05	0.55	1.87	0.60	3.95							
Jamaica	Eocene Yellow or Chapelton formations.	24	4.75	0.38	15.32	339	55	506	31	8	128	37.3	7.0	84.0	31.5	0.4	63.0	411	395	427	0.12	0.07	0.20	0.52	0.37	0.62							
Jamaica	Eocene White Limestone	10	0.12	0.08	0.16	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	0.40	0.38	0.44							
Jamaica	Cretaceous	88	0.47	0.05	1.60	46	8	127	69	20	175	0.37	0.10	1.07	0.80	0.10	2.28	438	420	493	0.21	0.06	0.73	0.99	0.51	1.60							
Chrorotega	Middle-Late Cretaceous Loma Chumico Whole samples	116	5.24	0.02	28.54	359	33	931	48	4	300	45.49	0.03	271.33	31.91	0.03	175	419	383	441	0.25	0.02	0.83	n.d	n.d	n.d							
Chrorotega	Organic Rich Middle–Late Cretaceous Loma Chumico	28	15.31	0.52	28.54	782	314	931	12	4	39	134.32	1.70	271	91	8	175	418	411	441	0.06	0.02	0.18	n.d	n.d	n.d							85
Chrorotega	Middle Miocene Gatun Formation.	35	4.81	0.13	40.61	220	89	307	n.d	n.d	n.d	11.13	4.87	38.04	n.d	n.d	n.d	434	426	437	0.07	0.05	0.11	0.39	32.00	0.48	1.32	1.31	132	0.07	0.01	0.14	
Chrorotega	Late Miocene Pucro Fm.	30	1.51	1.23	1.84	92	61	158	n.d	n.d	n.d	1.61	0.82	3.27	n.d	n.d	n.d	426	416	435	0.08	0.04	0.11	0.36	0.30	0.44	1.34	1.31	137	0.07	0.01	0.14	
LMVB Sinu Basin	Late Cretaceous Cansona Fm. whole samples	138	2.18	0.09	14.41	239	19	1161	115	2	278	11.19	0.22	72.12	13	0.02	155	429	308	497	0.14	0.01	0.77	n.d	n.d	n.d							
LMVB Sinu Basin	Organic Rich Late Cretaceous Cansona Formation.	65	3.64	0.51	14.41	283	24	1161	44	2	248	15.34	0.17	72.12	19.7	0.12	155	438	402	497	0.16	0.01	0.77	n.d	n.d	nd							100–200
LMVB Plato and San Jorge Basin	Oligocene/ Early Miocene Cienaga de Oro and Lower Porquero fms.	340	1.48	0.11	51.30	116	14	579	77	1	608	3.97	0.13	216	5.01	0.02	41.5	430	406	448	0.11	0.01	0.54	0.48	0.25	0.80							
LMVB Sinu San Jacinto	Oligocene/ Early Miocene El Carmen Formation	131	1.56	0.22	20.17	58	2	964	112	52	956	2.30	0.05	157	0.63	0.02	8.75	426	410	479	0.11	0.01	0.43	0.42	0.34	0.59							

Nicaraguan Rise—Source Rock 1

Fourteen exploratory wells (Atlantico-1; Escondido-1; Huani-1; Ledecura-1; Nica-1; Perlas-1, 2, and 3; Tuapi-1; Zelaya-1; Coco Marina-1; Caribe-1; Gorda bank-1; and Main Cape-1) with available geochemical data were utilized for the source rock evaluation and analysis offshore Honduras and Nicaragua (Figure 2). A total of 37 exploratory wells have been drilled throughout the Nicaraguan Rise, principally offshore Honduras and Nicaragua, but only these 14 wells have complete geochemical data, which will permit us to identify and evaluate proven and potential source rocks within the Cretaceous and Tertiary sequences (Table 1) along the Nicaraguan platform and the Honduras Mosquitia Basin. Even though Jamaica Island is part of the Nicaraguan Rise, it will be evaluated separately, given the availability of different geochemical datasets.

Source Rock Analysis

The analysis and interpretation of geochemical data from 14 wells along the Nicaraguan platform suggests that only the early and middle Eocene section has the potential to generate hydrocarbons. The Oligocene and Miocene successions are normally organic-matter lean; thus, they are not potential source rocks in this area. Out of the 14 wells drilled in the shelf, only the Coco Marina-1, Perlas-2, Perlas-3, and Perlas-1 wells (Figure 2; green circles in Figure 5) contain good source rock within the early–middle Eocene section, with TOC values ranging from 0.5% to 16%, but averaging 3.6 for the Coco Marina-1 and 2.2% for the Perlas wells. Hydrogen index (HI) ranges from 31 mg HC/g rock to 902 mg HC/g rock, with the presence of kerogen Types II, II/III, and III; nevertheless, kerogen Type II/III predominates (Figure 4). The two wells shown in yellow circles in Figure 5 have TOC values up to 3% within the early–middle Eocene section, but with gas-prone kerogen Type III.

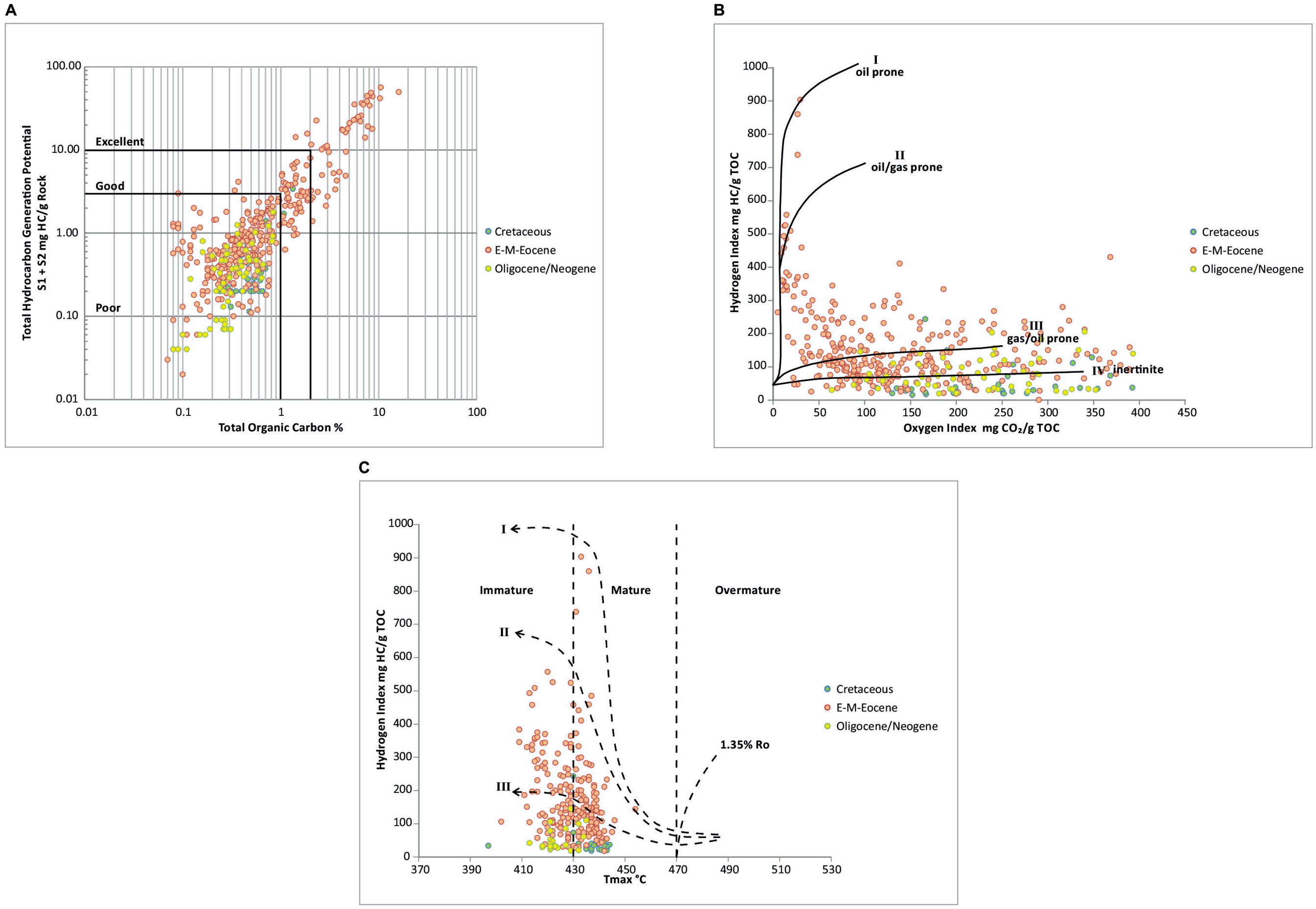


Figure 4. Geochemical plots from the Nicaraguan Rise: (A) Total organic carbon vs. total hydrocarbon-generation potential, (B) hydrogen index vs. oxygen index, (C) $T_{\max}$ vs. hydrogen index.

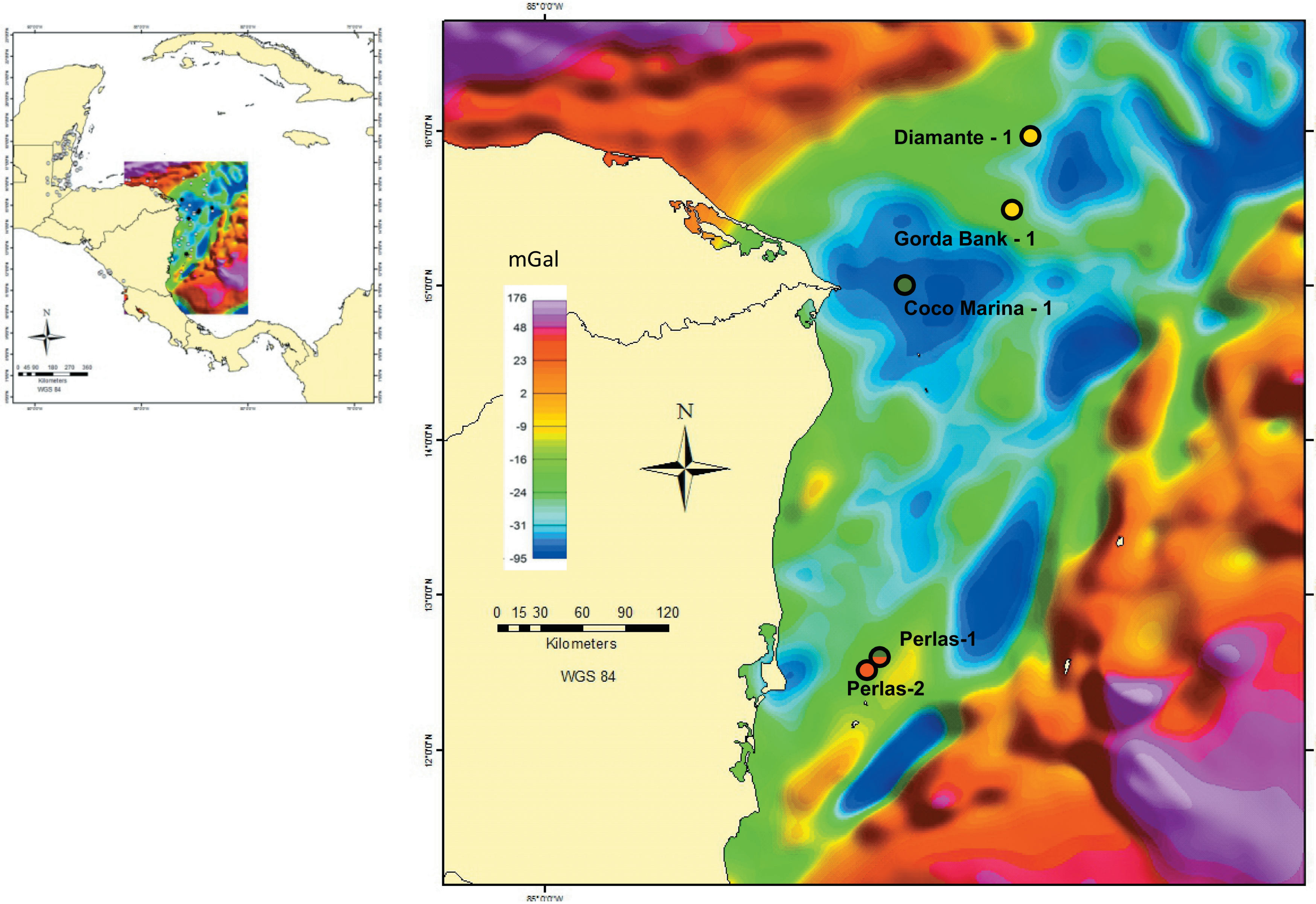


Figure 5. Bouguer anomaly map of part of the Nicaraguan rise showing (A) well locations; (B) Perlas-1 and Perlas-2 are wells with hydrocarbon production and shows (green/red circles); (C) Coco Marina-1 and Perla-1 wells, which have good oil source rock (green circles); and (D) wells with fair gas source rock (yellow circles), and their location with respect to depocenters. 15 km (9.3 mi)

The approximate thickness of the generative sequences estimated in wells Coco Marina-1 and Gorda Bank-1 ranges from 100 m (328.08 ft) to 500 m (1640.41 ft), but these thicknesses could be overestimated because of well caving. The early to middle Eocene source rock thermal maturity ranges from immature to early mature, and it has just reached the early oil window (R_o% 0.6–0.8) in Coco Marina-1, Tuapi-1, and Perlas-2 wells. Thermal indicators of the wells analyzed suggests that thermal maturity of the Eocene section is an issue throughout the Nicaraguan Rise region. The maximum maturity reached by the generative sequences is just above early oil window generation ($R_o < 0.7\%$). Petroleum is proof of a system, but it may not be commercial. Another issue of concern is that the early–middle Eocene generative section lacks lateral continuity along the Nicaraguan Rise, mainly because of very drastic lateral facies changes that rapidly affect source rock distribution, quality, and organic matter content. A good example of lateral facies changes is expressed at the Huani-1 and 2, Tuapi-1, Ledacura-1, and Main Cape-1 wells, which were drilled between 30 km (18.64 mi) and 50 km (31.068 mi) from the Coco Marina-1, a well with more than 500 m (1640.41 ft) of high-quality middle Eocene source rock; however, they are devoid of source rocks. Apparently the distribution, nature, and preservation of early–middle Eocene source throughout the Nicaraguan Rise was restricted to northeast–southwest-trending depocenters bound by basement structural highs (Figure 5), where the conditions for accumulating and preserving organic matter were favorable. The regional Bouguer map clearly evidences that the only well that was drilled in a depocenter is Coco Marina-1 in the Mosquitia Basin, and that is why an anoxic environment and preservation of the organic matter took place in early–middle Eocene time. The other exploratory wells with good source rock potential but with negative exploratory results are the Perlas wells (see earlier text). These wells were drilled on an inverted structural high behind the Nica Ridge, a prominent positive feature in the Nicaraguan Rise. These observations might indicate that the source rock was deposited during the early–middle Eocene along the Nicaraguan Rise platform (where organic primary productivity was apparently high), particularly in structural lows bounded by structural highs, controlling thus seawater circulation and preservation of organic matter.

Although petroleum has been recovered from seven exploratory wells in the Nicaraguan Rise (Perlas-1, Main Cape-1, Miskito-1, Huani-1, Touche-1, Tuapi-1, and Tinkham-1), no geochemical data were available to analyze the oils or gases.

None of the offshore exploratory wells drilled along the Nicaragua platform penetrated the Cretaceous section. Conversely, in the Tela and Mosquitia Basins (Figure 1), offshore Honduras, the middle and upper Cretaceous section has been penetrated by wells Castilla-1, Castana-1, Gracias a Dios-1, Caribe-2, Caribe-3, Diamante-1, and Turquesa-1. Geochemical analyses of the Honduras wells suggest in general that the organic matter content is low, usually lower than 1.0%, indicating a lack of oil generation potential for this section. The HI, on the other hand, is commonly lower than 100 mg HC/g rock (Figure 4), and the kerogen type, even though it is rich in amorphous material, is oxidized and/or exhausted, and therefore lacks oil potential. The thermal maturity of the Cretaceous section in Honduras shows a variable range of thermal maturities (TAI, R_o), which generally range from mature to over mature. The high maturity levels of the Cretaceous samples reveal the complex geologic and thermal history of the Nicaraguan Rise during the Mesozoic. In summary, the low organic matter content and the type of kerogen in the Cretaceous samples offshore Honduras are not indicative of source rock potential. However, the presence of Cretaceous source rocks with petroleum potential may exist anywhere else along the western Caribbean region.

Jamaica—Source Rock 2

Eleven exploratory wells have been drilled in Jamaican territory since 1955 (Figure 2). Nine exploratory wells were drilled onshore and only two wells offshore: Pedro Bank-1 and Arawak-1. Absolutely all 11 wells were abandoned as dry, although minor hydrocarbon indications were reported in wells (Content-1, Windsor-1, Retrieve-1, and Pedro Bank-1 wells). In this study, geochemical information from six wells and from outcrop samples were available and analyzed in detail. In addition, geochemical analyses of two gas seeps reported from Jamaica Island were also studied to understand their source.

Source Rock Analysis

In Jamaica, the only sedimentary sequence with the potential to generate important volumes of hydrocarbons is the middle Eocene Yellow Limestone Group, which consists of the Freemans Hall, the Stettin, the Guys Hill, and Chapelton Formations (Rodrigues, 1991; Mitchell, 2003). The rest of the successions do not contain enough quantity and good quality organic matter to be considered a potential source rock. The middle Eocene Yellow Limestone Group lithologies are fossiliferous, thin-bedded calcareous shale, marl, and shaly limestone, usually silty, and with a few siltstone beds. Some lignite horizons are common in the section. The entire Eocene sequence was apparently deposited in a relatively shallow water marine environment. The most important information to evaluate the middle Eocene as a petroleum-generative sequence came from the

Content-1 well (Rodrigues, 1991), which was drilled to a total depth of 2425 m (739.14 ft) in the Yellow Limestone Group strata. The TOC ranges from 0.38% to 15.32%, with an average value of 3.88%. The Yellow Limestone sequence contains significant amounts (ca 40–70%) of amorphous and herbaceous macerals and HIs that range from 260 mg HC/g rock TOC to 530 mg HC/g rock TOC. The latter data permit to classify the kerogen as Type II, Type II/III, and Type III (Figure 6). However, it is worth mentioning that the real thickness of the effective source rock interval is a concern because sampling was done selectively, particularly in lithologies with dark colors and in lignite layers, indicating a clear bias for organic-richer intervals. Therefore, the sampling methodology could have yielded exaggerated TOC values, which are not representative of the source rock interval. Yellow Limestone outcrop samples from the Albert Town outcrop yielded a TOC of 12.54%, which is a very good organic matter content; however, the HI value from the same sample is only 87 mg HC/g TOC, indicating a poor hydrocarbon-generative capacity. Based on our evaluation, the Eocene section is thermally immature in wells and outcrops. Vitrinite reflectance, on the other hand, is generally lower than 0.6%. The distribution of this generative sequence (Yellow Limestone Group), in Jamaica, could be limited just to the places where this shallow marine clastic sequence was deposited, and it is known only from two places (Content-1 well and Albert Town outcrop).

Traditionally, the Cretaceous has been suggested as a possible source rock in the region, and it has been evaluated in exploratory wells and outcrops in Jamaica Island without good results. The average TOC for all Cretaceous samples is 0.47%, and the highest TOC value is 1.6% from one sample in the Windsor-1 well. The HI in all Cretaceous samples is lower than 100 mg HC/g rock, and the kerogen is dominantly (higher than 60%) inertinite and vitrinite macerals, which are, respectively, Type IV and III kerogen. In the best of the case scenario, a Type III kerogen could be

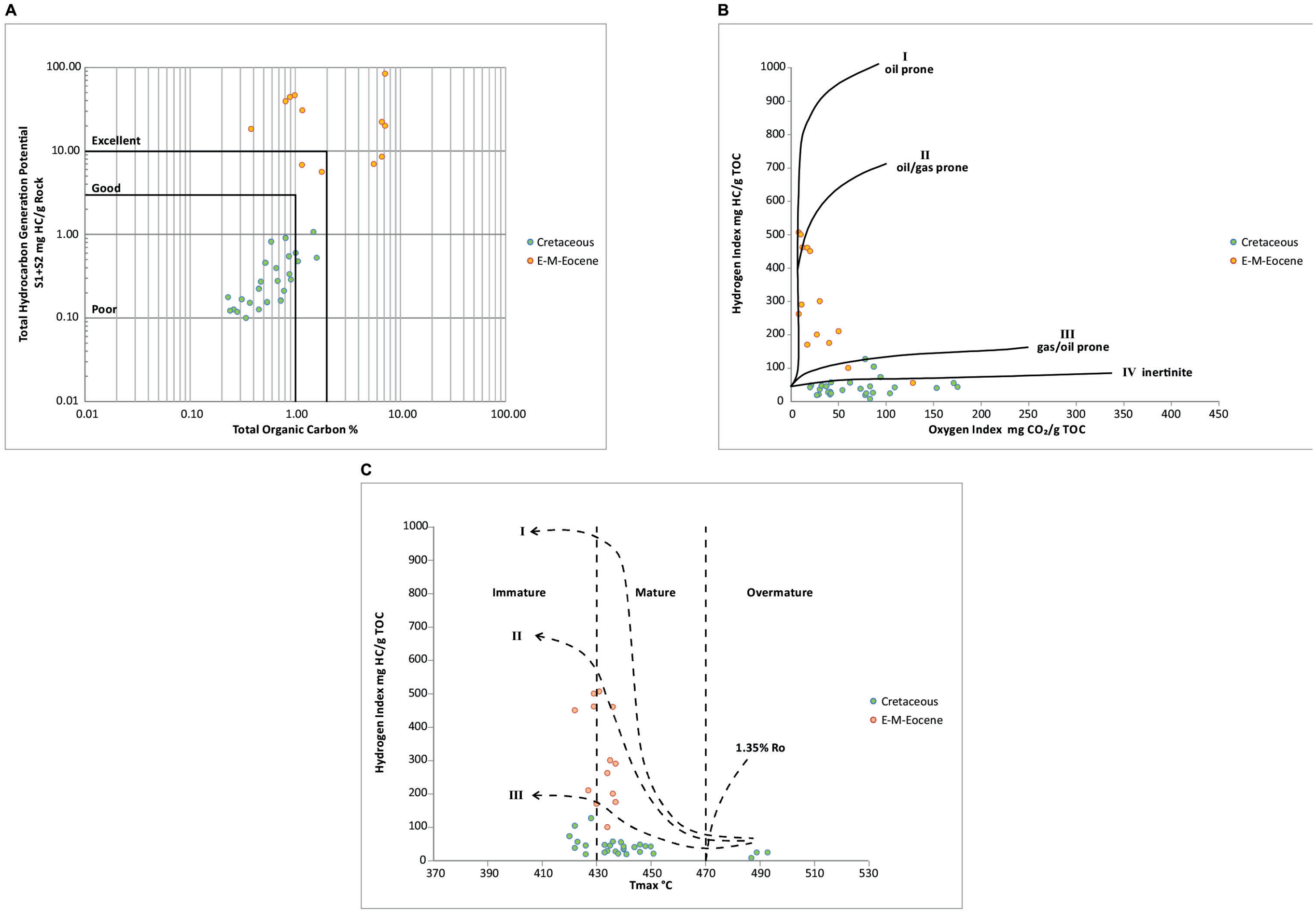


Figure 6. Geochemical plots from Jamaica Island: (A) total organic carbon vs. total hydrocarbon-generation potential, (B) hydrogen index vs. oxygen index, and (C) T_{max} vs. hydrogen index.

considered, but TOC values are lower than 1.0%. The thermal maturity of the Cretaceous samples range from early mature to overmature (early gas window), as suggested by T_{max} values between 425°C and 489°C, and Vitrinite Reflectance ranges from 0.55% to 1.6%, indicating the entire oil window phase. The thermal maturity values of the Cretaceous section are encouraging, but unfortunately the kerogen types (inertinite and vitrinite) do not allow us to be optimistic.

Onshore Gas Seeps

Geochemical data from two gas seep samples from Jamaica Island were available. One sample from the St. Anna Creek, nearby where the Windsor-1 well was drilled, is dry gas (99% methane). The methane carbon isotopic ratio of 48‰ corresponds to a thermogenic associated gas generated in a very early stage of the oil window (R_o 0.6–0.7%). The lack of wet hydrocarbons (C2+) along with the heavy methane carbon isotopic ratio of this gas seep, suggests that this gas was probably generated by a lean source rock. The same organic Cretaceous lean interval that possibly generated the gas seep is comparable to the Cretaceous section drilled by Windsor-1 well. A sample from the Marchont inlier is a wet gas (50% methane and 27.1% C2+ alkanes), with a carbon isotopic ratio of −58‰, a lighter carbon isotopic ratio than the St. Anna gas sample. The Marchont gas sample could be interpreted as a thermogenic wet gas associated with an early stage of the oil window and most likely mixed with biogenic gas. The source of the thermogenic part of the gas is difficult to identify, but it might be an organic-richer sequence as compared to the one that generated the St. Anna Creek gas seep.

Costa Rica and Panama—Source Rocks 3 and 4

More than 50 exploratory wells have been drilled along the continental Caribbean and Pacific Margins of Panama and Costa Rica (Figure 2). The majority of these wells were drilled from the 1950s to the early 1980s, and thus geochemical data are scarce, and final drilling reports are difficult to find. Since the available geochemical information is not systematic or uniform, an evaluation cannot be conducted with full confidence. Nonetheless, the data are good enough to recognize proven and potential source rocks. Information on source rocks came from only five wells: Cemaco-1, Corvus-1, Plaris-1, Morote-1, and Manzanillo-1. Even though the wells Cemaco-1, Corvus-1, and Plaris-1 were drilled in the Gulf of Panama in the Pacific Ocean (Figure 2), they were incorporated into the study, because they penetrated early Neogene sequences that were originally deposited around the Caribbean–Pacific seaway, prior to the collision of the southern Panama Block (Choco Block) and South America, completing the closure of the Pacific–Caribbean seaway sometime 3 Ma ago (Coates et al., 2004). In this paleotectonic framework, source rocks with similar characteristics could have been deposited on the Caribbean and Pacific sides of Panama–Costa Rica, as the present Gulf of Panama (Pacific) was communicated with the Caribbean Sea from Paleogene to middle Miocene time (Coates et al., 2004).

Source Rock Analysis

Geochemical data from the wells above (Figure 2) indicate that the middle Miocene Gatun Formation is a widespread source rock in this region. In general, the middle Miocene sequence has good to excellent organic matter content, and kerogen types vary from Type II to Type III. The TOC of all the samples after removing the coal-rich intervals ranges from 0.13% to 4.69% with an average value of 2.7%. The type organic matter, as defined by the HI of wells Plaris-1 and Cemaco-1, records kerogen Type III and Type II/III. HI values range from 107 mg HC/g rock to 307 mg HC/g rock TOC, suggesting a potential to generate mainly gas and some oil (Figure 7). The thermal maturity of the entire Tertiary sedimentary sequence drilled in the Chorotega Block is thermally immature, with vitrine reflectance values that range from 0.37% in the late Miocene to 0.48% in the Oligocene sequence, T_{max} values that are lower than 437°C, and the PI values that are lower than 0.11 (Figure 7). Although geochemical modeling is out of the scope of this work, several one-dimensional (1-D) geochemical models have done within the main depocenters of the Chorotega Block have proven that the Gatun Formation could have reached the beginning of the oil window.

Along the Caribbean Margin, north of the Chorotega Block, the Limon Basin is a back-arc basin that is part of the Central America arc-trench system and is located underneath the continental platform and the coastal plain of eastern Costa Rica. A small oil field, oil seeps, and a number of exploratory wells with oil and gas shows (Patino-1 and Patino-2 oil shows; Limon-1 and Victoria-1 oil and gas shows; and Moin Marine-1, Porvenir-1, Punta Cahuita, and Colon-1, Colon-2, and Colon-3 wells gas shows) support the existence of an active petroleum system in this basin (Figure 2). The most impressive hydrocarbon evidence came from the Cocoles field located in the Limon Basin, Costa Rica, which produced 1800 BOPD of 45° API oil, apparently from an Oligocene carbonate-fractured reservoir. No geochemical evidences were available to suggest which was the source of these oils. Since the Gatun Formation is a proven source rock in the Gulf of Panama (Derksen et al., 2003), the presence of the Gatun source rock in the Limon Basin, Costa Rica (Goudkoff and Porter, 1942), may suggest that the middle Miocene Gatun Formation could be the source for those hydrocarbons.

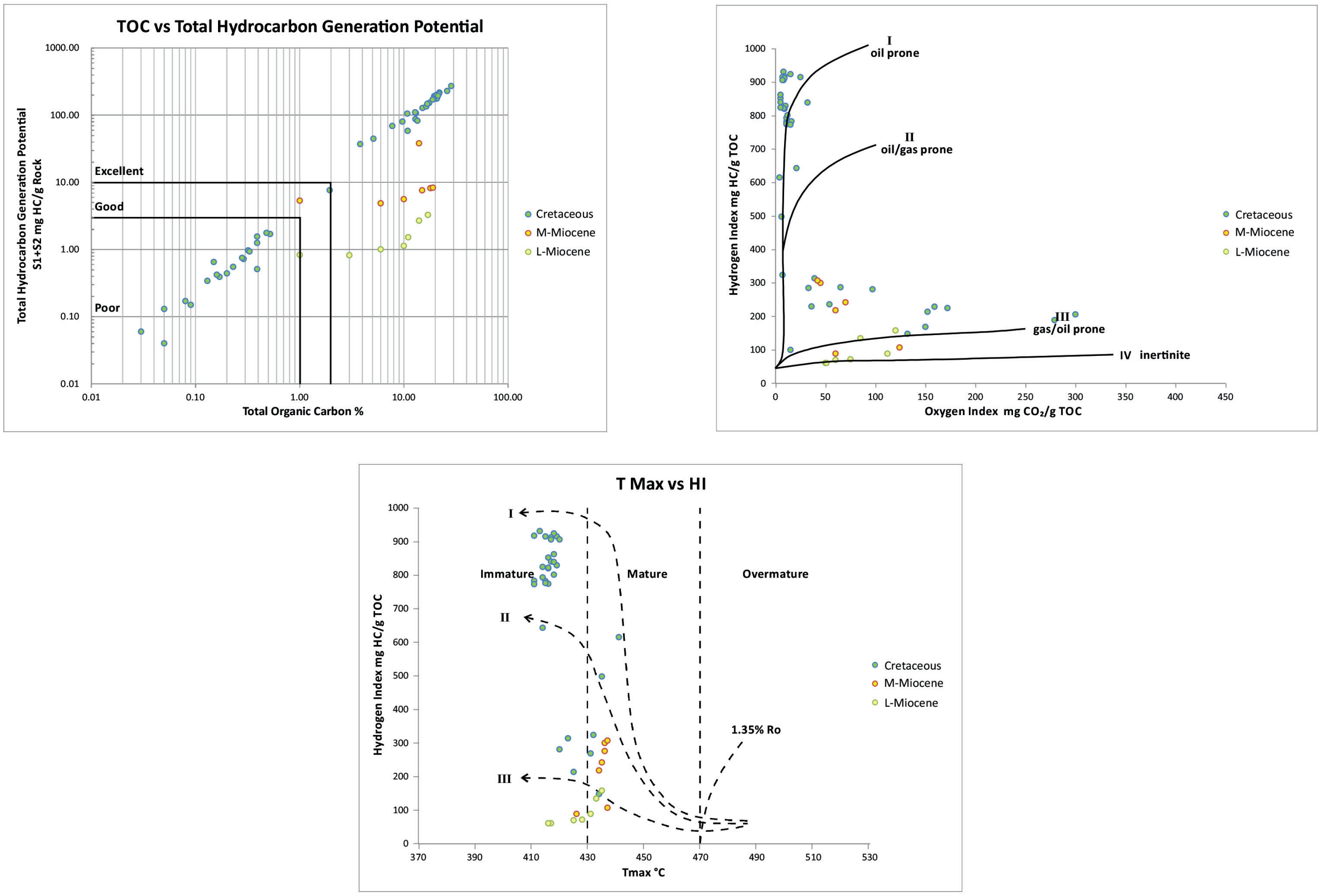


Figure 7. Geochemical plots from Panama–Costa Rica: (A) total organic carbon vs. total hydrocarbon-generation potential, (B) hydrogen index vs. oxygen index, and (C) T_{max} vs. hydrogen index.

Geochemical information from wells Morote-1 and Manzanillo-1 (Figure 2) comes from Erlich et al. (1996). These two wells were drilled entirely through a succession of laminated to massive siliceous shale, chert, ash fall beds, and volcaniclastic sandstones deposited in middle shelf to outer slope environments adjacent to an active island arc during the Cenomanian–Campanian (Erlich et al., 1993). Denyer and Kussmaul (2000) have proposed that the rocks of the Loma Chumico Formation are Cretaceous anoxic sequences deposited in a pelagic environment above the Jurassic–lower Cretaceous igneous rocks of Nicoya Complex. According to Erlich et al. (1996), the Loma Chumico Formation contains organic-rich and organic-lean units. TOC values of all organic-rich horizons is up to 28.54%, with an average value of 15.31%. These organic-rich layers have a total combined thickness of 85 m (278. 87 ft). Hydrogen and oxygen indexes range from 324 mg Hc/g rock to 935 mg Hc/g rock TOC and 4 to 31 mg CO_2/g rock TOC, respectively. The organic-lean intervals have TOC values lower than 0.5% without the potential to generate hydrocarbons. T_{max} and Production Index PI values from the Loma Chumico in wells Morote-1 and Manzanillo-1 (and T_{max} values provided by Robert Erlich, written communication, 2015), as well as biomarker distributions from the organic-rich intervals indicate that the sequence is thermally immature. The petroleum potential (PP) (sum of the S1 and S2 peaks of the Rock Eval pyrolysis) of the organic-rich units is higher than 60, with values up to 270 mg HC/g rock. All of these geochemical parameters suggest that some layers in the Loma Chumico Formation contain Type I/II kerogen, indicating an excellent potential to generate oil at higher maturity levels. The sequences of the Loma Chumico Formation belong only to the Pacific domain, as they are part of allochthonous oceanic assemblages of the Nicoya Complex, which was accreted to Costa Rica and western Panama Pacific Margin (Denyer et al., 2006). Erlich et al. (1996) combined major element geochemistry, bulk mineralogy, Rock Eval data, and extract biomarker analysis to interpret the types and distributions of the different late Cretaceous source rocks from Costa Rica to west Africa. They recognized that upwelling and excessive fluvial runoff were apparently the dominant sources of nutrient supply to coastal productive systems throughout this region during Cenomanian to Coniacian.

Two oil seeps have been reported from Panama. One oil seep is found near the border limit with Costa Rica, relatively close to the location where Cocoles-2 well was drilled in the Limon Basin. The other oil seep is found in the Garachine area in eastern Panama, where several exploratory wells have also been drilled (Figure 2), but they only had oil and gas shows. We have geochemical information only from the Garachine oil seep. The geochemical characteristics of the Garachine oil seep are shown in Tables 2 and 3. The Garachine oil seep is a naphthenic heavy oil with 17° API. The oil may be a mixture of a severely biodegraded oil in the surface and non-biodegraded oil reaching the surface recently. The chromatogram shows a prominent hump but also some normal *n*-alkanes are present. The extremely low presence of 25 norhopanes is a key evidence for biodegradation in surficial aerobic conditions. The main feature of this oil is the heavy isotopic 13 carbon ratio of saturate and aromatic fractions (−21.98‰ and −20.97‰). This heavy carbon isotopic ratio is typical of oils generated by Tertiary source rocks (Chung et al., 1992), principally associated with deep basin diatom blooming and high nutrient upwelling along continental margins, such as the Talara oils in Peru offshore (Fildani et al., 2005) and the Monterey oils (Peters et al., 1994) in southwestern United States. This geochemical signature is common along the western margin of the Americas.

Biomarker distribution of Garachine's oil (Panama onshore; Figure 2) defines a Tertiary oil, which records deposition in a transitional depositional environment, as indicated by the presence of predominantly marine organic matter with minor terrestrial input. Organic matter was deposited in disoxic conditions within siliciclastic-dominated facies and clay-poor content. Table 2 depicts the main geochemical parameters of the Garachine oil seep. Biomarkers show a pristane/phytane ratio of 1.3, low-to-moderate C35/C34 homohopane, relatively low abundance of tricyclic terpanes, low diasterane index, and a 0.18 dibenzothiophene/phenantrene (DBT/PH) ratio from the aromatic fraction of the oil seeps. The latter ratio is an excellent indicator of source rock lithology, being greater than 1 in (0.083 ft) carbonates and less than 1 in (0.083 ft) siliclastics (Hughes et al., 1995). Based on the aforementioned parameters, it is reasonable to propose that the oils in the Garachine area were generated by a siliclastic source rock poor in clay content and under disoxic conditions. The low values of gammacerane, the oleanane index of 30%, and the regular sterane abundance of C27>C28=C29 are typical of a transitional oil, with marine and terrestrial organic matter input. The high oleanane ratio also supports a Tertiary age for this oil. The isomerization maturity parameters of the C29 steranes (C29 $\alpha\beta\beta/\alpha\beta\beta + \alpha\alpha\beta$ and C29 S/S + R) and C32 terpane (C22S/C22S + R) (Table 3) show that this oil was generated in an early stage of the oil window, and this probably explains the low tricyclic terpane presence in the terpane family. The geochemical characteristics of the Garachine oil seeps are most likely correlative with the middle Miocene Gatun source rock, which in the main depocenters of the Gulf of Panama could reach the beginning of the oil window (0.65–0.8% R_o), as proven by geochemical modeling.

Lower Magdalena Valley Basins—Source Rocks 5 and 6

Plato, San Jorge, Sinu, and San Jacinto Basins

Source rocks of Tertiary and Cretaceous ages have been long recognized to have generated hydrocarbons along the Sinu–San Jacinto Basin. Oil seeps, rock extracts, and

Table 2. Bulk and source correlation parameters of oils from the Chorotega and Colombia Caribbean Margin.

Oil	API°	Sulfur %	Saturate δ C13‰	Aromatic δ C13‰	Pr/Ph	Hopane/ Sterane	Oleanane/ C30 Hopane	Diasterane Index	Regular Sterane C27 %	Regular Sterane C28 %	Regular Sterane C29 %
Garachine Oil seep	17.6		−21.98	−20.97	1.3	1.8	0.3	0.21	42	31	27
Cicuco	37.6	0.052	−25.8	−24.4	2.54	4.7	1	0.74	45.5	23.0	31.5
Boquete	36	0.05	−25.5	−24.7	2.55	4.5	0.89	0.74	38.8	27.0	34.2
Zenon	30	0.05	−25.6	−24.5	2.55	4.3	1	0.72	39.7	28.5	32.8
El Dificil	54.1	0.028	−25.6	−25.9	3.19	5.5	1.1	0.74	43.9	24.2	31.8
Floresanto	43.5	0.099	−27.4	−26.8	4.69	7.5	0.6	0.47	37.1	29.0	33.9
San Sebastian	23.5	0.354	−28.8	−28.6	1.67	4.1	0.14	0.37	37.8	31.8	30.4
Guepaje	31.2	0.155	−27.6	−27.7	4.91	1.3	1.19	0.16	33.2	25.0	41.8
Perdices	43.7	0.033	−26.73	−25.93	5.31	3.3	0.5	0.56	37.7	30.9	31.4
Ligia	43.2	0.063	−25.7	−25.54	2.7	6.2	1.13	0.64	39.9	25.5	34.6

Table 3. Thermal maturity parameters for oil samples in the Chorotega and Colombia Caribbean Margin areas.

Oil	Tricyclic Index	$T_s/T_s + T_m$	C29 $\alpha\alpha\alpha$ Sterane 20S/20S+R	C29 Sterane $\alpha\alpha\alpha$/ $\beta\beta + \alpha\alpha\alpha$	C32 Homohopane S/S + R
Garachine oil seep	0.27	0.38	0.50	0.62	0.59
Cicuco	0.27	0.79	0.47	0.62	0.49
Boquete	0.37	0.71	0.47	0.62	0.60
Zenon	0.36	0.74	0.51	0.59	0.51
El Dificil	0.68	0.63	0.48	0.61	0.61
Floresanto	0.81	0.65	0.47	0.59	0.54
San Sebastian	2.25	0.21	0.44	0.54	0.60
Perdices	1.53	0.61	0.47	0.58	0.60
Ligia	0.27	0.67	0.46	0.50	0.53

crude oil samples from the Sinu–San Jacinto Basin were analyzed by Sanchez and Permanyer (2006) to identify the source rock facies and their petroleum-generative potential. According to their study, the crude oil in some wells and oil seeps indicates a correlation with a Tertiary source rock that records marginal marine to marine-deltaic environments. Oil seeps, on the other hand, correlate with the extracts from the source rocks of the upper Cretaceous Cansona Formation. Niño et al. (2004) carried out the geochemical study of 2396 samples from 33 exploratory wells, samples from 20 outcrops, crude oil from core and one rock extract. The results indicate that the oils from the northern Sinu–San Jacinto Basin are correlative with a Tertiary deltaic source rock, whereas the oil from the fractures in cores correlates with an upper Cretaceous marine source rock. An extensive study of source rocks in the Plato Basin conducted by Vargas and Mantilla (2006) included the geochemical analysis of cuttings, rock samples, and crude oils. The authors concluded that both the Cienaga de Oro Formation (Oligocene–lower Miocene) and Porquero Formation (middle–upper Miocene) have very similar source rock characteristics of a kerogen Type II and II/ II, gas- and oil/gas-prone source rock.

Geochemical rock data from 18 wells located along the onshore Lower Magdalena Valley basins (Plato, San Jorge, and Sinu and San Jacinto Basins) and from four outcrops in the Sinu–San Jacinto Basin (Arroyo Chalan, Cantera San Sebastian, Cantera Purgatorio, Cantera Golf) (Figure 2) were evaluated to determine the potential to generate hydrocarbons from these sequences. Additional information from eight oil samples from oil and gas fields onshore was evaluated primarily to identify oil families in the region and to attempt to define the source rock that could have generated the hydrocarbons.

Source Rock Analysis

Several hydrocarbon-generative sequences are known to exist along the Lower Magdalena Valley basins. Multiple lines of evidence include (1) the existence of several oil and gas accumulations onshore, (2) abundant oil and gas seeps in the Sinu–San Jacinto Basin, (3) numerous oil slicks (offshore), (4) gas fields, and (5) very prominent BSRs throughout the offshore area. Based on the geochemical characterization of samples from wells and outcrops, efficient source rocks have been documented to occur in the Oligocene to early Miocene and Cretaceous sequences. The other sedimentary sequences have very low TOC values and Type III to Type IV kerogen type. The first generative sequence corresponds with the Cienaga de Oro and the lower Porquero Formations in Plato and San Jorge Basins. Strata of this formation were deposited in a deltaic to restricted marine platform environment and are characterized by thick intercalations of shale, sandstone, siltstone, and minor limestone. The Cienaga de Oro and lower Porquero source rocks contain TOC values lower than 2% but systematically higher than 0.4%, with an average value of 1.48%. The HI averages 116 mg HC/g TOC with values up to 540 mg HC/g TOC (Figure 8). The thickest sequence with fair to good generative hydrocarbon potential recognized in the region was penetrated by the El Castillo-1 well (Figure 3). In addition, the Cienaga de Oro and lower Porquero source rocks are characterized by the presence of few thin intervals of limited lateral extension, with TOC values higher than 2% and in some cases some shaly coal (TOC values between 10% and 50%) and HI between 150 mg HC/g TOC and 300 mg HC/g TOC. Thus, some petroleum potential is identified in the Cienaga de Oro and lower Porquero Formations in the Plato and San Jorge Basins. The wells that penetrated this sequence show that is mainly thermally immature, and only in a couple of wells the Cienaga de Oro source rock-bearing strata are found in the oil window (El Castillo-1 and Pijiño-1 wells); however, most of these wells drilled structural highs around the main depocenters of the Plato and San Jorge Basins. The lateral sequences of the Cienaga de Oro toward the western area (Sinu–San Jacinto Basins) are grouped into the El Carmen Formation; this unit has less hydrocarbon potential than the eastern part of the Lower Magdalena Valley basins, with TOC values a little bit lower than the sequences of the eastern part, with an average TOC of 1.56% and HI typical of Type IV kerogen (lower than 100 mg HC/g TOC) (Figure 8). Nevertheless, there are a few intervals with geochemical parameters similar to the Cienaga de Oro in the eastern part of the area. The Carmen Formation rock evaluated in the western part of the Lower Magdalena Valley basins has not reached the oil window, and all the samples are immature. However it is possible that this sequence has reached the oil window in some parts of the western part (Sinu–San Jacinto). Thus, the Oligocene to early Miocene sequence in the Lower Magdalena Valley Basin has only fair potential to generate gas and minor oil. The large thickness of theses sequences, which in some areas exceeds 1.5 km (0.932 mi), compensates the low quantity and quality of the organic matter present in the region. Geochemical data suggest that the expected thermal maturity of the source rock should have been reached in the deepest part of the Plato and San Jorge Basins.

The second sequence with the potential to generate hydrocarbons is the Coniacian to Maastrichtian Cansona Formation, which crops out in the Sinu–San Jacinto Basins. This unit consists of a succession of bedded chert, limestone, and sandstone which record deposition in a bathyal environment. The Cansona is overlain by sandstone turbidities of the Paleocene–lower Eocene San Cayetano Formation (Duque and Duenas, 1987). Geochemically, the late Cretaceous source rocks in the Cansona Formation are of good to excellent quality to generate oil and gas. TOC values range from 0.52% to 12.22%, with an average value of 4.45%. The petroleum potential (S1 + S2) average value is 17 mg HC/g rock, with a maximum of 72 mg HC/g rock. The HI

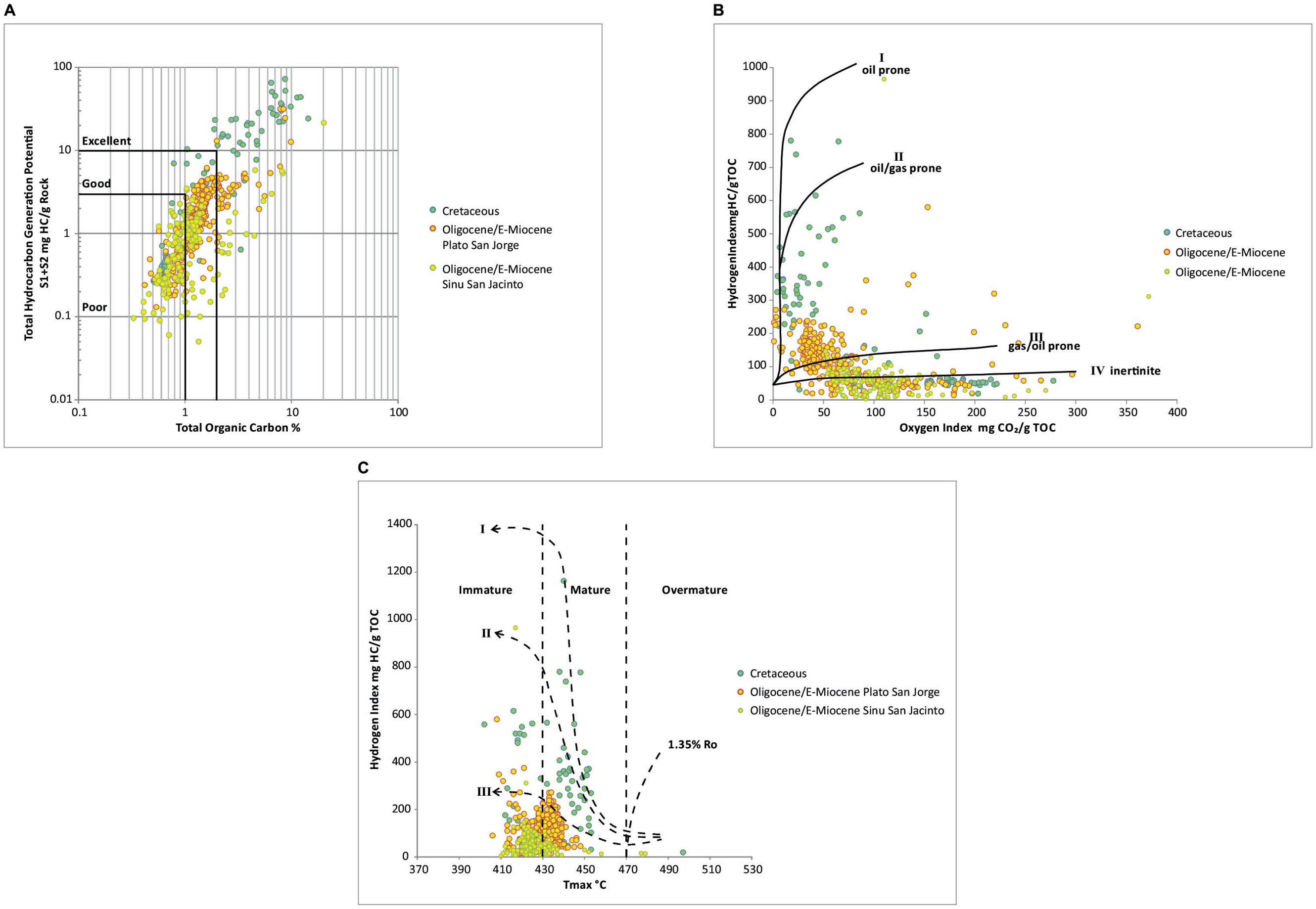


Figure 8. Geochemical plots from the Colombia Caribbean basins: (A) total organic carbon vs. total hydrocarbon-generation potential, (B) hydrogen index vs. oxygen index, and (C) T_{max} vs. hydrogen index.

ranges from 20 to 1160, with an average value of 318 mg HC/g TOC. The pseudo-Van Krevelen diagram (Figure 8) shows that most of the Cansona samples are plotted within the Type II kerogen area. No vitrinite reflectance data are available to better understand the thermal maturity reached by this sequence. Rock Eval's thermal indicator parameters suggest that this sequence has reached an early stage of the oil window based on T_{max} values ranging between 440°C and 450°C, with an average of 442°C and an average production index value of 0.14.

Geochemical information from eight oil fields in the Lower Magdalena Valley basins (Tables 2 and 3) supports the identification of three oil families in the region: (1) a Tertiary terrestrial oil family mainly found in the Plato and San Jorge Basins (eastern region); (2) a marine oil family (San Sebastian oil field, Sinu–San Jacinto Basin); and (3) a transitional oil family from the Perdices and Floresanto oil fields, Sinu–San Jacinto Basin. This family could be a mixture of the first two families or, alternatively, a Tertiary paralic or transitional sequence perhaps different from the one that generated family I.

Tables 2 and 3 show that the first oil family is a Tertiary terrestrial oil sampled at the Cicuco, Boquete El Dicifil, Zenon, and Ligia oil fields, which are located in structural highs above the depocenters in Plato and San Jorge Basins (east of the Romeral Lineament). This oil family is characterized by an Oleanane ratio close to 1, which is a clear indicator of a Tertiary age with terrestrial organic matter input. The source rock that generated this oil family was deposited in a dysaerobic environment, as recorded by the pristane/phytane ratio between 2.5 and 3.2, and the homohopane ratio lower than 1. The abundance distribution of the regular sterane shows the following order: C27 > C29 > C28. The diasterane/sterane ratio of this family is higher than the other two groups, which is indicative of more V_{clay} sediments in the source rock interval, assuming the same thermal maturity for all the oils analyzed (Table 3). The low abundance of tricyclic terpane may simply reflect a low maturity. Thermal maturity indicators (Table 3) show that this oil was generated in an early stage of the oil window (R_o between 0.7% and 0.8%).

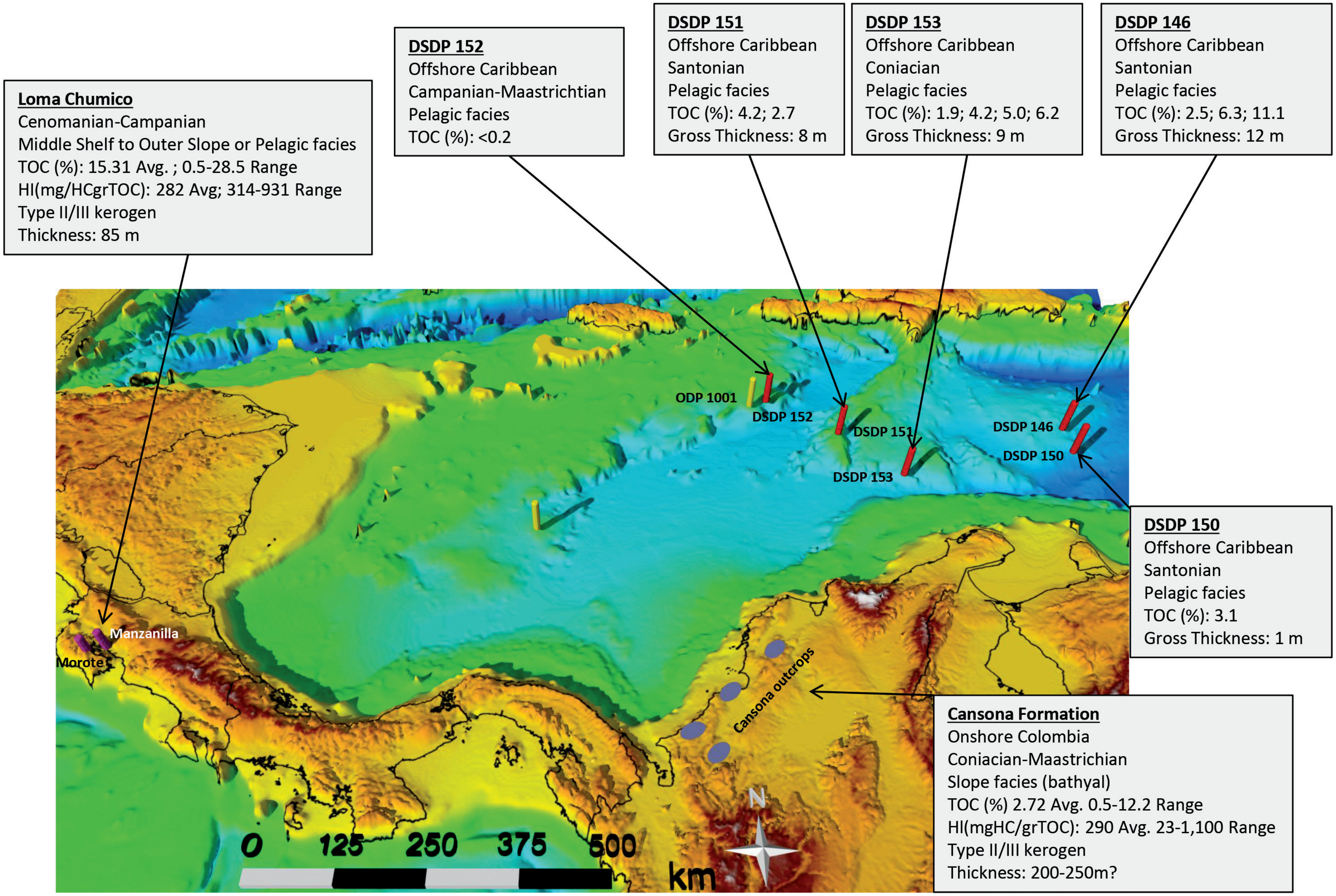
The second identified family includes only the oil of the San Sebastian field, which is located to the south of the Sinu–San Jacinto Basin and very close to one of the Cansona Formation outcrops. The San Sebastian field oil sample is moderately biodegraded. The whole oil chromatogram shows complete removal of the *n*-alkanes, but there still are some iso-alkanes present. Although the oil is biodegraded, it shows biomarker and isotopic features that are diagnostic of a carbonate marine source rock. The main parameters that suggests a more marine origin for this oil as compared to the other two families are (1) the typical regular sterane distribution of a marine oil, where the C27 is more abundant than the C28 and C29, respectively; (2) the very low oleanane presence and Pr/Ft ratio; (3) the high sulfur content; (4) the lighter C13 isotopic ratio; and (5) relatively high abundance of tricyclic terpanes. The stereoisomer thermal indicator of the steranes and terpanes suggests that this oil was generated at the beginning of the oil window at a vitrinite reflectance value between 0.7% and 0.85%.

The third family corresponds to a transitional oil that includes the oil from the Perdices and Floresante fields, which is located in the Sinu–San Jacinto Basins. Most of the biomarker ratios as well as the Carbon isotopic ratios fall between the ratio values of Family I and II. This is one of the reasons to propose that this oil (Family III) could be the resulting mixture of Families I and II. An alternative interpretation is that a different source rock deposited in a transitional depositional environment, such as a pro-delta or outer platform could have also generated these oils, given these known geochemical parameters: (1) pristane/phytane of about 5, (2) relative high abundance of oleanane, but lower oleanane/C30 hopane ratio than family I, (3) very low sulfur content; (4) moderate relative abundance of tricyclic terpanes; and (5) regular abundance of Sterane of C27 > C29 > C28. The carbon isotopic ratio for the saturate and aromatic fractions is around −27‰, which is lighter than Family I but higher than Family II. These resulting characteristics suggest a marine-deltaic, distal dysaerobic depositional environment.

Speculatively, integrating the geologic setting, the geochemical characteristics, the types of organic facies, and source rock distribution allows inferring that the source rock that generated the hydrocarbons of the first family corresponds to the Cienaga de Oro and the lower Porquero Formations in Plato and San Jorge Basins. The late Cretaceous Cansona Formation seems to be the source for the marine oil generated in the San Sebastian field (second family). The third oil family could possibly be a mixture of the oil generated by the Cansona and Cienaga de Oro Formations or just simply the more marine facies of the Cienaga de Oro, which were deposited to the west of the Romeral lineament.

The Colombian and Venezuelan Basins—Source Rock 7

Only scientific wells of the ODP and DSDP program in the Colombian and Venezuelan basins have been used to analyze, to evaluate, and to infer the presence of the source rock in the ultra-deep Colombian Basin. These wells have very limited geochemical information, mainly TOC values. The geochemical and geologic information comes from the ODP-999,



Loma Chumico
Cenomanian-Campanian
Middle Shelf to Outer Slope or Pelagic facies
TOC (%): 15.31 Avg. ; 0.5-28.5 Range
HI(mg/HCgrTOC): 282 Avg; 314-931 Range
Type II/III kerogen
Thickness: 85 m

DSDP 152
Offshore Caribbean
Campanian-Maastrichtian
Pelagic facies
TOC (%): <0.2

DSDP 151
Offshore Caribbean
Santonian
Pelagic facies
TOC (%): 4.2; 2.7
Gross Thickness: 8 m

DSDP 153
Offshore Caribbean
Coniacian
Pelagic facies
TOC (%): 1.9; 4.2; 5.0; 6.2
Gross Thickness: 9 m

DSDP 146
Offshore Caribbean
Santonian
Pelagic facies
TOC (%): 2.5; 6.3; 11.1
Gross Thickness: 12 m

DSDP 150
Offshore Caribbean
Santonian
Pelagic facies
TOC (%): 3.1
Gross Thickness: 1 m

Cansona Formation
Onshore Colombia
Coniacian-Maastrichian
Slope facies (bathyal)
TOC (%) 2.72 Avg. 0.5-12.2 Range
HI(mgHC/grTOC): 290 Avg. 23-1,100 Range
Type II/III kerogen
Thickness: 200-250m?

Figure 9. Location map of ODP and DSDP wells in the Colombia and Venezuelan basins and outcrops and wells with potential Cretaceous source rock in the Caribbean Plate showing organic richness and kerogen type. Very limited geochemical data from these wells are shown in gray boxes. DSDP-152 was used only to show the Cretaceous age rocks penetrated by the well, and the low TOC, as compared to other Cretaceous sequences deposited in the Caribbean plate. 125 km (77.7 mi)

ODP-1001, DSDP-151, DSDP-152, and DSDP-153 wells in the Colombian Basin and wells DSPD 146 and DSDP 150 from the Venezuelan Basin.

Source Rock Analysis

Other than the Coniacian–Santonian section, where the best source rock intervals are found, the rest of the sequences encountered by ODP and DSDP wells are mainly white to light grey argillaceous and siliceous limestone and thin-bedded chert with TOC values lower than 0.2%, indicating the lack of potential to generate hydrocarbons.

In the Venezuelan Basin, wells DSDP 146 and 150 penetrated Santonian pelagic facies characterized by the presence of thin source rock intervals (5 cm) with high TOC values. The DSDP 146 well has a 12-m thick section containing at least four thin intervals with TOC ranging from 2.5% to 11.1%, whereas DSDP 150 well has approximately 1 m (3.280 ft) thick section with 3.1% TOC. DSDP 153 well in the Colombian Basin encountered Coniacian pelagic facies with a 9-m (29.527 ft) thick interval (gross) containing thin intervals with TOC values between 1.9% to 6.2%. Well DSDP 151 contains 8 m (gross thickness) with very thin horizons containing 4.2% and 2.7% TOC. Well DSDP 152 in the same basin encountered Campanian–Maastrichtian pelagic facies with poor organic content (<0.2%), and wells ODP 999 and 1001 penetrated Maastrichtian and Campanian barren sections.

The organic matter content of the upper Santonian–Maastrichtian sequences is poor, with TOC values lower than 0.2%. The only Coniacian–Santonian sequence with high organic matter content seems to be associated with the late Cretaceous oceanic anoxic event (Coniacian to Santonian) (Meyers et al., 2006). In fact, thin layers with excellent organic matter content have been identified in the Coniacian–Santonian interval in wells DSDP-151, DSDP-153, DSDP-146, and DSDP-150 (Figure 9). The Cretaceous section in the Colombian and Venezuelan basins are thermally immature, but these same sequences may have higher maturity along the continental margins, where they are buried under thick Tertiary successions.

Figure 9 outlines the wells and outcrops where the Cretaceous sequences have potential source rocks along the western Caribbean region. There are not clear lateral correlations of the Cansona and Loma Chumico sequences with the DSDP wells organic-rich intervals. In theory, the Cansona and Loma Chumico Formations were deposited above an oceanic volcanic island arc, which was apparently accreted to the South America (Cardona et al., 2012) and Chorotega Blocks (Rogers et al., 2007a) sometime in the Cretaceous respectively. Conversely, the organic-rich intervals found in the DSDP wells were deposited in a pelagic depositional environment along the Caribbean oceanic plate. A critical event recorded by the Coniacian–Santonian sequence in the Colombian and Venezuelan basins is the deposition of organic-rich intervals during the late Cretaceous anoxic event. Thus, it is reasonable to speculate that the thickness of the Coniacian–Santonian organic-rich sequences could increase along the continental margins, where the probability of finding good source rocks may be greater.

CONCLUSIONS

An integrated analysis of limited geochemical data coming from hydrocarbon fields, exploration and scientific wells, oil and gas seeps, and outcrop source rock samples along the western Caribbean region permits the identification of the ages of existing source rocks, their organic characteristics, and broad geographic distribution. Multiple lines of evidence (oil fields, DSTs, well hydrocarbon shows, oil and gas seeps and sleeks, and BSRs) support the generation of hydrocarbons in the western Caribbean area. The analysis and interpretation of available geologic and geochemical data allows for the identification of seven main source rocks in this region: (1) lower–middle Eocene, Punta Gorda, and Touche Formations along the Nicaraguan Rise (SR1)—source rock distribution in this area are characterized for drastic organic facies changes from a typical marine source rock with good potential Type II kerogen to extremely poor or lean generative sequences; (2) middle Eocene Yellow Limestone Group in Jamaica Island (SR2)—source rock within this unit has a TOC content that varies from good to excellent, containing kerogen Type II to III; source rock is immature, and its distribution is very limited and poorly constrained; (3) late Cretaceous, Cenomanian–Campanian Loma Chumico Formation present mainly in the northwestern side of Costa Rica (SR3)—the Loma Chumico is an excellent potential marine source rock; (4) middle Miocene Gatun Formation in the Chorotega Block (Costa Rica and Panama Pacific and Caribbean Margins; SR4)—good to excellent organic matter content and kerogen Types II and III; (5) late Cretaceous (Coniacian–Campanian) Cansona Formation localized only in the Sinu–San Jacinto basins along the Colombian Caribbean basins (SR5)—this source rock has good to excellent TOC, Type II organic matter, and excellent potential to generate oil and gas; (6) Oligocene to early Miocene Cienaga de Oro and lower Porquero Formations (and their age-equivalents) in the Lower Magdalena Valley basins (SR6)—this sequence has fair to good potential to generate gas and some oil, and the huge thickness of the sequence compensates the low-to-moderate potential;

and (7) late Cretaceous Coniacian–Santonian section in the Colombian and Venezuelan basins (SR7), associated with the late Cretaceous oceanic anoxic event in the region. Despite the very thin, organic-rich layers in the DSDP wells along the Colombian and Venezuelan basins, it should be taken into account that these same strata may have a stronger petroleum potential near the continental margin. An evaluation of the generative potential of upper Cretaceous (Campanian–Maastrichtian) rocks, very limited data from DSDP/ODP wells, outcrop information, and oil fields, suggests that these successions are generally thin to very thin and poor in organic matter, normally with TOC values <0.5%. The lean nature of the upper Cretaceous section, if same everywhere in the region, could impede the generation of hydrocarbons.

The existence of these seven source rocks of Cretaceous and Tertiary ages with distinctive organic facies, aerial distribution, and petroleum-generative potential is encouraging for future hydrocarbon exploration efforts in the western Caribbean region. Our preliminary regional assessment, interpretations, and conclusions about the existence, geographic distribution, ages, and types of source rocks throughout the western Caribbean area are highly limited by the availability of geochemical data. The present knowledge on the petroleum systems and types of generated hydrocarbons is only partially understood, particularly in areas where available local information is fairly good.

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