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Lithospheric Structure and Supracrustal Hydrocarbon Systems, Offshore Eastern Trinidad

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ABSTRACT

To facilitate an evaluation of hydrocarbon systems elements in offshore eastern Trinidad, we generated regional cross sections and a 1000-km-long conceptual, lithospheric-scale cross section from the Aves ridge to the Demerara plateau. The sections are based on interpretation of 2-D and 3-D seismic data, gravity and magnetics surveys, and published literature. Our results indicate that convergent-margin tectonism and rapid sedimentation first impacted the deep-water area of offshore eastern Trinidad in the latest Miocene. As much as 12 km of post-middle Miocene sediments are present south and east of the Caribbean–South American Plate boundary zone in the Columbus basin foredeep. The basin formed in response to subduction, tectonic loading, and progradation of the Orinoco delta. Well-imaged, northeast-trending buckle folds occur above the detachment fault(s) and are an important trap-forming element in the deep-water area. Deep-penetrating, active growth faults are the principal hydrocarbon migration pathways on the continental shelf but are absent in the deep-water exploration area. Seismic quality diminishes rapidly to the north of 11°N latitude, in an area where highly irregular sea-floor topography marks active deformation and dewatering in the internal part of the Barbados accretionary complex.

We propose that the change in crustal type across the Mesozoic passive margin of northern South America controls the style and magnitude of strain above the main décollement associated with the Cenozoic convergent margin. Contractional structures developed in Trinidad when continental lithosphere of the South American plate impinged on the subduction zone at the leading edge of the Caribbean plate. The positive buoyancy of continental lithosphere resists subduction, resulting in more earthquakes, a fold and thrust belt from eastern Venezuela to offshore eastern Trinidad with as much as 100-km shortening, and the southern limit of the Lesser Antilles volcanic arc. The transition to oceanic crust in offshore eastern Trinidad marks a change in tectonic environment from continental fold and thrust belt to accretionary prism above subducting oceanic crust.

INTRODUCTION

Hydrocarbon systems viability in the deep-water exploration area east of Trinidad is fundamentally linked to large-scale tectonic processes (Figure 1). Rapid Neogene-Quaternary sedimentation and proximity to a subduction-zone complex have potential significance for all play elements. In this paper, we describe a model for tectonic evolution of the deep-water area based on new seismic interpretation, gravity and magnetic data, and published literature. A key objective for this project is to understand the geologic setting of the Trinidad deep-water area relative to adjacent tectonic domains.

To the north of the deep-water exploration area (Figures 1 and 2), Ocean Drilling Program Legs 110 and 156 conducted rigorous geologic and geophysical investigations of the Barbados accretionary complex. The accretionary complex is a sedimentary prism at the leading edge of the Caribbean Plate formed by off-scraping and bulldozing of incoming sediments on Atlantic oceanic crust (Moore et al., 1988). As Atlantic oceanic crust is subducted beneath Caribbean oceanic crust, deformation and uplift also occur by underplating at the base of the detached sedimentary wedge.

The accretionary complex is likely to be a less favorable environment for oil prospectivity because of lean or discontinuous source rocks, structural complexity, and a vigorous hydrodynamic system. Mud volcanoes in accretionary complexes worldwide are associated with predominantly thermogenic and biogenic methane but little wet gas and oil (Moore et al., 1988; Robertson et al., 1998; Suess et al., 1998). Economic oil accumulations in accretionary complexes built on oceanic crust are rare (World Oil Map, 1998), and exploration wells often are costly undertakings in such settings. Petroleum exploration in the Barbados accretionary complex proper is minor; only small volumes of oil and gas production have been produced on Barbados Island (Speed et al., 1991). Given these considerations, identification of the poorly constrained southern extent of the Barbados accretionary complex is critical for understanding the hydrocarbon system in the deep-water exploration area of offshore eastern Trinidad.

Southwest of the deep-water exploration area (Figure 1), a fold and thrust belt is documented in onshore Trinidad and eastern Venezuela (Kugler, 1961; Salvador and Stainforth, 1968; Babb and Mann, 1999). These structures developed in the Miocene when continental lithosphere of the South American Plate impinged on the subduction zone at the leading edge of the Caribbean Plate (Algar and Pindell, 1993). The Maturin and Columbus foredeep basins developed as a product of tectonic subsidence in response to emplacement of the fold and thrust belt (Leonard, 1983; Erikson and Pindell, 1993). Eastward-propagating strike-slip faults accommodate continued eastward relative motion of the Caribbean Plate (Robertson and Burke, 1989). Large growth faults cut the contractional structures on the eastern side of the fold and thrust belt, forming important potential migration pathways from deep hydrocarbon sources (Heppard et al., 1998; Wood, 2000).

In contrast to the Barbados accretionary complex, eastern Venezuela and Trinidad contain significant oil and gas reserves. In the center of the Maturin Basin, the El Furrial/northern Monagas area contains estimated oil reserves of ~6 billion bbl (Prieto and Valdes, 1992). In offshore and onshore Trinidad, proven oil and gas reserves are also large. The majority of hydrocarbon occurrences are typed to oil-prone Cretaceous source rocks (Persad et al., 1993; Goodman et al., 1998). Abundant oil seeps, pitch lakes, and tar mats attest to the prolific vertical migration of hydrocarbons in this structural province (Suter, 1960; Higgins and Saunders, 1974). Mud volcanoes with hydrocarbons are abundant in the offshore region as well, and suggest a continued active hydrocarbon system (Tenney and Hoppe, 2000).

To establish a framework for hydrocarbon systems analysis, we discuss in this report key elements

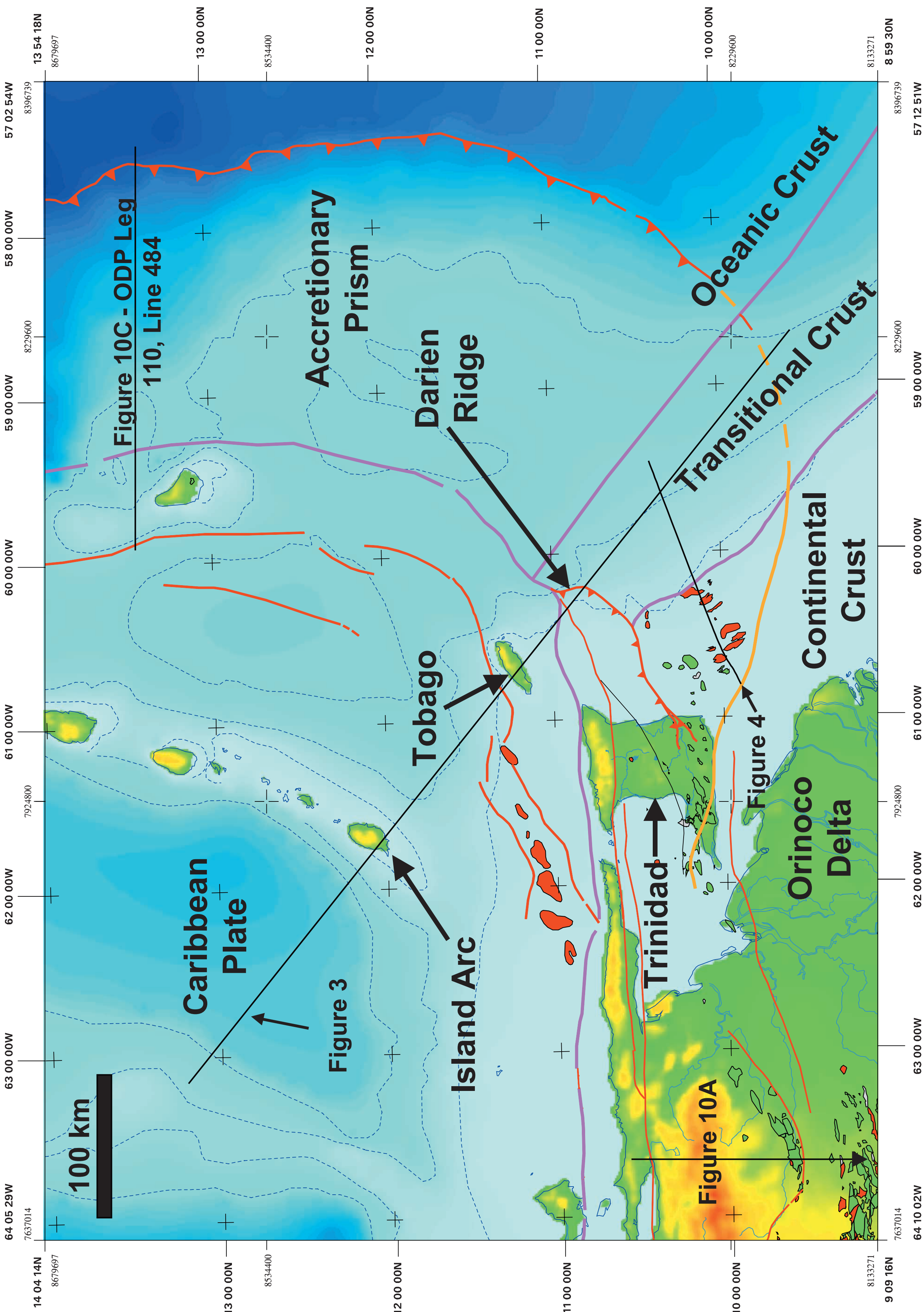

Figure 1. Tectonic map of southeastern Caribbean region with bathymetry and topography; oil fields in green, gas fields in red.

related to large-scale tectonics including: crustal type, total sediment fill and mechanism for development of the Columbus basin, lithospheric buoyancy and impact on the subduction zone, and tectonic control on thermal state of crust. The primary results of this study are displayed on a conceptual, lithosphere-scale cross section and a structure section based on new seismic interpretation. We conclude that the change in crustal type across the Mesozoic passive margin of northern South America fundamentally impacts the style and magnitude of strain above the main décollement associated with the Cenozoic convergent margin.

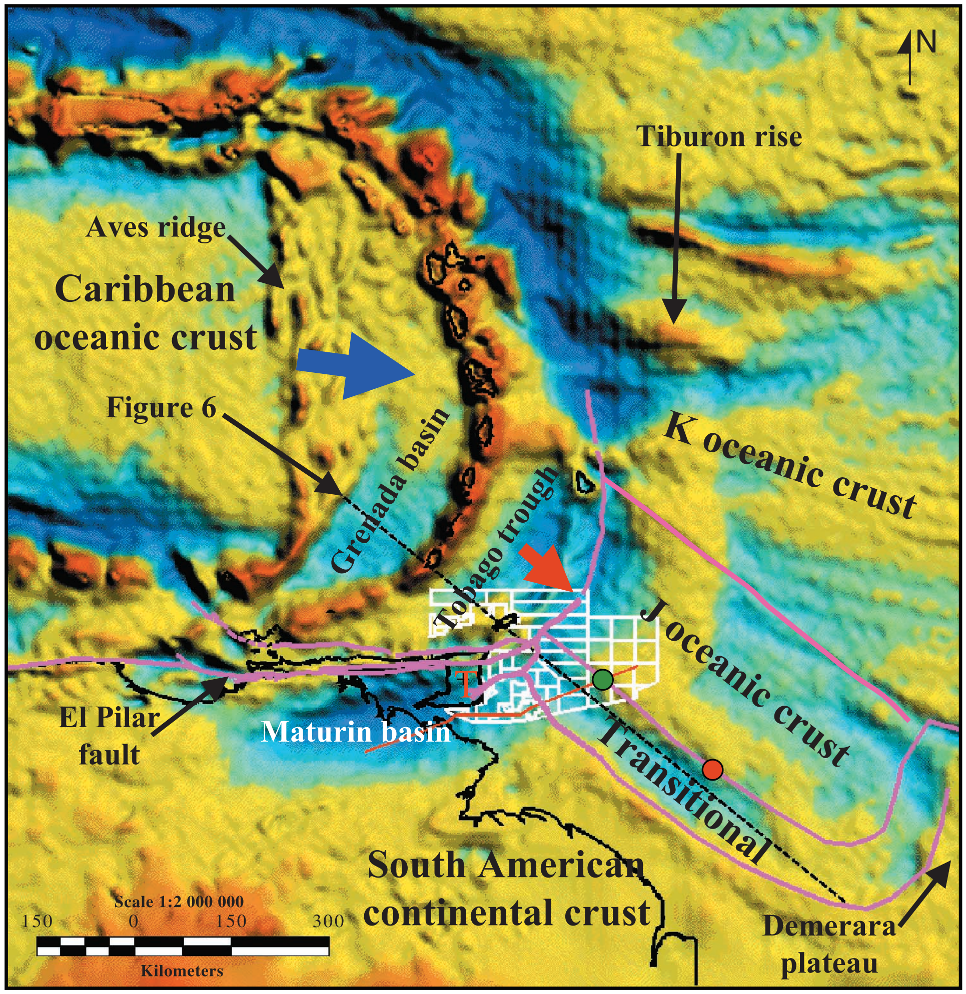

Figure 2. Free-air gravity map with interpretation of crustal types. Isostatic correction applied to onshore areas. Red dot = seismic tie with interpreted edge of oceanic crust; green dot = seismic tie with basement fault; blue arrow = relative motion of Caribbean plate from regional plate reconstructions; red arrow = direction of maximum shortening from local strains. Gravity lows in blue, highs in red.

EVALUATION OF LITHOSPHERIC STRUCTURE

We generated a 1000-km-long conceptual cross section through the lithosphere in conjunction with development of depth structure sections based on seismic data (Figures 3 and 4). Our model for lithosphere-scale structure formed a framework for interpreting structurally complex areas with limited or no seismic data. The regional cross-section line crosses the plate boundary zone near the northeastern end of the Darien ridge and extends from the Aves ridge to the Demerara plateau (Figure 1). The Darien ridge is the offshore extension of the onshore Trinidad Central Range; the Galeota ridge forms part of the southern Trinidad fold and thrust belt (Figure 5). Cumulatively, these structures generate significant relief (>10 km) in the Mesozoic section and we interpret them to be a product of successive thrust imbrication and fault-bend folding (Figure 3). To the north and east, on oceanic crust, the fault-bend folds in the plate boundary zone decrease in magnitude and merge with the Barbados accretionary complex.

Crustal Type

Unattenuated continental crust can be traced confidently to the first sharp transition from free-air gravity high to low, offshore of Guyana (Figure 2). This transition extends northeastward toward Trinidad and is roughly coincident with the modern shelf edge (Figure 1). The southwestern limit of oceanic crust characterized by rough surface and diffractions on unmigrated data is imaged in the offshore Guyana region (see Figure 1 for tie point). The limit of well-imaged oceanic crust coincides with a northwest trending boundary on both free-air and Bouguer gravity maps (Figure 2). This boundary coincides with a high-angle basement fault (Figures 2 and Figure 6) and projects toward the northeastern end of Tobago. Thus, an approximately 100-km-wide transition zone exists between continental and oceanic lithosphere (Figures 1 and 2). We interpret the transition zone to

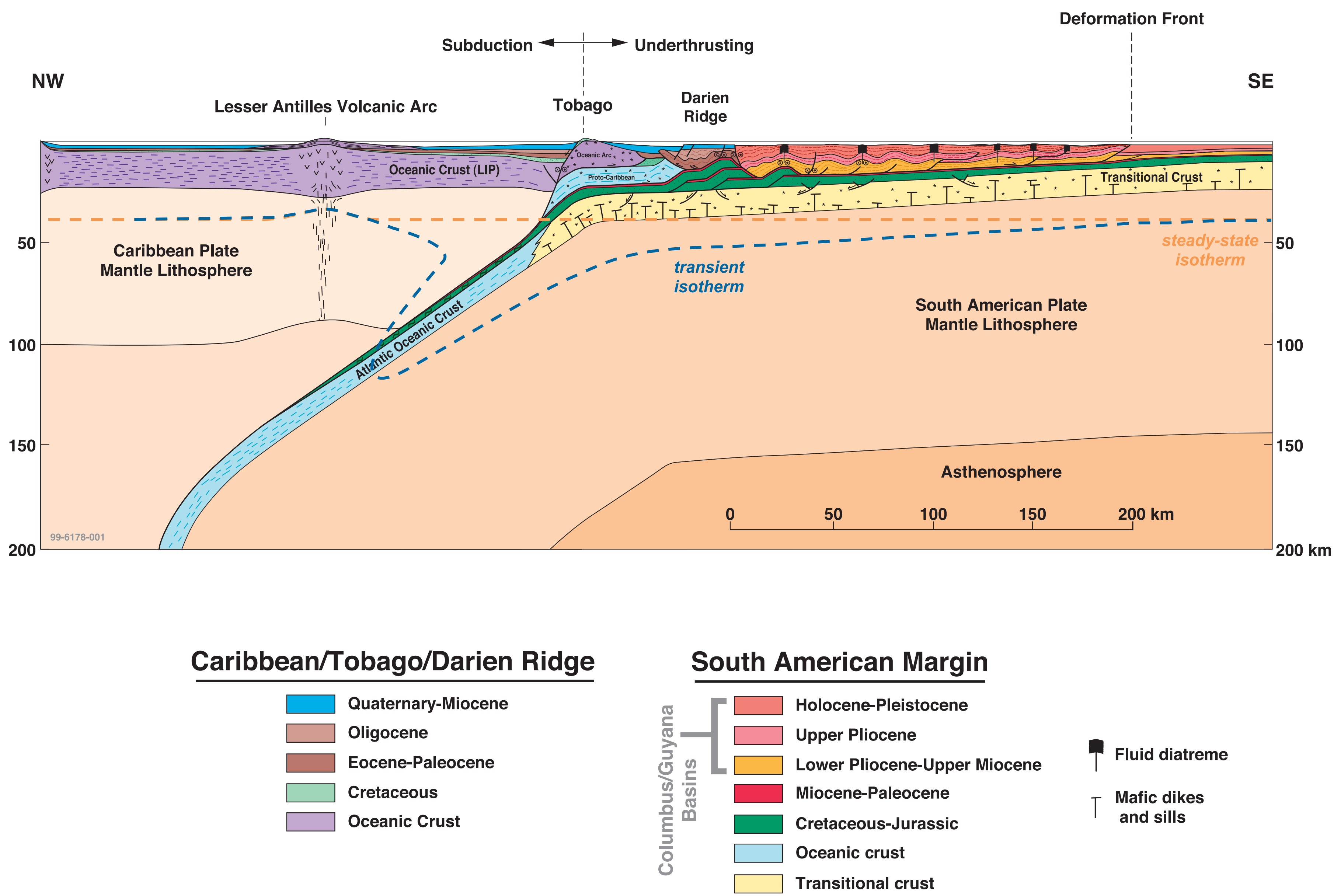

Figure 3. Conceptual, lithospheric-scale cross section, offshore eastern Trinidad. See Figure 1 for line location; southeastern third of line (Guyana basin) is omitted. Data sources: ExxonMobil: regional 2-D seismic data, 3-D seismic data on blocks 25B and 26, bathymetry, hydrocarbon systems analysis; see text for integration with published literature.

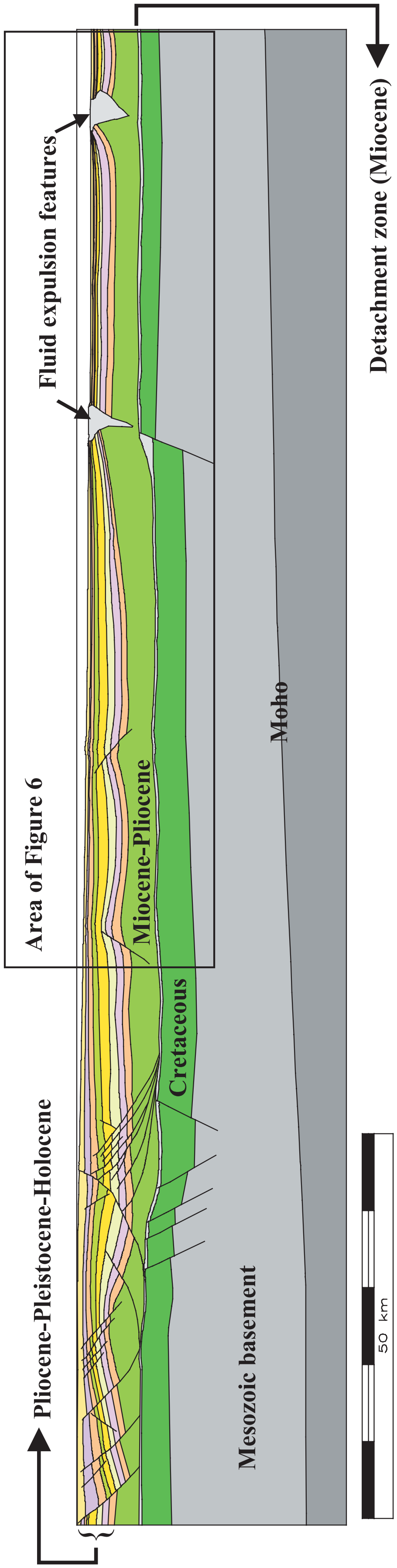

Figure 4. Regional cross section across shelf and upper slope, offshore eastern Trinidad. Constructed from interpretation of regional 2-D seismic data and 3-D seismic data on blocks 25B and 26. See Figure 1 for line location.

be 10–15-km thick, highly attenuated crust that is strongly intruded by mafic dikes and sills.

Plate tectonic models (e.g., Pindell et al., 1991) for spreading between North America and South America suggest that offshore northern South America was the site of transform faults linked to small rift segments in the Jurassic, followed by cooling and subsidence in the Cretaceous. Approximately a 150,000 km^2 area of oceanic crust north of the transition zone contains northwest-southeast-trending fracture zones. They are oblique to east-west-trending fracture zones in the much larger area of Cretaceous oceanic crust located east of Barbados (Figure 2). This fragment of oceanic crust may have formed in the Jurassic during initial separation of North America from the Demerara plateau. Sea-floor spreading between Africa and North America occurred north of the transform boundary in the Early Cretaceous, forming the bulk of oceanic crust east of Barbados (Pindell et al., 1991).

Foredeep Basins

Total sediment fill calculated from free-air gravity data shows as much as 18 km of sediment in the Columbus basin foredeep (Figure 7). Maximum depth to basement from interpretation of a limited set of deep-record 2-D seismic lines is 16 km. The maximum sediment fill in the basin is in the deep-water exploration area. The basin formed in response to subduction-driven tectonic loading and sediment loading from the prograding Orinoco delta. Its tectonic setting and genesis is similar to older foredeep basins along the northern Venezuelan margin, including the Falcón and Maturin basins. Together, these foredeep basins represent progressive eastward migration of a foredeep along northern South America's late Mesozoic passive margin (Goodman et al., 1998; Erikson and Pindell, 1993).

Sediments derived from the Orinoco drainage system extend northward to the Tiburon rise (Brown and Westbrook, 1988) located east of Barbados (Figure 2). A decrease in total sediment thickness from >15 km to <4 km occurs gradually over 300 km (Figure 7). North of the Tiburon rise (Figure 2), where sedimentary cover is thinnest, the accretionary prism narrows considerably. The area of thickest sediment accumulation in the deep-water exploration area occurs immediately to the southeast of the Darien ridge, above a northwest-trending gravity low (Figure 2). The northeastern limit of the Darien ridge coincides with the southwestern limit of accretionary prism deformation along the line we interpret as

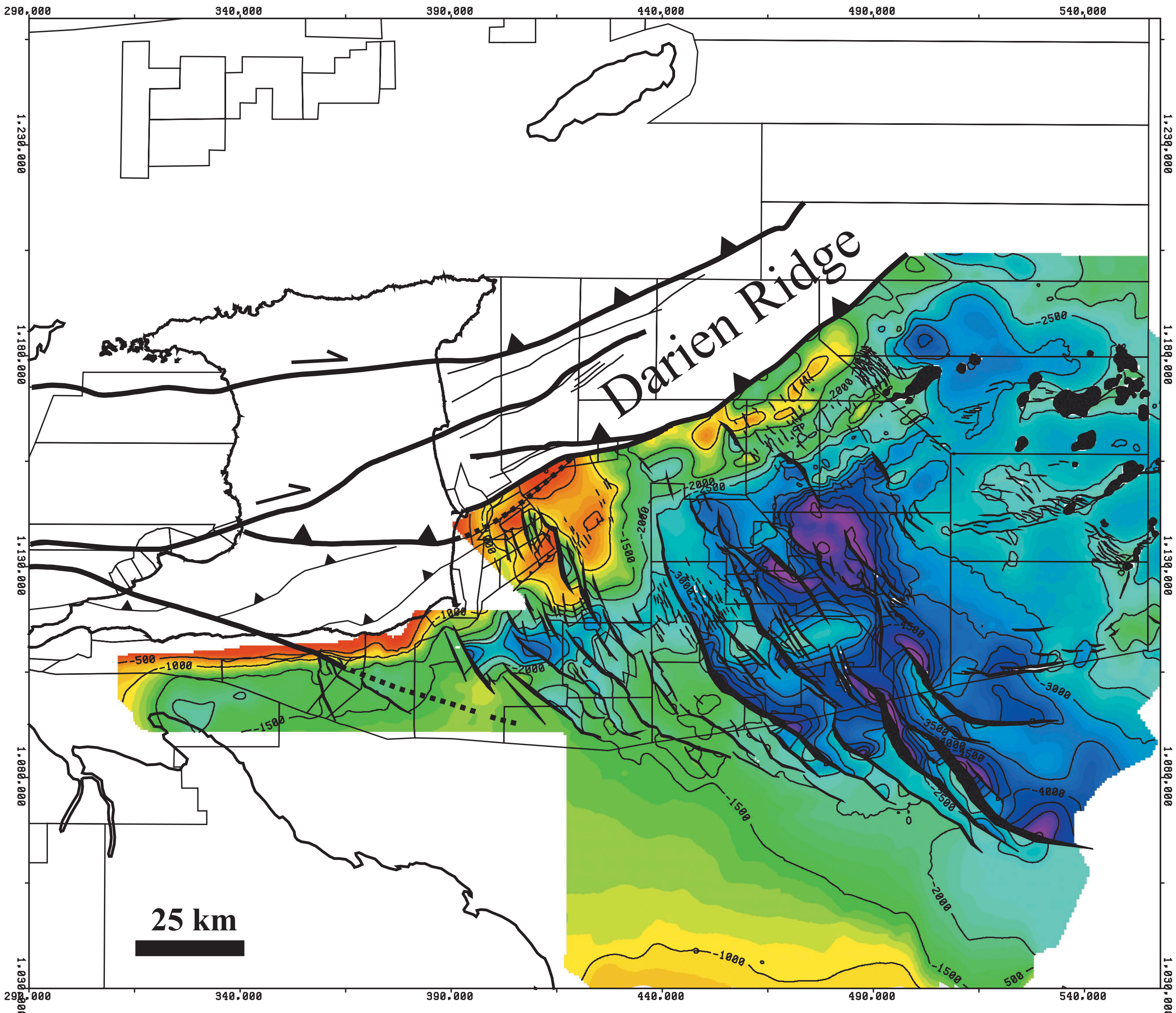

Figure 5. Depth-structure map on near-base Pleistocene surface from interpretation of regional 2-D seismic data. Onshore/near-shore thrust and strike-slip faults shown in black with triangles and relative motion arrows; shelf normal- and oblique-slip faults shown in black; slope strike-slip and normal faults shown in black; slope fluid expulsion features shown in black.

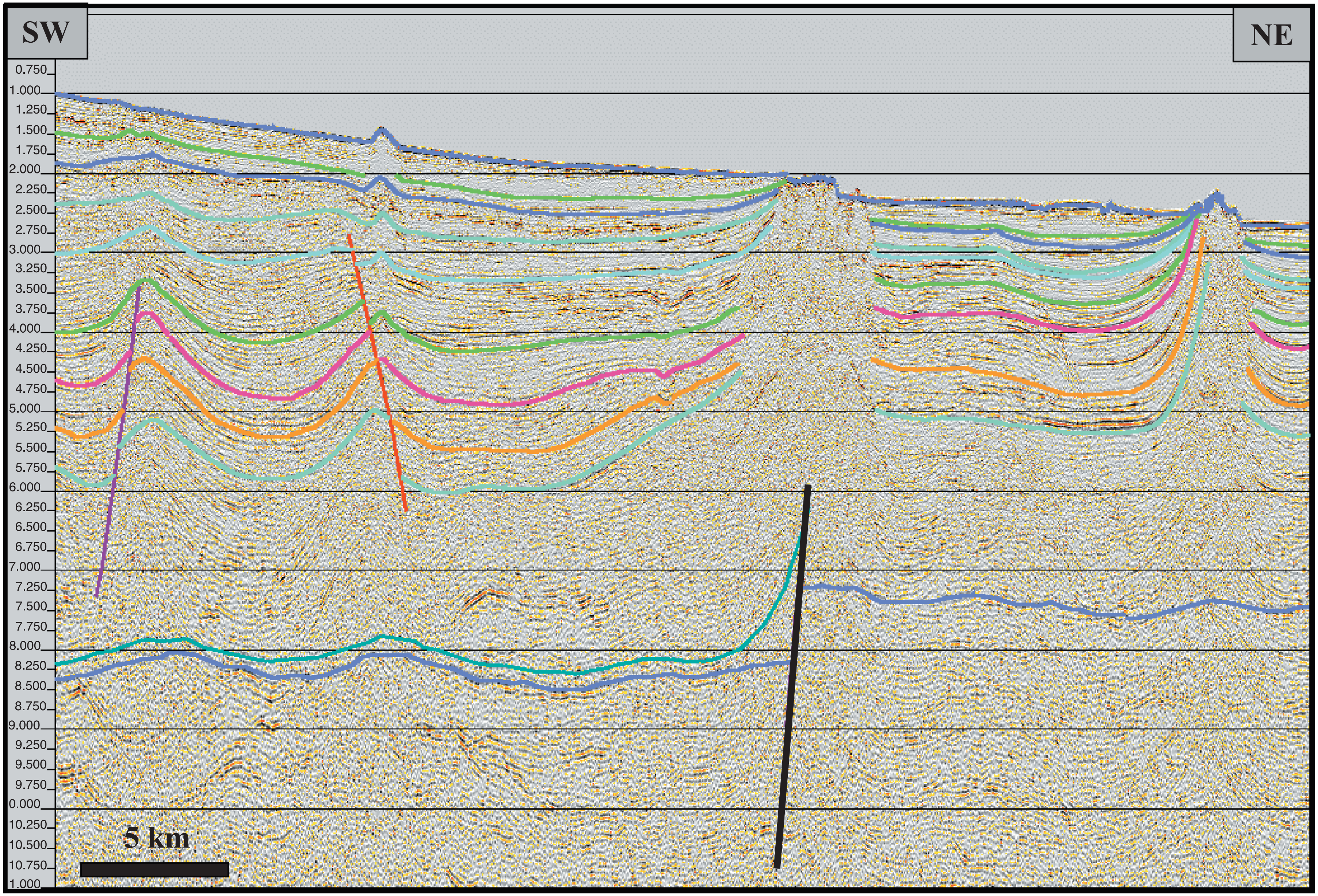

Figure 6. Seismic line showing interpretation of deep basement fault. Fault occurs at the mapped boundary between oceanic crust (right, NE) and transitional crust (left, SW). See Figure 2 for tie point.

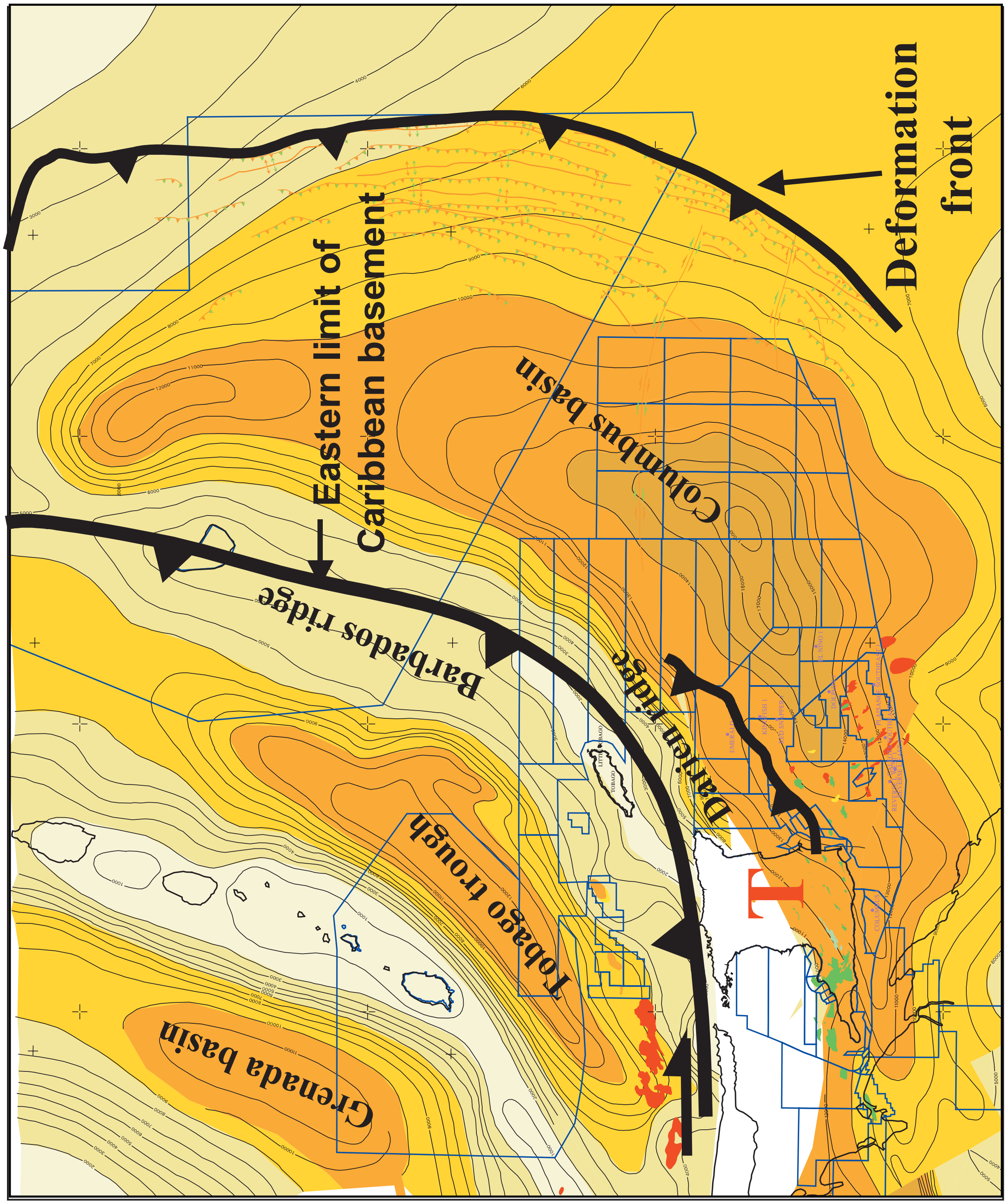

Figure 7. Total sediment-fill map for southeastern Caribbean region. Contour interval is 1 km; deepest contour is 18 km. Map is constructed from interpretation of seismic, gravity, and magnetic data.

the inner limit of Jurassic-age oceanic crust. We develop these relationships in more detail below.

LITHOSPHERIC BUOYANCY AND IMPACT ON SUBDUCTION ZONE

The change in crustal type across the Mesozoic passive margin of northern South America fundamentally influences the style and magnitude of strain above the main décollement associated with the Cenozoic convergent margin. Buoyancy differences between continental and oceanic crust impact the ability of lithosphere to subduct (Cloos, 1993). North and east of the Darien ridge, negative buoyancy of oceanic lithosphere drives subduction. However, where continental lithosphere enters the subduction zone, its positive buoyancy resists subduction. The subduction zone becomes jammed and produces collisional orogenesis. Tomographic images and gravity data from eastern Venezuela suggest that oceanic lithosphere has broken off a jammed piece of continental lithosphere and is sinking into the asthenosphere (Van der Hilst, 1990; Russo and Speed, 1992).

The capacity of transitional crust to subduct depends on its density and coupling to adjacent crustal types. In offshore eastern Trinidad, the ocean-continent boundary zone is nearly orthogonal to the subduction-zone trace. In this geometry, we believe the transitional crust and underlying lithosphere accommodate the differential subduction/underthrusting of oceanic and continental crust. Steeply dipping, northwest-striking shear zones (old transform faults?) with left-lateral, normal-sense displacement allow oceanic lithosphere to subduct independently of continental lithosphere to the southwest. Earthquakes with left-lateral first motion on northwest-striking planes support this interpretation (e.g., March 25, 1988, event east of Trinidad; Russo et al., 1993). In addition, many more earthquakes occur southwest of the transition zone than to the northeast (Russo et al., 1993). We interpret most of the left-lateral, normal-sense displacement to occur near the outer (northeast) limit of transitional crust. Key observations include:

1) fracture zone at the northeastern limit of the transitional crust that could serve as the locus of decoupling (Figures 2 and 6);
2) continuation of Darien ridge past the Cretaceous shelf edge onto transitional crust until termination near interpreted boundary with the oceanic crust (Figures 2 and 5); and
3) end of the Lesser Antilles volcanic arc at the northwestward projection of the boundary between oceanic and transitional crust. (Figure 1, 2).

We believe that the present-day accretionary prism proper is restricted to the area of active ocean-ocean subduction mostly to the north of the deep-water exploration area. Our mapped boundary coincides with the end of the Darien ridge and a series of east-west-trending ridges east of the Darien ridge termination. These ridges may be cored by detached strike-slip faults (right-lateral) that accommodate differential shortening between the accretionary complex to the north and gently folded strata to the south (in the offshore equivalent of the southern Trinidad fold and thrust belt).

Based on the concepts outlined above, our conceptual, lithosphere-scale cross section (Figure 3) can be divided into four tectonic regimes: Caribbean Plate, plate boundary zone, Columbus basin, and Guyana basin. The Caribbean Plate extends from Aves ridge to Tobago along the line of section (Figure 1). The stratigraphy is generalized (Ysáccis, 1997); the basement consists of anomalously thick (8–20 km) oceanic crust of Late Cretaceous age (Kerr et al., 1997). We describe the plate boundary zone and the Columbus basin in more detail below.

Plate Boundary Zone

The plate boundary zone extends from Tobago to the Darien ridge along the line of section (Figures 1 and 3). The structurally highest units are Cretaceous arc rocks on Tobago that were uplifted to the near surface at ~45 Ma (Cerveny and Snoke, 1993). We interpret this to be the time during which Tobago was emplaced over proto-Caribbean oceanic crust and overlying trench-slope facies metasedimentary rocks. Its emplacement may have been coeval with a trench jump to the east, resulting in extinction of the Aves ridge and onset of volcanism in the Lesser Antilles. The new subduction zone became jammed from west to east as it encountered promontories of South American continental or coupled transitional lithosphere. The youngest area of orogenesis involves the northeastern end of the Darien and Galeota ridges. The Emerald-1 well encountered Cretaceous strata at multiple levels (Figure 8); the structurally highest level is at ~1.5 km below mud line. From well and seismic data, we interpret the ridges to be a product of successive fault-bend folds that incorporate Cretaceous to middle Miocene strata originally deposited on the South American margin into the overriding block. In our model, fault-bend folds in the Darien and Galeota ridges accommodate 72 km (40%) shortening. On the northwestern side of the deformation front, west- and northwest-vergent folds are well imaged in the Tobago Trough. We interpret these folds to accommodate an order of magnitude less crustal shortening than southeast-vergent deformation because of apparent lack of major structural relief, no associated foredeep, and a lesser number of earthquakes with slip vectors in this orientation (Russo et al., 1993).

Columbus Basin

The Columbus basin extends from the Darien ridge to the deformation front along the line of section. It includes Pliocene and Pleistocene strata on the Galeota ridge, which we show to be cored by a fault-related fold based on one deep-record seismic line (Figure 9). Thrust faults are confined to the upper Miocene–lower Pliocene interval in the interior part of the basin; they become progressively younger to the east. The basin is detached on the middle Miocene interval (offshore equivalent of Freites Shale; Di Croce, 1995); buckle folds at the top Pliocene horizon accommodate 16 km of shortening in the model (7%). Extensional faulting occurs out of the plane of the section and likely shares the same detachment level (Figure 4). Fluid expulsion features (diatremes) are common in this area; we interpret them to be narrow conduits of fluidized mud, water, and lithic clasts that nucleate mostly from anticlines in the upper Miocene–lower Pliocene section (Barboza and Boettcher, 2000). Two mapped strike-slip faults cut the section, each with relatively small magnitude displacement compared to shortening in the Darien ridge (Figures 3, 5, and 9). The boundary between Darien ridge and the Columbus basin probably has a strike-slip component as well. Thus, the entire basin is detached and undergoing right-lateral oblique shear.

Convergent margin tectonism and rapid sedimentation first impacted the deep-water exploration area in the middle Miocene. We mapped an angular unconformity near our interpreted Pliocene base that separates an early (poorly imaged) phase of folding, thrust faulting, and normal faulting from a younger structural style of broad buckle folds and associated fluid-expulsion features. A series of northwest-trending regional and counter-regional faults developed on the continental shelf starting in the middle to late Miocene and appear to be synchronous with (orthogonal) shortening in the deep-water exploration area (Figures 4 and 5). The easternmost regional normal fault contains a large growth section expanding to the southwest. Early strike-slip faults (late Pliocene) locally enhanced the larger growth basin through development of small pull-apart basins. Younger east-trending strike-slip faults appear to link northeast-trending buckle folds in the Pleistocene section. En echelon faulting close to the mud line indicates continued oblique shear (Figure 5).

The Guyana basin extends from the deformation front to the Demerara plateau along the line of section (Figure 1). Stratigraphy in this area is highly generalized and meant to show bulk thickness of strata only. We have omitted most of this area from Figure 3 so that details of the plate boundary zone are visible.

TECTONIC CONTROL ON THERMAL STATE OF CRUST

Given our interpretation that the deep-water exploration area is situated on both transitional and oceanic crust, we expect thermal models to include a basal heat-flow density at the base of the crust that is consistent with values seen in other mature passive-margin settings. However, available downhole temperatures and other data sources from the Columbus basin indicate a moderately depressed thermal gradient throughout most of the offshore region (Leonard, 1983). Depression of the geotherm results in a transient situation wherein the observed geothermal gradient is out of equilibrium with, and is significantly lower than, the expected steady-state geotherm. In the Columbus basin, three possible forces result in isostatic depression of the lithosphere and development of a thermal transient. These forces are described briefly below.

Slab Pull

As the proto-Caribbean oceanic lithosphere descends into the adjacent subduction zone, its density exerts a significant force of ''slab pull'' on the attenuated South American crust. Thus, the South American lithosphere is similar to a rigid beam weighed down at one end. The lithosphere adjacent to the subduction zone is pulled downward, displacing hot asthenospheric mantle with colder lithospheric mantle, thereby upsetting geothermal equilibrium in this area (Figure 3).

Crustal Thickening

From the late Miocene to the present, several pulses of contractional deformation affected the deep-water

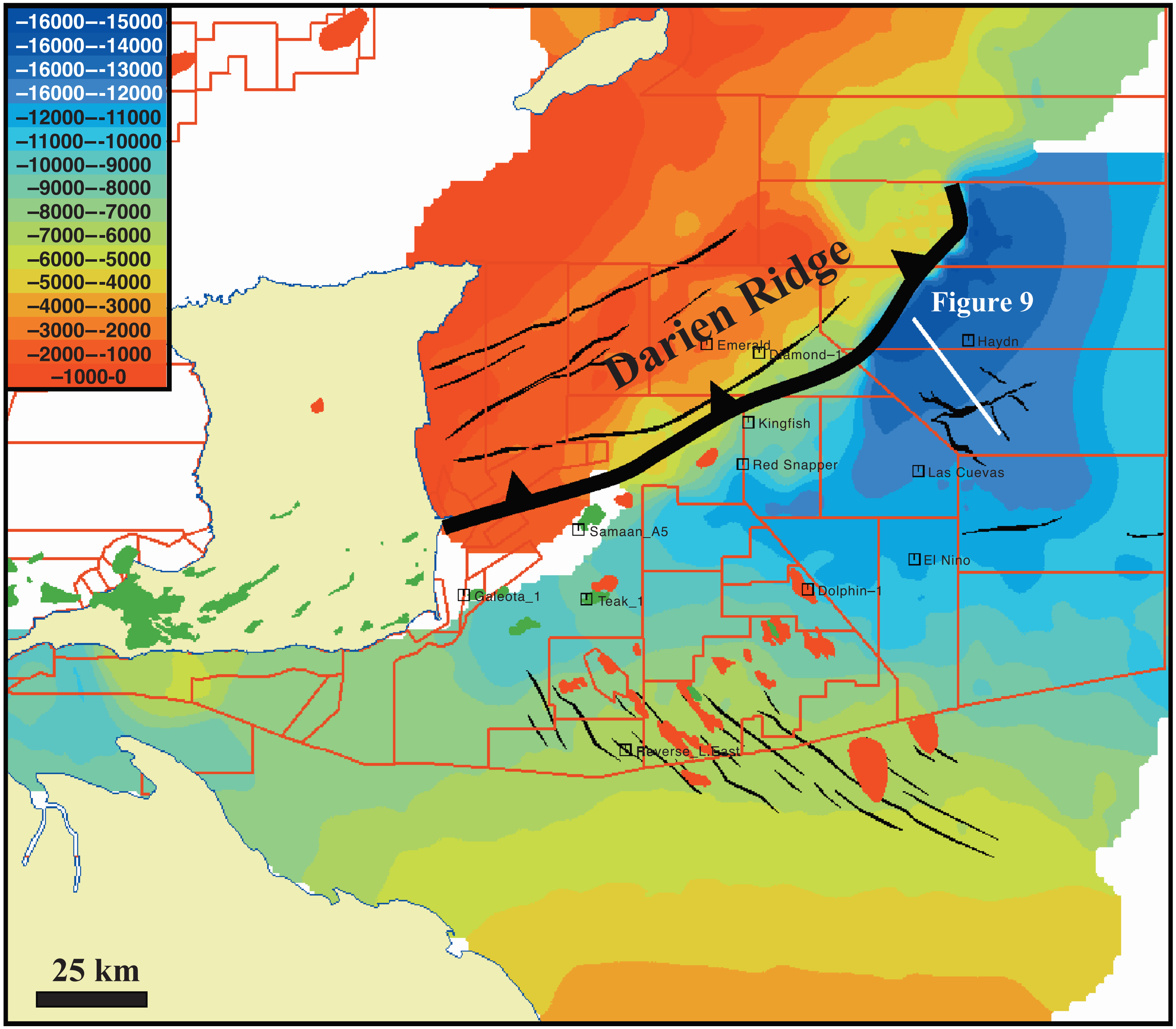

Figure 8. Depth-structure map on near-top Cretaceous surface; map is extrapolated at eastern end based on total sediment-fill map. Note structural relief across Darien ridge. Oil fields are in green, gas fields are in red.

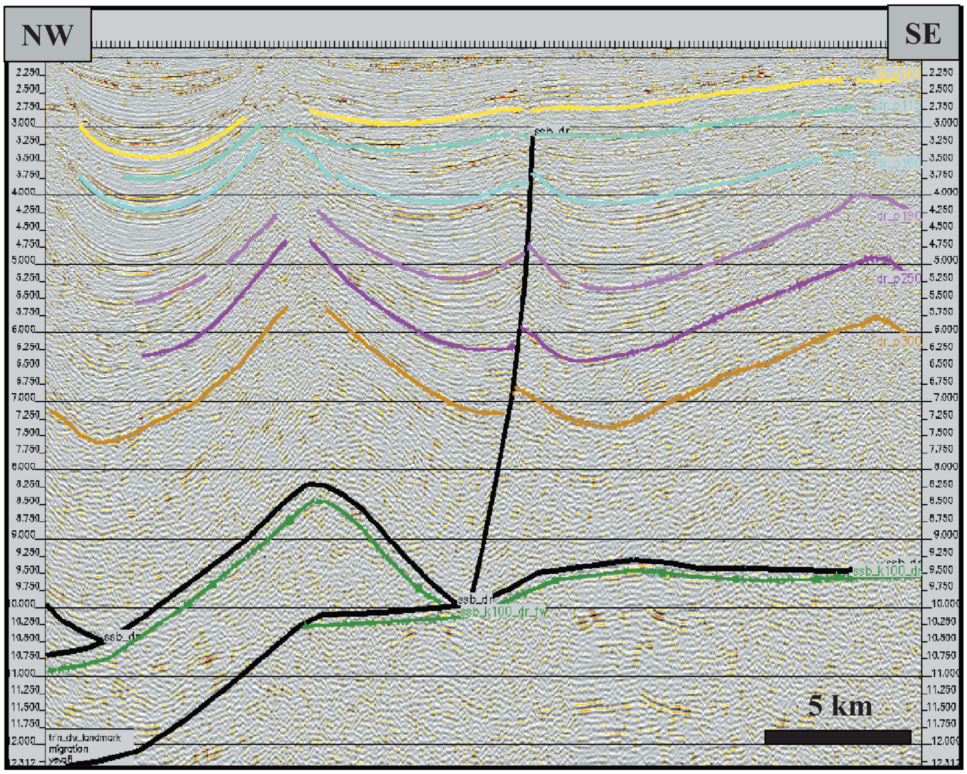

Figure 9. Seismic line showing interpretation of fault-related fold beneath the Galeota ridge in upper continental slope region, block 25B. See Figure 7 for line location.

area of offshore eastern Trinidad. Regional seismic interpretations show that structural amplitude and magnitude of shortening increase toward the northwest, in areas more proximal to the plate boundary. Furthermore, significant structural relief (>10 km) is interpreted for the top Cretaceous seismic horizon as it continues from the Darien ridge to the Columbus basin (Figures 3 and 8). As a result, our structural models include a zone of significant thrust duplication and crustal thickening in the area immediately to the northwest of the deep-water exploration area (Figure 3). This zone of structural duplication is important with respect to thermal models because it alone constitutes a significant load on the lithosphere.

Rapid Neogene Sedimentation

Since the late Miocene, the Orinoco River system has been focusing large volumes of sediment from the Venezuelan mainland across the continental shelf and into the deep water Columbus basin (Figures 1 and 2). As much as 12 km of Pliocene-Pleistocene sediment has accumulated in the deep-water area, which constitutes another load on the lithosphere. The relatively recent and rapid deposition of this sedimentary pile depresses the geotherm still further from a steady-state condition.

COMPARISON TO EASTERN VENEZUELA AND BARBADOS

When scaled approximately to the same dimensions, the eastern Venezuela, offshore eastern Trinidad, and Barbados (Ocean Drilling Program) cross sections illustrate the changes in magnitude and style of strain across the region (Figure 10). These changes in tectonic setting contribute to important hydrocarbon systems variations across the region.

In eastern Venezuela, a south-verging fold and thrust belt is built on continental crust. The thrust belt accommodates as much as 100 km of shortening and is buried by 5–7 km of postdeformation sedimentary fill (Goodman et al., 1998; Babb and Mann, 1999). Oil fields are predominantly located on basin flanks (Erlich and Barrett, 1992), with the notable exception of the El Furrial trend. Prolific oil-prone Cretaceous source rocks form the main hydrocarbon system. Subsidiary Tertiary hydrocarbon source rocks are interpreted to be present in the Oficina trend, located between the El Furrial trend and Orinoco heavy oil belt (Goodman et al., 1998) and in the Carapita Formation north of the El Furrial trend (Tocco et al., 1993).

In deep-water offshore eastern Trinidad, a southeast-verging fold belt is built on transitional crust. The folds accommodate small strains, and most deformation occurs in the plate boundary zone. A basal detachment fault separates potential Cretaceous and Tertiary hydrocarbon systems. Producing fields on the shelf are located on the flank of the basin, where an extensional growth-fault province provides potential pathways for hydrocarbons migrating up from the detachment level (Heppard et al., 1998; Wood, 2000). Exploration targets in the deep-water exploration area are located in the center of the basin. Older growth faults and strike-slip faults

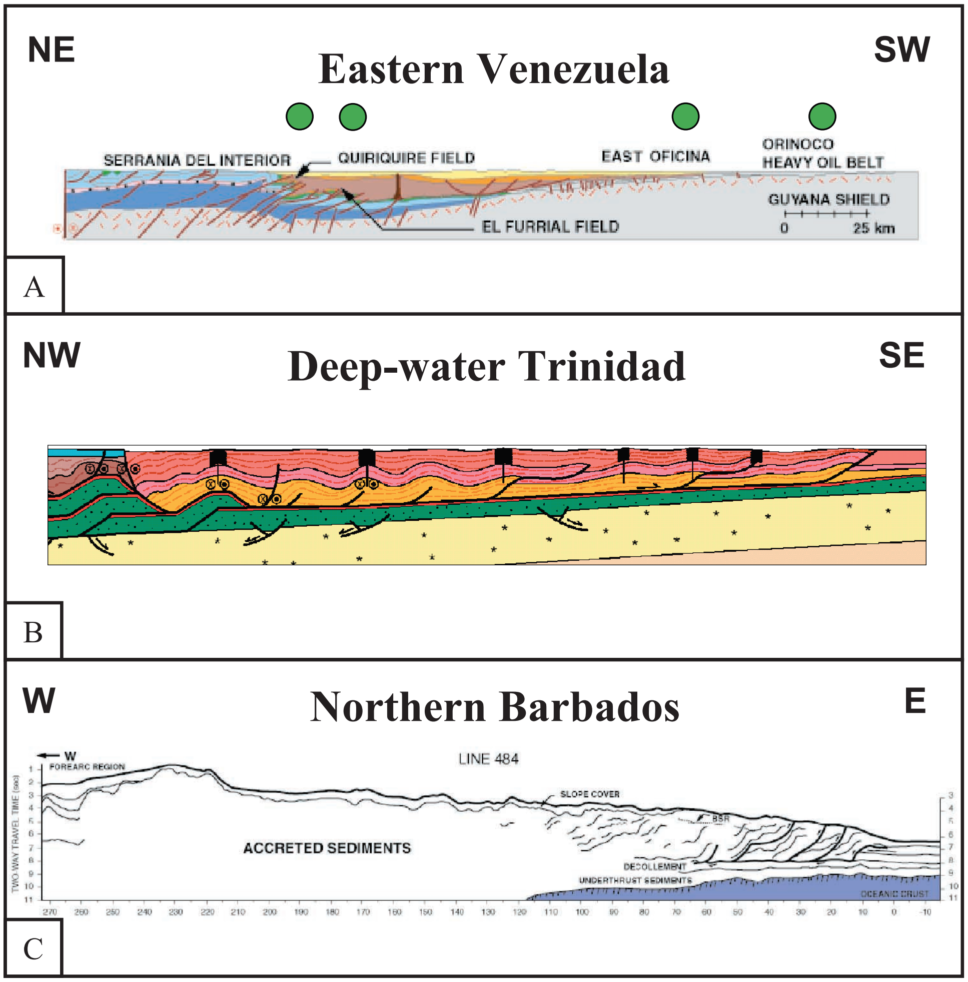

Figure 10. **Cross sections showing regional variability across the southeastern Caribbean region. (A) eastern Venezuela, see Figure 1 for line location; (B) continental slope, offshore eastern Trinidad, central part of Figure 5; (C) northern Barbados, vertical scale in time, ODP Leg 110, Line 484, see Figure 1 for location.**

cut down to detachment level in some targets, but migration pathways linking effective source rocks to reservoir intervals are far less common than on the continental shelf. Northeast-trending buckle folds that we interpret to be an offshore extension of the southern Trinidad fold and thrust belt are an important trap-forming element.

East of Barbados, a well-developed accretionary prism is built on oceanic crust (Mascle et al., 1986; Moore et al., 1988; Moore et al., 1998). The sedimentary section is phighly disrupted by closely spaced faults and/or dewatering conduits. The hydrodynamic system is vigorous, with pronounced lateral migration of fluids along parts of the basal detachment (Kastner et al., 1991). Active deformation of the sea floor is manifest by rough bathymetry, especially near the toe of the prism. Potential source rocks are generally lean; biogenic and thermogenic gases are associated with mud volcanoes.

SUMMARY OF TECTONIC EVOLUTION

Below, we summarize key elements in the late Tertiary evolution of offshore eastern Trinidad. Evolution of the deep-water exploration area begins with Jurassic and Lower Cretaceous rifting, leading to the development of transitional continent/ocean crust. A passive-margin phase follows rifting and contains the only proven source rocks in Trinidad— marine clastic/carbonate Upper Cretaceous Gautier and Naparima Hill Formations (Persad et al., 1993).

As Caribbean Plate deformation impinged on northeastern South America in the middle Miocene, a foredeep basin formed, resulting in shelfal transgression and deposition of deep-marine shales (Carapita and Freites Formations) in the Maturin and proximal Columbus basins (Di Croce, 1995). The foredeep flexure ponds deposition into these basins, even clastics associated with a major eustatic fall in the upper-middle Miocene (10.5 Ma, Haq et al., 1987; 11.2 Ma, de-Graciansky et al., 1998). The impact on deposition in the deep-water exploration area is continued condensed-section deposition, facilitating the development of a regional detachment surface at this horizon.

Shortening along the Darien ridge and the southern Trinidad fold and thrust belt propagated from onshore Trinidad to the deep-water exploration area between 6–4 Ma (Babb and Mann, 1999). Initial deformation of late Miocene to early Pliocene sediment resulted in folds and thrust faults. Small (~10 km across?) depocenters formed during shortening and subsequent normal faulting. The initial structures were quickly buried by the Orinoco delta and shielded from further major deformation as shortening became concentrated along the Darien and Galeota ridges.

Between 4–2 Ma, the growth fault province (Figure 5) migrates past the present day shelf-slope break onto western edge of the deep-water exploration area. Large growth basins, several tens of kilometers across, developed in the hanging-wall blocks of listric normal faults. Significant sand-prone reservoir facies are interpreted to first encroach on the deep-water area during this time. Strike-slip faults and associated small pull-aparts cut the older growth basin but predate an episode of folding, inversion, and enhancement of structural closure between 3–1 Ma. At present, shortening and strike-slip faulting are concentrated along the Darien and Galeota ridges, and the deep-water area is undergoing continued rapid burial near the center of the modern day foredeep basin.

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