Chronostratigraphy and tectonostratigraphy of the Columbus Basin, eastern offshore Trinidad

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ABSTRACT

The Columbus Basin, forming the easternmost part of the Eastern Venezuela Basin, is situated along the obliquely converging margins of the Caribbean and South American plates. The two primary structural elements that characterize the basin are (1) transpressional northeast-southwest–trending anticlines and (2) northwest-southeast–oriented, down-to-the-northeast, extension normal faults. The basin was filled throughout the Pliocene and Pleistocene by more than 40,000 ft (>12,200 m) of clastic sediment supplied primarily by the Paleo–Orinoco Delta system. The delta prograded eastward over a storm-influenced and current-influenced shelf during the Pliocene–Pleistocene, depositing marine and terrestrial clastic megasequences as a series of prograding wedges atop a lower Pliocene to pre-Pliocene mobile shale facies.

Biostratigraphic and well log data from 41 wells were integrated with thousands of kilometers of interpreted two-dimensional and three-dimensional seismic data to construct a chronostratigraphic framework for the basin. As a result, several observations were made regarding the basin's geology that have a bearing on exploration risk and success: (1) megasequences wedge bidirectionally; (2) consideration of hydrocarbon-system risk across any area requires looking at these sequences as complete paleofeatures; (3) reservoir location is influenced by structural elements in the basin; (4) the lower limit of a good-quality reservoir in any megasequence deepens the closer it comes to the normal fault bounding the wedge in a proximal location; (5) reservoir quality of deep-marine strata is strongly influenced by both the type of shelf system developed (bypass or aggradational) and the location of both subaerial and submarine highs; and (6) submarine surfaces of erosion partition the megasequences and influence hydrostatic pressure, migration, and trapping of hydrocarbons and the distribution of hydrocarbon type.

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ACKNOWLEDGEMENTS

The regional chronostratigraphic framework and tectonostratigraphic model for development of the Columbus Basin is a product of 3 years' regional work by many, many individuals. I would like especially to thank Peter Bentham, David Pocknall, Maria Henry, and Ken Ortmann for direct input into ideas, correlations, and implications. I would also like to thank Amoco Energy Company of Trinidad and Tobago for permission to publish the results of this work and the company geoscientists for many stimulating conversations regarding the geology of the Eastern Venezuela Basin. Much appreciation to M. Wade, F. Krause, and an anonymous reviewer, too, for reviews of this manuscript, as well as to Martin Jackson for conversations regarding the diapirs of the Columbus Basin. Finally, thanks to the graphics and editing staff at the Bureau of Economic Geology, University of Texas at Austin, for assistance in completing final figures and manuscript.

Manuscript received September 2, 1997; revised manuscript received March 23, 1999; final acceptance May 15, 2000.

INTRODUCTION

The Columbus Basin, defined by Leonard (1983), forms the easternmost part of the Eastern Venezuela Basin (EVB) off the east coast of Trinidad (Figure 1). The basin is bordered on the north by the Darien Ridge, an offshore extension of Trinidad's Central Range, and on the south by the stable Delta Amacuro Platform (Figure 2). To the east of the basin is the South American continental shelf, and to the west, onshore Trinidad and the EVB. Downwarping of the west margin of the EVB began during the Oligocene in association with subduction of the Caribbean plate from the north (Parnaud et al., 1995). A diachronous series of en echelon east-northeast–oriented depocenters developed across the northern South America region in response to this downwarping as the foredeep migrated eastward. The depocenters were successively filled by more than 40,000 ft (>12,000 m) of sediment, the Columbus Basin being the easternmost depocenter (Figure 1). The Orinoco River has been the primary source of sediment filling these depocenters; since the mid-Miocene, its course has been heavily influenced by the progressive downwarping of the eastward-migrating foreland basin (Hedberg, 1950; Hoorn et al., 1995; Diaz de Gamero, 1996). Local tectonic features, such as the Urica arch (Figure 1), were intermittently active during the Miocene to Holocene, significantly affecting the character of the proto–Orinoco River feeding the Columbus Basin (Erlich and Barrett, 1994). In addition, phases of thrusting and thrust-load subsidence along the east margin of the northern Andes Cordillera influenced the discharge rate and sediment load of the river throughout the late Tertiary (Hoorn et al., 1995).

The EVB is a prolific hydrocarbon province, having produced more than 7 billion bbl of oil in the Venezuelan part of the basin (Erlich and Barrett, 1994) (Figure 1). Production has come mainly from Oligocene to Miocene fluvial-deltaic and shallow-marine deposits (Figure 3). Onshore and offshore hydrocarbon exploration in Trinidad has been active since the 1860s, and the first commercial production was established in 1902 (Tiratsoo, 1986). Eastern offshore exploration for hydrocarbons in the Columbus Basin began in the late 1960s, resulting in the discovery

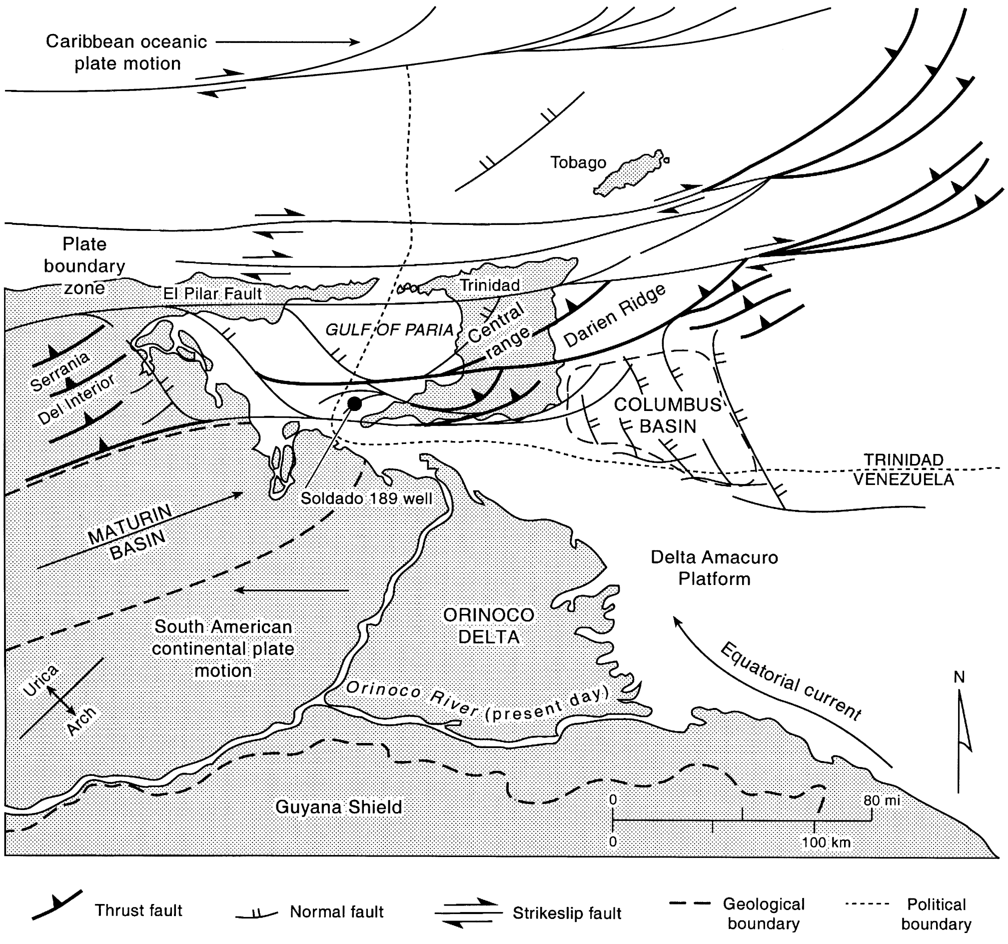

Figure 1. Tectonic map (after Pocknall et al., 1999) showing regional structural features of northern South America, including the island of Trinidad, as well as the modern outlet of the Orinoco River and location of the present-day delta relative to the Columbus Basin. Soldado 189 well is indicated in the Gulf of Paria.

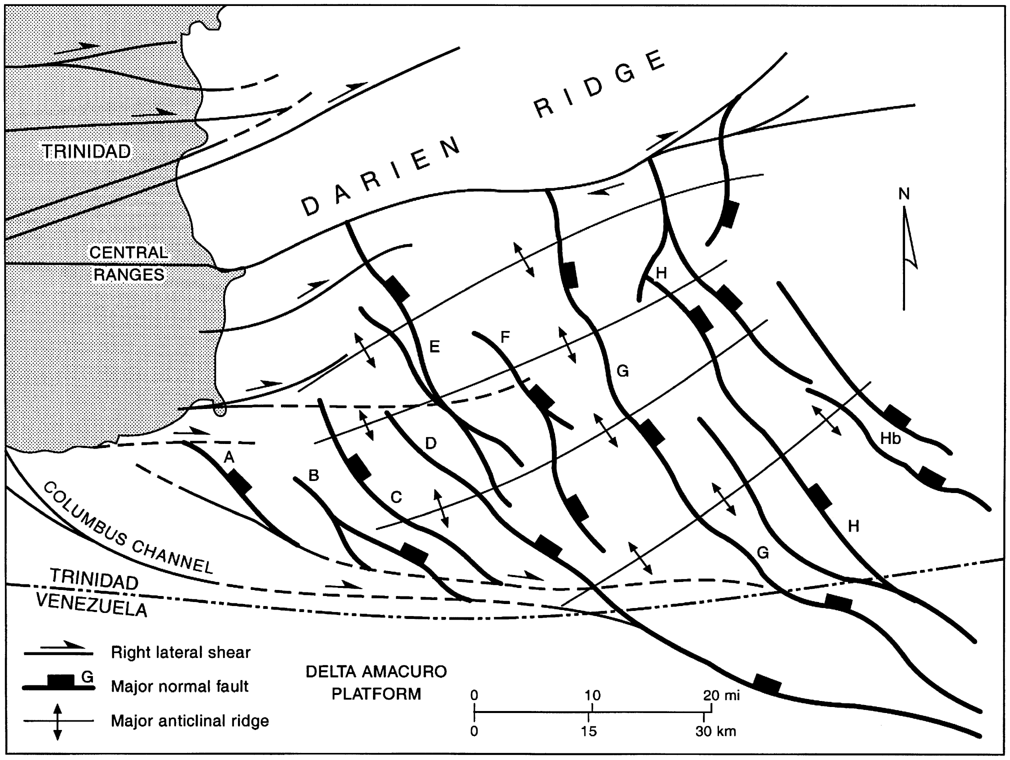

Figure 2. Major structural features of the Columbus Basin, offshore eastern Trinidad, including regional normal faults, right lateral strike-slip faults, and offshore structural ridge trends.

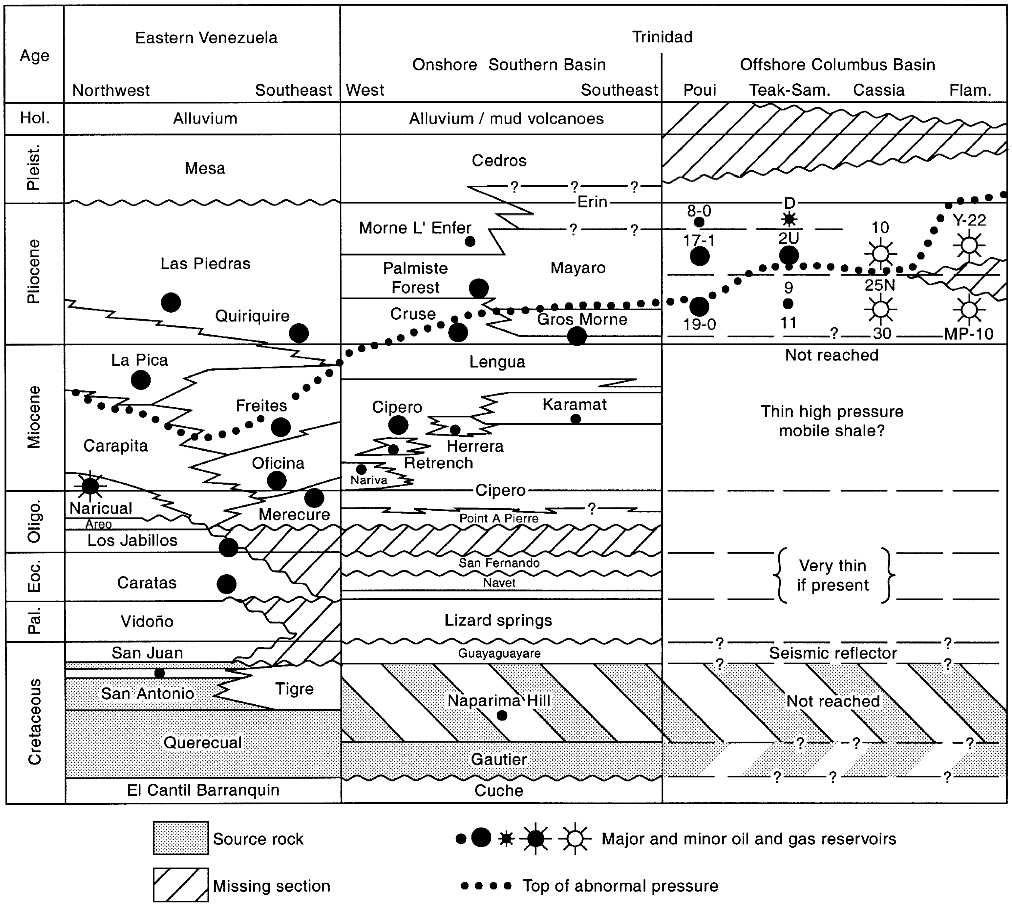

Figure 3. Simplified stratigraphic chart of the Eastern Venezuela Basin (after Heppard et al., 1998). Major source rock intervals have been identified as the Upper Cretaceous San Antonio and Querecual formations in eastern Venezuela and the Naparima Hill and Gautier formations in Trinidad. Units that have been important reservoirs are also indicated. The dotted line indicates the diachronous nature of top overpressure as it climbs stratigraphically to the east.

of Teak field (SDT2) (Figure 4). Subsequent activity has resulted in more than 2.6 billion bbl of oil having been produced in these areas from fluvial-deltaic, shallow-marine, and deep-marine turbidite deposits of the Miocene–Pliocene (Rodrigues, 1998). Further estimates indicate more than 3.27 billion bbl of oil in place and 20 tcf of gas in place.

PROBLEM

The complex interplay of regional tectonics, extension normal faulting, high rates of sediment supply, and sea level change has created a complicated stratigraphy in the Columbus Basin, one that resists many standard methods of sequence stratigraphic analysis. Classic sequence analysis techniques and models that were developed in passive-margin settings (Vail et al., 1977; Posamentier and Vail, 1988) typically operate on the assumption that sea level has been the dominant mechanism driving stratigraphic sequence development. Application of sequence stratigraphic models from foreland-basin (Swift et al., 1987; Devlin et al., 1993; Posamentier and Allen, 1993) or passive-margin settings (Mitchum et al., 1991) oversimplifies the complexity of transpressional settings. Transpressional basins, such as the Columbus Basin, contain elements of thrust belt–foreland models, the growth-normal faulting and mobile substrate movement common to passive-margin settings, and extension structuring common along strike-slip plate margins (Babb and Mann, 1999). Structural complexity, syndepositionally active structures, high rates of sedimentation, and high-frequency sea level change all influenced the Pliocene–Pleistocene sequence stratigraphy of the Columbus Basin. The dearth of understanding of the relative magnitude of influence these elements have on stratigraphic sequence geometry, character, and distribution has led to mixed exploration and production results. Understanding of the true age and nature of the basin's stratigraphic section will decrease uncertainty in reservoir and seal prediction, hydrocarbon-generation modeling, migration analysis, and pressure prediction, as well as many other variables involved in an integrated exploration solution. As petroleum exploration in the basin matures, there is a need for more detailed understanding of the reservoir, seal geometry and distribution, and the timing of all elements that make up the hydrocarbon system. The syndepositional nature of structure in the basin has created opportunities for the occurrence of stratigraphic and combination stratigraphic/structure plays. However, these play types cannot be pursued with any degree of confidence at the current level of un-

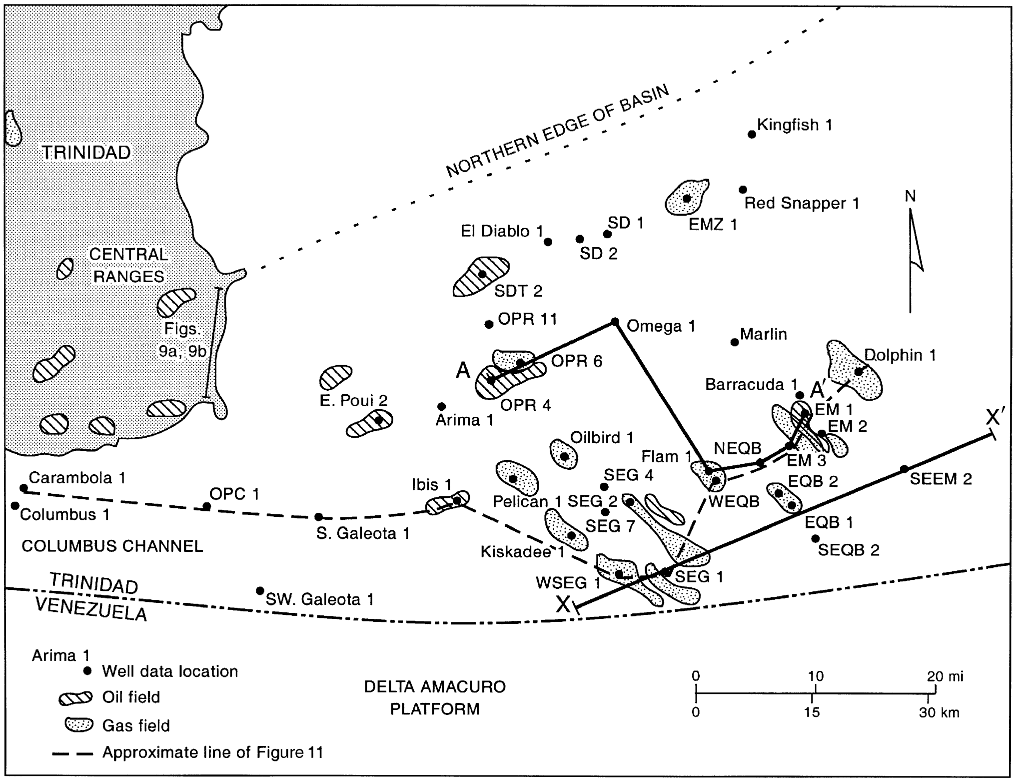

Figure 4. Columbus Basin and the island of Trinidad showing wells used in this study and location of major oil and gas fields. Cross section AA′ and seismic line XX′ are shown in Figures 7 and 5, respectively. Outcrop photographs are shown in Figures 9a and 9b.

derstanding stratigraphic sequence development in the Columbus Basin.

The goals of this article are to

1. Detail a chronostratigraphic framework of the Columbus Basin;
2. Outline a tectonostratigraphic model for sequence development in the Pliocene and Pleistocene of the Columbus Basin, one that may serve to describe sequence stratigraphic development in other transpressional settings;
3. Compare and contrast the Columbus Basin with similar settings, such as the Niger Delta; and
4. Discuss implications of the results of this work on exploration in the Columbus Basin and other transpressional settings.

METHODOLOGY AND DATA

A multidisciplinary data set, including well logs, palynology, benthic and planktonic foraminifera, oxygen isotopes, lithologic samples, core and outcrop descriptions, and seismic-line interpretations, was used to develop a chronostratigraphic and sequence stratigraphic framework for the Pliocene–Pleistocene deposits of the Columbus Basin. Data from 41 wells included paleontology assemblages and abundance and occurrence data, as well as gamma-ray, resistivity, and caliper logs. These data formed the ground truth for correlation of additional logs in the basin and were integrated with thousands of kilometers of interpreted two-dimensional (2-D) and three-dimensional (3-D) seismic lines to construct regional chronostratigraphic cross sections and to generate a chronostratigraphic framework for the Pliocene–Pleistocene of the basin.

The methodology employed in this study included the following:

1. Reconciliation of multiple data types into an integrated depositional sequence analysis for each well in the study area. This required recognition of surfaces of reworking, flooding, and condensed sedimentation, as noted from well log motif and seismic data. In addition, casing points, sampling intervals, and drilling data were used to resolve in-situ from non-in-situ paleostratigraphic data and to refine environments of deposition. Key data for detailed interpretation of environments of deposition included benthic foraminifera and palynomorph assemblages, well log motifs, observable seismic facies, and location of specific wells within the context of the regional paleogeography.
2. Use of palynomorph and planktonic foraminifera first uphole occurrence, extinction, and acme events in each well to age-date stratigraphic horizons.
3. Use of seismic data to correlate specific time markers between wells within each fault block and to identify significant event surfaces within each fault block (bypass surfaces and basinward equivalent conformities, transgressive surfaces, condensed sections, flooding events, etc.).
4. Definition of parasequences within each fault block, using identified key event surfaces and parasequence bounding surfaces.
5. Reconciliation of the chronostratigraphic framework of each fault block with adjacent fault blocks by using seismic and well-data loops to ensure cross-fault correlation of time-equivalent depositional sequences and to construct regional chronostratigraphic cross sections.
6. Correlation of chronostratigraphic packages between fault blocks, definition of basinwide depositional sequences, and construction of chronostratigraphic diagrams.
7. Integration of chronostratigraphy and paleogeography with seismic data to develop a tectonostratigraphic model and to constrain the time of movement of major structures in the basin.

GENERAL GEOLOGY OF THE COLUMBUS BASIN

Structure

The Columbus Basin is located along the south margin of the obliquely converging Caribbean–South American plate boundary, a zone of intense structural deformation (Figure 1) (Speed, 1985; Robertson and Burke, 1989). Primary structural elements in the basin include (1) a series of transpressional northeast-southwest–trending ridges and (2) northwest-southeast–oriented, down-to-the-northeast, normal faults (Figures 2, 5). Most reservoirs have been discovered where compressional deep ridges are juxtaposed against major normal growth faults to produce structural closure. Fold axial traces and normal fault orientation, both less than 45° to the plate boundary zone, indicate a transpressional rather than a transcurrent or transtensional setting for the Columbus Basin. Gravity tectonics along a thin-

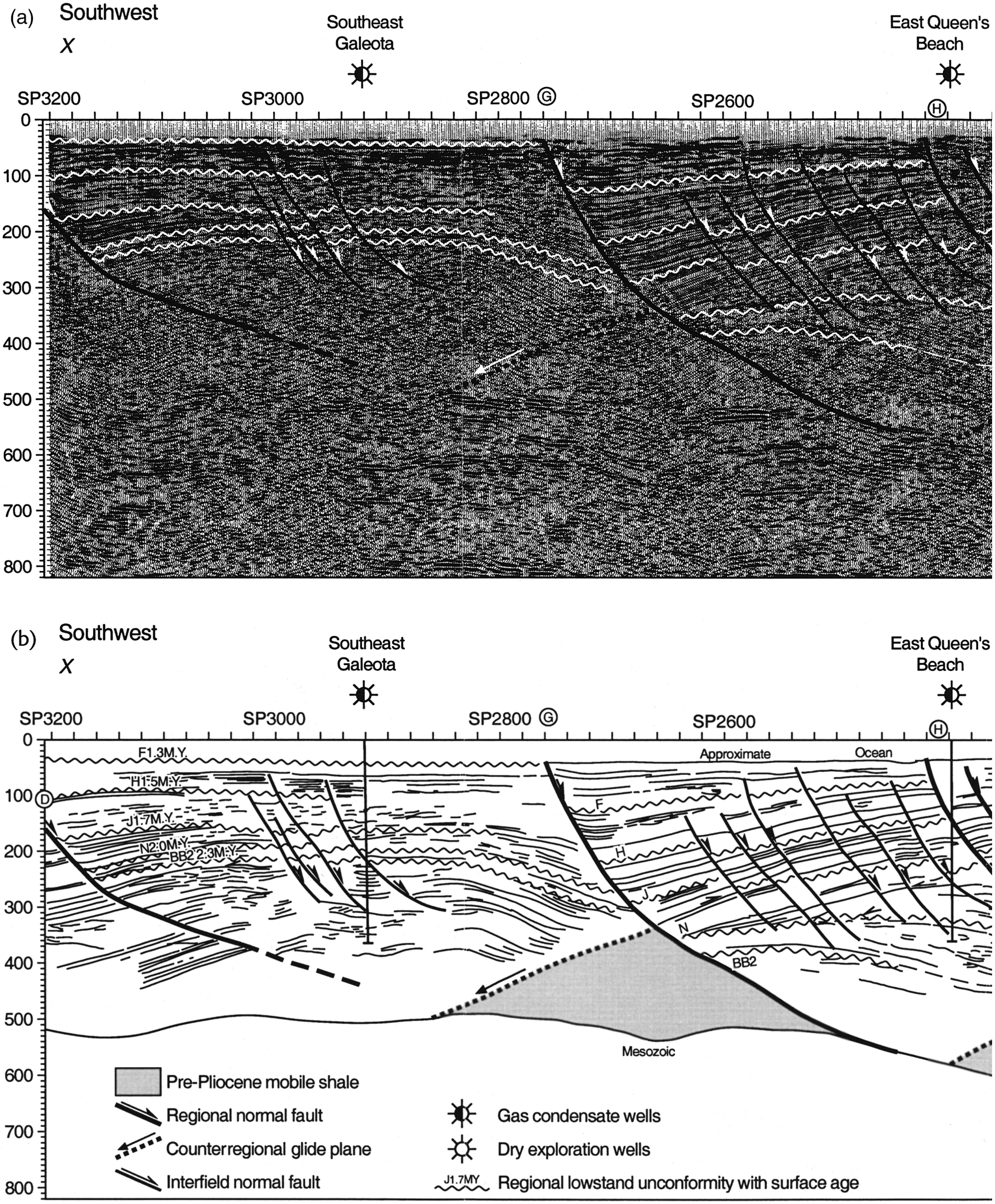

Figure 5. (a) Southwest-northeast–trending seismic line XX′ (see Figure 4 for location) and (b) accompanying line drawing illustrating the two-dimensional geometry of normal fault and counterregional glide surface and their relationship to one another. Regionally extensive lowstand surfaces (unconformities) and their basinward-equivalent correlative conformities that bound megasequences are shown. Note the thickening of sediments down into the counterregional surface and the upturned toe reflectors associated with sediment drag as shale evacuates from beneath the sediment wedge (SP1800–1600 between 3.0 and 5.0 s). (*Continued*)

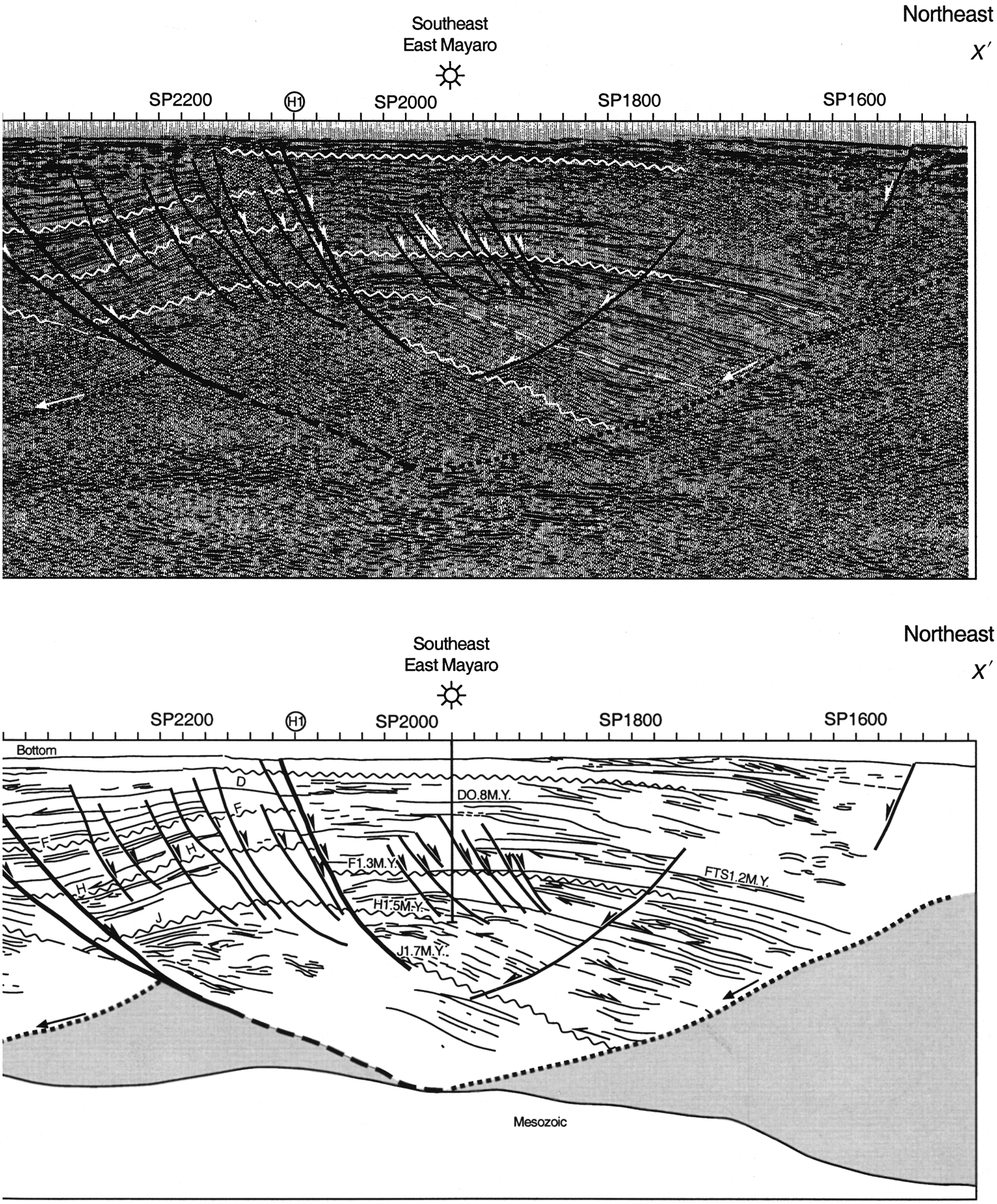

Figure 5 continued. Sediment wedges thin landward (southwest) and show truncation of their upper parts by means of the lowstand surface of the overlying sequence. Significant thickening of sediments occurs across major normal faults (SP2100, SP2740). Although similar seismic facies are identifiable in different fault blocks at approximately the same seismic depth, they are of different ages, as shown by biostratigraphic data (see Figure 10).

skinned detachment surface dipping to the east-northeast, however, may have also influenced the orientation of these structural features, as well as masked the appearance of other structures associated with these regimes, such as positive or negative flower structure. The interpretation of a transpressional structural regime for this area was well documented by Babb and Mann (1999), and the reader is referred to this article for many data documenting the structural framework of the Caribbean–South American margin in this area. Because a more detailed discussion is beyond the scope of this article, the reader is additionally referred to Perez and Aggarwal (1981), Robertson and Burke (1989), Erlich and Barrett (1990), Ave Lallemant (1991), and Russo and Speed (1992).

Stratigraphy

The sedimentary column of the eastern Columbus Basin consists mainly of thick Pleistocene and Pliocene strata overlying mobile, pre-Pliocene shales. Cretaceous marine facies deposited along a generally west-trending to east-trending paleo-Cretaceous shelf break dip deep northward into the subsurface and underlie the Tertiary sediments (Persad et al., 1993; Pindell and Erikson, 1993; Heppard et al., 1998) (Figure 5). Although they remain undrilled in the Columbus Basin, the mobile units of pre-Pliocene age are thought to consist dominantly of Miocene shales and perhaps a thin veneer of Paleocene, Eocene, and Oligocene deposits. This interpretation is supported by penetrations of pre-Pliocene units to the north (Robertson and Burke, 1989) and south (Di Croce et al., 1999) of the basin, as well as onshore Trinidad (Persad et al., 1993).

Reservoirs off the east coast of Trinidad are all Pliocene–Pleistocene in age, either trapped in four-way structural closures or trapped as downthrown or upthrown faulted three-way closures. The strata are marine and terrigenous clastic sediments deposited as a series of northeastward-prograding strand-plain/nearshore sediment wedges and downdip slope/basin fan wedges (Wood et al., 1994; Wood, 1995, 1996; Heppard et al., 1998; Di Croce et al., 1999). These extremely thick, prograding megasequences were rapidly deposited; accumulation rates during the Pliocene–Pleistocene ranged from 7 to 20 ft (2 to 6 m) per thousand years. These high accumulation rates resulted from high sediment supply from the proto-Orinoco and rapid generation of accommodation space by extension tectonics.

Character of the Upper Tertiary Orinoco Delta

The modern Orinoco Delta is a complex hybrid deltaic system composed of distinctly defined zones of wave-dominated, tide-dominated, and river-dominated morphology (Warne et al., 1999a, b). The lower Tertiary Orinoco Delta differed in character, however, from its modern successor. The Orinoco Delta of the later Tertiary was a wave-dominated delta system prograding onto a storm-influenced and current-influenced shelf (Figures 6, 7). The delta occupied successively more eastward positions on the shelf throughout the late Tertiary, and upon reaching each successive shelf-edge break, the deltaic system became more aggradational in response to increased accommodation space. The shelf-to-slope break was oversteepened as a result of bed rotation along the counterregional glide surface formed on the landward side of rising shale diapirs. Such rotation is reflected in seismic data by the downdip thickening of sediments into the remnant shale bulge, as well as the drag exhibited at the toe of the progradational wedges (Figure 5). Most of the basin's accommodation was focused in northwest-southeast–oriented depocenters very near the shelf-slope break. Low accommodation on the shelf resulted in the paleo–Orinoco Delta repeatedly prograding to the edge of the shelf. This lowstand delta was exposed to the reworking processes of the open ocean, having little or no outboard shelf to attenuate wave activity. The cuspate, strike-continuous (northwest-to-southeast), cleanly winnowed reservoir sands of the Columbus Basin are a product of this setting. Modern analogs to this style of deltaic sedimentation are the Sao Francisco Delta, offshore Brazil (Dominguez, 1996), and the Nayarit Coast, offshore Mexico. Ancient examples include the lower Wilcox Formation of the Tertiary Gulf of Mexico (Galloway et al., 1982).

Few if any incised valleys that must have fed the lowstand Orinoco Delta can be identified on 2-D or 3-D seismic lines. Paleoenvironmental data from fauna and flora, however, indicate that brackish to terrestrial conditions did exist across the basin during periods of lowstand delta deposition to the east. Local tectonic activity at the depositional shelf break focused lowstand accommodation space in shelf-break locations. High rates of sediment supply filled all available proximal accommodation space, creating a broad, low, sloping-gradient coastal plain. As a consequence, the Orinoco Delta distributary system was most likely characterized by dispersed, low-velocity

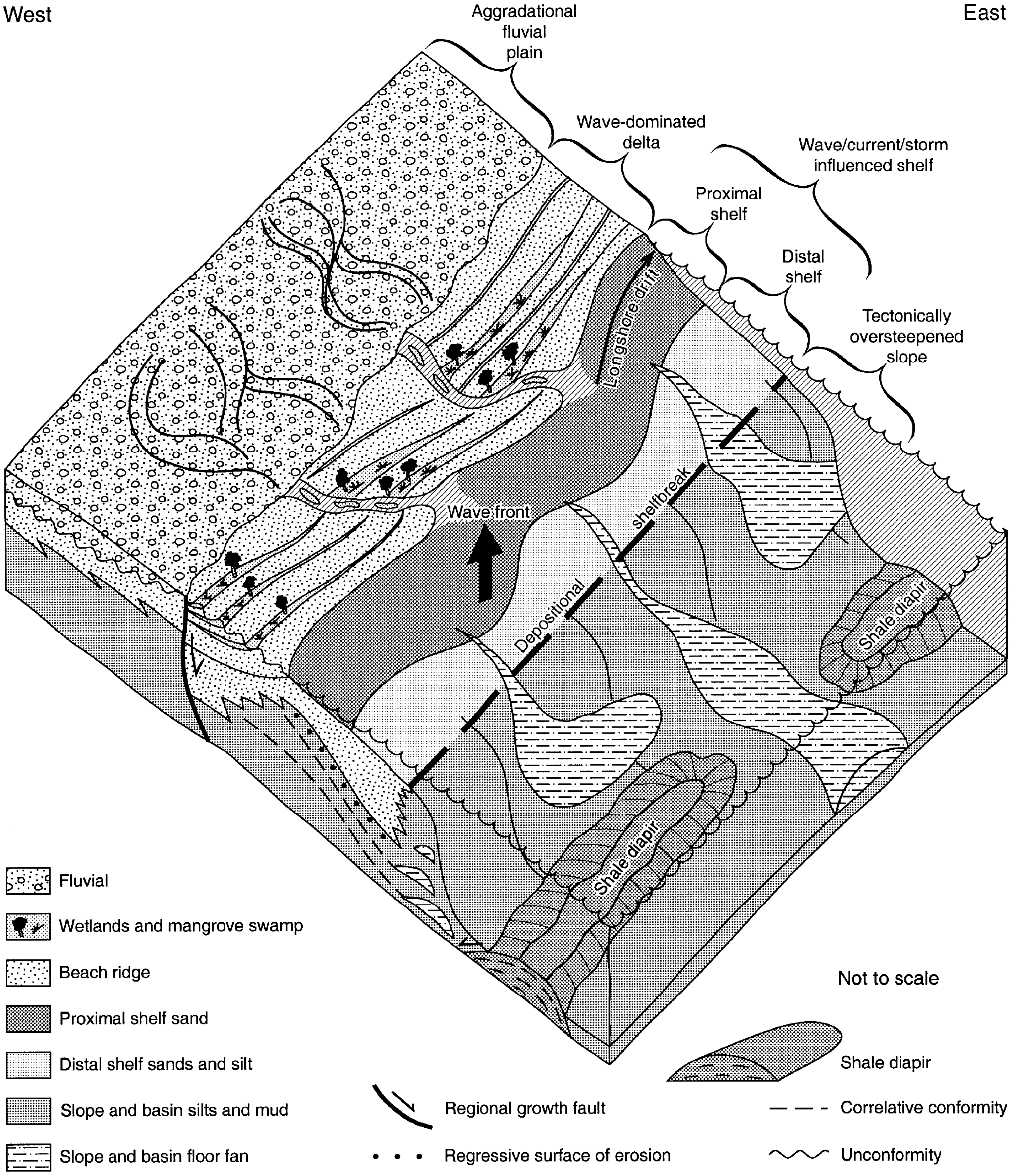

Figure 6. Paleogeography of the lowstand paleo–Orinoco Delta in the Pliocene and Pleistocene. Low-sloping broad fluvial distributary plain feeds line-source, wave-modified strand-plain shoreline systems. These systems in turn feed line-sourced slope and fan deposits. Rising shale diapirs at the toe of the slope helped focus slope and basin floor deposition and ponded thick sediments on the basin floor in toe-of-slope sediment sinks.

flows and low stream powers that were forced to transport large volumes of sediment to shelf-edge-break depocenters. Low slopes along the continental margin mean little change in base level as sea level fell, resulting in the wide, shallow, distributary-channel incision in the coastal plain. Truncation of older shelf deposits by feeder valleys is shallow, commonly below the seismic resolution. In some locations, such as the East Queen's Beach (EQB) area (Figure 4), late-stage pop-up structures may have confined distributaries to specific pathways, resulting in point-source deltas, but for the most part late Tertiary Orinoco deltas were line-source distributary systems producing line-source slope deposits. Slope and basinal gravity deposits were, however, subject to direction by submarine topography building out in front of the shelf break.

Hydrocarbon System

Upper Cretaceous organic-rich mudstones acted as source rock for many of the hydrocarbons in Trinidad (Rodrigues, 1988; Talukdar et al., 1988; Heppard et al., 1990). Thicknesses of as much as 3280 ft (1000 m) of the Cretaceous source interval have been penetrated in the Soldado 189 well, Gulf of Paria (Figure 1). Cretaceous organic matter exhibits both terrigenous and

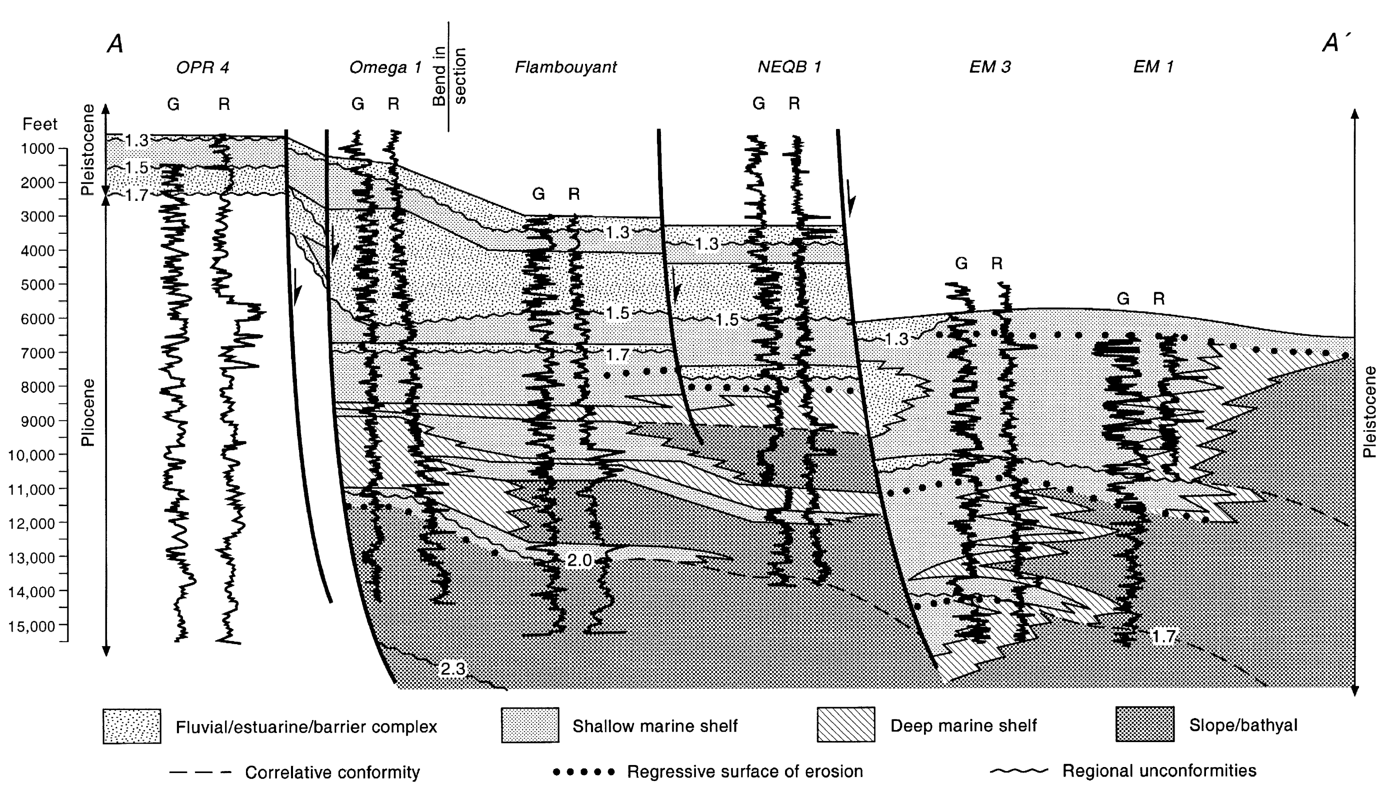

Figure 7. Southwest-northeast well log cross section AA′ from Poui field to East Mayaro field across the Columbus Basin, illustrating the typical gamma-log (left) and resistivity-log (right) signatures associated with depositional facies that make up the prograding megasequences. Note the abrupt stratigraphic thickening across the major normal growth faults in the depositional dip direction (OPR4-Omega and Flambouyant-NEQB-EM3-EM1), as well as the continuity of facies in the depositional strike direction (Omega-Flambouyant). Logs and base Pleistocene pick in OPR4 and Flambouyant are from Heppard et al. (1998). Environments of deposition are based on interpretation of integrated biostratigraphic data, well log motifs, seismic facies, and regional paleogeography. Line of section shown in Figure 4.

marine organic affinities; total organic carbon (TOC) values range from 2 to 12% (Persad et al., 1993).

Previous workers have suggested two primary mechanisms for hydrocarbon migration within the Columbus Basin. Strong evidence suggests that the large, down-to-the-basin, normal faults serve as primary migration pathways for hydrocarbons (Figure 5). Such migration routes have been documented in the Columbus Basin, in the upper 2300 ft (700 m) of strata (Wood and Nash, 1995), and similar mechanisms are thought to be active at depth (Leonard, 1983; Heppard et al., 1990, 1998). Faults in Miocene strata in southern Trinidad appear to have acted as primary migration conduits into Miocene and Pliocene reservoirs (Persad et al., 1993). All offshore Trinidad fields are associated directly or indirectly with deep faults, some of which are thought to extend into underlying Cretaceous source rocks (Leonard, 1983). The occurrence of numerous hydrocarbon seeps on the island supports the notion that hydrocarbons are migrating directly along faults. Other workers have suggested that most faulting in the fields postdates generation and migration of hydrocarbons (Heppard et al., 1998). They have proposed an alternative mechanism, namely, that hydraulically induced fractures within a highly overpressured section are the conduit for migrating hydrocarbons (Miller, 1995; Heppard et al., 1998). A third possible migration pathway is via carrier beds, which downlap onto or structurally abut onto the underlying source rocks across glide planes (Figure 5) (Heppard et al., 1998). In this scenario, updip migration is also aided by significant overpressuring of fluids in the section. Most hydrocarbons in the Columbus Basin probably migrate through some combination of these three mechanisms. The result is a stair-step pattern of migration, whose tortuous nature helps explain the fractionated and variable character of the hydrocarbons in Columbus Basin reservoirs (Ross and Ames, 1988; Talukdar et al., 1990; Persad et al., 1993).

Faunal and Floral Biostratigraphy and Environments of Deposition

Regional and local factors render more difficult the task of applying conventional biostratigraphy to define the Pliocene–Pleistocene chronostratigraphic framework in the Columbus Basin. The Orinoco and proto-Orinoco rivers have drained the Andean highlands since the early Miocene, but only since the late Miocene has the Orinoco had an established outlet through the Columbus Basin (Hoorn, 1995; Hoorn et al., 1995; Diaz de Gamero, 1996) (Figure 1). The river and its associated marginal and deep-marine depositional systems have supplied more than 45,000 ft (14 km) of post-Miocene sediment into the basin (Erlich and Barrett, 1990). This rapid rate of sedimentation has reduced the number of nannofossils and planktonic foraminifera species that are used in other basins for chronostratigraphic correlation. In addition, the overthick section creates time-resolution problems across the basin because age-range–limited fauna or flora are scarce relative to the thicknesses of strata. Thickening of stratal packages across regional growth faults creates the need for some form of time marker to aid in accurate correlation (Leonard, 1983). Those planktonic faunal markers that are present commonly suffer from suppressed extinction because of the high sedimentation rates, causing them to appear much shorter lived than their worldwide ranges. The high rates of sediment supply, high marine energy levels, and the incising nature of the riverine-sediment transport system within the basin also complicate faunal and floral correlations by reworking microfossils in many environments. This reworking not only confuses age relationships but also contaminates the in-situ environmental assemblages. Active thrusting on the island of Trinidad during the late Pliocene and the resulting high-relief terrain also obscure age relationships by providing reworked microfossils of all ages to the active depositional system. Finally, the rapid rates and high volumes of sediment being deposited in the basin have produced a very young and poorly consolidated section that is prone to downhole caving during drilling, resulting in spurious tops and bases (Pocknall et al., 1999). Data types must be integrated carefully to establish true ages and depositional environments of the sections of interest.

Faunal and floral extinctions and evolutions, as well as some abundance acme, derived from data in more than 41 wells (Figure 4) have been used in the Columbus Basin to aid in creating a chronostratigraphic framework for the Pliocene–Pleistocene. The age significance of planktonic foraminifera and palynomorph occurrences is detailed in Pocknall et al. (1996, 1999) (Figure 8).

Depositional Environments and Facies

In addition to the use of palynomorphs and planktonic foraminifera as age indicators, assemblage and abundance data of these fossils have been used, along with geophysical log motif, to define five distinct deposi-

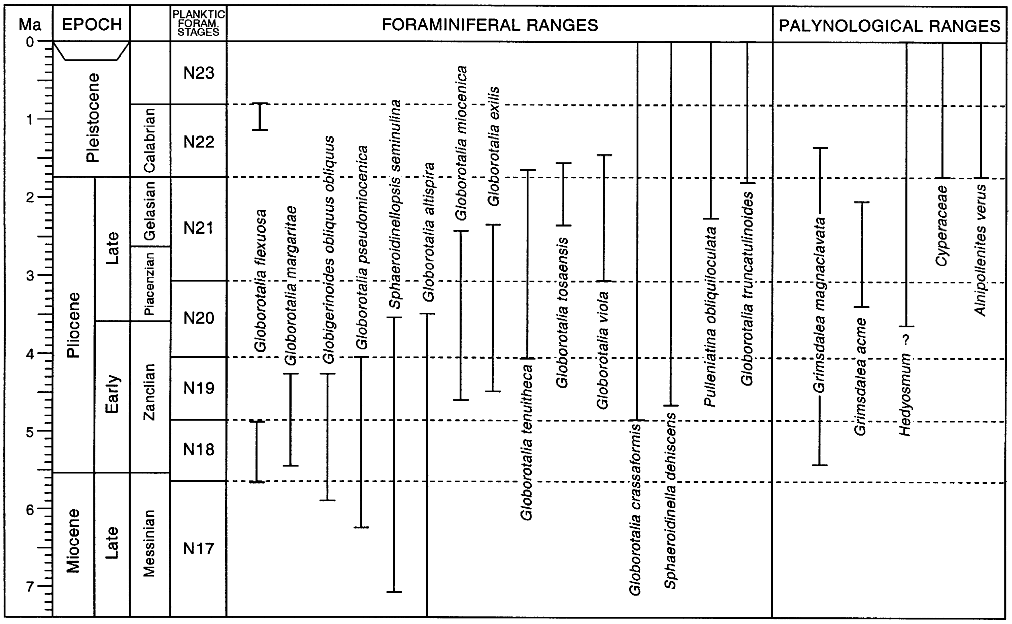

Figure 8. Biostratigraphic ranges defined by Pocknall et al. (1999) and derived in conjunction with this study to differentiate chronostratigraphy of the Columbus Basin.

tional facies that characterize the Columbus Basin: (1) fluvial/estuarine/transitional barrier island, (2) prograding shoreface, (3) slope fan, (4) basin-floor fan, and (5) condensed section facies. Details of the faunal and floral assemblages and their environments that characterize these elements are detailed in Pocknall et al. (1999) and are summarized in a following section.

Fluvial/Estuarine/Transitional Barrier

Fluvial/estuarine/transitional barrier depositional facies are composed of sediments deposited either subaerially or within the zone of tidal influence. Environments include active and abandoned channel fills, flood plains, swamps, estuarine sand bars, lagoons, beaches, marshes, and tidal flats. Mangrove pollen (derived from *Rhizophora*, *Avicennia*, and *Pelliciera)* is common in estuarine valley-fill sediments. Other significant components include the benthic foraminifera *Milliammina telemaquensis*, *Arenoparrella mexicana*, *Ammonia beccarii*, and *Ammobaculities dilitatus;* pollen derived from swamp plants such as *Symphonia (Pachydermites diederixi)* and *Ceratopteris (Magnastriatities howardi);* and *Gramineae* pollen derived from the swamp-marsh grass.

Log character for the fluvial and transitional barrier-complex facies consists of a blocky or occasional upward-fining motif commonly having a serrated texture. Sandier units are generally interbedded with alluvial overbank, fine-grained deposits and crevasse splay sands and fine-grained estuarine facies. In some wells, these finer grained intervals are several hundreds of feet thick. The sands that characterize these facies are well sorted and friable and in outcrop exhibit ripples, low-angle cross-beds, and some bidirectional cross-bedding. Interbedded dark-black, organic-rich siltstones and silty mudstones show ripples and wavy laminations. Reworked shells and plant and organic material are common. In outcrop, these facies exhibit soft sediment deformation. Little evidence of coal or lignite can be found in cutting samples from these facies, but in outcrop coals and laterally continuous lignites both are not uncommon.

Prograding Shoreface

Prograding shoreface consists of the lower, middle, and upper shoreface subfacies deposited predominantly below sea level and within the zone of wave, tide, and storm influence. Faunal assemblages reflect an overall upward-shallowing succession from *Buliminella* spp., *Planulina foveolata*, and *Bolivina multicostata*, to increasing occurrences of *Uvigerina peregrina* in the middle shelf, and, finally, *Amphistegina lessonii*, *Nonionella atlantica*, and *Bolivina spinata* in the inner shelf sediments. Finer grained shelfal units are characterized by abundances of dinoflagellates, whereas sandier shelf systems show a decrease in dinoflagellates. In outcrop these facies consist of thick, clean, fine-grained sands (10 to 20 ft [3 to 6 m]) separated by interbedded silts and clays. Isolated beds of coarse-grained to medium-grained sand can occur at the top of upward-coarsening sequences. Sorting varies from moderate to good as one moves distally in the shoreface system. Thicker sands, having sharp scoured bases, contain abundant large-scale and medium-scale trough cross-beds. Thick, fine-grained sandstone/siltstone intervals have abundant vertical burrowing and shell fragments. *Ophiomorpha* dominate the ichnofauna assemblage. Silt/sand intervals underlying coarser grained sands contain abundant evidence of dewatering structures and convoluted bedding. Log motifs of these facies are characterized by an upward-coarsening stack of progradational parasequences whose final top is commonly sharply truncated and whose thickness may range to almost 1000 ft (330 m).

Slope Fan

Slope-fan sediments are deposited as slope fans and slope-leveed channel complexes in depths ranging from 600 to 3000 ft (200 to 1000 m) of water. Assemblages characteristic of these facies include the consistent occurrence of *Guppyella miocenica*, *Trochamina trincherasensis*, *Cyclammina cancellata*, planktonic foraminifera, and the occasional presence of *Haplophragmoides carinatum*, *H. narivaensis*, *Bathysiphon* spp., and *Reticulophragmium venezuelanum*. Transported *Rhizophora* pollen is commonly seen in high numbers in these facies. These facies are poorly exposed in outcrop and core data are extremely limited. They are dominantly composed of gray, micaceous, highly calcareous silts and silty clays, rich in foraminifera, interbedded with fine-grained, laminated, micaceous sands containing some carbonaceous streaks. Sands are swaley bedded, having abundant bioturbation, and coarsen upward from very fine to fine. Shales show some soft sediment deformation, and siltstones show evidence of low-angle cross-bedding. Well logs in these deposits are characterized by ratty, sand-shale log character, which typically fines upward in packages as thick as 1000 ft (330 m).

Basin-Floor Fan

Basin-floor–fan facies are deposited in very deep water (>3000 ft [1000 m]) near the toe of the slope. They contain much reworked middle to outer neritic fauna mixed with in-situ, deeper water, agglutinated fauna. In-situ fauna include common to abundant planktonics; benthic forms include *Recurvoides obsoletum*, *Cyclammina cancellata*, *Ammodiscus* spp., and *Alveovalvulina suteri*. Flora present include abundances of dinoflagellates and land-derived *Rhizophora* and various species of fern spores. Basin-floor–fan facies have not been described in outcrop or core. Well log motif of these sediments is sharp to sharply gradational at the base, overlain by several stacked packages (each ~100 ft [~30 m] thick), which show a blocky to slightly serrated character.

Condensed Section

Deep-water, fine-grained silts and shales compose the condensed section facies. Consistent and abundant *Glomospira charoides*, *Alveovalvulina suteri*, and *Reticulophragmium venezuelanum* are found in these facies. Dinoflagellates are common and commonly consist of monospecific assemblages of *Nematosphaeropsis lemniscata*. Well logs indicate very low resistivities and high (hot) gamma signatures associated with these deposits. Although condensed sections have not been cored in the basin, they are thought, on the basis of log character, to consist dominantly of silts and clay.

Rates of Sediment Accumulation

Sediment supply throughout the Pliocene and Pleistocene in the Columbus Basin was enormous, having the bulk of these sediments derived from the Andes Mountains and associated regions far to the southwest of Trinidad. Rates of sediment accumulation in the basin during this time period surpassed those seen in other Tertiary deltaic settings, such as the Mississippi, Niger, or Nile deltas. Sediment accumulation rates of as much as 15 to 20 ft (5 to 6 m) per 1000 yr are typical across the basin, having rates of as much as 26 ft (8 m) per 1000 yr in some depocenters (Figure 7). Evidence of these rapid rates of accumulation can be seen in the sedimentary structures that characterize the upper Tertiary clastic section. Outcrops of Pliocene strata on the island of Trinidad exhibit dewatering structures, flame structures of as much as 3 ft (1 m) in height, fluidized flow features, large ball and pillow features, and large-scale convoluted bedding (Figures 9a, 9b). Deposits characterized by such features are commonly mistaken for deeper marine, mass-flow facies. However, careful examination of these deposits reveals coinciding ripple cross-laminations, climbing ripples, large-scale trough cross-beds, tidal bedding and in-situ shelfal ichnofauna (*Skolithos*), some vertical burrows reaching as much as 5 ft (15 m) in length (Farrelly, 1987). All evidence supports an interpretation of a shallow-water, shelfal setting for deposition of these units.

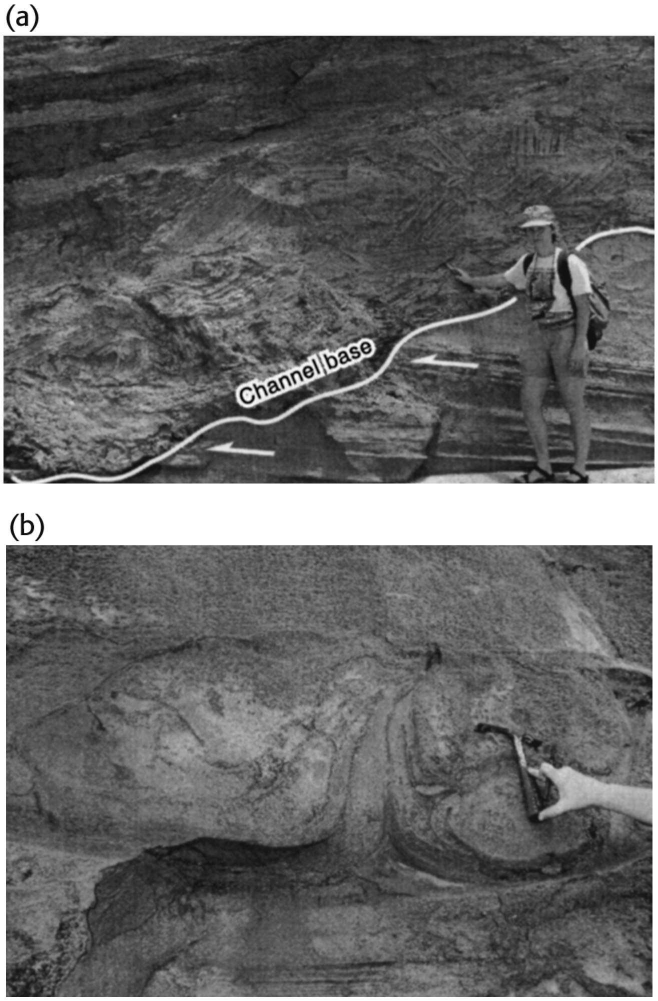

Figure 9. Photographs of Pliocene shelf-deltaic deposits of Gros Morne Formation of the Columbus Basin outcropping along the southeast coast of Trinidad show soft-sediment deformation, including (a) large channel scour truncating underlying fine-grained sandstone, siltstone, and claystones deposited in a shelf deltaic setting. The channel scours into structurally tilted sediments. Its irregular base is filled with large rectangular blocks, which were semicohesive when deposited and are composed of the substrate material. The remainder of the channel is filled with alternating wavy-bedded silty sands and shales. (b) Flame structure, characteristic of these rapidly deposited sediments. Location of photos shown in Figure 4.

Pliocene–Pleistocene sediments in the subsurface of the basin are virtually unconsolidated. Sand porosities, even at burial depths exceeding 12,000 ft (>3660 m), can have 25 to 35%; permeabilities of several hundreds of darcys are not atypical. Overpressure problems exist throughout the basin and are partly due to the rapidly deposited, stacked, shallow, clastic shelf deposits overlying deeper outer-shelf and upper-slope facies (Heppard et al., 1998). All of these characteristics are evidence of a depositional setting having extremely rapid accumulation of sediment, occurring in a shallow-marine shelf setting.

SEQUENCE STRATIGRAPHY OF THE COLUMBUS BASIN

A series of progradational clastic wedges form the Pliocene–Pleistocene stratigraphic architectural package of the Columbus Basin (Figure 10). Development and character of these wedges are driven by three primary elements, namely, tectonic activity, sediment supply, and marine-process redistribution of sediments. Although they progress from oldest in the west to youngest in the east, the wedges exhibit many similar characteristics. Each clastic wedge prograded from southwest to northeast across a part of the basin, and each exhibits a high degree of lateral facies continuity along depositional strike (northwest-southeast) (Figure 7). Within each wedge, the depositional facies deepen progressively from southwest to northeast, changing from (1) terrigenous fluvial/estuarine to (2) progradational or aggradational shoreface to (3) middle and outer neritic shelf to (4) slope and, finally, to (5) basinal facies over a distance of a few kilometers. Distal parts of each prograding wedge downlap onto a mobile substrate thought to be the top of thick Miocene marine shales (Figure 5). Megadepositional sequences (defined here as genetically related strata bounded by regionally unconformable surfaces and their basinward correlative conformities) average 10,000 to 12,000 ft (3000 to 3660 m) in thickness and accumulated over relatively short periods (300,000 to 500,000 yr).

The megasequences are internally composed of five to eight progradational parasequences, each averaging 550 to 980 ft (170 to 300 m) in thickness and

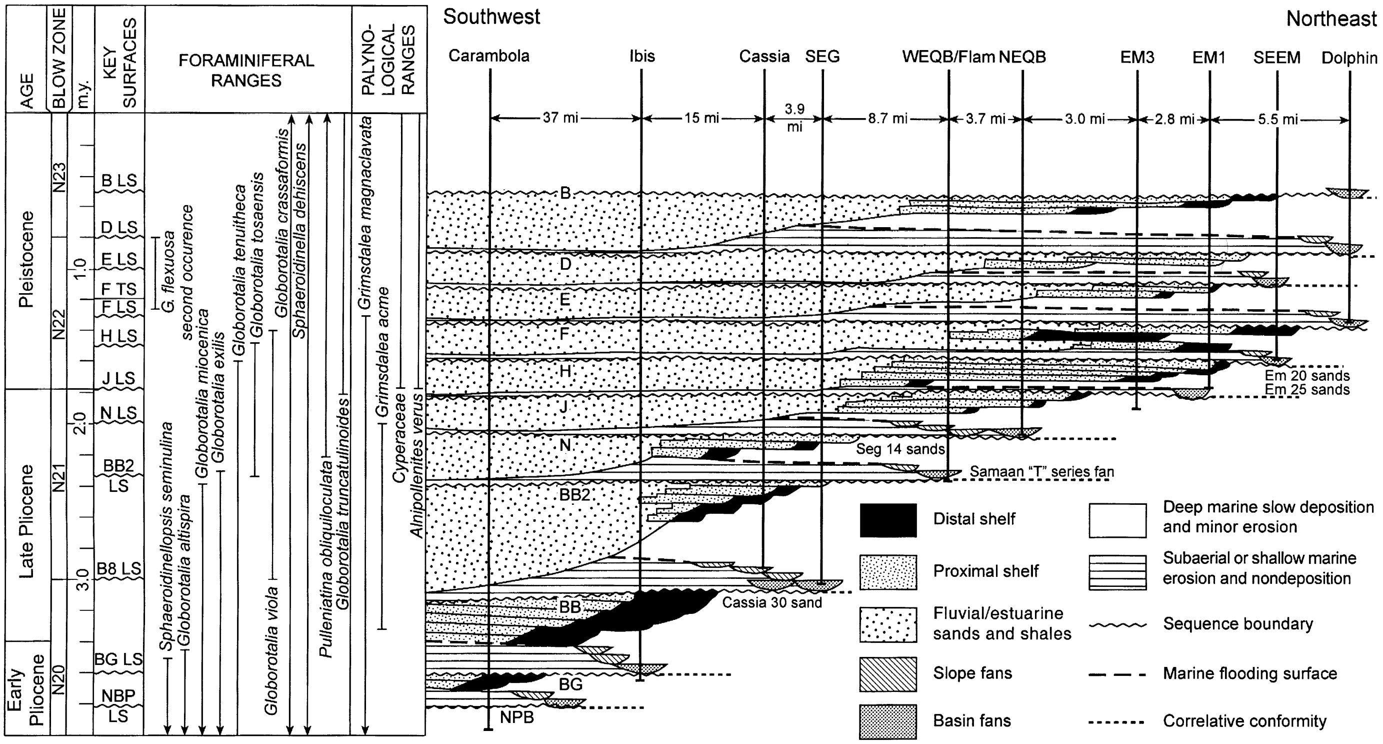

Figure 10. Chronostratigraphic chart of the Columbus Basin, showing progradational character of the basin fill throughout the Pliocene and Pleistocene. Regional subsidence in the southwest parts of the basin resulted in continuous aggradation of mixed fluvial and estuarine deposits over much of the area. Unconformities exhibit the greatest amounts of missing time in locations central to the structural hinge of each megasequence. Foraminiferal and palynological ranges are from Pocknall et al. (1999).

deposited over 50,000 to 100,000 yr (Figures 7, 10). These parasequences contain reservoir sand bodies elongated along depositional strike. Facies within each parasequence show a high degree of continuity in the depositional strike direction but give way in a depositional dip direction (generally, north-northeast) and within a few kilometers to deep-marine environments. Parasequences are bounded by subregional regressive surfaces of erosion at their bases and by subregional deepening events at their tops. These flooding events, extensive along strike, result in accumulation of shales that make excellent local seals, although these same shales are limited in the dip direction. They therefore make poor correlation markers regionally (i.e., beyond the extent of a single megasequence) and cannot be assumed to form high-quality seals across a regional area.

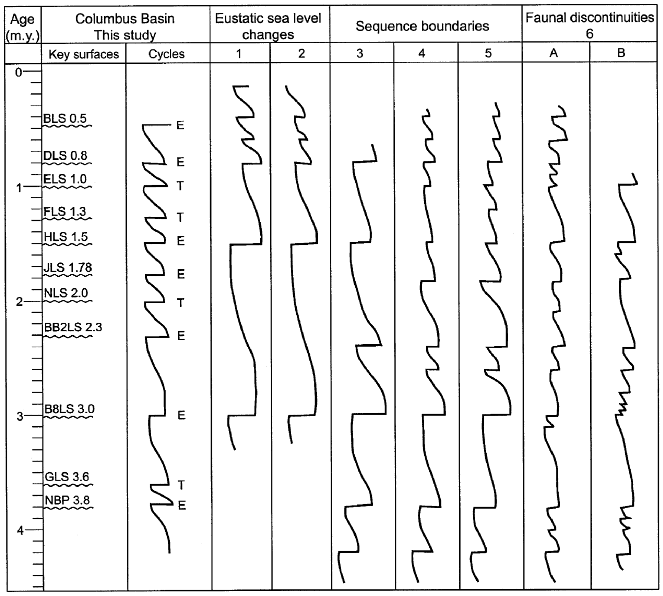

Figure 11. Curves showing sea level change, fauna discontinuities, and sequence boundaries for the world (columns 1, 2, 3) (Haq et al., 1988), the U.S.A. margins of the Gulf of Mexico (columns 4, 5, 6), and the Columbus Basin, Trinidad. Some sequence boundaries in the Columbus Basin appear correlative with time-equivalent sea level falls and associated sequence boundaries identified in other areas of the world. These sequence boundaries in the Columbus Basin are most likely a function of eustatic base-level change (E); others appear to have a more local tectonic origin (T). The tectonic nature of these boundaries is supported by the presence in some wells of Cretaceous, Eocene, and Oligocene fauna and flora identified as reworked in association with these boundaries (Pocknall et al., 1999). Sources for the curves are (1) Beard et al. (1982); (2) Lamb et al. (1987); (3) Haq et al. (1988); (4) Wornhardt and Vail (1990); (5) Pacht et al. (1990); and (6) Armentrout and Clement (1990).

Key Surfaces

Several key surfaces have been identified that are important in defining the megasequences that fill the Columbus Basin. From youngest to oldest, the regionally extensive surfaces (see Figures 10, 11) are (1) the near base Pliocene lowstand surface (LS) (NBPLS; 3.8 m.y.), (2) the base green LS (BGLS; 3.6 m.y.), (3) the base 8 sand LS (B8LS; 3.0 m.y.), (4) the base braided 2 sand LS (BB2LS; 2.3–2.4 m.y.), (5) the "N" LS (NLS; 2.0 m.y.), (6) the "J" LS (JLS or base Alnus lowstand; 1.78 m.y.), (7) the "H" LS (HLS; 1.5 m.y.), (8) the "F" LS (FLS; 1.3 m.y.), (9) the "F" transgressive surface (FTS; 1.2 m.y.), (10) the "E" LS (ELS; 1.0 m.y.), (11) the "D" LS (DLS; 0.8 m.y.), and (12) the "B" LS (BLS; 0.5 m.y.). These surfaces, with the exception of the FTS, mark basinwide episodes of basinward facies shifts and the progressive northeastward progradation of the Orinoco Delta system. Each episode is characterized by a rapid thickening of the stratigraphic section across successively eastward growth faults. Stratigraphic architecture within these fault blocks typically consists of deep-water marine clastics grading upsection into successively shallower shelf deposits and finally culminating in the sudden deposition of a series of stacked shelf parasequences (Figures 5, 10). Each sequence is capped by an unconformity associated with sediment bypass of the next-younger sequence. The FTS is a regionally extensive surface of deepening that corresponds to mid-Pleistocene marine flooding and landward translation of facies across the basin. This event initiated a distinct change in the basin toward higher frequency and larger magnitude translations of shoreline. The result is a series of large-magnitude lowstand progradational and highstand retrogradational events occurring across the area during the mid to late Pleistocene, having thin, shallow, widespread lowstand systems tracts alternating with thick, deep-water, transgressive shales (Figures 7, 10). The apparent increase in number of Pleistocene sequences (six) relative to Pliocene sequences (three) is superficial and a function of an increased abundance of key faunal and floral extinctions and first occurrences in the Pleistocene and uppermost Pliocene sections. This fact allows for a more detailed resolution of regionally extensive surfaces in the younger sections.

A second level in the hierarchy of surfaces is the subregionally extensive surfaces that developed as a function of more localized, structurally driven variations in accommodation space. The most pronounced of these localized surfaces are several large-magnitude marine unconformities that are somewhat angular and appear to divide the stratigraphic sections in each megasequence into a lower and an upper stratigraphic interval (Figures 5, 7). The lower stratigraphic intervals, characterized by a few specific shallowing events, are dominated by deeper marine facies. In contrast, the upper intervals are dominated by shallow-marine to fluvial facies, which contain abundant and distinct parasequence-scale shoreface cycles. These diachronous marine unconformities postdate the preceding maximum flooding surface and early highstand systems tract deposits. These unconformities appear to be regressive surfaces of marine erosion, which precede the most dramatic and continuous phases of late highstand progradation and aggradation in the basin. These surfaces form as a result of submarine tide, wave, and storm processes active on the depositional shelf. Similar regressive surfaces of marine erosion have been identified in both ancient and modern deposits (Plint, 1988; Posamentier et al., 1992; Posamentier and Allen, 1993), albeit not having the pronounced expression seen in the Columbus Basin, which is likely a function of syndepositional tectonism. Large-scale flexuring in the basin created a structural hinge along which marine erosion was enhanced.

INFLUENCE OF TECTONICS ON STRATIGRAPHIC SEQUENCE DEVELOPMENT

Tectonostratigraphic Model

The Columbus Basin regional chronostratigraphic framework discussed on preceding pages has been used to explain the complex relationships between larger, regionally extensive normal faults, mobile shale diapirs, and the deposition of large, clastic-rich megasequences that make up the stratigraphic architecture of the Columbus Basin.

Regional extension, associated with the oblique transpression of the Caribbean plate to the north and the South American plate to the south, creates sites of weakness for prograding sediments to load, further enhancing failure along normal faults. The initiation of movement on these extension faults is reflected in the stratigraphy on their downthrown side. There the stratigraphic units most proximal to the downthrown side of the fault are deep-marine deposits overlain by an initial progradational shallow-marine sand, overlain by another deep flooding event marking early activity on the normal fault. Once the tectonic accommodation space closest to the fault is filled, the succession progrades east of the proximal normal fault, eventually stalling near the depositional shelf break. These faults, once initiated, bound the proximal side of a single megasequence (Figure 12). Aided by loading from the weight of progressive sediment deposition, mobile shales are forced northeastward and begin to rise. Accommodation space is generated beneath the basinal edge of the megasequence by shale withdrawal, and subsidence begins along a counterregional glide plane, creating distal accommodation space. Growth occurs across the proximal bounding faults (G in Figure 12) as sediments from the proto-Orinoco strive to fill proximal accommodation space. Stratigraphic thickening likewise occurs toward the diapir in response to progressive downward rotation of beds along the counterregional glide-plane surface (Figure 12).

A typical sequence of fault initiation and strata development is illustrated in Figure 13. Fault G, active pre–time marker 1 (T1), shows growth and terminates glide plane F at depth. The sediment wedge to the northeast of fault G begins to be rotated above counterregional glide plane G, creating a shelf break and locus of sediment accumulation landward of the outlying shale diapir. Fault H is initiated in response to continued extension and mobile-shale withdrawal. Sediment loading proximal to the diapir and subregional subsidence enhance shale withdrawal, severing the subsurface glide plane G. Subregional withdrawal subsidence within fault block G–H ceases. Sediments fill remaining accommodation space in the area and prograde the shelf break eastward of fault H. Fault G continues to show limited activity and growth well into time 2 (T2), but the bulk of extension and growth between T1 and T2 is taken up at fault H. Rotation occurs at depth above the more eastward counterregional glide plane H, and both the shelf break and loci of accumulation reside east of fault H and proximal of glide plane H (Figure 13c). Expansion and growth continue along the H fault (T3), stratigraphic thicknesses increasing by shale withdrawal and counterregional rotation. The H fault eventually proves unable to keep pace with further extension because of exhaustion of mobile material at depth. Any remaining accommodation space is filled and there is a progressive eastward shift of extension faulting, shelf-slope break location, and lateral shale withdrawal.

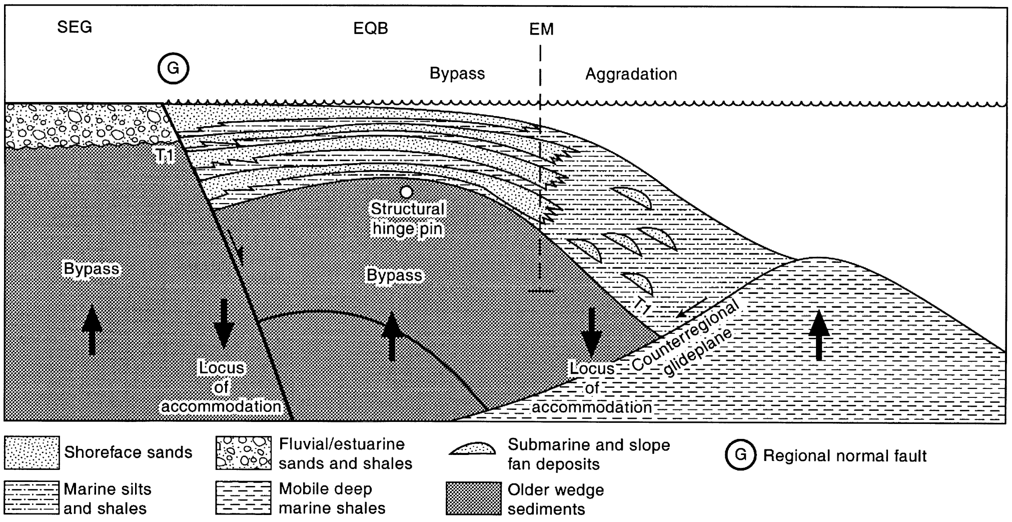

Figure 12. Illustration of a single lower Pleistocene megasequence deposited across the Southeast Galeota (SEG), East Queen's Beach (EQB), and East Mayaro (EM) areas between the JLS (T1) and the HLS (top surface). This sequence includes many of the hydrocarbon productive sands of East Mayaro field and is bounded in the proximal direction by the G fault (G) and in the distal direction by a lower Pleistocene counterregional surface moving along a mobile shale body located northeastward of the EM1 and EM2 wells (Figure 4).

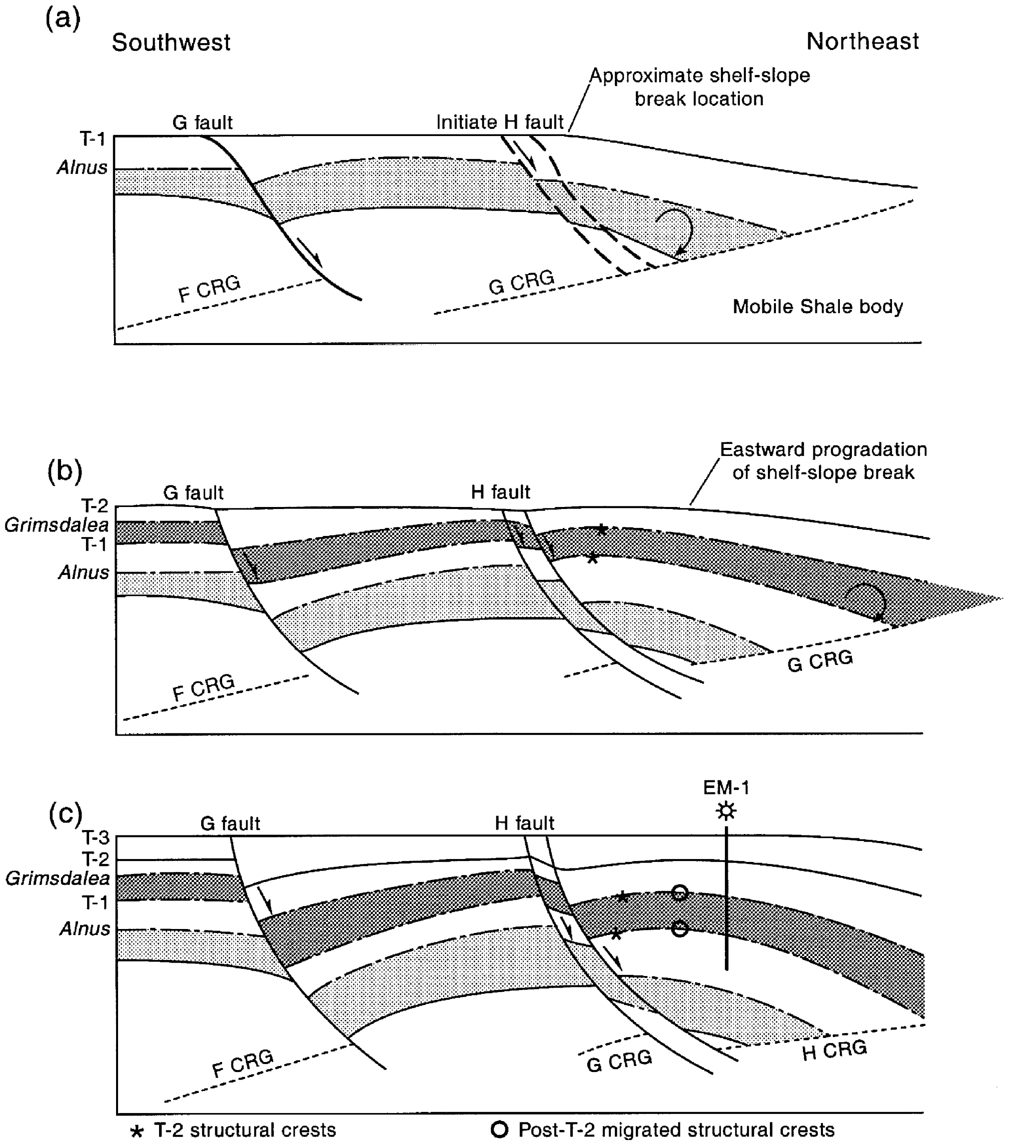

Figure 13. Illustration of the timing of formation (from oldest to youngest, a to b to c, respectively) of various aspects of a typical megasequence across the gas trend area from Cassia field (shown by the WSEG well [Figure 4]; southwest) to East Mayaro field (shown by the EM wells [Figure 4]; northeast). See text for detailed discussion. CRG = counterregional guideplane.

Comparison with the Niger Delta

The relationship between structure and stratigraphy in the geologic evolution of the Columbus Basin resembles that identified by Evamy et al. (1978) in the Niger Delta (Figure 14). In the Niger Delta model, shale migration establishes a bathymetric high in front of the progradational Niger shelf system, forming a break between paralic/deltaic sedimentation, which has been trapped behind the bulge and slope/bathyal sedimentation outboard of the bulge crest. Beds deposited behind the bulge show progressive downward rotation and steepening of dip along a counterregional glide plane associated with progressively basinward migration of the mobile shale. Large growth faults develop landward in response to extension and mobile shale withdrawal at depth.

Although similarities between the offshore Nigeria tectonostratigraphic processes and those of Trinidad's Columbus Basin are obvious, a few notable differences exist. The most obvious of these differences is the location of the shelf-slope break with respect to the migrating shale bulge. In the Niger Delta model, the break between shelfal water depths and slope/bathyal water depths occurs at the crest of the shale bulge (Figure 14). This configuration limits distribution of deep-marine facies to the distal side of the bulge, having little primary depositional dip across the sedimentary shelf system, proximal to the bulge. In contrast, the Orinoco Delta strata exhibit a distinct break from shelf to slope/bathyal water depths on the proximal side of the shale bulge. The result is a significant bathymetry change across the sedimentary shelf and slope systems. Slope and basinal facies are thus able to downlap and onlap the underlying mobile shales. This difference creates significant primary depositional dip across the Columbus Basin depositional system proximal to the shale bulge.

A second difference between these two models is the discrepancy in the height of the shale bulge (Figure 14). Although Evamy et al. (1978) suggested that the shale bulges in the Niger Delta rise to near sea level,

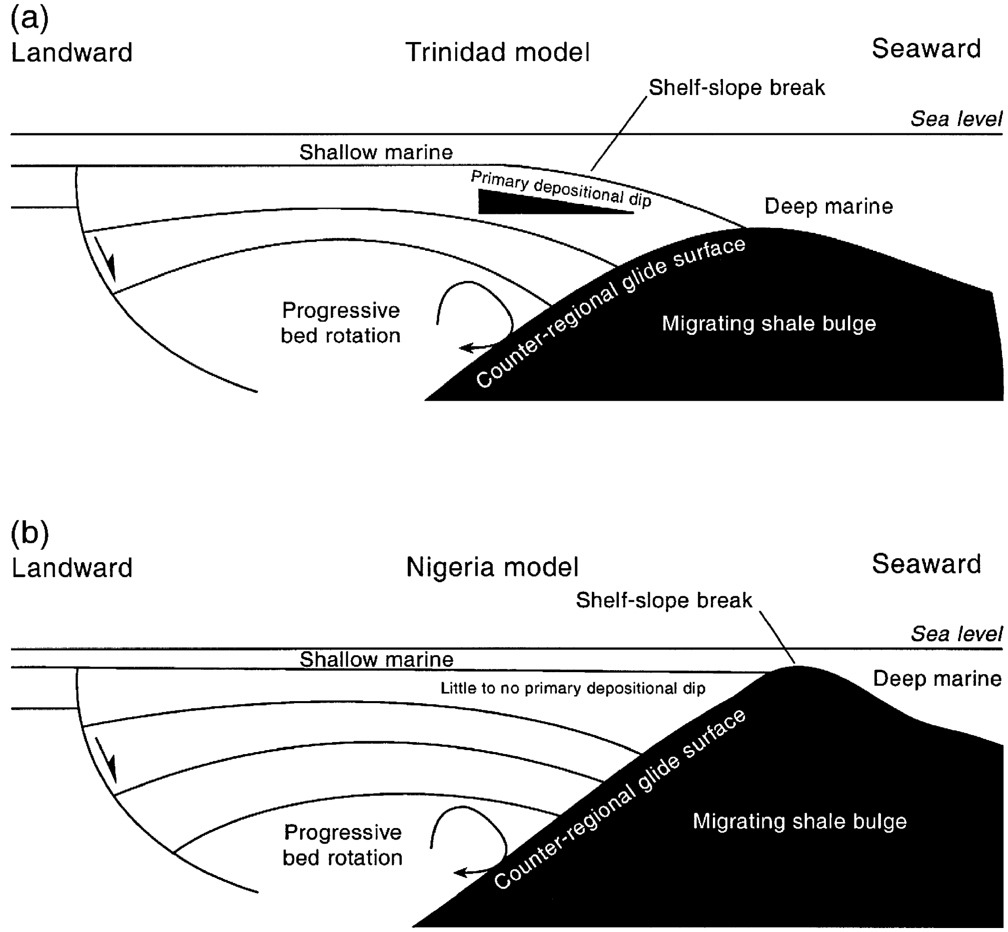

Figure 14. Illustration of the similarities and differences that exist between the tectonostratigraphic characteristics of the Columbus Basin, Trinidad, model (a) and that of Evamy et al. (1978) Niger Delta, Nigeria, model (b). Note the bidirectional wedging of sediments, both distal toward the shale diapir and proximal toward the normal fault, in the Columbus Basin, as compared with the unidirectional wedging proximally that occurs in the Niger Delta.

the crests of the shale bulges in the Columbus Basin, Orinoco Delta, never rose to shelfal water depths. This interpretation, based on paleobathymetric data and seismic facies analysis of deposits that onlap the shale bulges, suggests outer neritic to bathyal water depths and facies associated with these deposits. Finally, shale bulges in the Columbus Basin were probably subjected to reworking by geostrophic currents, longshore currents, slumps, and slides that were more effective than similar features in the offshore Nigeria area. This inference is based partly on the high magnitude of offshore submarine forces reworking the Columbus Basin area throughout the late Tertiary and today, as well as the tectonic activity of the basin.

Niger Delta oil fields are characterized by structural crests that migrate back into the fault in successively younger strata (Weber, 1987). This pattern indicates syndepositional wedging back into bounding growth faults (Figure 15a). In the Columbus Basin, however, some of the structures, such as East Mayaro field, have structural crests that migrate away from the normal fault in successively younger strata. This pattern may reflect postdepositional modification of the original locations of the structural crest by late growth across the field-bounding normal fault. Figures 5 and 13 illustrate these differences, showing post-Grimsdalea (FLS) depositional growth along the H fault causing migration of the structural crests of T1 (HLS) horizons to successively more eastward positions.

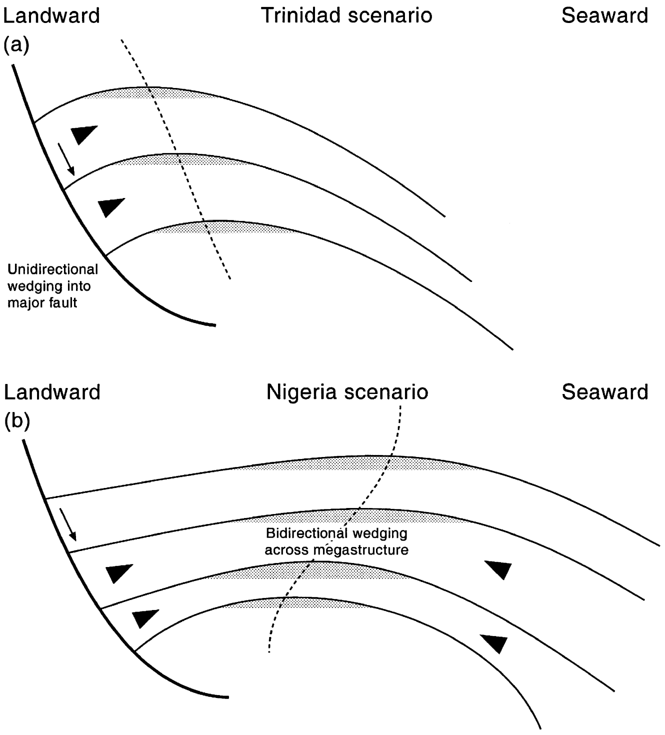

Figure 15. Illustration of the difference in alignment, deep to shallow, of structural crests in some fields of (a) the Columbus Basin, Trinidad, vs. (b) the Niger Delta, Nigeria (after Weber [1987]).

A final noted difference between the Trinidad and Nigeria sequences is that of bidirectional wedging of sediments within the Columbus Basin megasequences vs. unidirectional wedging of strata proximally in the Niger Delta (Weber, 1987). This difference is a function of the location of the depositional shelf break, which occurs proximal of the eastward-migrating shale diapir in the Columbus Basin system. Sediments thicken in response to distal accommodation along the associated counterregional surface, as well as thickening, similar to that in the Niger Delta setting, along the proximal normal fault.

Structural Control on Depositional Systems and Accommodation Space

Structural uplifts associated with Miocene and early Pliocene thrusting to the west of Trinidad contributed sediments to the basin and focused fluvial feeder systems into the basin (Speed, 1985). As this compressional deformation wave moved progressively southward and eastward, compressional ridges, oriented northeast-southwest were formed in the offshore areas of the Columbus Basin. Today these ridges form the productive offshore trends (Figure 4) and are as young as Pleistocene in age. Earlier formed ridges in the northwestern areas served to channel late Pleistocene distributaries along lows in the proximal coastal plain. Such focusing of fluvial feeder systems aided in transport of sediment across what was a very low, broad coastal plain.

Limited accommodation space in the coastal plain and most inner-shelf areas meant rapid progradation of depositional systems during the early stages of any sea level fall. In some cases, shorelines most likely moved basinward as a result of sediment outbuilding only to stall as they impinged upon high-accommodation zones at the shelf break, steepened by focused zones of shale withdrawal (see Figures 6, 12). Sediments from the proto–Orinoco Delta were most likely swept northeastward by strong longshore currents until abutting against the offshore bathymetric highs formed by eastern extension of the Darien Ridge. The linear (northwest-southeast) nature of shale bulge fronts led to northwest-southeast–oriented loci of deposition and subsequent lineation of strand-plain deposits.

Two types of parasequences make up these stacked shoreface parasequence sets: (1) bypass and (2) aggradational shorefaces. Bypass-shoreface development occurred in areas of limited accommodation space, either proximally along the structural hinge of a megasequence or at the shelf break during times of low subsidence. These systems exhibit a thin progradational base, indicating rapid progradation and little accumulation of sediments. The parasequence overall is of limited thickness, bypassing most sediment basinward early in lowstand time to form slope and basin-floor fan systems.

In contrast, aggradational shoreface development occurred during times of high rates of accommodation-space development, typically at the depositional shelf break. These systems may possess either thin or thick progradational bases, depending on the availability of early highstand accommodation space. Where large amounts of lowstand sediments are stored in the aggrading lowstand shoreface, little sediment is left over to form gravity deposits on the slope and basin, resulting in limited development of slope fan and basin-floor fan reservoirs. This concept was illustrated in modeling studies by Ross (1990), and these relationships between deep-water and shallow-water deposition are documented in strata across the basin.

Because of the high sediment-supply rates of the Orinoco Delta system, accommodation space is almost always completely filled during lowstand cycles. The late lowstand fill leaves little space to accommodate transgressive systems tract sediments. Biofacies associated with sediments, typically shales, overlying lowstand shoreface deposits show rapid deepening above these systems. This rapid deepening is reflected in the limited, to unresolvable, thickness of many transgressive systems tracts and limited ability to resolve shelf onlap on conventional seismic lines. Such onlap in other basins is commonly used as evidence of transgression. In addition, these rapid flooding events create an excellent reservoir/seal relationship (Figure 16). In a few locations within the basin, transgressive subsidence is greater than sediment supply, and transgressive sediments back step above the lowstand shoreface system. The resulting transgressive systems tract can form a hydrocarbon "waste zone" that has limited productivity (Figure 16) as compared with highstand and early lowstand deposits.

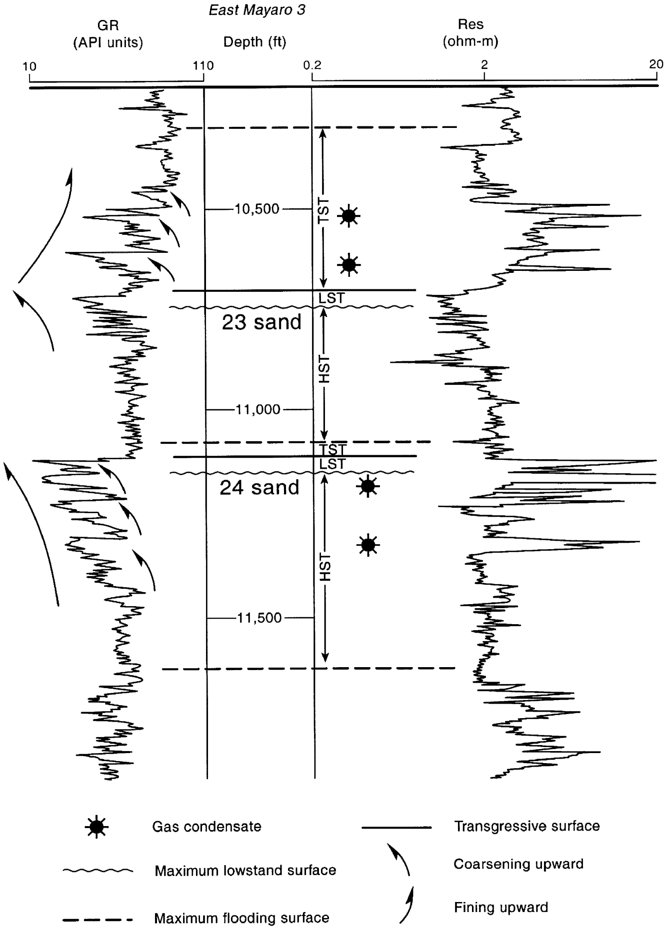

Figure 16. Electric log from the East Mayaro 3 well (see Figure 4 for location), illustrating hydrocarbon-bearing transgressive system tract (TST) waste-zones in the 23 sand interval vs. the late-highstand systems tract (HST) to lowstand systems tract (LST) hydrocarbon accumulations in the higher quality 24 sand interval.

IMPLICATIONS AND RECOMMENDATIONS FOR EXPLORATION IN THE COLUMBUS BASIN

Several observations have been made throughout the course of this work that bear on future exploration risk and success in the Columbus Basin and in other high-sediment-supply, transpressional basins, including the following.

1. Large megasequences define distinct episodes of sedimentation across the Columbus Basin; they wedge bidirectionally as a result of thickening along a proximal normal fault and along a distal counter-regional glide-plane surface. Consideration of reservoir risk across such a megasequence requires looking at it as a complete paleofeature. Failure to

do so could lead to an incomplete understanding of reservoir quality, thickness and distribution, and fault timing across a prospect area and result in failure to find adequate reservoir sands and problems in assessing migration risk.

2. Original structural crests associated with bidirectional roll are commonly modified by subsequent growth along the proximal normal faults, resulting in posthydrocarbon migration of structural crests basinward as the section youngs upward. Such postmigration structuring can breach in-place traps. The implications for remigration of hydrocarbons from original crestal traps should be considered in assessing migration risk.
3. Megasequences are composed of bypass shorefaces along the structural hinge and a combination of bypass and aggradational shoreface parasequences along the depositional shelf break. The relative abundances of aggradational and bypass shorefaces developed at the shelf break are a function of continuous vs. episodic subsidence. Understanding the distribution of accommodation-space loci and bypass loci within the megasequence in turn results in an accurate understanding of reservoir and seal risk for distinct horizons at different locations.
4. Bypass shoreface systems feed early, sand-rich, lowstand slope and basin-floor fan deposits. Aggradational shorefaces bypass limited amounts of sandy sediment to slope and basinal deposits.
5. Thickness of sediment accumulation is a function of available space to fill. The thickness of sediment accumulated on a proximal bypass surface has no relationship to the volume of sediment being bypassed across it. More important is the degree of shallowing associated with the surface. If sediment is not accumulating above a surface at a proximal locality, it simply means that the sediment is in either a distal or lateral location of accommodation.
6. The character (i.e., thickness, rate of thinning, angle of termination, etc.) of classic seismic stratal terminations (onlap, offlap, toplap, downlap) is strongly affected by the relative relationship of progradation vs. aggradation in a system. If the setting is high accommodation, great thicknesses of sediment may aggrade before a basinward, progradational step of the delta. Conversely, low-sloping depositional surfaces (i.e., low-accommodation space) and high-energy depositional conditions (i.e., low-preservation settings) may combine to produce thin, laterally extensive delta coverage of the shelf. At a fixed vertical resolution of seismic data, classic stratal relationships used typically to classify deposits genetically above and below a surface of termination are obscured. It is important to recognize the effect that changes in accommodation and energy have on classic seismic stratigraphic interpretation criteria.
7. The depth of a quality reservoir in any megasequence increases with movement more proximal to the normal fault that bounds the proximal edge of a megasequence (Ortmann and Wood, 1996). Drilling deeper in the more proximal locations of a megasequence may produce a higher quality reservoir than that found in the time-equivalent section to the northeast. Drilling deeper may bring penetration of the lowstand progradational strata that initiated failure on the proximal bounding fault, encasing them in postfailure, deeper water shales.
8. The stratigraphic top of overpressured strata within the basin is diachronous. Regressive surfaces of erosion closely approximate the transition into the overpressured section within each megasequence. Heppard et al. (1998) pointed out that hydrostatic-pressure relationships across the Columbus Basin exert a strong influence on the migration and trapping of hydrocarbons and the distribution of hydrocarbon type within the basin. Understanding the genesis and distribution of regressive surfaces of erosion within each megasequence may lead to improving understanding of hydrocarbon-type distribution across the basin.

SUMMARY AND CONCLUSION

The Columbus Basin is a world-class hydrocarbon basin of Pliocene and Pleistocene age, having some of the highest accumulation rates of any basin in the world. The sediments are unconsolidated, and the stratigraphic section is more than 49,000 ft (>15,000 m) thick. A chronostratigraphic framework of the basin is presented herein that is based on several key lowstand horizons identified in the Pliocene and Pleistocene section. Using these key lowstand surfaces, we can subdivide the stratigraphic interval into at least nine megasequence units. Megasequences become progressively younger to the east and are bounded at the base and top by regionally extensive unconformities and correlative basinal conformities. Sediments within these sequences were deposited by the wave-dominated paleo–Orinoco Delta system that prograded onto a storm-influenced and current-influenced shelf to very near the shelf-slope break. At shelf-edge locations, the delta was exposed to high wave and current energy that formed sands into cuspate, strike-continuous, clean reservoir bodies that characterize the basin. Megasequences do not exhibit the classic Exxon "slug" geometries seen in passive-margin basins. Instead, these "bow-tie" sequences (Figure 12) fan down and seaward (east) into the counterregional glide surface along the shale diapir, which marks their east edge. Sedimentary packages thin landward (west) along the megasequence hinge then thicken again farther landward into the proximal, megasequence-bounding normal fault.

The megasequences range between 9800 and 13,000 ft (3000 and 4000 m) thick, and each was deposited over a period of 300,000 to 500,000 yr. Their deposition was driven by a combination of controls, including eustatic sea level and regional tectonics. Megasequences are internally composed of a series of stacked parasequences, some of which are more than 820 ft (>250 m) thick, deposited over periods of 50,000 to 80,000 yr. They are bounded at their base by local unconformity surfaces and at their top by local flooding events. Parasequence bounding surfaces are continuous in a depositional strike direction (generally northwest to southeast) but are poor horizons for regional correlation work. In this structurally complex setting, compressional structural features tended to focus transport systems, whereas extension structural features focused depositional systems.

Many similarities exist between the Columbus Basin and the Niger Delta, although there are subtle differences that have important implications for reservoir type within megasequences. In contrast to the Niger Delta setting, as structural crests in the Columbus Basin migrate progressively basinward, the younger the section becomes. This geometry reflects postdepositional alteration of some of the original structural crests, suggesting implications for secondary migration within large structures.

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