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Introduction

Petroleum generation in the North Cuba Basin is primarily the result of thrust loading of Jurassic and Cretaceous source rocks during formation of the North Cuba fold and thrust belt in the Late Cretaceous to Paleogene. The fold and thrust belt formed as Cuban arc-forearc rocks along the leading edge of the Caribbean plate translated northward during the opening of the Yucatan Basin and collided with the passive margin of southern North America in the Paleogene. Petroleum fluids generated during thrust loading migrated vertically into complex structures in the fold and thrust belt, into structures in the foreland basin, and possibly into carbonate reservoirs along the margins of the Yucatan and Bahama carbonate platforms. The U.S. Geological Survey (USGS) defined a Jurassic-Cretaceous Composite Total Petroleum System (TPS) and three assessment units (AU)—North Cuba Fold and Thrust Belt AU, North Cuba Foreland Basin AU, and the North Cuba Platform Margin Carbonate AU—within this TPS based mainly on structure and reservoir type (fig. 1). There is considerable geologic uncertainty as to the extent of petroleum migration that might have occurred within this TPS to form potential petroleum accumulations. Taking this geologic uncertainty into account, especially in the offshore area, the mean volumes of undiscovered resources in the composite TPS of the North Cuba Basin are estimated at (1) 4.6 billion barrels of oil (BBO), with means ranging from an F95 probability of 1 BBO to an F5 probability of 9 BBO; and (2) 8.6 trillion cubic feet of of gas (TCFG), of which 8.6 TCFG is associated with oil fields, and about 1.2 TCFG is in nonassociated gas fields in the North Cuba Foreland Basin AU.

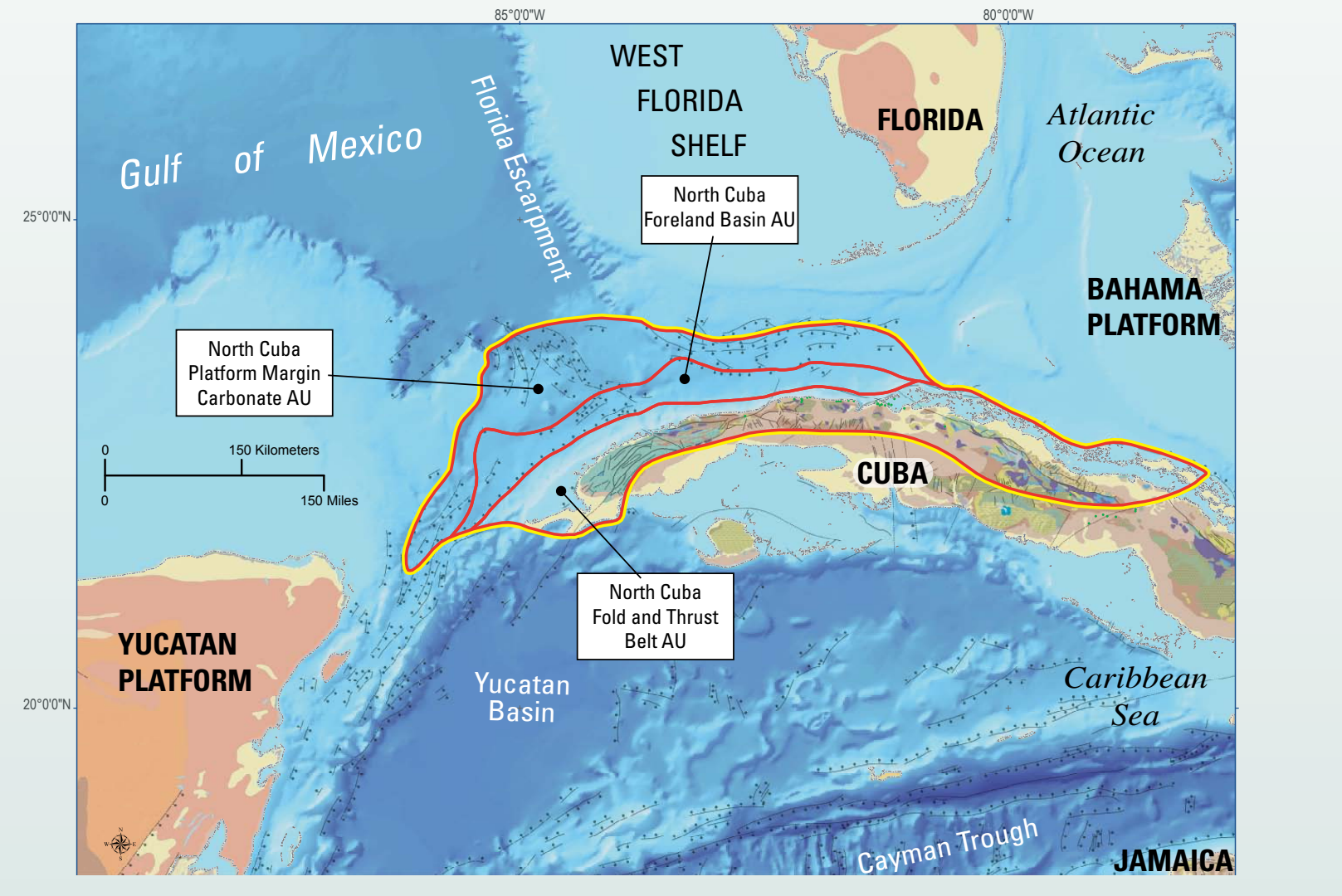

Figure 1. Locations of Cuba, Yucatan Platform, Yucatan Basin, Florida, Florida Escarpment, West Florida Shelf, Bahama Platform, and the general bathymetry of parts of the Gulf of Mexico, Yucatan Basin, Cayman Trough, Caribbean Sea, and Atlantic Ocean. Jurassic-Cretaceous Composite TPS shown by yellow line. North Cuba Basin boundary is same as composite TPS boundary in this study. Faults are shown as black lines; ball and bar on downthrown side of fault (after French and Schenk, 2004).

Geological Evolution of the Northern Caribbean Area

The geology of the Caribbean area in general and Cuba in particular is complex, and many decades of geologic investigations have pieced together the main elements of the geologic evolution of Cuba, the Gulf of Mexico Basin, and the proto-Caribbean oceanic basin (Pardo, 1975; Schlager and others, 1984; Ball and others, 1985; Lewis and Draper, 1990; Pindell and Barrett, 1990; Hempton and Barros, 1993; Pindell, 1993, 1994; Piotrowska, 1993; Draper and Barros, 1994; Iturralde-Vinent, 1994; Gordon and others, 1997; Meschede and Frisch, 1998; Kerr and others, 1999; Pszczolkowski, 1999; Cobiella-Reguera, 2000; Pindell and Kennan, 2001, 2003; Pszczolkowski and Myczynski, 2003; Pindell and others, 2005; Iturralde-Vinent, 2006; Fillon, 2007; Rojas-Agramonte and others, 2008). From the earliest studies, the geology of Cuba was recognized as a series of north-verging thrust-fault-bounded tectonostratigraphic units (TSU), and the geologic definition of many TSUs was the focus of many previous investigations. Eventually, tectonic studies in Cuba and in the northern Caribbean placed these TSUs in a framework of modern tectonic theory (Pindell and Kennan, 2001, 2003; Pindell and others, 2005). Detailed work demonstrated that the TSUs were the product of the collision between shelf, slope, and basinal sediments of the Mesozoic passive margin of the Yucatan and Bahama Platforms and the arc-forearc rocks of the leading edge of the Pacific-derived Caribbean plate as the Yucatan Basin opened in the Paleogene (Pindell and others, 2005). The stratigraphy of Cuba is complex, and many stratigraphic studies reflect the stacked thrust sheets produced during plate collision (fig. 2). However, the general stratigraphy of many TSUs has been interpreted and restored, documenting general stratigraphic relations.

Major events in the geologic history of northwestern Cuba include (1) rifting between North America, South America, and Africa in Late Triassic-Early Jurassic time; (2) the tectonic evolution and passive-margin sedimentary history of the southeast Gulf of Mexico; (3) the development of the proto-Caribbean ocean basin and its passive margin; (4) movement of the Caribbean plate since the Early Cretaceous; and (5) Paleogene development of the Yucatan Basin and resultant collision and suturing of allochthonous Cuba terranes with the passive margin of the Bahama Platform (Case, 1975; Haczewski, 1976; Salvador, 1987, 1991; Marton and Buffler, 1993, 1994; Sheridan and others, 1983; Angstadt and others, 1985; Ladd and Sheridan, 1987; Sassen and others, 1987; Rosencrantz, 1990; Pindell, 1993; Walles, 1993; Magoon and others, 2001; Wagner and others, 2003; Iturralde-Vinent, 2003; Magnier and others, 2004; Pindell and others, 2005) (fig. 3). The tectonic evolution of the northern Caribbean was summarized for this assessment by Schenk (2008).

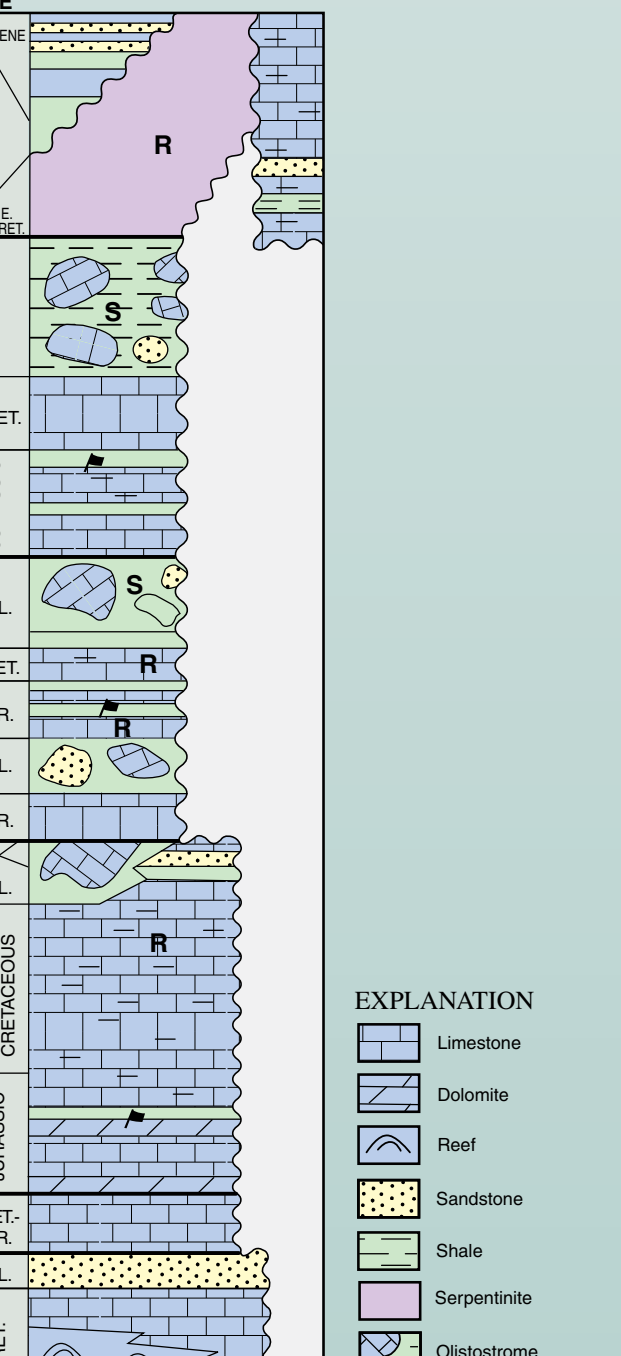

Figure 2. Stratigraphic column showing thrust repetitions in the Jurassic through Tertiary section in the Cuban fold and thrust belt in northern Cuba (modified from Cubapetroleo, 2002).

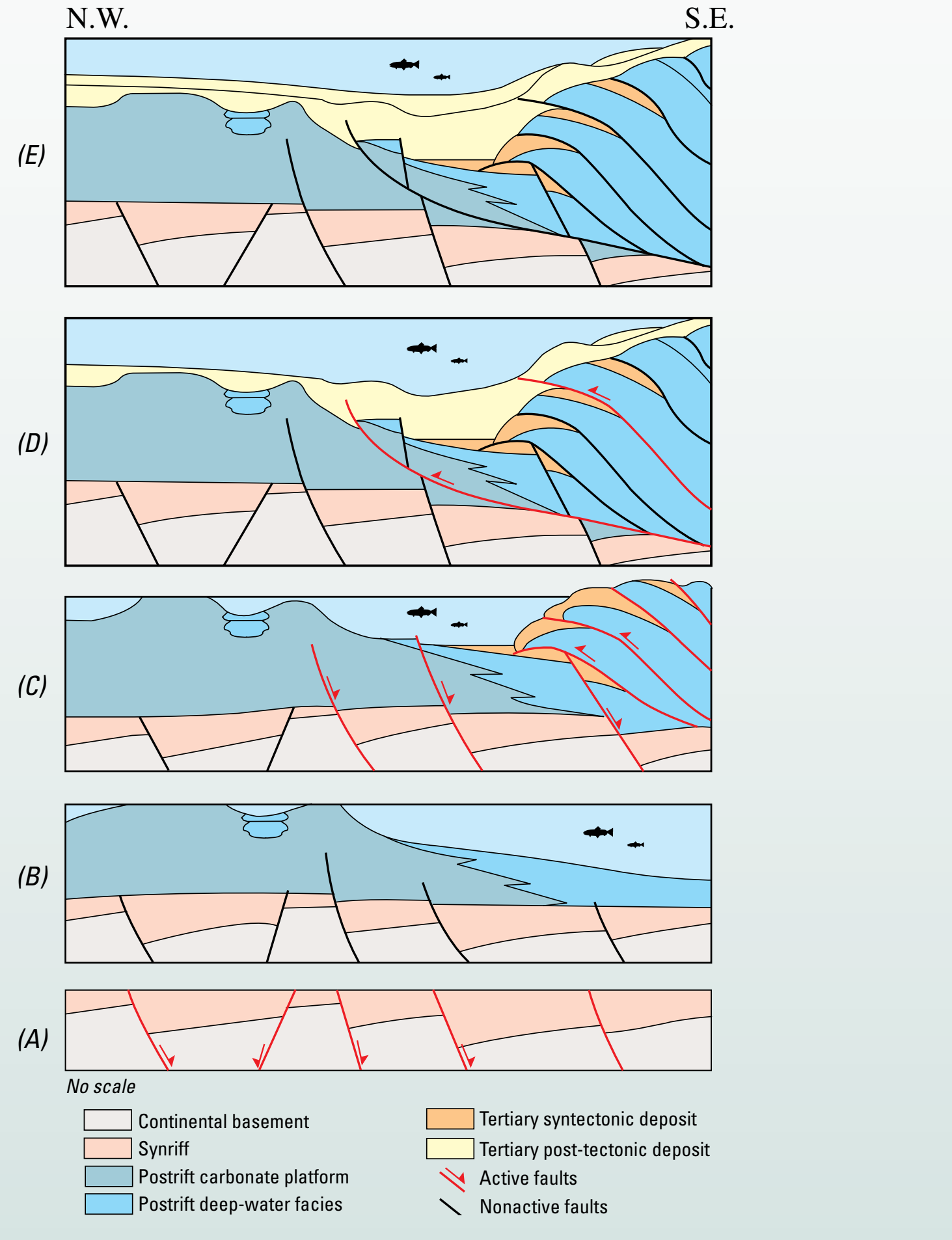

Figure 3. Sequential development of the northwest Cuban fold and thrust belt and the foreland associated with the fold belt. *(A)*, proto-Caribbean synrift (Early to Middle Jurassic) development of rift basins; *(B)*, post-rift subsidence; *(C)*, end of Greater Antilles orogeny in early Eocene; *(D)*, infilling of basin, which began as foreland in previous phase; *(E)*, passive subsidence caused by sediment influx from Cuba (after Moretti and others, 2003b).

Jurassic-Cretaceous Composite Total Petroleum System

A TPS is an integration of the tectonic, sedimentary, and thermal history of an area and is defined to encompass all fluids that have been generated from genetically related pods of thermally mature petroleum source rocks. In the North Cuba Basin, three major types of oils are present, which reflect the presence of potential source rocks. However, it is not possible on the basis of currently (2008) available geochemical information to isolate and define separate petroleum systems. Accordingly, a single petroleum system—The Jurassic-Cretaceous Composite TPS—was defined for the North Cuba Basin (fig.1).

Petroleum Source Rocks

Geochemical analyses and interpretations of samples of potential petroleum source rocks, oils, and gases have quantitatively defined several source rocks and potential petroleum systems of the North Cuba area (Maksimov and others, 1986; Lopez-Quintero and others, 1994; Navarette-Reyes and others, 1994; Lopez-Rivera and others, 2003a,b; Moretti and others, 2003a,b; Magnier and others, 2004). These are (1) Lower to Middle Jurassic rift-related mudstones; (2) Upper Jurassic and Lower Cretaceous deep-water, organic-rich carbonate mudstones; (3) Upper Cretaceous deep-water carbonate mudstones; and (4) possibly Paleogene mudstones (fig. 4). Of these, the Upper Jurassic and Lower Cretaceous deep-water carbonate mudstones are considered to be volumetrically the most significant petroleum source rocks in the basin (Moretti and others, 2003a,b). Paleogene source rocks and fluids also have been reported, but these fluids are not considered to be volumetrically significant because of the low level of thermal maturation of these sediments (Magnier and others, 2004) relative to the generative windows in the foreland basin.

Moretti and others (2003b) discussed the results of thermal modeling aimed at determining the timing of petroleum generation in several source-rock intervals in the North Cuba Basin. For the synrift source rocks, modeling results indicate that the synrift source rocks are overmature with respect to oil generation within the thrust belt and foreland basin areas. Within the deep offshore area, synrift source rocks are interpreted to be just within the oil generation window. For the Upper Jurassic and Lower Cretaceous fine-grained carbonate source rocks, modeling indicates probable thermal maturity within the thrust belt and possibly also in the deeper parts of the foreland; however, in the majority of the foreland and platform areas, modeling indicates the rocks are thermally immature for oil generation. This conclusion is corroborated by the findings from the Deep Sea Drilling Project (DSDP) Site 535 well (Herbin and others, 1984; Katz, 1984; Palacas and others, 1984 a,b; Patton and others, 1984; Rullkoter and others, 1984; Summerhayes and Masran, 1984). Modeling also indicates that gas generation may have occurred within the thrust belt and the deeper parts of the foreland (Moretti and others, 2003b).

The source rocks may be thermally mature at depth in the fold and thrust belt and in the deeper parts of the foreland basin, but the shallower stratigraphic intervals of potential Cretaceous source rocks to the west of the fold and thrust belt are not thermally mature. Petroleum from the thrust belt and from the foreland basin might have migrated updip into traps in the thrust belt and in the foreland basin (Lopez-Rivera and others, 2003a,b), and possibly also migrated laterally to the margins of the Yucatan and Bahama carbonate platforms. Oil shows in core from DSDP Site 535 and from wells along the southwest margin of the Bahama Platform indicate that migration of petroleum occurred within the Jurassic-Cretaceous Composite TPS. Although oil is the hydrocarbon in the onshore fields in Cuba, oil and nonassociated gas accumulations might be present in the deeper parts of the thrust belt and in the foreland basin.

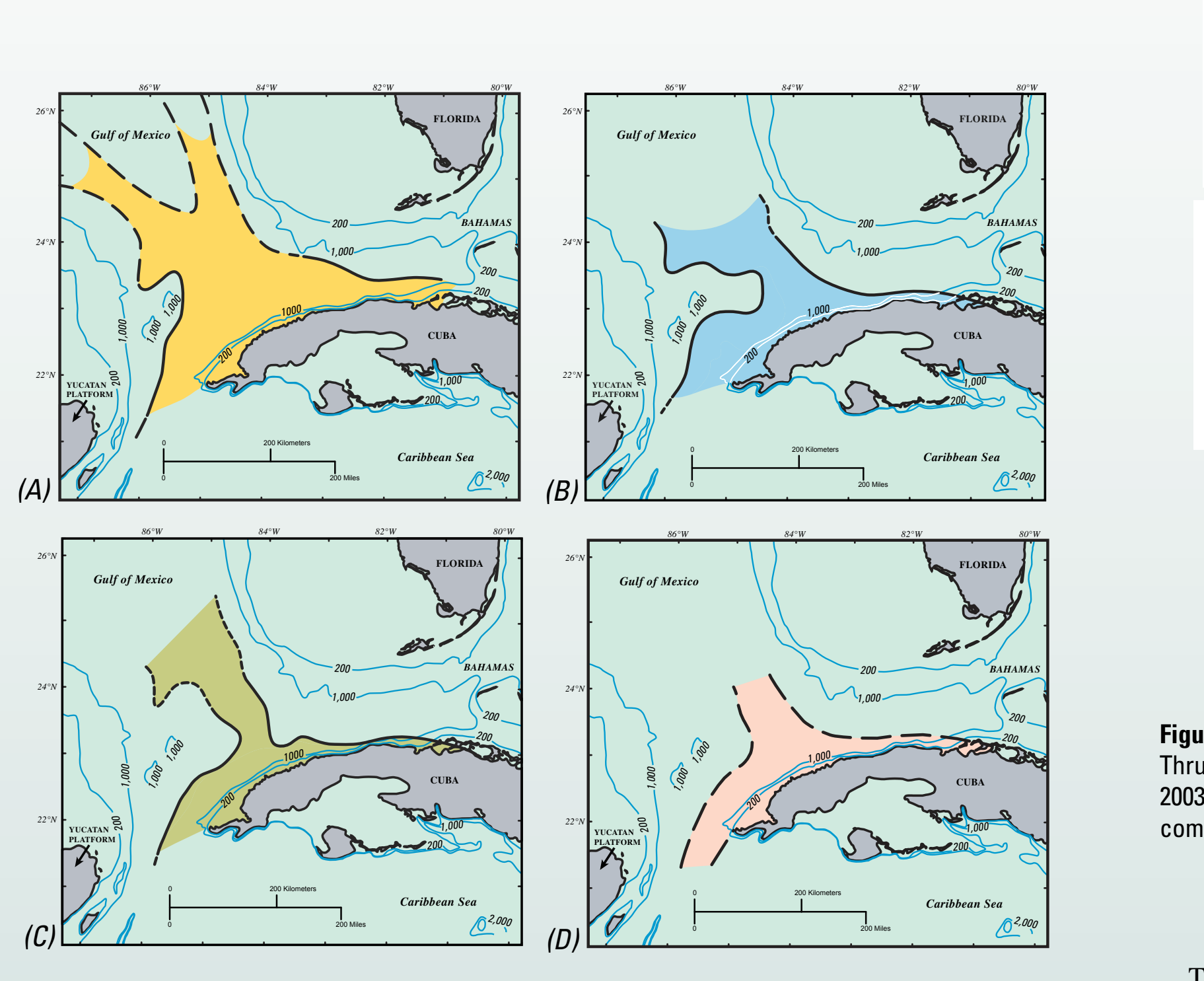

Figure 4. *(A)*, Present-day distribution of postulated synrift Jurassic source rocks; original extent most likely was farther south prior to thrust shortening. *(B)*, Present-day distribution of Upper Jurassic deep-water carbonate source rocks (shaded blue); original extent most likely was farther south overlying proto-Caribbean crust prior to thrust shortening in the Paleogene. *(C)*, Present-day distribution of Lower Cretaceous deep-water carbonate source rocks (shaded green); original extent most likely was farther south prior to thrust shortening in the Paleogene. *(D)*, Postulated present-day distribution of Cenomanian-Turonian source rocks (shaded orange); original extent most likely was farther south prior to thrust shortening in the Paleogene. Dashed lines reflect uncertainty of source-rock extent (from Moretti and others, 2003b). Contours are water depth, in meters.

Geologic Definition of Assessment Units

North Cuba Fold and Thrust Belt AU

The North Cuba Fold and Thrust Belt AU (fig. 1), which encompasses all reservoirs within potential structural traps of the fold and thrust belt, is mainly onshore, but a part includes some offshore areas (figs. 5 and 6). All of the known oil and gas fields of the North Cuba Basin lie within this AU. The source for petroleum is interpreted to be primarily from Upper Jurassic to Lower Cretaceous organic-bearing carbonates, but synrift mudstones, Upper Cretaceous carbonate mudstones, and Paleogene mudstones also might have contributed petroleum to this system.

The North Cuba Fold and Thrust Belt AU contains up to 12 km of Jurassic through Cretaceous carbonate rocks (Hernandez-Perez and Blickwede, 2000), which host the largest oil fields in Cuba (Valledares-Amaro and others, 2003a,b). The AU is dominated by structural traps, mainly folds, fault-related folds, faulted anticlines, and duplex structures. The structures have been investigated for decades, and many exploration plays have been developed within the fold and thrust belt. Seismic data generally illustrate a stack of thrust sheets forming the thrust belt. Stratigraphic traps might be present, but they are not considered to be significant in this AU. All of the known fields in this AU either produce or have produced from reservoirs within structural traps, and several published examples of fields have documented the structural complexity of fields within the Cuban fold and thrust belt. The oil in most of the reservoirs is heavy (API gravity less than 20 degrees), and the low gravities might be due to biodegradation related to the shallow depth of most reservoirs (Campos-Jorge and others, 1994).

Reservoirs in this AU are reported to be nearly all fine-grained carbonate rocks associated with structural traps. Fractures that formed during thrusting appear to be essential in developing porosity and permeability in carbonate rocks. Little published information is available on reservoir quality. However, Brey del Rey and Hernandez-Leon (1998) concluded that diagenesis is complex in these carbonates, and that secondary porosity developed at depth is important for improving reservoir quality. Some of the Cretaceous platform carbonates might have been subjected to karst-forming processes, which also would enhance reservoir quality (Valledares-Amaro and others, 2003a,b).

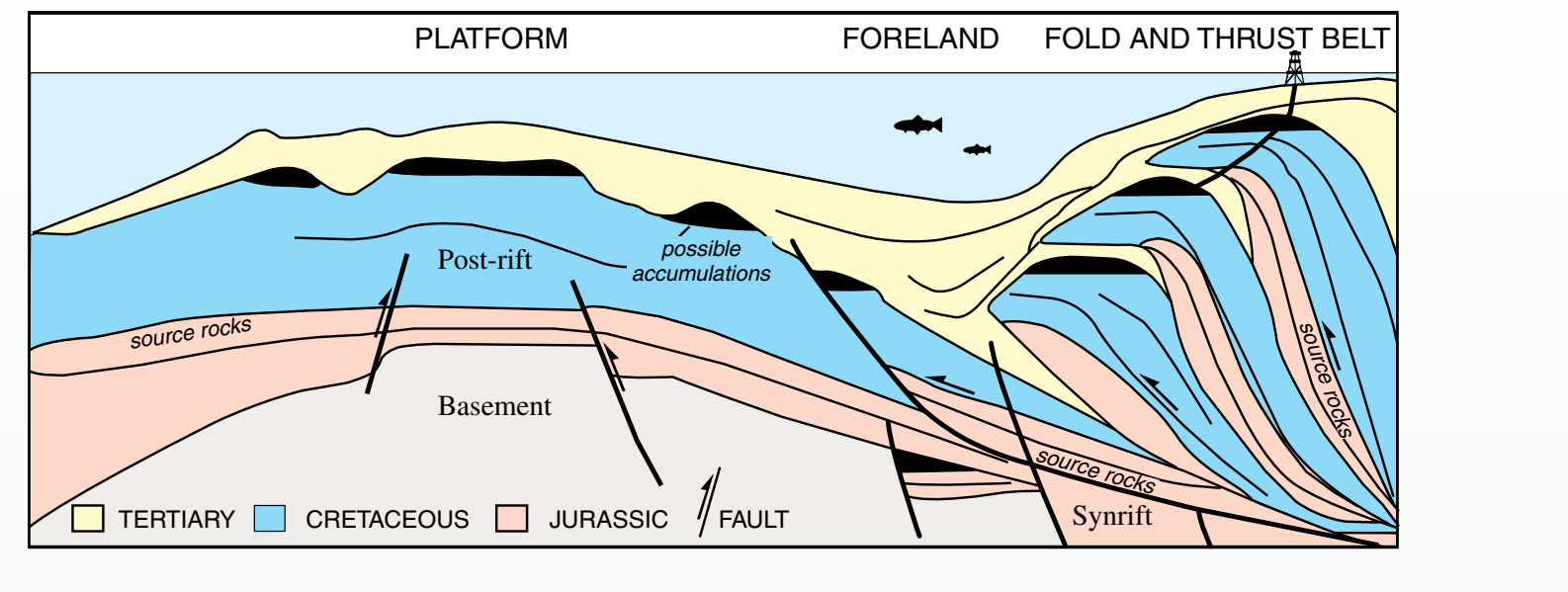

Figure 5. Geologic model for assessment of undiscovered petroleum resources in the Jurassic-Cretaceous Composite Total Petroleum System (from Moretti and others, 2003b).

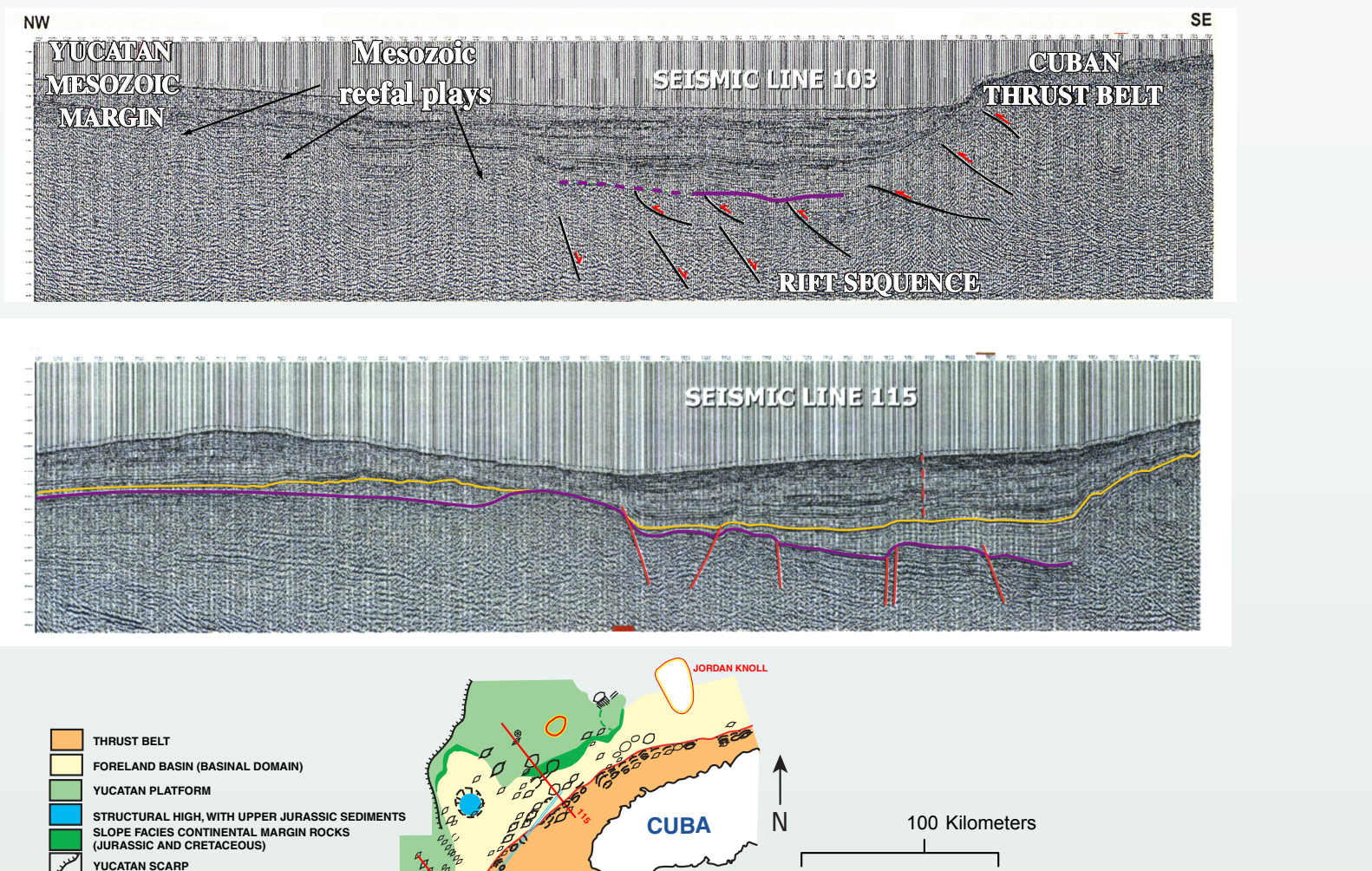

Figure 6. Two selected seismic sections showing general expression of the North Cuba Fold and Thrust Belt AU, foreland, and margin of the carbonate platform (from Lopez-Rivera and others, 2003a). The foreland basin structures in Line 115 might have been inverted during the Paleogene compressional event.

The geologic model for this AU includes (1) structural trapping of oil and possibly gas that was generated within the fold and thrust belt; and (2) vertical migration into complex structures, where the shallow depth of many reservoirs led to degradation of the hydrocarbons, resulting in low API gravities.

Geologic Model for Assessment

Petroleum, both oil and gas, generated in the Paleogene by thrust loading of Upper Jurassic and Lower Cretaceous source rocks, migrated vertically along faults and into carbonate reservoirs within the fold and thrust belt. Petroleum might be biodegraded in shallow reservoirs, but not in deeper accumulations. Although exploration has focused on the shallower accumulations, significant resources might be present in deeper reservoirs, including oil and nonassociated gas. Seals are provided by intraformational mudstones and possibly by diagenesis within the Upper Jurassic and Lower Cretaceous strata. This AU also might have reservoirs within synrift strata that potentially contain petroleum. There is a possibility that Paleogene source rocks might have contributed some petroleum, but volumes from this source are considered to be minor compared to those from the Upper Jurassic and Cretaceous source rocks. More than 20 oil fields have been discovered in this AU, but production data are not available for all fields, nor is the status of several fields presently (2008) known.

North Cuba Foreland Basin AU

The North Cuba Foreland Basin AU (fig. 1) encompasses all reservoirs in the foreland basin part of the North Cuba Basin, including potential reservoirs in the deeper, rift-related part of the AU. This AU is entirely offshore, and to date (2008) only one well has been drilled; the well reportedly penetrated rock with light hydrocarbons but no more is presently known about the test results. Trapping in this AU is interpreted to be mostly structural, with structures having formed as a result of (1) rifting in the Triassic and Jurassic, (2) extensional structures in the Mesozoic, (3) extensional structures inverted in the Paleogene compressional event (Letouzey and others, 2003), and (4) folds in foreland-basin strata. Stratigraphic traps might be present in clastic rocks of the foreland, with the south-dipping clastics possibly forming updip pinch-out traps (Hernandez-Perez and Blickwede, 2000).

Reservoirs in the North Cuba Foreland Basin AU, although in the hypothetical category, are interpreted to be mainly in carbonate rocks. In the area that is now the foreland (and within this AU), a shallow-water carbonate “megabank” existed during Aptian and early Albian time (Denny and others, 1994). This feature was subaerially exposed in the late Albian, most likely because of a sea-level drop, and the exposed surface was extensively karsted, which would have resulted in excellent porosity at this stratigraphic level (Valladares-Amaro and others, 2003a,b). Subsequently, the megabank foundered and broke up, and the blocks were covered by finer grained sediments (Denny and others, 1994; Chambers and others, 2003; Sanchez-Arango and others, 2003). Under these conditions, many reservoirs with zones of excellent porosity might have formed, all of which were subsequently sealed by finer grained rocks. Reservoirs also might be present in the deep synrift grabens that underlie the foreland basin.

Modeling indicates that some of the potential source rocks in the North Cuba Foreland Basin AU might have passed into the thermal generative windows for oil and gas, but there is considerable uncertainty as to the hydrocarbon phase that might exist in this AU. An estimate was made that undiscovered fields would be 90 percent oil fields and 10 percent gas fields.

Geologic Model for Assessment

Petroleum generated in the fold and thrust belt during Paleocene thrust loading and (or) petroleum generated from the deeper part of the foreland basin migrated vertically and laterally into carbonate reservoirs trapped in broad compressional structures, and within clastic reservoirs in the foreland basin sedimentary sequence. Potential reservoirs within the deep synrift section also are included in this AU, but models indicate that source rocks in the synrift section probably are overmature. Pooled petroleum is predicted to be oil and gas; some geochemical data from fields in the thrust belt indicate that thermally evolved or mature gas might be present in some reservoirs. Reservoirs in broad compressional structures may require fracturing to improve productivity because carbonates generally make up the fine-grained facies. Some of the carbonate rock in core from Site 535 is fractured, and the site is not in proximity to structure. Seals are predicted to be adjacent to nonfractured fine-grained carbonates. Some of the carbonate rocks in this AU might have been subjected to karst-forming processes during the formation of the fold and thrust belt (Rosenfeld and Blickwede, 2006), and the karst zones could form adequate hydrocarbon reservoirs. However, the presence of adequate reservoir quality is a significant geologic risk in this AU.

There are no oil or gas fields in the North Cuba Foreland Basin AU. Only one well has been reported, and it was drilled in the offshore in 2004 by the Spanish oil company Repsol. Although details of production tests are not available, Repsol announced that tests showed that the well penetrated a noncommercial light-oil accumulation. Two delineation wells are planned but have not been drilled as of early 2008.

North Cuba Platform Margin Carbonate AU

The North Cuba Platform Margin Carbonate AU (fig. 1) encompasses all potential reservoirs developed in carbonate-platform-margin environments along the Yucatan and Bahama margins. The area of this AU is somewhat limited compared to the other AUs, but the potential reservoirs—including reef, fore-reef, and carbonate debris-flow reservoirs—might be prolific. These reservoirs might be stacked because the platform margin remained relatively stable from Late Jurassic through Cretaceous.

By analogy, carbonate reservoirs are well known in equivalent-age rocks from the southern Gulf of Mexico (Enos, 1977; Enos and Moore, 1983; Cook and Mullins, 1983; Magoon and others, 2001). Reef trends are well documented around the Gulf Coast (McFarland and Menes, 1991), especially in the Lower Cretaceous. Porosity can be high in these reservoirs and, as with all carbonate rocks, porosity is largely dependent upon the diagenetic history. Fore-reef and debris-flow reservoirs are especially significant in the Mexican part of the Gulf of Mexico. Generally defined as Tamabra-like reservoirs (Magoon and others, 2001), these rocks contain some giant oil accumulations in the Mexican Gulf Coast. The reservoirs generally represent reef talus or debris flows of reef and shelf detritus that accumulated on the slope or in the basin; then they became encased in finer grained rocks that are excellent seals. Porosity can be high, possibly enhanced by processes associated with sea-level drawdown in the Paleogene (Rosenfeld and Pindell, 2003).

The lack of drilling prevents anything more than general speculation as to the reservoir and trapping conditions that might exist in the North Cuba Platform Margin Carbonate AU. However, by analogy with carbonate rocks described above for the Mexican Gulf Coast, there is a high probability that geologic characteristics are similar. Another major source of geologic uncertainty concerns hydrocarbon migration and reservoir charge. For reservoirs to have been charged with oil, the oil must have been generated in the North Cuba Fold and Thrust Belt or North Cuba Foreland Basin AUs followed by lateral migration into potential reef, fore-reef, or slope-basin reservoirs. The only evidence for lateral migration of oil is the staining of carbonate rock in the DSDP Site 535 core. Questions remain as to how much fluid might have migrated and whether there was enough fluid to adequately charge a potential reservoir of minimum size.

The petroleum phase in this AU is interpreted to be oil, but this interpretation involves considerable geologic uncertainty. Nonassociated gas was not assessed in this AU.

Geologic Model for Assessment

Petroleum generated by thrust loading of Upper Jurassic and Lower Cretaceous source rocks in the Paleogene during the formation of the fold and thrust belt would have to migrate laterally for a great distance for it to have accumulated within reservoirs of this AU. The geologic model involves petroleum being generated in the thrust belt or possibly from the deeper part of the foreland basin, then migrating laterally into reservoirs formed along the margins of the Yucatan and Florida/Bahama carbonate platforms. Reservoirs are postulated to be largely reef, fore-reef, and carbonate debris-flow units along the platform margins, similar to the reservoirs in the Mexican part of the Gulf Coast (Magoon and others, 2001). These types of reservoirs are fundamental to petroleum systems of the Mexican Gulf Coast, and debris-flow reservoirs in particular might represent one of the highest quality reservoir types in the Jurassic-Cretaceous Composite TPS. Another reservoir type might be karst zones within the platform carbonates (Valladares-Amaro and others, 2003b) because karst possibly developed during the formation of the fold and thrust belt (Rosenfeld and Blickwede, 2006).

Although the reservoir type is analogous, migration distances in the Mexican Gulf Coast example appear to have been less than in this composite TPS. Distance of migration required for the Cuban reservoirs might therefore constitute a significant geologic risk in the estimation of undiscovered oil resources in this AU. No oil and gas fields are known, and there has been no exploration to date (2008).

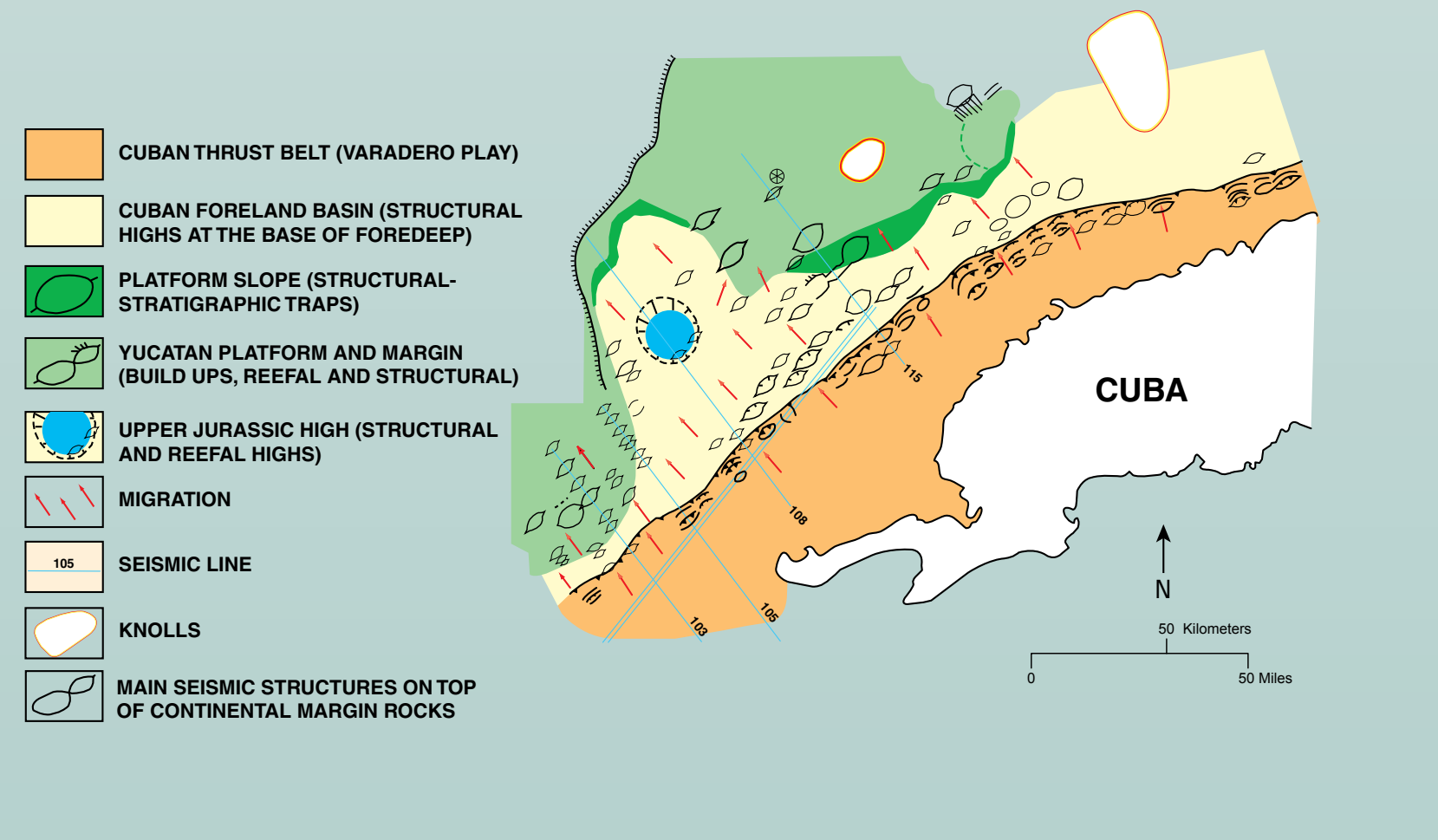

Figure 7. Oil and gas prospect map for northwestern Cuba, based on interpretation of seismic data (from Cubapetroleo, 2002).

Assessment Results

Table 1. North Cuba Basin assessment results.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS is Total Petroleum System. AU is Assessment Unit. Gray shade indicates not applicable]

	Total Petroleum Systems (TPS) and Assessment Units (AU)	Field Type	Total Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
	Jurassic-Cretaceous Composite TPS													
Conventional Oil and Gas Resources	North Cuba Fold and Thrust Belt AU	*Oil*	142.22	464.25	941.03	493.64	159.47	540.32	1,200.27	591.56	8.87	31.53	75.66	35.47
		Gas					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	North Cuba Foreland Basin AU	*Oil*	781.13	3,014.17	6,374.50	3,218.85	1,464.93	5,863.30	13,421.82	6,451.18	137.43	569.20	1,406.66	644.74
		Gas					141.29	862.16	3,418.47	1,190.46	7.09	44.07	184.63	63.13
	North Cuba Platform Margin Carbonate AU	*Oil*	131.66	759.73	2,036.87	883.13	221.42	1,330.19	3,841.07	1,588.79	20.71	129.67	399.05	158.90
		Gas					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total Undiscovered Oil and Gas Resources		**1,055.01**	**4,238.15**	**9,352.40**	**4,595.62**	**1,987.11**	**8,595.97**	**21,881.63**	**9,821.99**	**174.10**	**774.47**	**2,066.00**	**902.24**

The USGS assessed undiscovered conventional oil and gas resources in the North Cuba Basin, exclusive of reserve growth. The USGS estimated means of 4.6 billion barrels of oil (BBO), 9.8 TCF of natural gas (8.6 TCF of associated-dissolved gas and 1.2 TCF of nonassociated gas), and a mean total of 0.9 billion barrels of natural gas liquids for the three AUs (table 1). Of the estimated mean of 4.6 BBO, about 0.49 BBO are in the North Cuba Fold and Thrust Belt AU, about 3.2 BBO are in the North Cuba Foreland Basin AU, and about 0.9 BBO are in the North Cuba Platform Margin Carbonate AU (table 1). All of the nonassociated gas (1.2 TCF; gas in gas fields) was assessed in the North Cuba Foreland Basin AU.

Summary

The potential for undiscovered petroleum resources of the North Cuba Basin historically has focused on the heavy oil fields of the onshore fold and thrust belt (Echevarria-Rodriguez and others, 1991; Pindell, 1991; Petzet, 2000; Oil and Gas Journal, 1993, 2000, 2002, 2005), but recent efforts have focused on the offshore potential (fig.7) (Vassalli and others, 2003; Moretti and others, 2003a,b; Magnier and others, 2004). This study indicates that the offshore of the North Cuba Basin might have significant potential for undiscovered oil and gas resources (Schenk, 2008).

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