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Controls on the Deposition of Upper Cretaceous Organic Carbon–rich Rocks from Costa Rica to Suriname

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ABSTRACT

The deposition of organic carbon–rich sediments during the Late Cretaceous in northern South America was controlled by global and local oceanographic, climatic, and tectonic variables. Key in establishing "source rock" depositional systems across the region were eustatic sea-level rise, warming global sea-surface temperatures, the formation of low-latitude saline bottom waters, and a relatively constant supply of fine-grained hemipelagic sediment (mostly derived from the south and east). Specific paleobathymetric conditions enhanced the development of stagnant water masses from the proto-Caribbean plate to Suriname. Organic-matter preservation was aided by the presence of these water masses across the region. Primary productivity was elevated above "normal" marine levels only in the protocentral Caribbean and along the ancestral Costa Rica/Panama island arc, or during seasonal upwelling in northern South America.

Cooler, wetter climatic conditions that began in the late Santonian also were modified by regional and local variables. The development of new intermediate/bottom-water masses, increased polar heat transport caused by improved deep-ocean circulation, and fluctuations in volcanogenic CO_2 provided a background effect for local variables such as bathymetry and topography. The development of oxygenated high-latitude water masses provided a means for ventilation of stagnant, low-oxygen bottom waters across northern South America and the central Caribbean. Stronger seasonal upwelling (increased wind stress caused by better polar heat transport, and northward movement of the South American

Plate into the zone of northward Ekman transport), more frequent fluvial outflow and deltaic deposition, and the submergence of key paleobathymetric barriers aided ventilation and subsequently diminished organic-matter preservation. Most of these variables had a positive impact on primary productivity and caused rapid changes in the diversity of planktonic foraminifera through the end of the Cretaceous.

INTRODUCTION

The existence of globally extensive Upper Cretaceous organic carbon–rich rocks has helped to spark broad investigations of the earth's plate-tectonic, climatic, oceanographic, and biologic history. Other than the K-T (Cretaceous-Tertiary) boundary, no single period or event that occurred during the Mesozoic has inspired more curiosity. That rocks of this age have generated trillions of barrels of oil and tril-

lions of cubic feet of natural gas have provided additional incentive for scientific study. Over the past 20 years, efforts to explain the conditions responsible for the deposition of these rocks have led to a proliferation of studies and models that focused on oceanic spreading, paleoclimate, paleoceanography, and paleoecology. This study focuses on the area from Costa Rica to Suriname (Figure 1), and incorporates much of our earlier work (e.g., Villamil, 1996, 1998, 1999; Villamil and Arango, 1998; Erlich et al.,

Figure 1. Northern South America/Caribbean study area. Mountain and basement areas are shown in dark blue. Central Caribbean Deep Sea Drilling Project (DSDP) sites are numbered.

1999a, b; Villamil et al., 1999; Erlich et al., 2000), as well as new data from Colombia, Venezuela, Trinidad, and Suriname.

In this study, we will attempt to identify, understand, and differentiate between local (basin-specific) and global or oceanwide controls on the deposition of Late Cretaceous organic carbon–rich sediments. This study differs largely from other recent efforts (e.g., Barrera and Savin, 1999) in that we focus on the impact of Late Cretaceous climatic and oceanographic changes over a broad range of marine depositional environments. This is especially relevant to the search for hydrocarbon resources. Specifically, we believe it is critical to develop a clear understanding of the way in which Cretaceous oceanic anoxic events (OAEs) influenced organic-matter deposition and preservation along the slopes, shelves, and epicontinental seaways of northern South America. Understanding the processes of hydrocarbon source rock formation can aid in evaluating new, yet unproven current and future exploration opportunities.

Litho- and Chronostratigraphy of Upper Cretaceous Organic Carbon–rich Rocks

The study of Cretaceous organic carbon–rich rocks in northern South America has spanned more than 70 years (starting with Hedberg, 1931). During this time, most investigations have centered around the physical description of the various Upper Cretaceous organic carbon–rich units and, later, on their environments of deposition (e.g., Hedberg, 1937, 1950; Hedberg and Sass, 1937; Liddle, 1946; Kugler, 1953; Rod and Maync, 1954; Renz, 1957, 1961; Bürgl, 1961; Ward et al., 1973; Galli-Olivier, 1979; Gursky and Schmidt-Effing, 1983; Astorga, 1987; Macellari, 1988; Parnaud et al., 1995). Much of the more recent work has focused on the geochemistry, biostratigraphy, and paleoceanography of Upper Cretaceous rocks.

Some correlation between the units must be made before any substantive discussion of the paleogeography of the region can occur (Figure 2). Upper Cretaceous organic carbon–rich rocks have been identified from the Tempisque Basin of Costa Rica (Astorga, 1987; Erlich et al., 1996), the central Caribbean Deep Sea Drilling Project (DSDP) sites (Saunders et al., 1973), Colombia (Zumberge, 1984; Mann and Stein, 1997; Villamil and Arango, 1998; Villamil, 1999; Villamil et al., 1999), western and eastern Venezuela (Hedberg, 1931, 1937; Talukdar et al., 1988; Alberdi and Lafarge, 1993; Talukdar and Marcano, 1994), Trinidad (Rodrigues, 1988; Requejo et al., 1994), and the Guyana-Suriname Basin (Berger and von Rad,

1972; Lawrence and Costner, 1985). The lithologies of these units are highly variable; however, a general pattern can be observed.

In the post-Albian record, siliciclastic rocks are predominant in the Guyana-Suriname Basin and Trinidad, the southern parts of the Guarico and Maturin Subbasins of eastern Venezuela, the Barinas-Apure Basin of western Venezuela, the Llanos, Magdalena, and Bogotá Basins of Colombia, and the post-Santonian of the central Caribbean (Figure 2). Carbonates or biogenic siliceous rocks (cherts, radiolarites) are dominant in the northern parts of the Eastern Venezuela Basin, the Maracaibo Basin, and the Tempisque Basin. We believe there is ample evidence to demonstrate that these variations were controlled by specific locally modulated tectonic, climatic, oceanographic, and ecologic variables that can be linked to more regional events.

Constraints on Paleogeographic Reconstructions

Inherent in all the paleogeographic reconstructions presented in this paper is a degree of uncertainty regarding the predeformational paleogeography of the study area. Compressive and transpressive deformation had the most significant impact on Late Cretaceous paleogeographies. Reconstructions could not be done without at least some attempt to determine the amount of crustal shortening (thin- or thick-skinned) that had occurred in each part of the study area (Erlich et al., 1999a).

In addition to unresolved estimates of crustal shortening, standard lithostratigraphic correlations of sequence bounding surfaces have caused confusion about issues such as estimates of original stratigraphic thickness and paleobathymetry. Condensed or unconformable surfaces produced in shallow-water settings may have correlative, conformable surfaces in deep-water settings that cannot be defined based on lithostratigraphic relationships. In these instances, chronostratigraphy, developed using a detailed biostratigraphic database, allows for a more accurate construction of original stratigraphic thicknesses for structural modeling (e.g., Villamil, 1998).

Costa Rica

There are no published estimates for thin- or thick-skinned thrusting in the Tempisque Basin area. Seismic data from the Golfo de Nicoya (center of the basin; Figure 1) show some basement-involved thrusting; determining the exact amount of post-Cretaceous shortening is very difficult. However, a value of 10 km of west-east shortening can be estimated for the
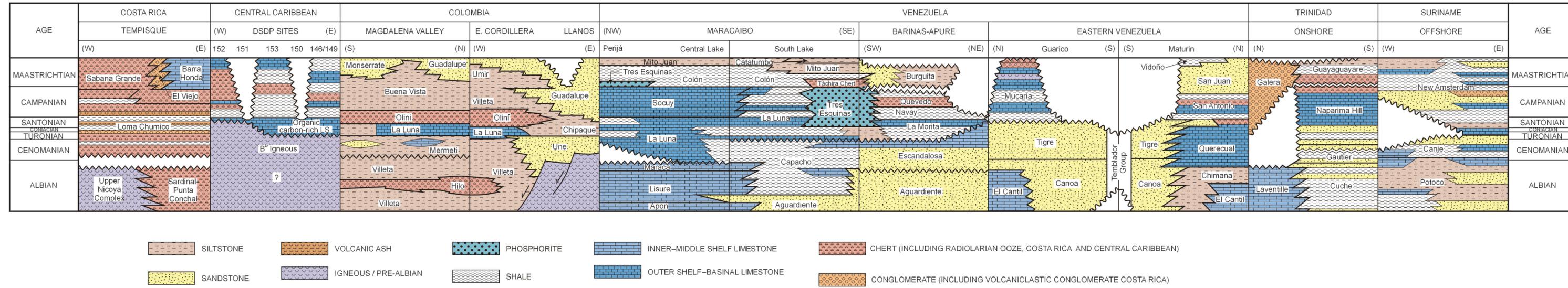
Figure 2. Chrono-lithostratigraphic columns for the Albian-Maastrichtian for key parts of the study area.

Tempisque Basin based on the deformation of Tertiary volcaniclastic units. This estimate is highly speculative nonetheless and can be regarded only as a minimum value.

Central Caribbean

Single-channel seismic data from the central Caribbean (Saunders et al., 1973) do not indicate significant shortening of igneous basement below the Cretaceous and Tertiary sedimentary cover. However, the overall size and shape of the Caribbean has been altered by the Tertiary formation of the Yucatán and Grenada Basins (Bouysse, 1988; Pindell and Barrett, 1990). The Nicaraguan Rise also is not considered part of the Caribbean Plate in the pre-Tertiary reconstructions of Pindell and Barrett (1990). Internal extension in the Colombian and Venezuelan Basins is difficult to estimate but here is considered to be at least 50 km in each basin. Removing the extension of these basins is tenuous but yields a reconstructed Caribbean Plate reduced in length (west-east orientation) by 200 km.

The original width of the plate is even more difficult to determine as a result of Tertiary subduction and underplating in northern South America and along the Greater Antilles. In addition, basement-involved imbricate thrusting in Cuba significantly shortened the ancestral Cuban island arc (Pindell and Barrett, 1990). Therefore, no attempt was made to estimate the original width (north-south orientation) of the Caribbean Plate, although migration of the Caribbean through the Colombia-Guatemala "gap" (Pindell and Barrett, 1990) and its origin in the eastern Pacific (Duncan and Hargraves, 1984; Mattson, 1984; Mann and Corrigan, 1990) is generally preferred to a less mobile model (Frisch et al., 1992).

Colombia

The structural history of Colombia is very complex, mainly because of its location in the northwest corner of South America, where three plates have interacted over long periods of geologic time. In order to understand the basin dynamics and depositional history of the Cretaceous of Colombia, it is necessary to account for post-Cretaceous tectonic events that affected the region. The geological history of Colombia has been punctuated by two significant orogenies that occurred after the deposition of the La Luna source rock interval and coeval facies. These orogenies (the pre-Andean and Andean) uplifted vast areas of the northwest corner of South America. These uplift events terminated a depositional system dominated by marine sedimentation and initiated a period of mostly fluvial and continental deposition in emergent areas.

During the late Miocene, the Andean orogeny inverted a large north-south elongated Jurassic to Cretaceous graben, producing the Eastern Cordillera (Cooper et al., 1995; Linares, 1996; Figure 1). This orogeny also reactivated Late Jurassic to Early Cretaceous extensional faults into thrust systems that bound the present-day Eastern Cordillera (Figure 3); these thrust systems bring Cretaceous strata, including the Albian-Santonian black shale sequences, to the surface.

The Eastern Cordillera is currently bounded by thrust-fault systems on the eastern and western margins (Figure 3). Eastern faults dip west (Guaicaramo–Borde Llanero thrust systems) and western faults dip east (Honda, Cambao, and Bituima thrust systems), thus structurally creating a large "pop-up" feature. In general terms, western faults are older than eastern faults and have a more complex tectonic history. Shortening values for the Eastern Cordillera of Colombia vary from 60–70 km (Cooper et al., 1995; Linares, 1996) to 100–150 km of complete shortening (Dengo and Covey, 1993) to 270 km (Roeder and Chamberlain, 1995). Differences in shortening values are the consequence of different views about the original configuration of the Eastern Cordillera Cretaceous graben and about the dips of the frontal thrusts east and west of the mountain range. Estimates of shortening also have been derived from the analysis of the Santa Marta–Bucaramanga strike-slip fault. The apparent left-lateral displacement of this fault system is absorbed by shortening, mainly in the eastern foothills of the Eastern Cordillera. Slip values for this fault system, however, are based on questionable data and are considered unreliable. Shortening values of 60–100 km in our opinion are reasonable and consistent with the current understanding of the mountain belt.

Western and Central Venezuela

Estimates of crustal shortening in western Venezuela have been summarized recently in Erlich et al. (1999a). Total shortening as a result of strike-slip motion is estimated to be 165 km of northward displacement and 90 km of eastward displacement. Total thrust-induced, northwest-southeast crustal shortening is estimated to be 110 km (Kellogg, 1984; Audemard, 1991; Colletta et al., 1997). In central Venezuela estimates of crustal shortening as a result of thrusting and emplacement of the Caribbean Nappes
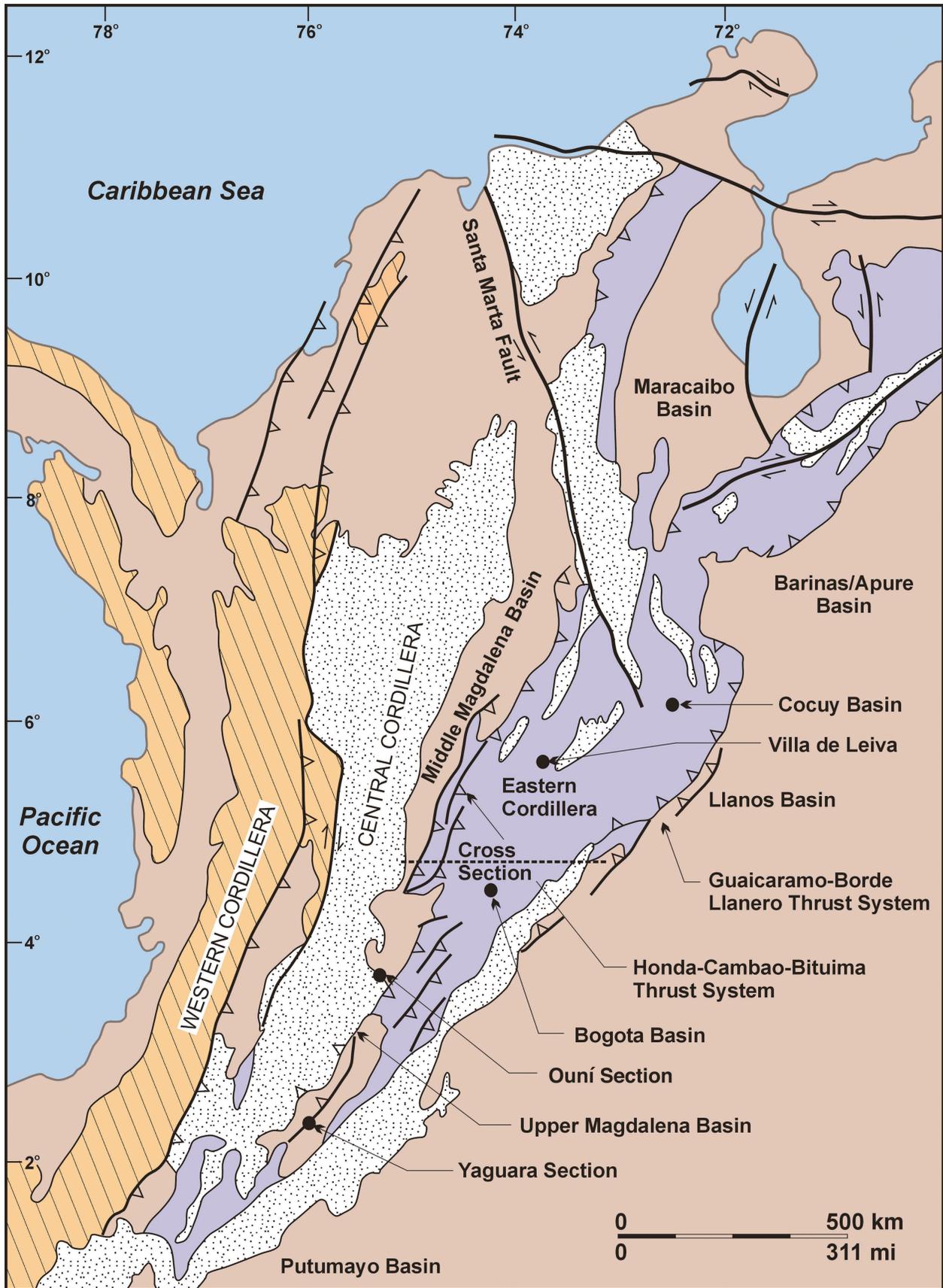
Figure 3. Location map for cross section 1 (Figure 6) and Figures 15 and 16. Stippled pattern = basement uplifts; lined pattern = accreted terranes; dark blue shaded areas = inverted sedimentary basins.

vary from 40–150 km (Beck, 1978; Stephan, 1985; Pindell and Barrett, 1990). Based on the available data, we estimate total crustal shortening along the northern and western Guarico area (Figure 1) to be at least 100 km.

Eastern Venezuela and Trinidad

Rossi et al. (1987) and Roure et al. (1994) estimated the amount of crustal shortening in eastern Venezuela to be 40–80 km, while Passalacqua et al. (1995) estimated the amount of shortening to be 70 km. Additional shortening as a result of strike-slip faulting that exists at thrust ramps may be as much as 40 km (Munro and Smith, 1984). Reconstructions presented in this paper, therefore, were made using a value of 80–120 km of shortening for eastern Venezuela.

In Trinidad, Algar and Pindell (1993) used field observations to estimate as much as 100 km of northwest-southeast shortening for the Cretaceous-Paleogene units found south of the Northern Range. This esti-

mate was made without the benefit of more recent multichannel seismic data (see Figure 4), which show that the younger Paleogene and Neogene strata are partially decoupled from older Paleogene and Cretaceous rocks. A revised range of 40–50 km of shortening, therefore, can be more accurately determined for the Cretaceous units. This also is consistent with estimates of shortening that can be derived from the data of Flinch et al. (1999).

Guyana–Suriname Basin

The lack of high-quality multichannel seismic data in the Guyana–Suriname Basin has led to great speculation surrounding the deformational history of the area (Gouyet, 1988; Pindell and Barrett, 1990). Seismic data collected in 1999 by Burlington Resources show that extension and transtension were the primary modes of deformation of the basin, and that most of the major active and passive deformation occurred prior to the Aptian. Passive margin-style vertical subsidence, rather than lateral offset,
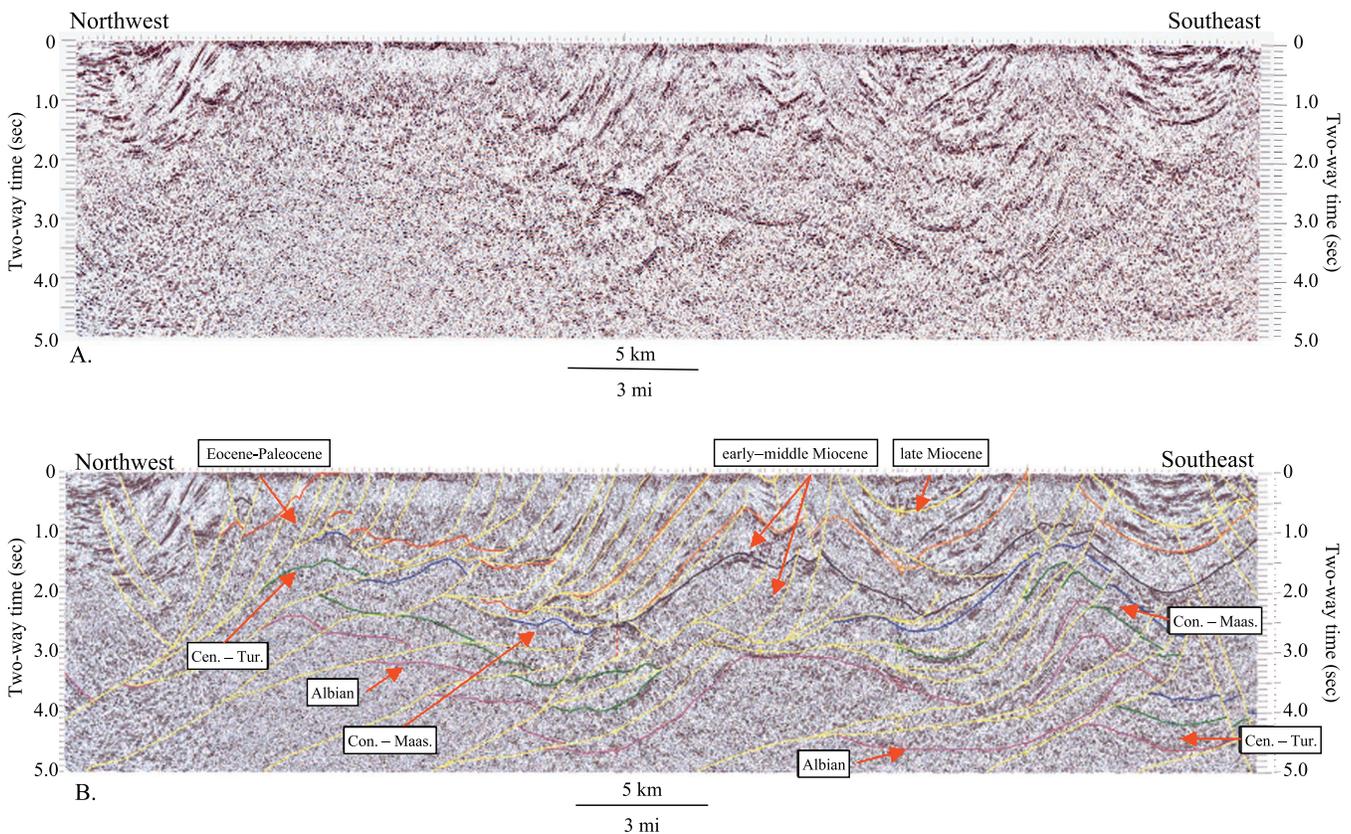

Figure 4. (A) Uninterpreted migrated time section (seismic Line 1) across Trinidad (see Figure 10 for location). (B) Interpreted migrated time section showing imbricate thrusting within the Cretaceous-Paleogene and Neogene. Faults are shown in yellow. Note the high number of imbricates interpreted within the Neogene on the northern end of the line relative to underlying Cretaceous-Paleogene thrusting. Cen. – Tur. = Cenomanian-Turonian. Con. – Maas. = Coniacian-Maastrichtian.

had the greatest impact on Albian-Maastrichtian sedimentation patterns. Paleogeographic reconstructions for this area, therefore, do not incorporate significant lateral or vertical displacement.

SETTING THE STAGE: IMPACT OF ALBIAN-CENOMANIAN CLIMATIC AND OCEANOGRAPHIC CHANGES

Climatic and oceanographic changes that occurred during the middle to late Albian had a major impact on the physical structure of the Tethyan ocean and, consequently, on marine biodiversity. These changes set the stage for the deposition of Cenomanian-Santonian organic carbon–rich sediments over southern Central America, the central Caribbean, and northern South America.

An increase in global sea-surface temperatures that began during the Aptian reached its maximum extent in the middle Albian (Frakes, 1999). The sudden drop in sea-surface temperatures that immediately followed triggered a change from dominantly eutrophic to dominantly oligotrophic conditions in the water column (Premoli Silva and Sliter, 1999). Planktonic foraminiferal diversity expanded rapidly in the stratified ocean with the establishment of a strong thermocline, and the Tethys and central North Atlantic for the first time exhibited characteristics typical of a ''modern'' ocean. The lithostratigraphy of northern South America records this dramatic shift from a well-mixed to a stratified water column (Figure 2). However, as the Tethys evolved during the Late Cretaceous, eutrophic to oligotrophic conditions shifted several times (Premoli Silva and Sliter, 1999), while shelf and slope areas from the proto-Costa Rican island arc to Suriname largely maintained an oligotrophic setting.

Costa Rica and the Central Caribbean

The proto-Caribbean Plate was a site of extrusive submarine volcanism during the Albian (Pindell and Barrett, 1990), typified by pillow basalts of the Nicoya Complex of Costa Rica (Erlich et al., 1996, p. 692–694; Figure 5). Basalts and dolerites associated with the B″ seismic event in the Venezuelan Basin (central Caribbean) may be no older than Turonian, but are floored by much older rocks (Saunders et al., 1973). Sedimentary rocks of this age are unknown from the central Caribbean. However, the Sardinal and Punta Conchal cherts (Albian) of Costa Rica reflect deposition of radiolarites adjacent to Pacific oceanic plateaus (Erlich et al., 1996).

Colombia

The pre-Albian Cretaceous strata of Colombia were deposited during the terminal rifting phase of continental margin formation. During this phase, Cretaceous strata were deposited over mainly nonmarine prerift or synrift strata. Sediment accumulation was restricted to sites of active basin subsidence that generally were located near sites of maximum crustal stretching. Later passive-margin deposition during the Hauterivian–early Albian was dominated by marine sedimentation that was punctuated by short periods of strong regression. Hauterivian–early Albian deposition was relatively continuous in the depocenters, and no major paleogeographic changes occurred over those areas (Figure 5). In other regions (e.g., the Upper Magdalena Valley; Figure 1), changes in paleogeography were quite profound because the entire region had been subaerially exposed for much of the early Mesozoic prior to burial by Cretaceous continental and marine units.

Marine conditions in the Upper Magdalena Valley were established after a series of transgressive episodes, represented by a diachronous transgressive surface above the pre-Albian section. The base of marine depositional systems in the Upper Magdalena Valley is approximately 25 m.y. younger than the base of similar units in the depocenters around the Bogotá, Cocuy, and Middle Magdalena basins (Figure 6), indicating major differences in basin evolution between the regions. Marine shales and claystones were deposited above the aforementioned transgressive surface. Shale deposition was interrupted by an abrupt regressive episode that caused the deposition of prograding sandstones of the westerly derived, early Albian Caballos Formation (Figure 6). Similar stratigraphic relationships occurred in other regions of Colombia during this time. In northeastern Colombia and western Venezuela, the transgression is expressed by the Rio Negro–Aguardiente–Capacho succession. In rapidly subsiding depocenters like the Bogotá and Cocuy Basins, this transgression and the punctuated regressions are difficult to identify because those regions were dominated by shale deposition, and most stratigraphic relationships have to be determined from shale-over-shale successions.

The stratigraphy represented by the early Albian–late Coniacian consists primarily of organic-rich shales cyclically interbedded with hemipelagic limestones in basinal settings and sand-rich facies near the sites
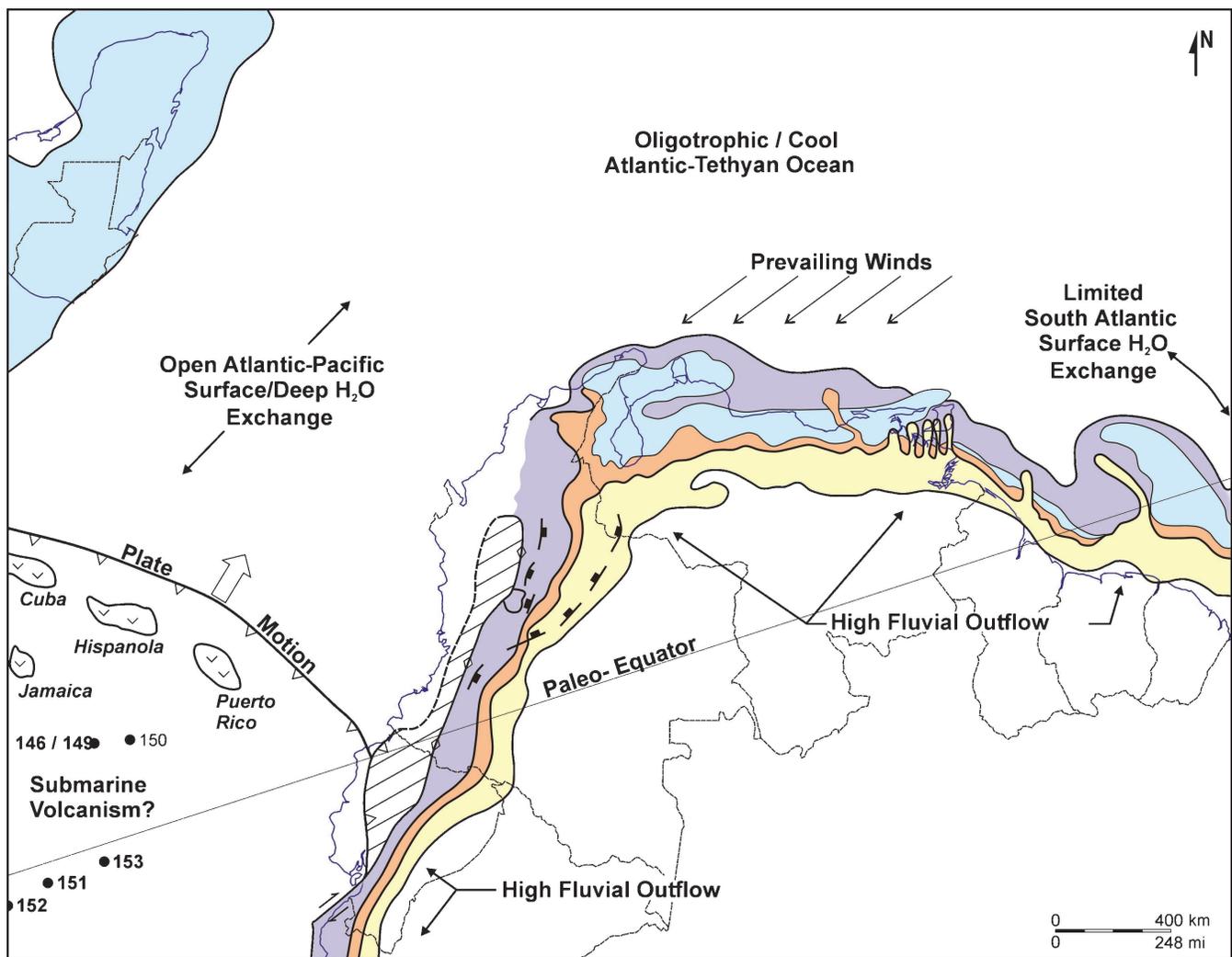
Figure 5. Mid to late Albian paleogeography of the study area. Yellow = continental to nearshore marine siliciclastics; orange = inner to middle shelf fine-grained clastics and carbonates; blue = inner to outer shelf carbonates; purple = outer shelf to slope shales; v = island arc volcanics; cross-hatched pattern = area uplift and erosion.

of sediment provenance. Regional thickness of this portion of the Cretaceous is relatively uniform (approximately 2.5 km), with no dramatic thickness or facies changes across faults, as with previously discussed units. Deposition of the principal Cretaceous source rocks occurred during this phase, but the richest levels, in terms of organic carbon, are associated with the middle Albian, the Cenomanian-Turonian, and the late Coniacian–early Santonian OAEs that coincide regionally with maximum flooding surfaces (Villamil, 1998; Rangel et al., 2000). The Albian-Santonian epicontinental seaway was open to the Pacific and flooded most, if not all, areas of the ancestral Central Cordillera (Figure 5). Sediment supply for Albian-Santonian times came primarily from the Guayana Shield east of the basin and, prob-

ably, from the Central Cordillera at times of sea-level lowstand.

Western Venezuela

Shallow shelf-platform carbonates of the middle to late Albian Lisure and late Albian Maraca Formations extended from the northwestern Maracaibo Basin toward the south, where they graded into pro-delta shales of the Capacho Formation and nearshore siliciclastics of the Aguardiente Formation (Erlich et al., 1999a; Figures 2 and 5). Equivalent nonmarine siliciclastic sediments were deposited over most of the Barinas-Apure and Guarico Basins during this time (Arnaud et al., 1999; Erlich et al, 1999a). This relatively stable shelf environment began to change toward the end of the Albian, reflected in a rapid
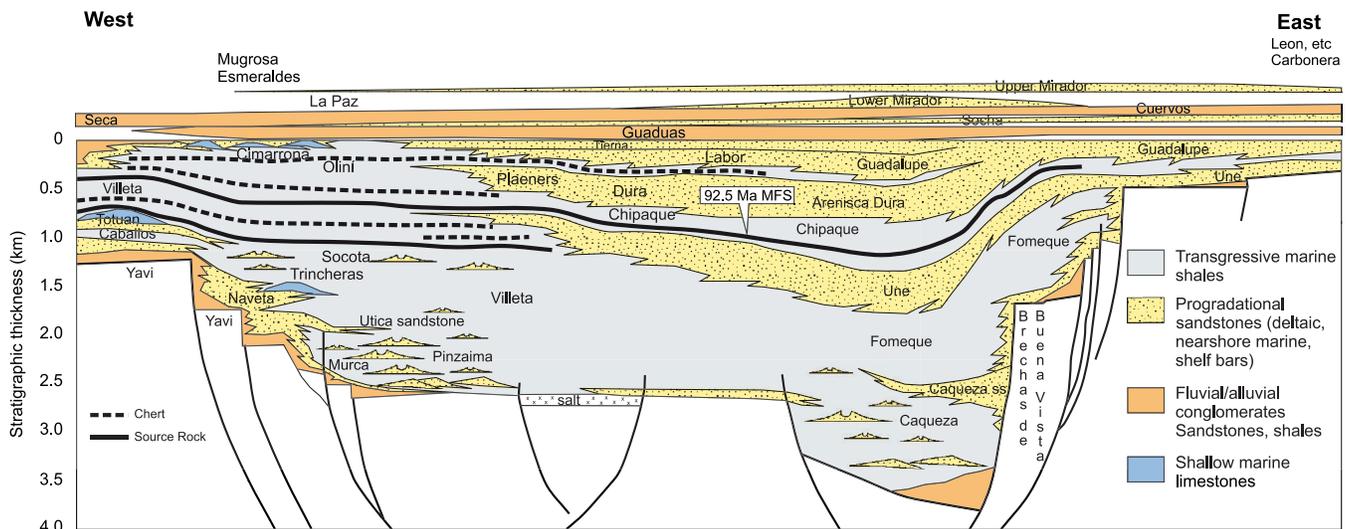
Figure 6. Predeformation west-east cross section through the Bogotá area showing the lateral distribution and provenance of Cretaceous siliciclastic units. Significant syndepositional Early Cretaceous growth faulting occurred parallel to a north-south-oriented graben (inverted during the Miocene). Stratigraphic thickness corresponds to the thickness of the Cretaceous section only (datum: Top Cretaceous). Similar syndepositional faulting occurred along the southwestern part of the ancestral Mérida Andes, Barinas-Apure Basin.

marine transgression and a shift of shallow-water facies toward the southeast.

Drowning of the late Albian Maraca Formation carbonate platform was caused by nutrient poisoning as inner shelf and terrestrial areas were flooded (Erlich et al., 1999b). Limited upwelling of anoxic bottom waters also may have contributed to platform drowning (Macellari and De Vries, 1987; Martínez and Hernandez, 1992; Villamil et al., 1999), but this is regarded as a secondary and possibly later effect of the initial transgression and climate shift that began in the middle Albian (Frakes, 1999). Cool, humid conditions that persisted over much of western Venezuela during the middle Albian–middle Cenomanian were replaced by hot, arid conditions in the late Cenomanian (Erlich et al., 1999b). Fluvio-deltaic sedimentation that had been common during the deposition of Capacho Formation prodelta shales ceased and was not reestablished until the Campanian.

Eastern Venezuela, Trinidad, and Suriname

Shallow-shelf carbonates of the El Cantil Formation covered most of eastern Venezuela and western Trinidad (Laventille Formation) during the middle Albian and graded southward (landward) into equivalent siliciclastics (Prieto, 1987; Di Croce, 1995; Villamil and Pindell, 1998; Di Croce et al., 1999; Figure 5). The El Cantil–Laventille carbonate platform continues toward the southeast in Guyana and Suriname as the Potoco Formation, where massive sandstones

and shales are more common in the lithologic section (Lawrence and Costner, 1985; Wong, 1998). The siliciclastic sediments changed facies seaward (northward) to shallow-shelf and platform carbonates in central offshore Suriname and on the Demerera High (Figures 5–8). However, beginning in the middle Albian, a major change in depositional environment occurred in eastern Venezuela and Trinidad.

Deposition of the Chimana Formation in eastern Venezuela and the middle part of the Cuche Formation in Trinidad marked the end of shallow-water carbonate platform sedimentation during the Mesozoic (Bolli et al., 1994; Villamil and Pindell, 1998; Figures 2 and 9). These units were deposited at first in forereef/slope environments; however, near the end of the middle Albian, Chimana and Cuche siltstones and shales transgressed the El Cantil–Laventille shelf as sea level rose and flooded the platform (Prieto, 1987; Di Croce, 1995; Di Croce et al., 1999; Sanchez, 2001). Basal Chimana Formation biofacies are characterized by benthonic foraminifera (including "low oxygen opportunists") (Bernhard, 1986; Ly and Kuhnt, 1994), ammonites, belemnites, rare mollusks, and echinoids, all typical of an intermittently oxygenated water column. However, biofacies from the upper parts of the Chimana are characterized by floods of calcispheres and *Heterohelix* sp. planktonic foraminifera, sponge and echinod spines, rare benthonic foraminifera, radiolaria, and fragments of shallow-water fauna (corals and calcareous algae). The presence of calcispheres, opportunistic planktonic and
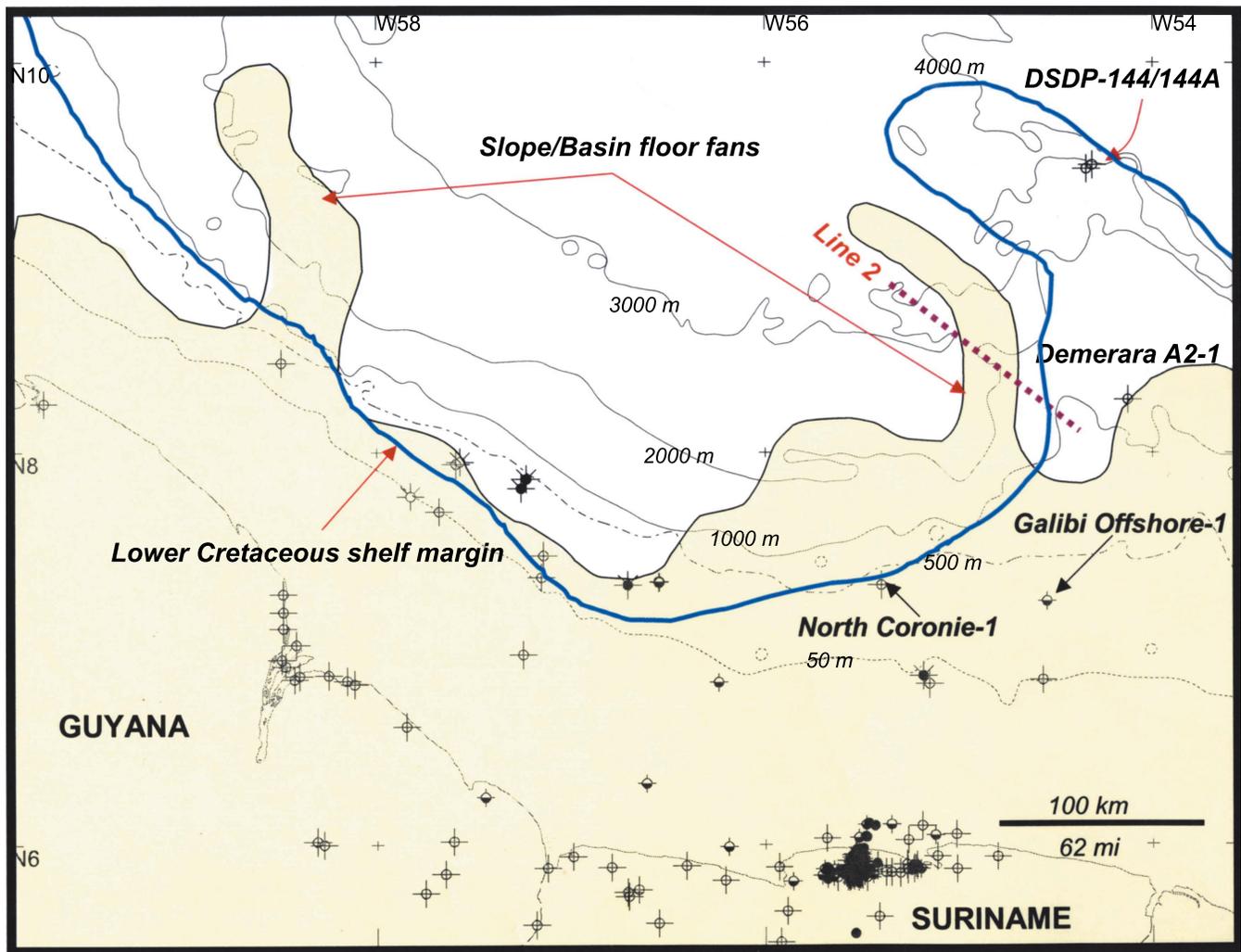
Figure 7. Albian-Turonian paleogeography of the offshore Guyana-Suriname area showing siliciclastic shelf and submarine fan deposits (yellow shaded). Blue line is the location of the Lower Cretaceous shelf margin. Submarine fan deposition was not widespread. Nonetheless, geographically confined drainage produced extensive shelf and basinal deposits in some areas. Line 2 is Figure 23.

benthonic foraminifera, and sponge spicules and echinoid spines indicate unstable nutrient levels in the water column, with at least intermittent intervals of low oxygenation (Erlich et al., 1999a; Premoli Silva and Sliter, 1999).

It should not be surprising that nutrient and oxygen levels in the water column were unstable during the latter stages of Chimana and Cuche deposition. Indeed, flooding of the El Cantil–Laventille platform must have released large amounts of organic carbon sequestered in coeval terrestrial clastics and probably contributed to the demise of shallow-water platform sedimentation (Hallock and Schlager, 1986; Erlich et al., 1993; Di Croce, 1995; Erikson and Pindell, 1998; Di Croce et al., 1999; Villamil et al., 1999; Sanchez, 2001). Platform carbonate sedimentation was similarly terminated by Canje Formation silt-

stones and shales in the Guyana-Suriname area (Figures 2 and 8).

Flooding of the shallow-carbonate platforms and the onset of surface-water exchange between the Tethys and South Atlantic had an impact on global paleotemperatures and thermohaline circulation. Diversity of planktonic foraminifera increased sharply during the late Albian, an indication that the Tethys had returned to a thermohaline state (Premoli Silva and Sliter, 1999). This diversity spike, plus the appearance of opportunistic specialist foraminifera such as those that comprise the *Rotalipora ticinensis* Zone support the existence of a stratified water column in the late Albian, possibly the result of increased midlatitude bottom-water formation (Brass et al., 1982; Hay, 1988; Premoli Silva and Sliter, 1999; Voigt et al., 1999).

The rapid release of nutrients that occurred during sea-level rise, coupled with increased water-column stratification, may have produced elevated levels of primary productivity, especially adjacent to the shelf-slope break along the West African and northern South American margins (Hofmann et al., 1999). Large amounts of CO_2 were sequestered in the sedimentary section through burial of organic carbon (Weissert et al., 1998); this led to rapid cooling at low latitudes in the late Albian–middle Cenomanian (Frakes, 1999). The result of this cooling was an increase in precipitation in northern South America, especially in northeastern South America, where large drainage systems transported siliciclastic sediments into deep water (Figures 5–11). Submarine fan deposition continued in the Trinidad to Suriname area, punctuated by brief dry periods (with little siliciclastic sedimentation), through the middle Coniacian.

DEPOSITION OF LATE CENOMANIAN–LATE SANTONIAN ORGANIC CARBON–RICH STRATA

The return of eutrophic conditions during the late Cenomanian signaled the first of several reversals in water-column stratification (Premoli Silva and Sliter, 1999) and the onset of regional upwelling in northern South America. Bottom-water exchange between the Atlantic and Pacific through the proto-Isthmus of Panama was probably restricted or impaired by formation of the ancestral Greater Antilles and Costa Rica–Panama island arcs (Figure 12). Surface-water exchange between the Atlantic and Pacific was more common (Johnson, 1999), as it was between the North and South Atlantic. Exchange of deeper intermediate or bottom waters between the North and South Atlantic probably did not occur until the Santonian (Wonders, 1980; Kennett, 1982; Premoli Silva and Sliter, 1999).

Eutrophic conditions in the Atlantic/Tethyan Ocean that were established in the middle Cenomanian were disrupted by the onset of cyclic oligotrophic/eutrophic conditions in the water column (Premoli Silva and Sliter, 1999). Elevated eustatic sea level (Haq et al., 1987, 1988), nutrient flux, and sea-surface temperatures combined to make the late Cenomanian–Turonian the most extensive period of organic matter deposition since the Aptian-Albian. Marine rocks that span the uppermost Cenomanian–lowermost Turonian stratigraphic interval exhibit widely distributed anomalous lithologic, geochemical, and faunal characteristics (Schlanger et al., 1987). Many stratigraphic sections of this interval are composed of dark, laminated, organic-rich shales interbedded with pelagic limestones or marlstones. Facies deposited during the latest Cenomanian–earliest Turonian are contemporaneous with a proposed global OAE (Schlanger and Jenkyns, 1976; Kuhnt et al., 1986; Kauffman, 1988; Jarvis et al., 1988; Hart and Leary, 1989; Gale et al., 1993). The Cenomanian-Turonian OAE has been interpreted as the result of increased organic carbon burial worldwide by Arthur et al. (1988) and is characterized worldwide by a series of pulses or steps of trace- and rare earth–element enrichment (Orth et al., 1993). Iridium and nickel enrichment peaks are among the most characteristic and are distributed widely; they occur as excursions of elemental assemblages in the geochemical record rather than as peaks of a single element.

The subsequent drawdown in atmospheric CO_2 caused by deposition of large amounts of organic matter eventually acted to cool sea-surface temperatures during the latest Turonian–Coniacian (Frakes, 1999). This resulted in a shift to seasonal upwelling during the Coniacian-Santonian and was marked by fluctuating wet/dry cycles, increased wind stress, and episodic siliciclastic input into slope and basinal depositional environments (Kruijs and Barron, 1990; Barron et al., 1995; Bush and Philander, 1997; Mikolajewicz and Crowley, 1997). Intensification of the easterly trade winds established regional upwelling along the eastern Pacific equatorial upwelling zone (EPEUZ of Erlich et al., 1996). Seasonal upwelling was not strong in western Venezuela until the early Santonian (Erlich et al., 1999b, 2000), although some upwelling may have occurred during the late Turonian–early Coniacian (Macellari and De Vries, 1987; Davis et al., 1999). Most of the global and local Coniacian-Santonian climatic and oceanographic changes can be linked to Milankovitch cyclicity (Herbert et al., 1995, 1999).

Costa Rica and Central Caribbean

Paleogeographic reconstructions of the Caribbean Plate suggest that the submarine volcanism that formed the basement of the later Cretaceous sedimentary units in Costa Rica continued within 10° of the equator during the late Cenomanian (Duncan and Hargraves, 1984; Mattson, 1984; Mann and Corrigan, 1990; Pindell and Barrett, 1990). Northward propagation of the Caribbean during the Turonian was accompanied by early paleobathymetric or even subaerial construction of the proto-Greater Antilles Arc and the island arc in Costa Rica and
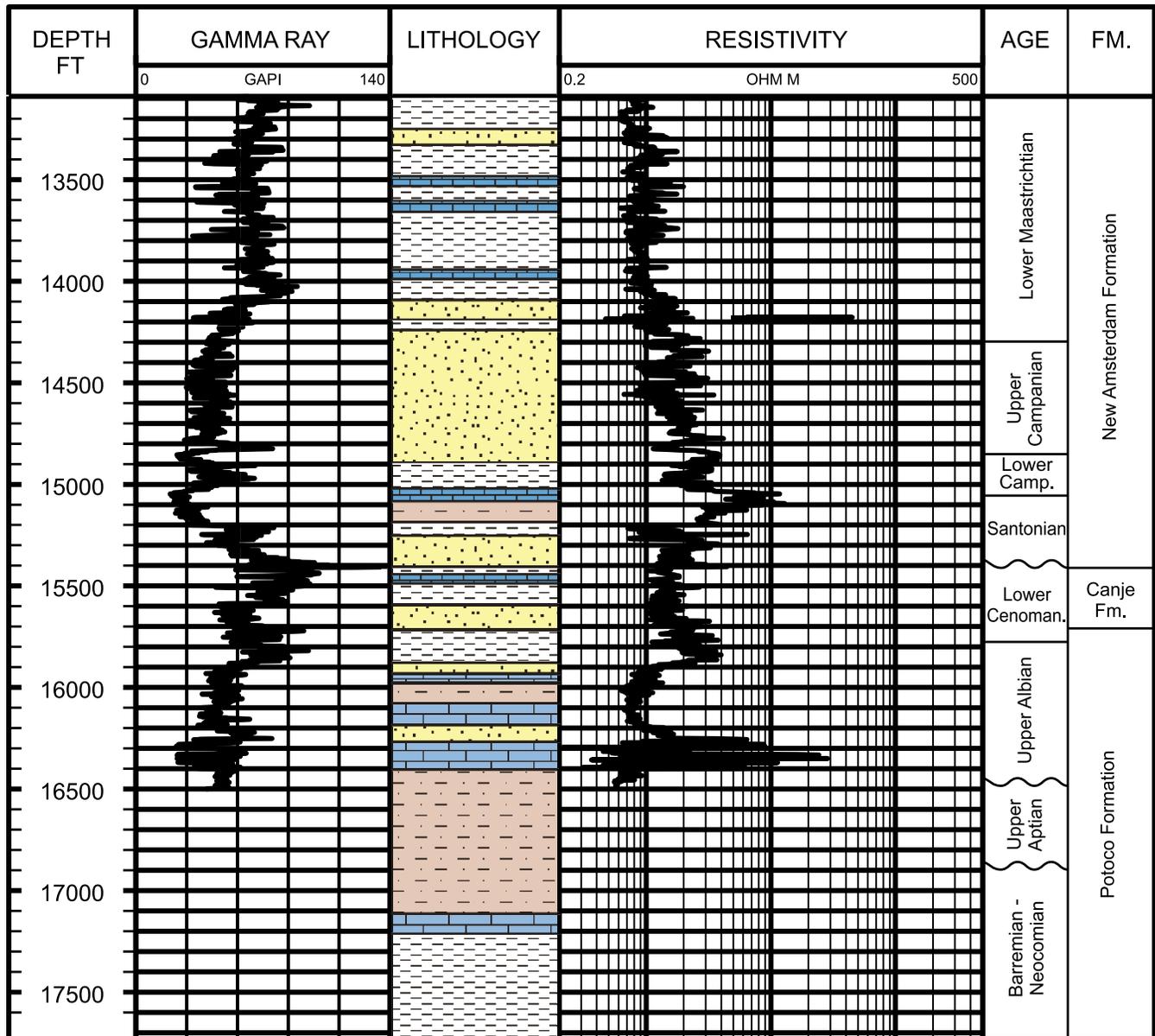
A

Figure 8. (A) Wireline logs, lithologies, formation tops, and ages for the North Coronie-1 well. (B) Wireline logs, lithologies, formation tops, and ages for the Galibi Offshore-1 well. See Figure 2 for pattern and color key. Note that major sandstone intervals extend from the Albian through the Campanian in both wells; however, the thickness and duration of each event generally decrease following the Cenomanian (with the exception of the Campanian shelf sandstones of the North Coronie-1 well). See Figure 7 for well locations, Figure 2 for pattern and color key.

Panama (Figure 12). In the central Caribbean, organic carbon–rich limestones were deposited at DSDP sites 146/149, 150, and 153, while basalts were deposited at sites 151 and 152.

During the Coniacian–early Santonian, the development of seasonal wet/dry cycles and variations in the intensity of the easterly trade winds intensified upwelling along the EPEUZ (Figure 13). Increased nutrient flux and the further development of paleo-

bathymetric barriers at both margins of the Caribbean Plate may have depleted the dissolved oxygen content of this potential stranded-water mass, thereby enhancing the preservation potential of sedimentary organic matter (Figure 14; Erlich et al., 1996).

Loma Chumico Formation radiolarian cherts (organic carbon–rich and carbon-lean) were deposited with volcaniclastic debris flows and volcanic ash in Costa Rica and Panama. Radiolarian and diatom
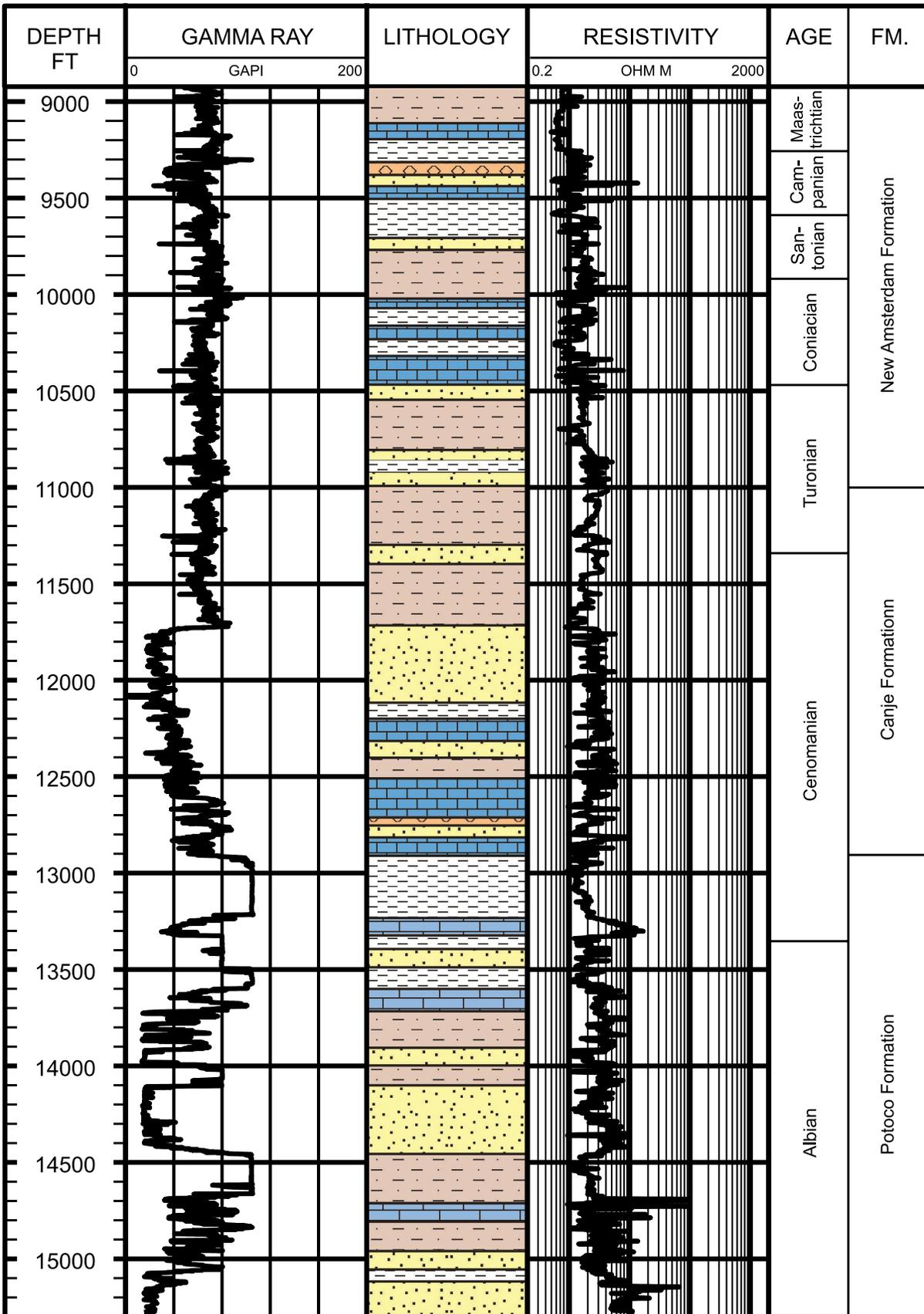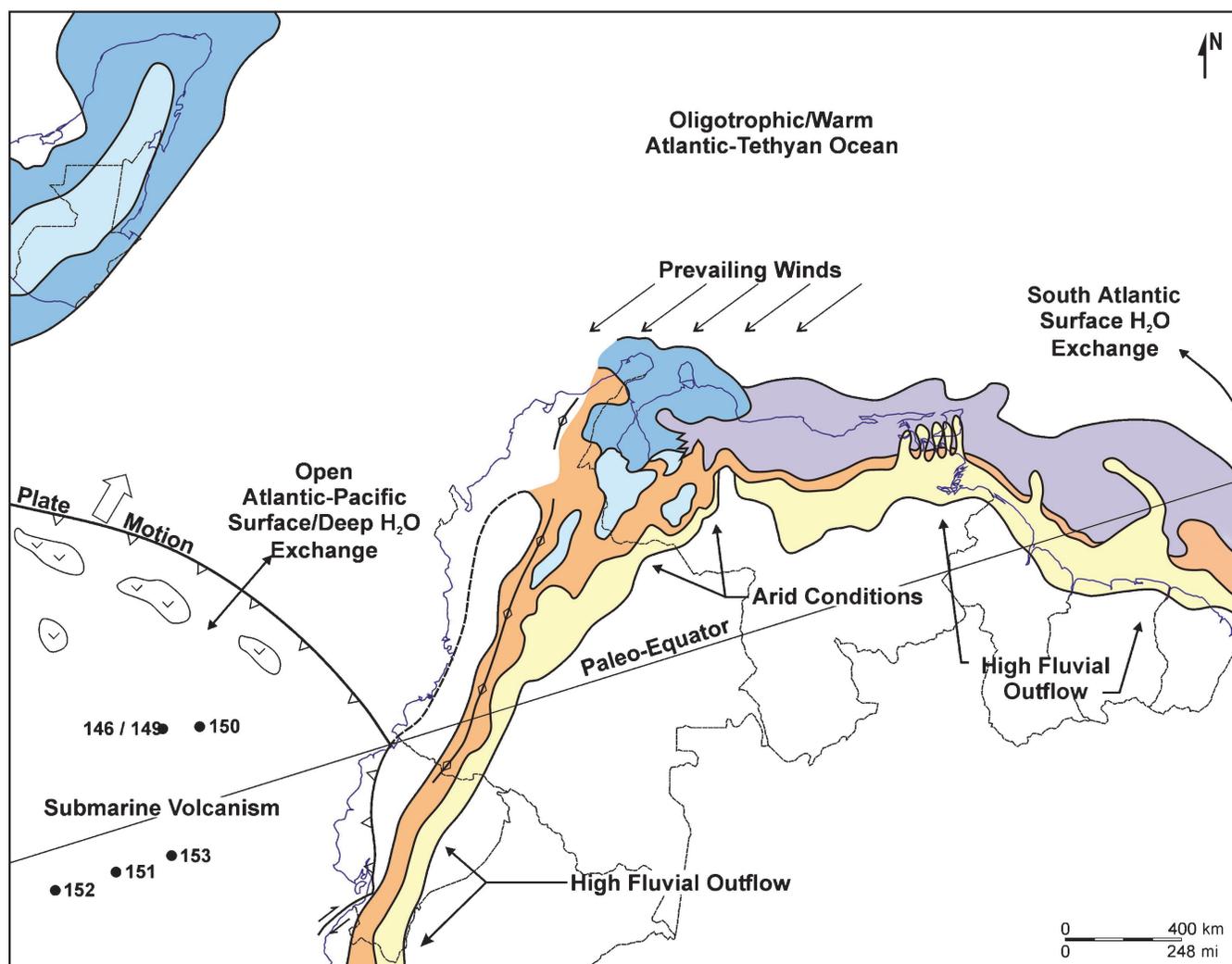
B

Figure 8. (cont.).

Figure 9. Late Albian–middle Cenomanian paleogeography of the study area. See Figure 5 for additional color codes for depositional environments; dark blue = drowned carbonate platform.

productivity benefited from the episodic input of volcanogenic silica, which increased organic matter flux to the sediment surface. Bacterial mediation of, and subsequent contribution to, the organic matter was a very important factor in the accumulation of sediments with postdepositional total organic carbon (TOC) content of more than 33% (Erlich et al., 1996).

Colombia

Evidence for volcanism is rare in Colombian Upper Cretaceous strata, consisting mostly of geographically dispersed groups of closely spaced (vertically) bentonites generally associated with condensed sections. The most significant period of ash bed preservation was during the latest Cenomanian–earliest Turonian, as evidenced by the concentration of more than 78 ash beds bundled in three to four stratigraphic meters at the Cenomanian-Turonian (C-T) boundary in the Upper Magdalena Basin (Villamil and Arango, 1998). Some of these ash beds have been traced throughout the entire country. Additional, but very few, bentonites have been found in different stratigraphic intervals, suggesting that volcanism was active marginally during most of the middle Albian through Santonian. The source of the bentonites is currently unknown, as they could have been transported long distances by oceanic and atmospheric means before deposition.

Cenomanian to Santonian stratigraphy in Colombia records significant changes in physical lithologic characteristics, in paleobiological assemblages and morphotypes, and in geochemistry. These changes allow the interpretation of fluctuations of relative
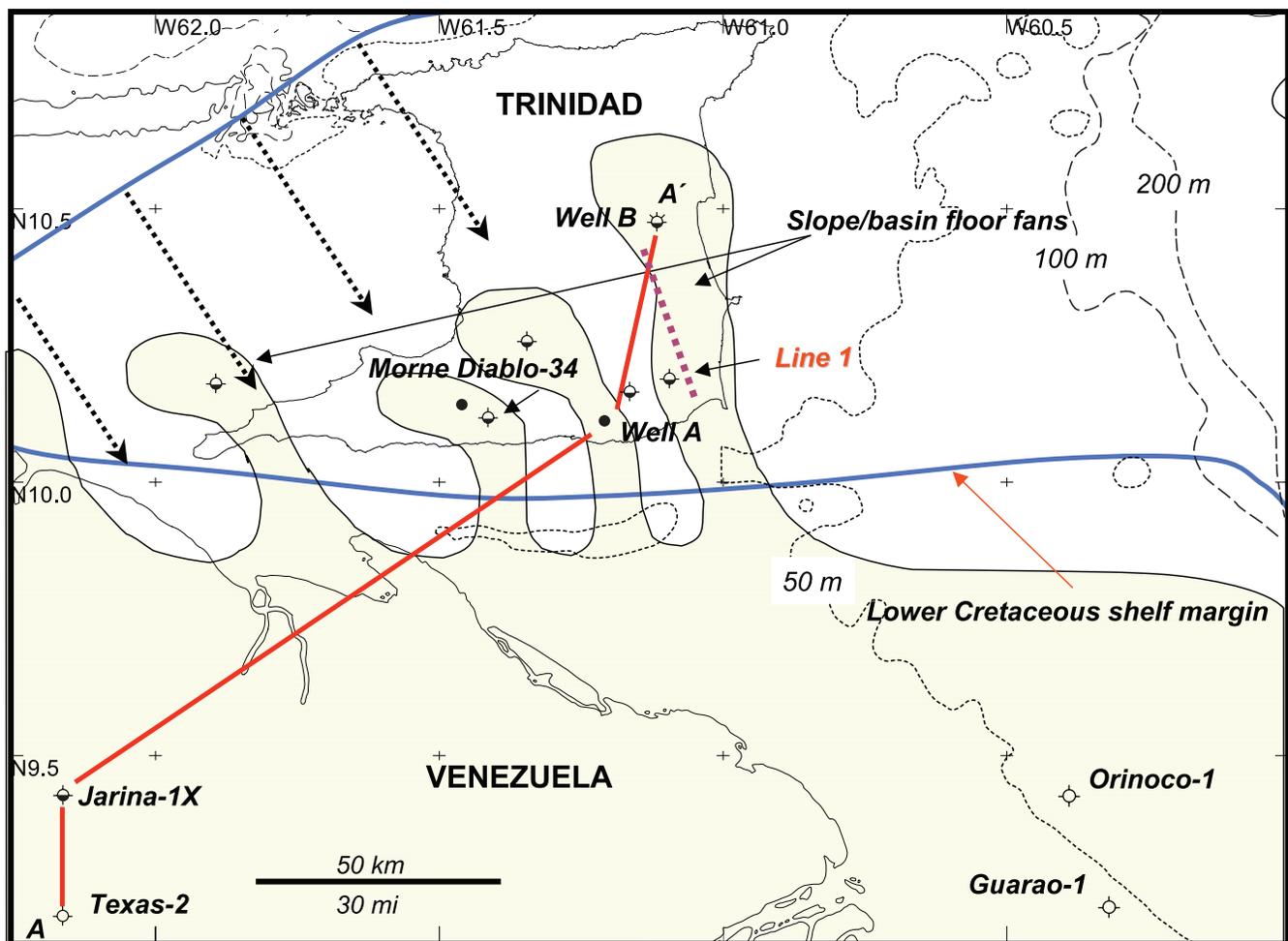
Figure 10. Albian–middle Cenomanian paleogeography of the Trinidad–eastern Venezuela area, showing siliciclastic shelf and submarine fans (yellow shaded). Blue line is the location of the Lower Cretaceous shelf margin. Dotted arrows show the direction and relative amount of Tertiary convergence in the area (original position of the Lower Cretaceous shelf margin used for reference). Line 1 is Figure 4; Cross section A-A′ is Figure 11.

sea level, of sea-surface and sea-bottom conditions, and of paleoceanographic events that affected this part of the northern margin of South America. In summary, from the earliest Cenomanian to Turonian, a marked regional rise in sea level was the main cause of widespread deposition of the La Luna Formation and equivalent units in Colombia and western Venezuela (Figure 15). This rise in sea level enhanced the deposition and preservation of fine-grained, organic carbon–rich strata in regions that were previously covered by oxygenated, relatively proximal sediments (Rangel et al., 2000).

During the late Cenomanian, there is a marked regional sequence boundary below the ''Caliza Mermeti'' (94.5 Ma). This sequence boundary is evident in the Upper Magdalena Valley, where it is expressed as coarse-grained, isolated, lenticular sandstone bodies abruptly overlying claystones (Figure 2). This sequence boundary is also the first appearance of fine-grained sandstones in the Villeta Group. In the Eastern Cordillera, the sequence boundary is represented by the upper sandstone unit of the Churuvita Formation. Near Bogotá, this upper Cenomanian sequence boundary is represented by the coarse sandstones of a unit that is unnamed but known in the literature (i.e., Hubach, 1957) as the ''Exogyra Mermeti limestone'' or ''Caliza Mermeti.'' In the Cocuy region, this boundary is the contact of the upper sandstones of the upper Une Formation with the underlying shales and siltstones (Figures 2, 5, and 6). This sequence boundary is overlain by the lowermost sandstone in the Yaguará section and the unit below the Chipaque Formation in the Cocuy region, and it represents the lowstand systems tract.

A marked transgressive surface (TS) occurs in the latest Cenomanian (93.5 Ma; Villamil and Arango, 1998). This transgressive surface represents a worldwide rapid rise in eustatic sea level (Arthur et al., 1988). In the Upper Magdalena Valley, the TS is represented by starved pelagic limestones resting abruptly over shallow-water sandstones or siltstones (Figure 2). In the Bogotá region (Figure 3), the TS is the contact between the La Frontera Formation and the "Caliza Mermeti." It is composed of pelagic concretional limestones abruptly overlying sandstones rich in shallow-water fauna. In the Villa de Leiva region, the TS is at the contact between the Churuvita and the San Rafael Formations; black organic-rich shales with calcareous concretions lie above shallow-water, thick-bedded sandstones. Black shales overlying lagoonal claystones and coarse-grained sandstones represent the TS in the Cocuy region.

In all of the sections, there is a relatively thin and very condensed transgressive systems tract that represents relative sea-level rise above the discussed TS. The facies reach peak transgression (maximum flooding surface, MFS) in the middle early Turonian (92.5 Ma) and are marked by a condensed section that can be determined lithologically, paleobiologically, and geochemically. This maximum flooding surface/condensed section represents the peak Mesozoic transgression in northern South America. Detailed stratigraphic relationships of this interval are documented from the Oliní section (Figure 15), the location of which is shown in Figure 3. This transgressive systems tract can be traced throughout Colombia into eastern Venezuela and can be correlated with more proximal equivalents (uppermost Une in Colombia, upper Capacho and Escandalosa in western Venezuela, and upper Tigre in eastern Venezuela; Figure 2).

In the Upper Magdalena Valley, Eastern Cordillera, and eastern Venezuela, this MFS is characterized by a highly fossiliferous concretion interval that contains unusually high quantities of fossil wood and a unique assemblage of small fossils (e.g., *Anomia* spp., *Nannovascoceras*, *Anagaudryceras*?). The same association can be recognized in the Bogotá and Villa de Leiva sections. The MFS in the Cocuy region (the most landward section) is represented by two thick (2–3 m), highly fossiliferous limestone beds of the lower Chipaque Formation located between siltstones (Figures 2 and 5). The highest stand of sea level occurred some time after this MFS, most probably during the late early Turonian (92 Ma; *Mytiloides mytiloides–Mytiloides labiatus* interval).

Facies across the C-T boundary (OAE II of Arthur et al., 1988) in Colombia are interpreted as deposited in an episodic but intense upwelling regime, as shown by the scattered occurrence of phosphate-rich shales, chert beds with abundant radiolarians, foraminifera filled with silica, changes in planktic foraminifera populations, high values of TOC (as much as 16%; Oliní reference section of Villamil and Arango, 1998) and anoxic to low-oxygen bottom waters. Episodic upwelling also may explain the very low occurrence of keeled foraminifers (e.g., *Rotalipora*) in the study area. Low concentrations of dissolved oxygen were probably widespread and affected the sediment-water interface and the water column.

Macrofossils and microfossils are, in general, poorly preserved across the C-T boundary because of dissolution. However, fossil preservation is excellent in some intervals of higher sedimentation rate. Complete small fish skeletons are commonly found in the black organic-rich shales, some of which are preserved in three dimensions, occasionally with soft body parts. Benthic macrofossils found across the boundary are low-oxygen-adapted genera such as the bivalves *Inoceramus*, *Mytiloides*, *Sergipia*, *Lucina*, *Phelopteria,* and the brachiopod species *Discinisca* (Harries and Kauffman, 1990; Harries, 1993). All other macrofossils found were nektonic. Trace fossils do not occur in the facies of the transgressive systems tract of distal sections; however, trace fossils in proximal sections consist of small and poorly developed *Thalassinoides* and *Planolites*. In one of the distal sections, there are probable micro-*Chondrites* or *Trichichnus*, but their preservation does not allow specific determination.

The lack or very low abundance of benthonic foraminifera across the C-T boundary also suggests low-oxygen conditions for the sea bottom. Deleterious conditions also were present in the upper water column as indicated by the change from inferred K-selected taxa to r-selected planktonic foraminiferal populations and back to K-selected above the C-T boundary (Villamil, 1998). The presence of heterohelicids and nonkeeled globigerinids suggests low-oxygen conditions in the photic zone (Koutsoukos et al., 1990). Low diversity of planktonic foraminifera at or near the C-T boundary in Europe have been interpreted by Leary et al. (1989) and Jarvis et al. (1988) as the expansion of the oxygen minimum zone (OMZ) in the water column. This interpretation is supported by ammonite data from Colombia; only ammonites that inhabited the uppermost part of the water column are found in the portions of the stratigraphic sections
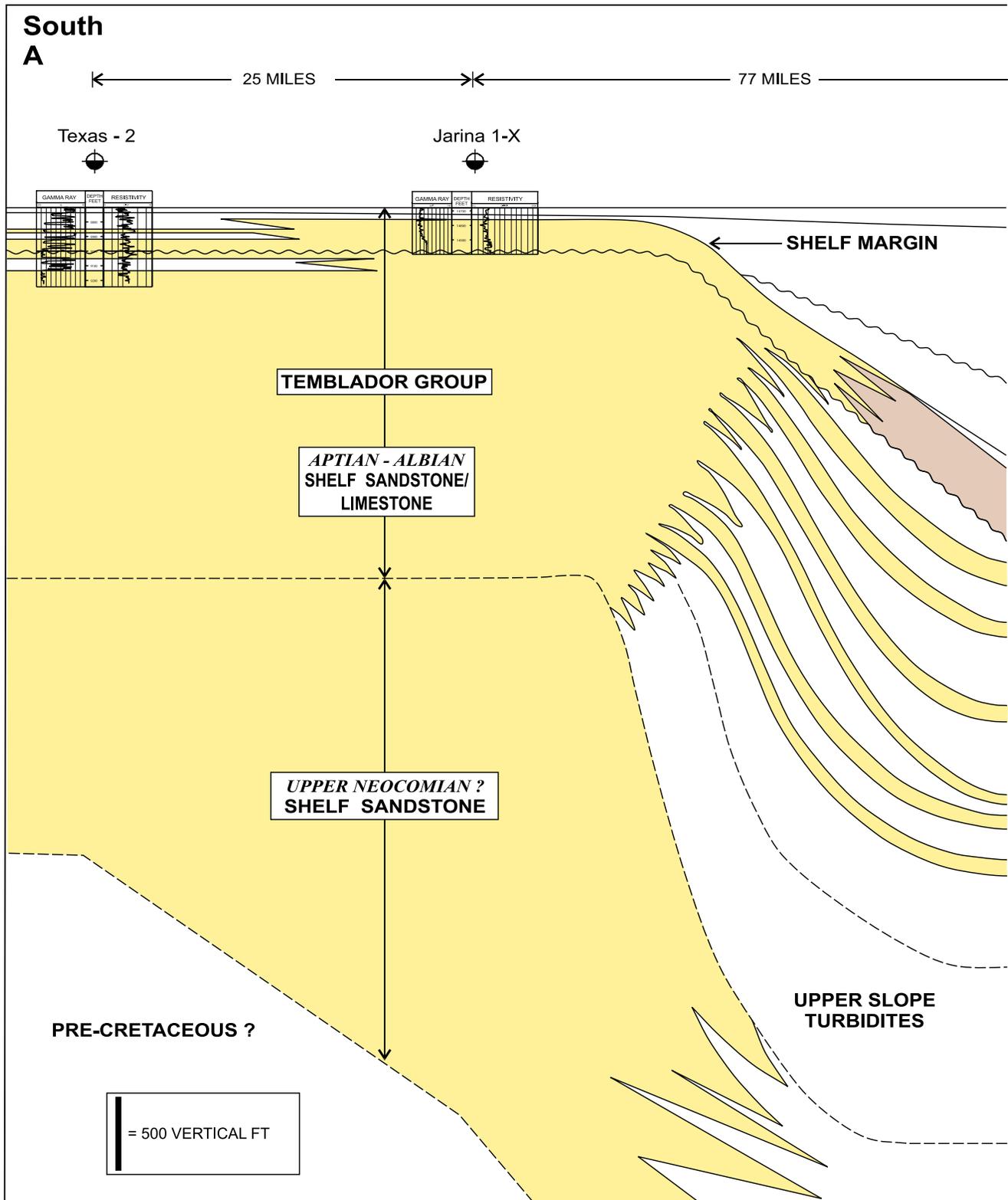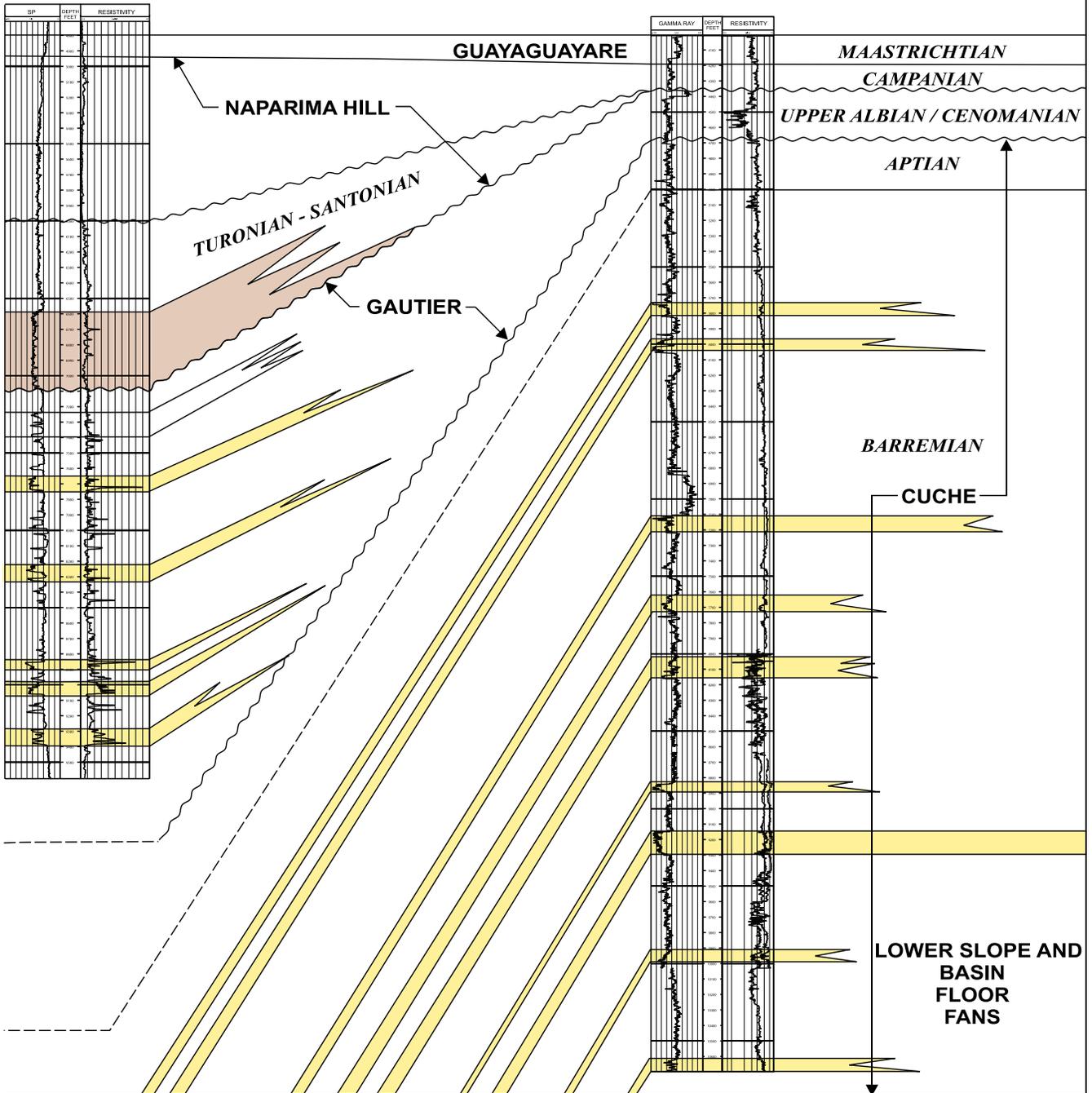
Figure 11. Stratigraphic cross section A-A′ (see base map, Figures 10 and 18), datum at the top of the Cretaceous. The relative positions of the Neocomian and pre-Cretaceous sections in eastern Venezuela were determined from seismic data. Yellow areas represent sandstones; brown shaded area represents siltstones or silty sandstones.
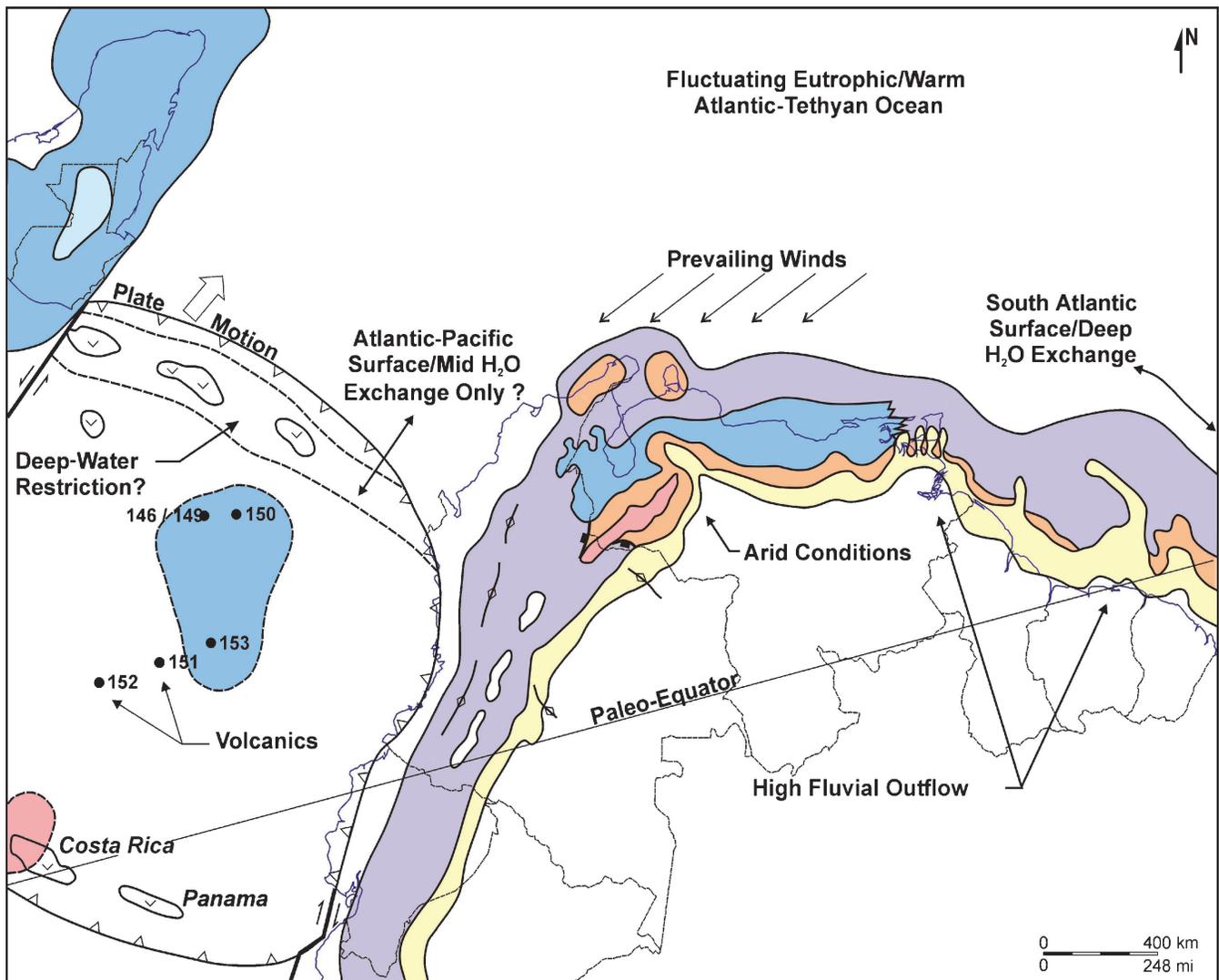
Figure 12. Late Cenomanian–Turonian paleogeography of the study area. See Figures 5 and 9 for color codes for depositional environments; pink = siliceous shales and cherts.

that coincide with the boundary (Villamil and Arango, 1998).

In Colombia, the C-T interval is seen in outcrop as a resistant calcareous unit in an interval composed primarily of shales and thus can be easily traced and mapped in the field. The color of the C-T outcrop surface in distal parts of the basin in the Colombian sections is generally red as a result of the alteration, oxidation and leaching of pyrite. The boundary itself occurs in a condensed section, for which evidence is abundant. For example, pelagic limestones and organic-rich shales above the Cenomanian-Turonian transgressive surface contain abundant phosphatic lags (Villamil and Arango, 1998). Analogous phosphatic lags have been termed condensed and allochthonous phosphates by Föllmi et al. (1991) and have been interpreted as indicators of very low sediment accumulation rates and/or sediment bypassing (Föllmi et al., 1991, 1992).

Trace-element concentrations at the C-T boundary, including Ir, Cr, Ti, Co, and Ni (Orth et al., 1993), are indicative of very slow sedimentation rates caused by an abrupt transgression. Changes in oxygen levels also may affect trace-element concentrations (Frakes and Bolton, 1984). Additional geochemical anomalies that cross the C-T boundary have been used by Schlanger and Jenkyns (1976), Pratt (1985), and Arthur et al. (1988) to interpret Cretaceous global oceanic and atmospheric conditions and paleoclimate. In Colombia, $\delta^{13}C$ and TOC anomalies are well developed, correspond to lithological and paleobiological evidence of oxygen depletion, and represent, therefore, the geochemical expression of OAE II (Villamil and Arango, 1998).
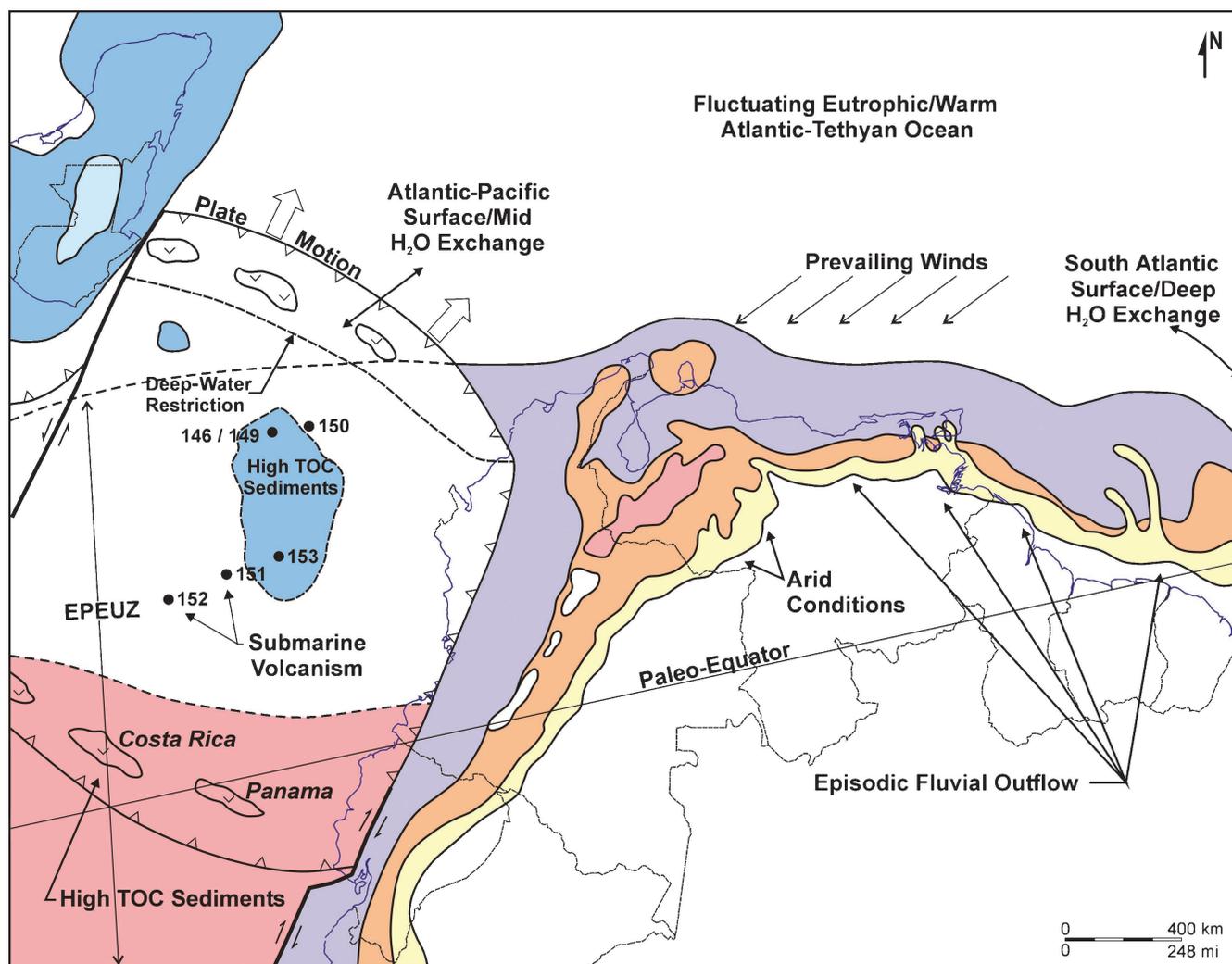
Figure 13. Coniacian–Early Santonian paleogeography of the study area. See Figures 5 and 9 for color codes for depositional environments; pink = siliceous shales and cherts. EPEUZ = eastern Pacific equatorial upwelling zone (see Erlich et al., 1996); OMZ = oxygen minimum zone.

The $\delta^{13}C$ anomaly also is interpreted as reflecting an intense increase in burial of ^{13}C-depleted organic carbon (Arthur et al., 1988); in facies around the C-T boundary of Colombia, the $\delta^{13}C$ anomaly coincides with a TOC anomaly (Figure 16) that reaches values of as much as 16%.

Western Venezuela

Geochemical and palynological data from western Venezuela and northern Colombia show that local climate changed from relatively humid and cool during the late Albian–middle Cenomanian to arid and hot during the late Cenomanian–early Santonian (De Monroy and Van Erve, 1988; Herngreen and Jimenez, 1990; Vergara-S., 1994; Helenes et al., 1998; Erlich et al., 1999b). This long interval of arid/

hot climate was punctuated by a rapid low-latitude cooling event at the end of the Turonian (Frakes, 1999), which may have introduced a period of minor instability in the Maracaibo/Barinas Basin water mass. In the northwestern and eastern Maracaibo Basin, paleobathymetric barriers trapped the local basinal water mass and permitted only limited surface-water exchange to the southwest into the Pacific Ocean (Vergara-S., 1997a; Johnson, 1999). Organic and inorganic geochemical data indicate that arid conditions probably contributed to the formation of saline, oxygen-depleted waters on the flooded Aguardiente Formation deltaic shelf and initially caused stratification of the Maracaibo and Barinas Basin water masses (Figure 17; Erlich et. al., 2000).
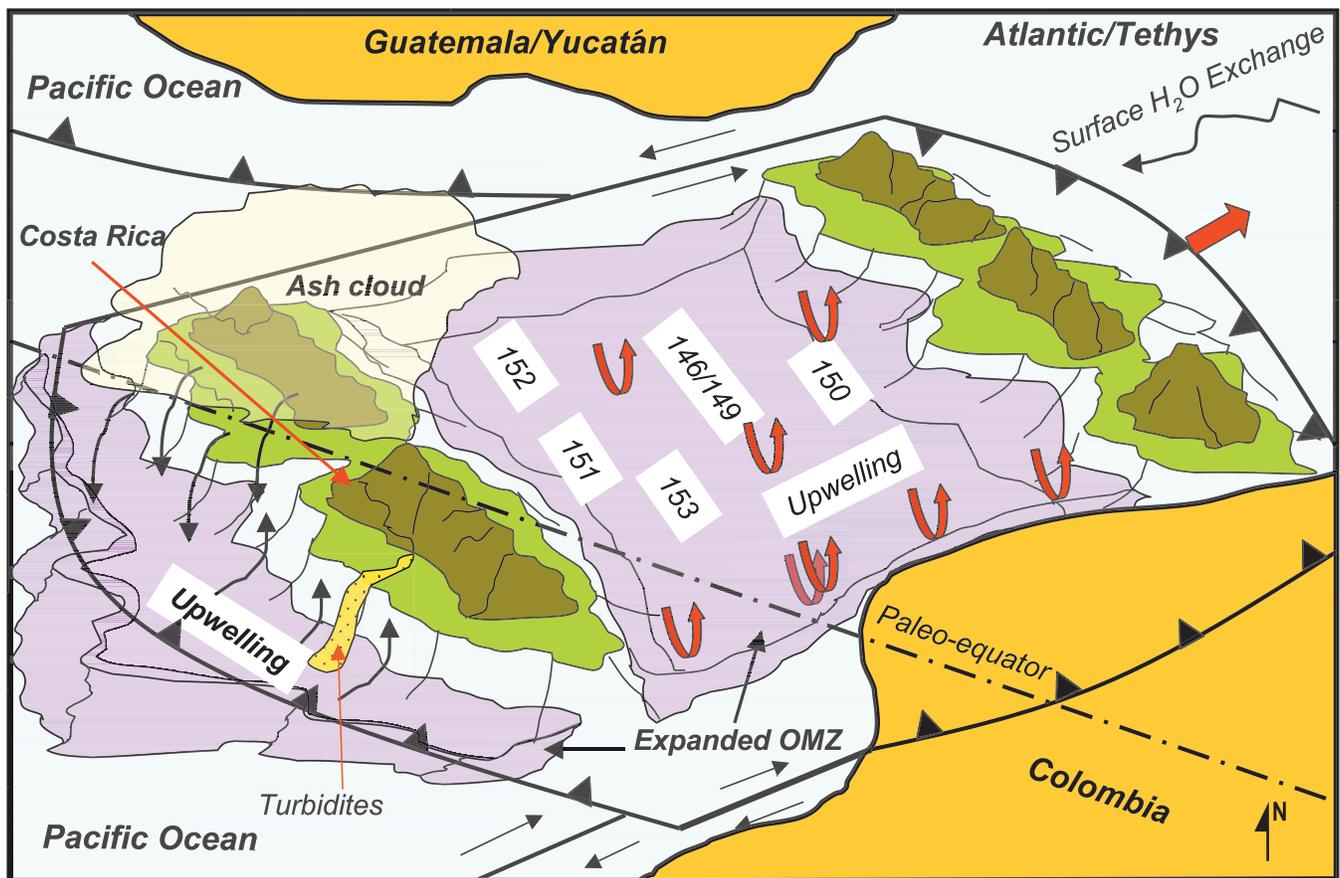
Figure 14. Turonian-Santonian depositional model for the central Caribbean; DSDP sites are numbered. Upwelling along the EPEUZ and the Costa Rica–Panama arc produced elevated levels of primary productivity and the deposition of large amounts of organic matter. Nutrient flux was augmented in the Costa Rica–Panama area because of the episodic input of volcanogenic silica (yellow ''ash cloud;'' see Erlich et al., 1996). The proto-Greater Antilles island arc produced a paleobathymetric or topographic barrier (green areas) and restricted the exchange of bottom waters between the Atlantic and Pacific. OMZ = oxygen minimum zone (violet area).

As in Colombia, organic carbon burial increased across the C-T boundary, as demonstrated by the presence of the $\delta^{13}C$ anomaly in the western Maracaibo Basin (Davis et al., 1994; Perez-Infante et al., 1996; Davis et al., 1999). However, overall primary productivity was probably low during the Turonian-Coniacian, with most organic matter contributed by bacteria and planktonic foraminifera (Erlich et al., 1999b). Seasonal upwelling that began in the early Santonian intensified in the late Santonian and was reflected by the rapid deposition of silica-rich La Luna Formation sediments along the eastern margin of the Maracaibo Basin (Figure 13; Villamil et al., 1999; Erlich et al., 1999a, 2000). The deposition of organic carbon–rich Navay Formation limestones and shales was influenced by the influx of terrestrially derived nutrients from nearby coastal environments (Figure 17; Erlich et al., 1999a, 2000).

Eastern Venezuela, Trinidad, and Suriname

During the Cenomanian-Turonian, the flooded eastern Venezuela shelf was the site of widespread organic carbon–rich limestone deposition, known locally as the Querecual Formation (Figures 2 and 12). Initially dry climatic conditions and seasonal upwelling yielded moderate primary productivity and high preservation rates for organic matter. Dry conditions were replaced during the late Cenomanian–middle Coniacian by seasonal wet/dry cycles and episodic and possibly catastrophic fluvial discharge into deep-marine environments in Trinidad (Figures 13 and 18). In fact, the relative stability of the low-oxygen shelf/slope water mass can be seen in the abruptness of turbidite and debris-flow sedimentary contacts in the Gautier and basal Naparima Hill formations (Figures 19 and 20). Low-oxygen conditions returned relatively rapidly, as demonstrated
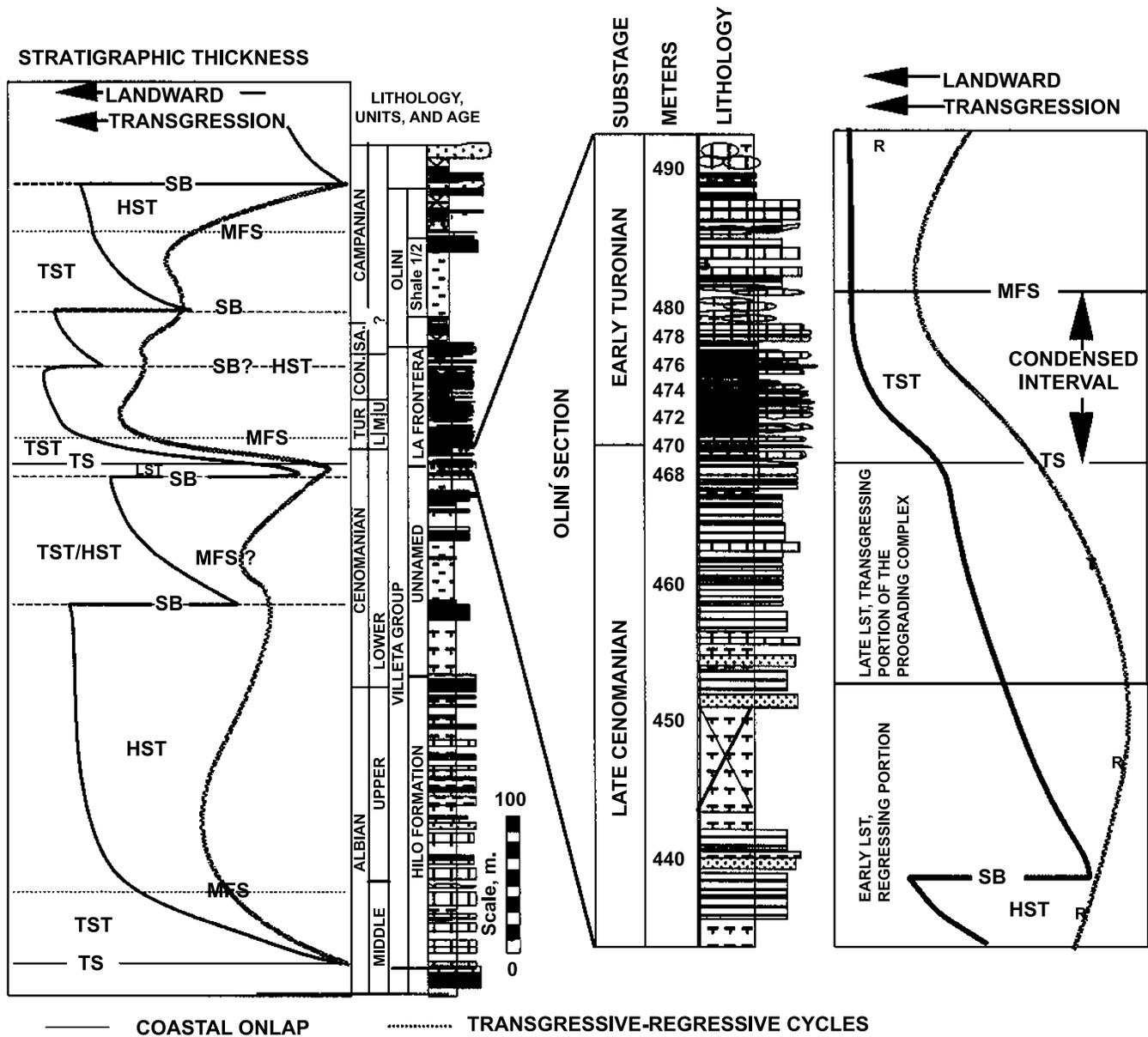
Figure 15. Coastal onlap curve suggesting behavior of relative sea level for Colombia. Curves are based on stratigraphy and geochemistry of the Oliní reference section, Upper Magdalena Valley (location is shown on Figure 3). The right side of the figure is an enlargement of the Cenomanian-Turonian boundary section, which shows the magnitude of the maximum Cretaceous transgression in Colombia.

by the interbedded nature of shallow-shelf siliciclastic sediments and laminated, organic carbon–rich slope shales (Prieto, 1987; Di Croce et al, 1999; Sanchez, 2001).

It is unclear what oceanographic and climatic conditions could have maintained the deposition of organic carbon–rich sediments for such a long period of time (more than 13.5 m.y.) in eastern Venezuela and Trinidad, especially in light of the episodic bottom water oxygenation caused by turbidity currents. A simple regional upwelling model (Erik-

son and Pindell, 1998; Villamil and Pindell, 1998; Villamil et al., 1999) does not account for the rapid return of stable, low-oxygen intermediate/bottom conditions, as observed in the sedimentary record (Figure 19). In an open-ocean setting such as the one envisioned by previous workers, deposition and preservation of organic carbon–rich sediments would have been strongly modulated by seasonal wet/dry cycles and ponding of shallow/intermediate waters in the shelf/slope environment (Figure 21). Dry climate cycles must have been punctuated by intense
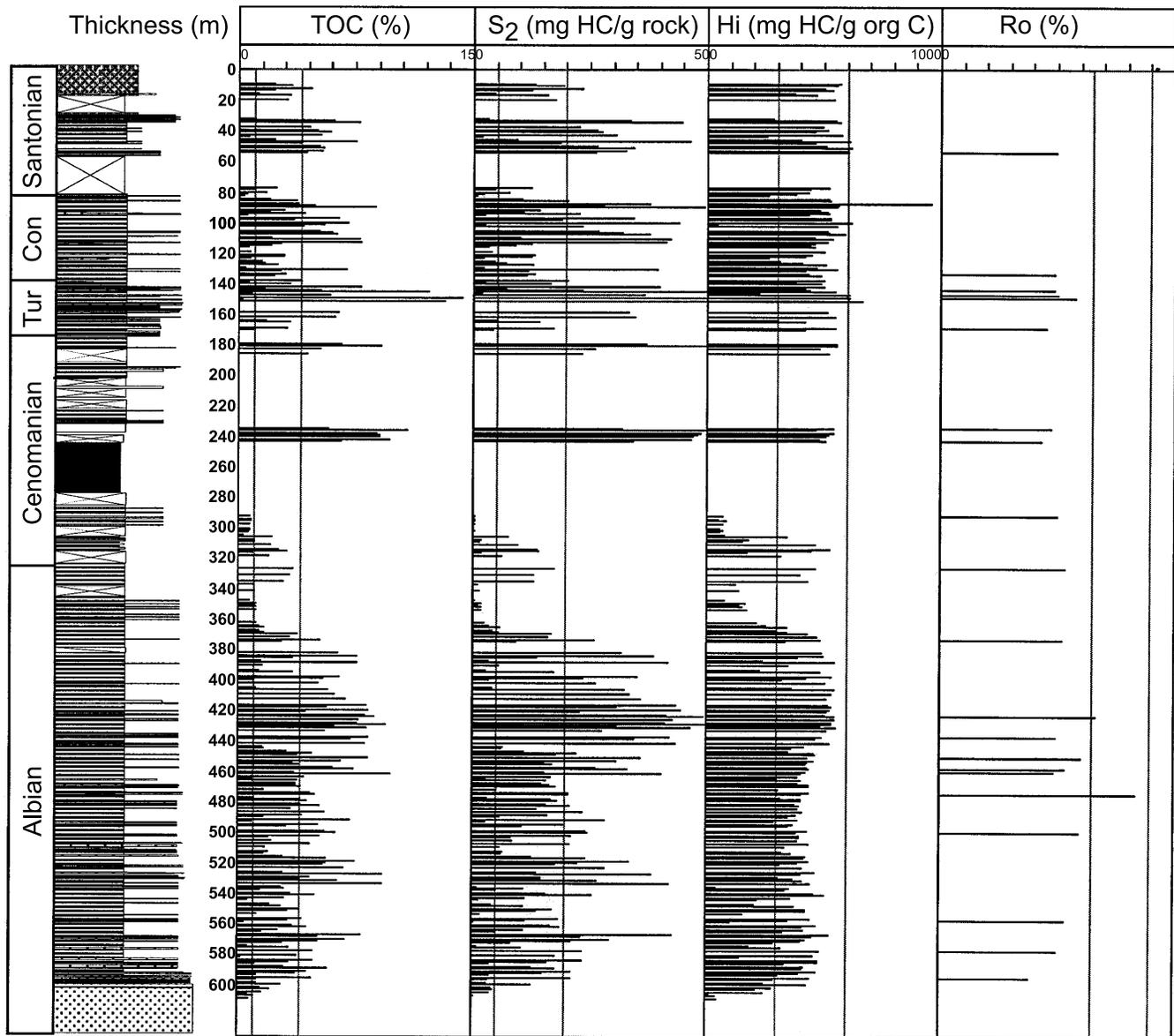
Figure 16. Geochemical profile (270 samples) of the Villeta Formation (La Luna Formation equivalent), Oliní reference section, Upper Magdalena Valley (see Figure 3). High TOC intervals within the Albian, Cenomanian, Turonian, and Coniacian suggest oxygen depletion and high rates of organic matter preservation, at least partially coincident with OAE II and OAE III.

upwelling and primary productivity, during which the outer shelf/upper slope water mass became nearly anoxic. The bulk of organic carbon–rich sediments were probably deposited during these intervals. Catastrophic floods and transport of fresh water into the deep-marine environment typified wet climate cycles. The cooler, sediment-laden waters were denser than the warmer marine waters and oxygenated local areas of the outer shelf/slope as the submarine fans and debris flows were deposited. Although phytoplankton productivity was high during these intervals (Requejo et al., 1994), the preservation and distribution of organic matter was inconsistent.

The wet/dry climatic cycles intensified in the Guyana-Suriname Basin, where large submarine fan systems of the Canje and lower New Amsterdam Formations were deposited in bathymetrically constrained troughs and canyons (Figures 22 and 23). Water masses entrained in the local troughs and canyons were unlikely to be ventilated easily during dry cycles (Figure 24), enhancing the preservation of high TOC sediments (as much as 13%).
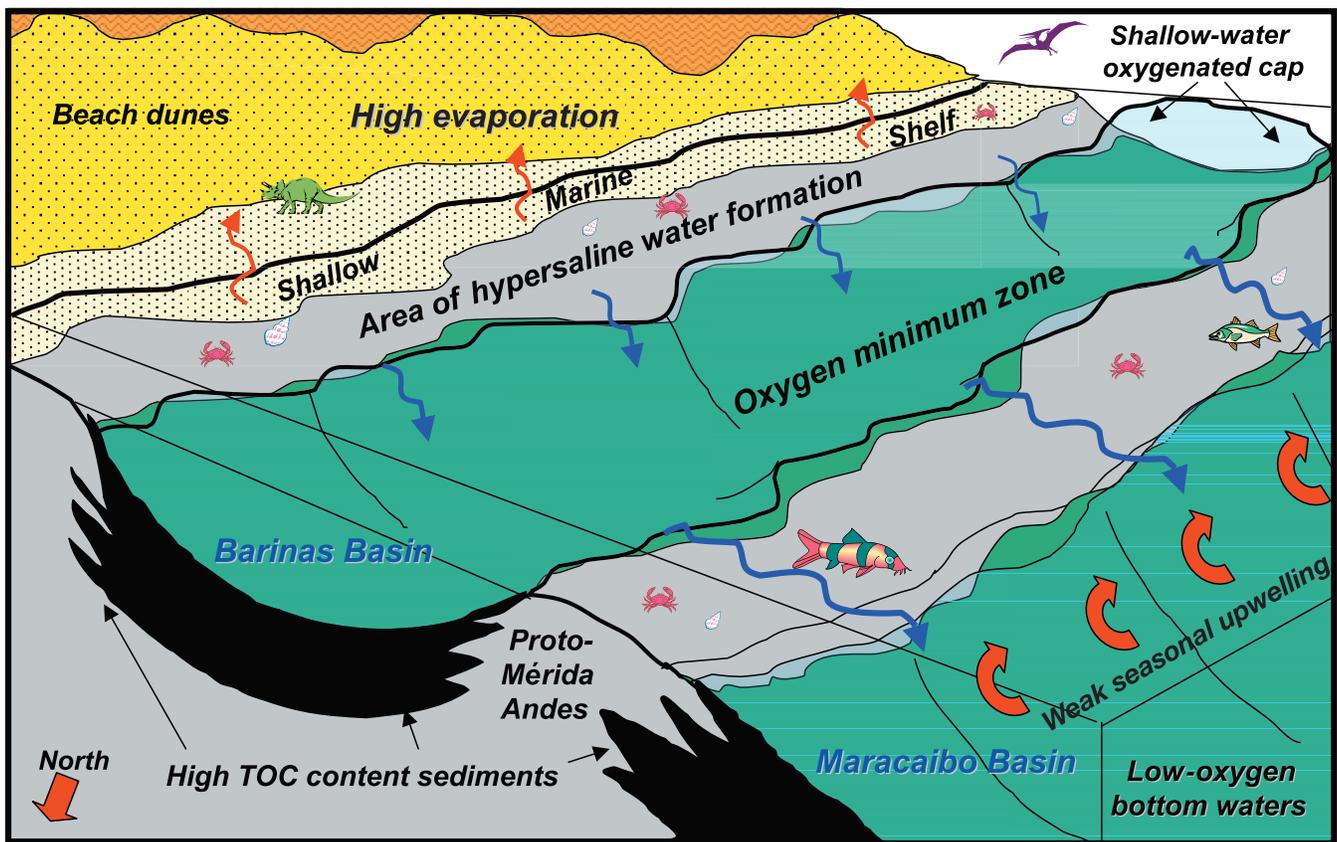
Figure 17. Cenomanian–early Santonian depositional model for the Barinas-Apure and northern Llanos Basins. High evaporation rates along flooded shelf areas produced hypersaline waters that filled the epicontinental seaway. Paleo-bathymetric highs along the proto-Mérida Andes permitted only surface-water exchange with the Maracaibo Basin to the northwest. However, benthonic foraminiferal data show that surface waters were oxygenated, at least intermittently. The lack of ventilation and inherently low dissolved oxygen concentration of Barinas/Llanos Basin waters greatly enhanced the preservation of organic matter in the seaway.

THE LATE SANTONIAN–LATE MAASTRICHTIAN: THE END OF SOURCE ROCK DEPOSITION IN NORTHERN SOUTH AMERICA

Low-latitude sea-surface temperatures rose from the late Santonian through the late Campanian as Atlantic and Tethyan circulation patterns changed in the deep ocean (Frakes, 1999). This probably resulted from initial bottom-water exchange between the Atlantic-Tethyan Ocean and the South Atlantic, which acted to more evenly distribute meridional heat flow through the surface ocean (Wonders, 1980; Erlich et al., 1996; Hay and DeConto, 1999; Premoli Silva and Sliter, 1999).

The reestablishment of oligotrophic conditions led to expanded diversity of planktonic foraminifera and a reduction in low-oxygen opportunists (Premoli Silva and Sliter, 1999). Upwelling-induced productivity became a local rather than regional process across most of northern South America, with the exception of the EPEUZ (Figure 25). This coincided with intermediate/bottom-water exchange between the South Atlantic and the Atlantic-Tethys and caused profound climatic change across northern South America.

Sea-surface temperatures dropped rapidly at the end of the Campanian and into the early Maastrichtian, reflecting the introduction of cool Antarctic intermediate waters into the Atlantic and proto-Caribbean (Lawver et al., 1992; Barrera and Savin, 1999; Frakes, 1999). Cooler high-latitude sea-surface temperatures had a profound impact on temperature and precipitation patterns in northern South America and resulted in increased fluvial outflow and intensified wind stress (Barron and Peterson, 1990; Kruijs and Barron, 1990; Ditchfield et al., 1994; Barron et al., 1995; Huber et al., 1995; Bush and Philander, 1997; Mikolajewicz and Crowley, 1997; Dingle and Lavelle, 1998).
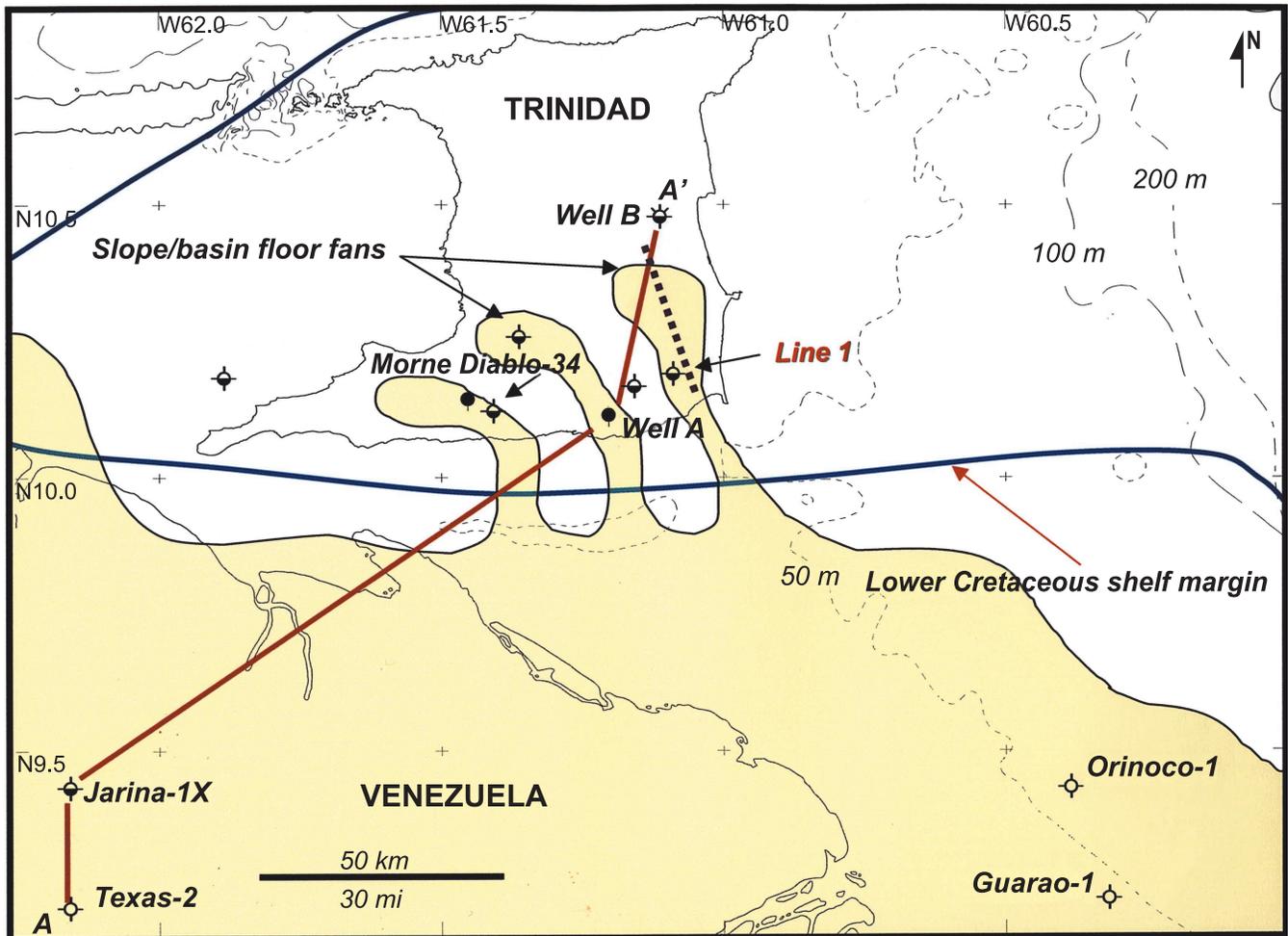
Figure 18. Late Cenomanian–middle Coniacian paleogeography of the Trinidad–eastern Venezuela area, showing the reduced geographic extent (when compared to Albian-Cenomanian deposition) of the siliciclastic shelf and submarine fans (yellow shaded). Blue line is the location of the Lower Cretaceous shelf margin.

A gradual increase in global sea-surface temperatures toward the end of the Maastrichtian reflected high atmospheric CO_2 levels brought on by increased volcanic activity (Huber et al., 1995; Dingle and Lavelle, 1998; Li and Keller, 1998; Barrera and Savin, 1999; Frakes, 1999). Oligotrophic conditions and high levels of diversity of planktonic foraminifera were disrupted at the end of the Maastrichtian as eutrophic water-column conditions reappeared in the Atlantic and Tethys (Premoli Silva and Sliter, 1999). Primary productivity dropped along northern South America and the deposition of organic carbon–rich sediments ceased (Figure 26).

Costa Rica and Central Caribbean

The late Santonian–early Maastrichtian was characterized by unrestricted shallow- and deep-water circulation from the Atlantic through the proto-Caribbean and into the Pacific (Figure 25; Bush and Philander, 1997; Mikolajewicz and Crowley, 1997; Johnson, 1999). The rapid influx of cooler, oxygenated South Atlantic intermediate waters diminished the preservation of organic matter in Sabana Grande Formation cherts in Costa Rica and Panama, even though primary productivity in the EPEUZ did not appreciably change (Figures 25 and 26). This also was true for the central Caribbean DSDP sites and continued through the end of the Maastrichtian.

Colombia

The Santonian-Maastrichtian marked an episode of extensive regional uplift of large areas of Colombia, particularly the ancestral Central Cordillera. This uplift event generated regressive tectonosequences,
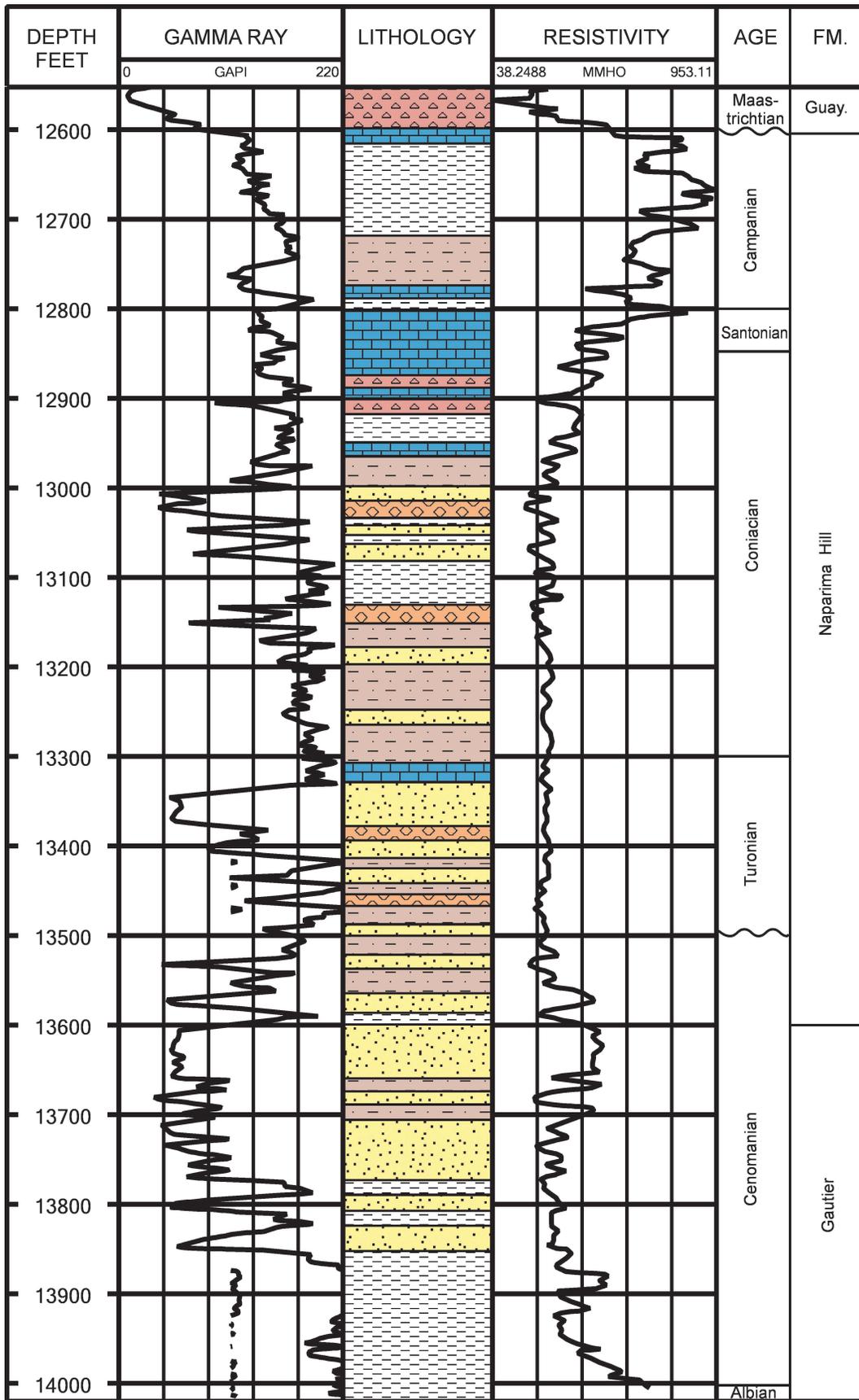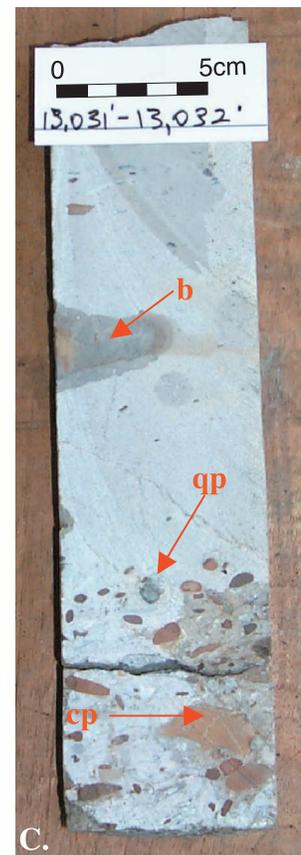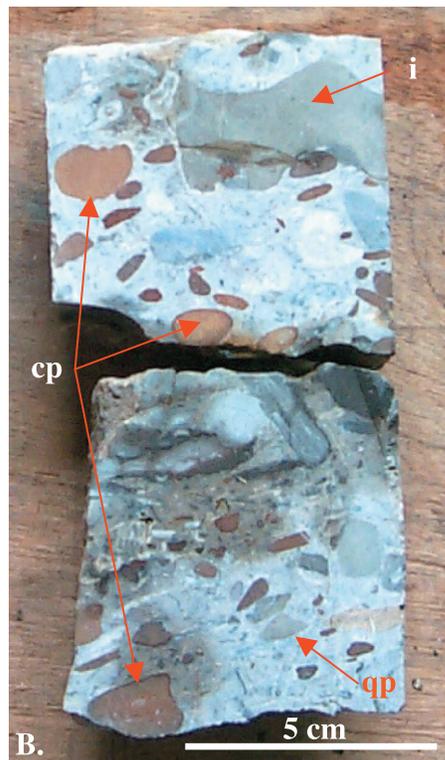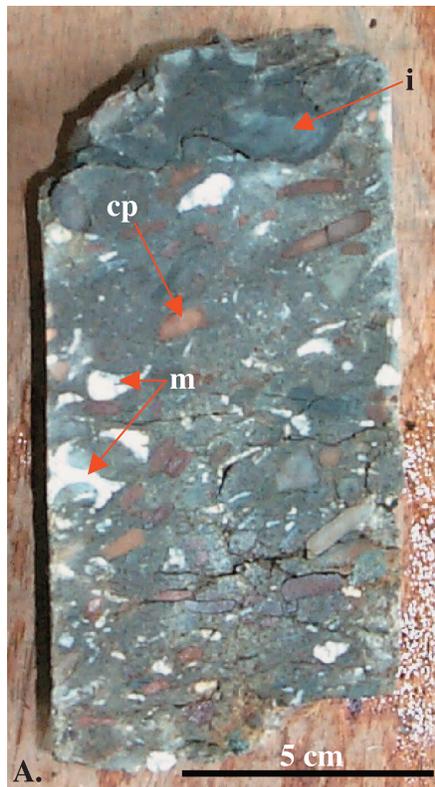
Figure 19. Wireline logs, lithologies, formation tops, and ages for the Morne Diablo-34 well. Note the decrease in sandstone and conglomerate units following the Coniacian. See Figure 2 for pattern and color key. See Figures 10 and 18 for well location.

which are manifested in the lithostratigraphic record as increasingly common fine- to coarse-grained siliciclastic interbeds in the Santonian to Campanian chert units (Figure 2). Generally speaking, bedded cherts were deposited in distal depositional environments during the Santonian and were lateral facies equivalents of shallow-water marine sediments in proximal areas (Barrio and Coffield, 1992). Distal cherts of the Oliní Group were deposited in the Upper Magdalena Valley and western regions of the Eastern Cordillera. They are equivalent to the upper parts of the La Luna Formation in the Middle Magdalena Valley and the Cocuy Basin and the Tres Esquinas Member of the La Luna Formation in western Venezuela (Figure 2). Coeval coarse-grained deposits belong to the lower portions of the Guadalupe Group in central and eastern portions of the Eastern Cordillera and the Llanos foothills and basin (Figure 6). Regionally, marine sandstones of the Guadalupe are interbedded with indurated, white, highly siliceous siltstones, cherts, and phosphorites (Bürgl and Dumit Tobón, 1954; Cathcart and Zambrano, 1967). These facies and coeval Santonian–Campanian-bedded black cherts of distal areas indicate the high levels of primary productivity that affected large regions of Colombia. This active upwelling event was discussed in detail by Villamil et al. (1999).

Siliciclastic sediments deposited in Maastrichtian units west of the western foothills of the Eastern Cordillera were sourced from the ancestral Central Cordillera, across the present-day Magdalena Valley. Units such as the Monserrate of the Upper Magdalena Valley and the Cimarrona of the eastern margin of the Middle Magdalena Valley (Figures 2 and 6) show conclusive evidence of western provenance (Diaz, 1994; Gómez and Pedraza, 1994). The Magdalena Basin of the latest Cretaceous was elongated north-northeast and narrowed to the south; progradation from the south, east, and west infilled the depocenter diachronously to the north. The marine seaway was open to the proto-Caribbean north of Colombia and probably to the Pacific to the northwest of the basin. The Maastrichtian depocenter is represented by shales of the Umir and Colón Formations in the Middle Magdalena Valley and in western Venezuela (Figure 2).

Marine conditions retreated at the end of the Cretaceous period as a result of continuous uplift of the Central Cordillera and lowering sea level. Latest Maastrichtian facies were deposited unconformably over Maastrichtian marine siliciclastic sediments and are represented regionally by coastal-plain deposits of the Guaduas and Barco Formations (Figure 6). This loss of accommodation continued to the latest Paleocene with regional lowering of base level and development of the Paleocene-Eocene regional unconformity.
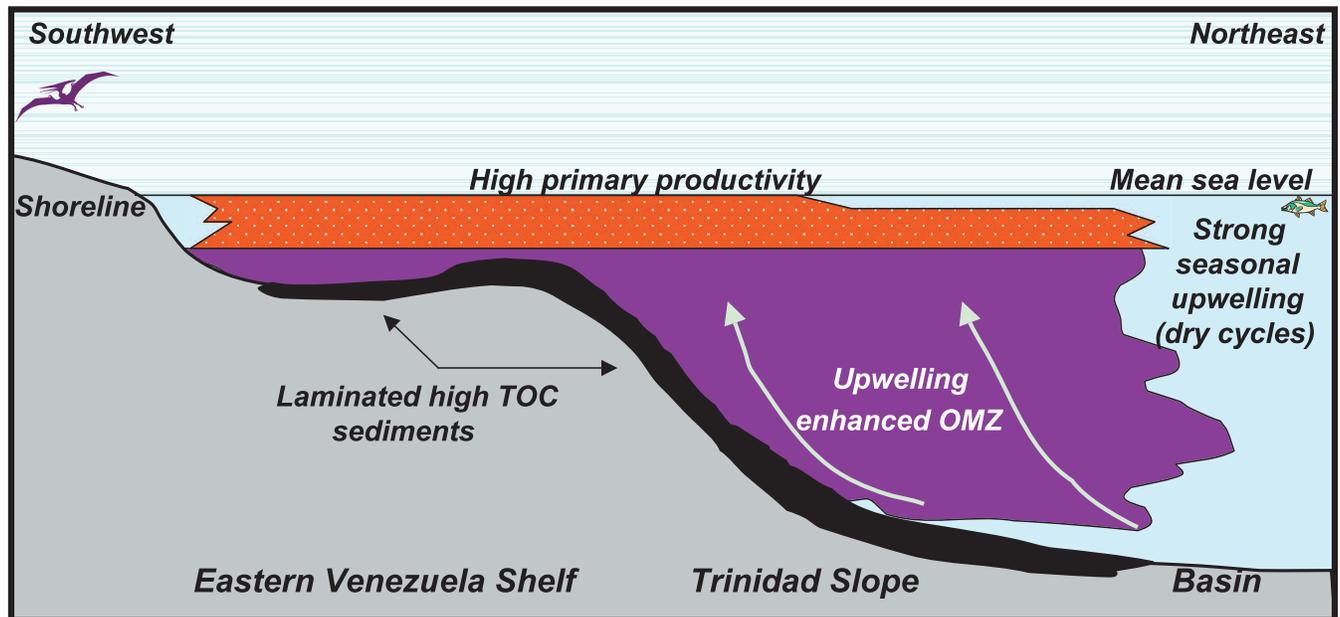
Western Venezuela

Strong seasonal upwelling driven by the easterly trade winds caused rapid and catastrophic overturn of the low-oxygen Maracaibo Basin bottom waters during the late Santonian–early Maastrichtian (Figures 25, 27, and 28; Erlich et al., 1999b, 2000). The reestablishment of seasonal wet/dry cycles also increased the seasonal nutrient flux to the Maracaibo and Barinas-Apure Basins and combined with upwelling to produce "red tides," massive blooms of red and brown marine phytoplankton (Premoli Silva and Sliter, 1999). The rapid nature of these events apparently led to major fish mortality and the formation of apatite-rich bone beds (Tres Esquinas Member; Figure 2) in southeastern Maracaibo and eastern Colombia (Erlich et al., 2000).

Biostratigraphic and geochemical data show that primary productivity was elevated during upwelling and runoff events; however, preservation of organic matter on the sea floor was significantly reduced from the pre-Santonian (Erlich et al., 1999b). This can be seen in the generally low (<1%) TOC content

Figure 20. Morne Diablo-34 core photos. See Figure 19 for location of core photographs. (A) 13,138 feet: unsorted debris flow with large amounts of shallow-water mollusk fragments (m), clay pebbles (cp), and intraclasts (i)—first phase of fan deposition. (B) 13,150 feet: poorly sorted clay and quartz pebble (qp) conglomerate—second phase of fan deposition. (C) 13,031–13,032 feet: transition from clay and quartz pebble conglomerate to massive, burrowed (b) medium- to fine-grained sandstone—third phase of fan deposition. (D) 13,365–13,366 feet: massive medium- to fine-grained sandstone (oil stained in this photo)—late third phase of fan deposition. (E) 13,071 feet: ripple laminated, very fine sandstone and siltstone with upward gradation to burrowed black shale—final phase of fan deposition. (F) 13,496–13,496 feet: unconformable contact (red arrow) between burrowed/bored fine-grained sandstone and bioturbated to laminated, high TOC, black shale; marks the C-T boundary. Bed boundaries can be either gradational (as in E above) or abrupt, representing intraformational unconformities that commonly occur along the Cretaceous paleoslope.
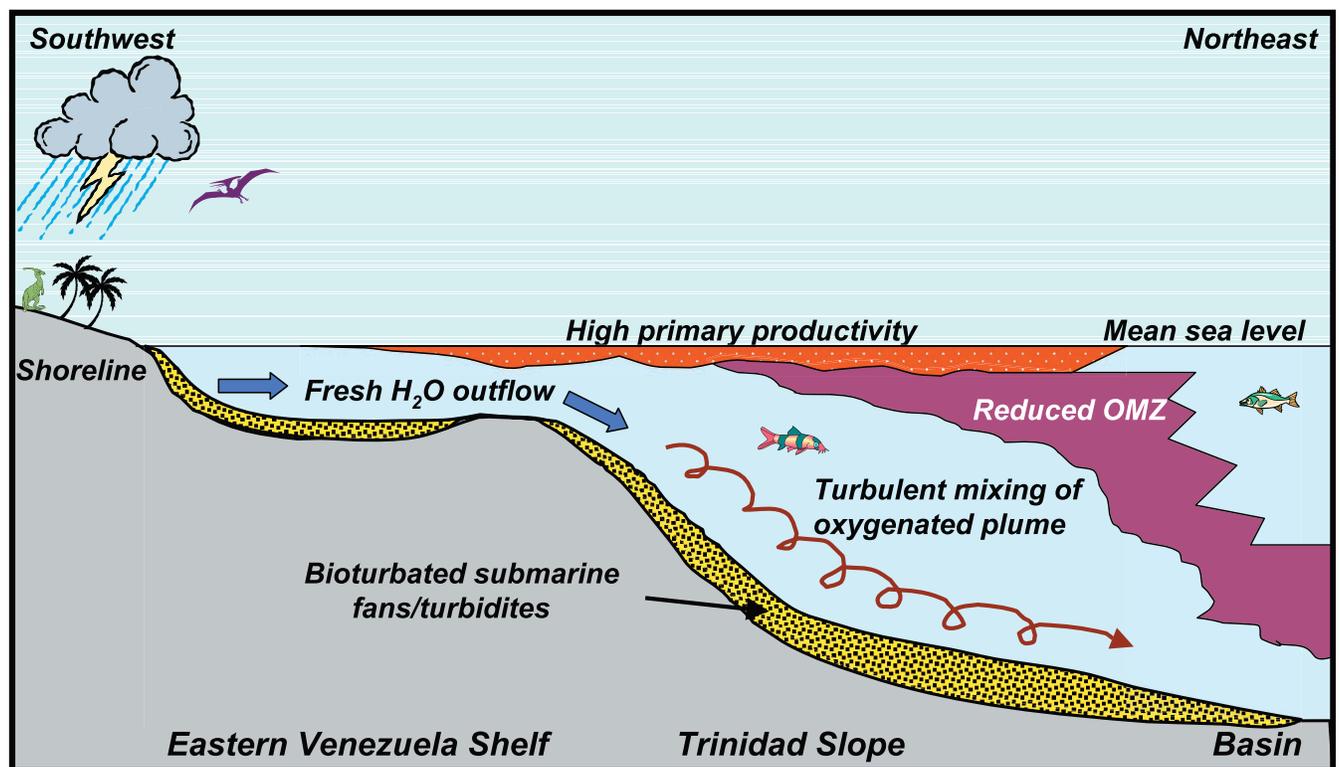
A

B

Figure 21. Cenomanian–early Santonian depositional models for eastern Venezuela and Trinidad. (A) Strong seasonal upwelling was common during the ''dry'' season; elevated primary productivity in the surface water column (red pattern area) led to an expansion of the OMZ (violet area) and accumulation of organic carbon from middle shelf to upper basinal depositional environments. The surface water column was generally oxygenated, as were deeper basinal areas toward the open Atlantic. (B) ''Wet'' season deposition was characterized by massive fluvial outflow; frequent floods injected plumes of cooler, oxygenated water into a previously stagnant OMZ (violet area), which caused turbulent mixing and oxidation of sedimentary organic carbon. Primary productivity (red pattern area) was slightly elevated as a result of fluvially supplied nutrients; however, dilution by siliciclastic sediments (yellow stippled pattern) and oxygenation reduced the preservation potential of organic matter in the water column and on the sea floor.
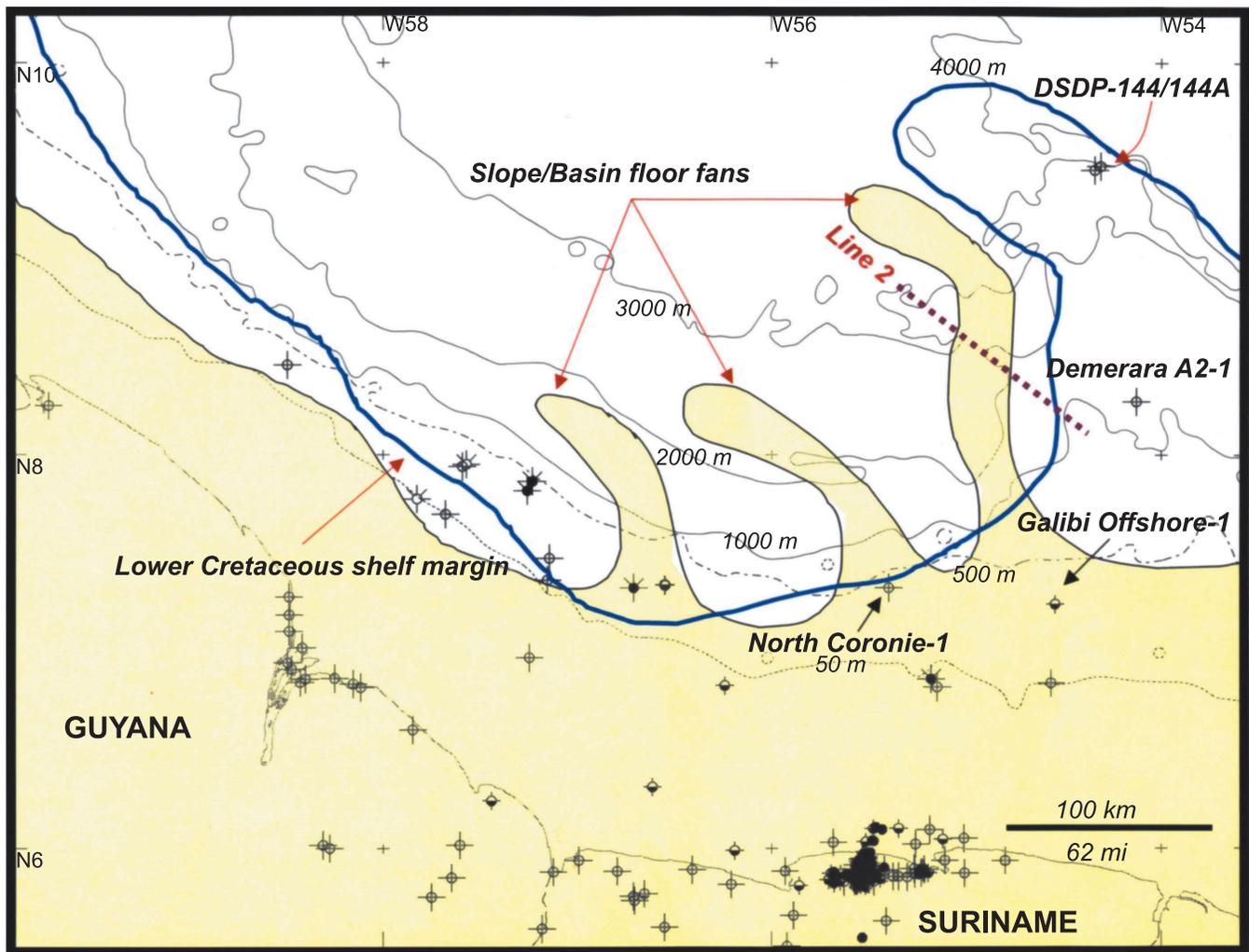
Figure 22. Coniacian-Maastrichtian paleogeography of the Guyana-Suriname area, showing siliciclastic shelf and submarine fan deposits (yellow shaded). Blue line is the location of the Lower Cretaceous shelf margin. While submarine fan and turbidite deposition was still common, the size and duration of discrete depositional events diminished through the end of the Cretaceous.

of upper La Luna Formation rocks.. Ventilation of the previously stagnant Maracaibo Basin bottom-water mass was aided by several factors. First, as discussed previously, more intense seasonal upwelling helped destabilize and overturn the water column, probably in a manner more similar to the seasonal overturn observed in modern high-latitude lakes. Second, a cooler late Campanian–early Maastrichtian climate and increased fresh-water runoff ended local production of hypersaline, low-oxygen waters on the shallow Barinas shelf. This removed the most likely source of low-oxygen bottom waters for the basin (Erlich et al., 1999b). Lastly, overthrusting and uplift of the Central Cordillera of Colombia and accompanying foreland basin subsidence in the Maracaibo Basin must have submerged paleobathymetric bar-

riers present in the northern part of the basin. This allowed previously stagnant Maracaibo Basin bottom waters to escape north into the open, more oxygenated Atlantic (Erlich et al., 2000). Stagnant, low-oxygen shelf waters of the Barinas-Apure Basin may never have ventilated in the manner suggested for the Maracaibo Basin; delta progradation of the Burgüita Formation (Figure 2) from the Guayana Shield to the east and south eventually filled the basin and terminated marine sedimentation until the Paleogene (Figures 25 and 26; Kiser, 1989).

Cooler global temperatures during the late Santonian–early Maastrichtian combined with uplift of the Central Cordillera of Colombia (Figure 1) to alter rainfall patterns in western Venezuela (Figure 25). Uplift of the Central Cordillera of Colombia (Figure 1;
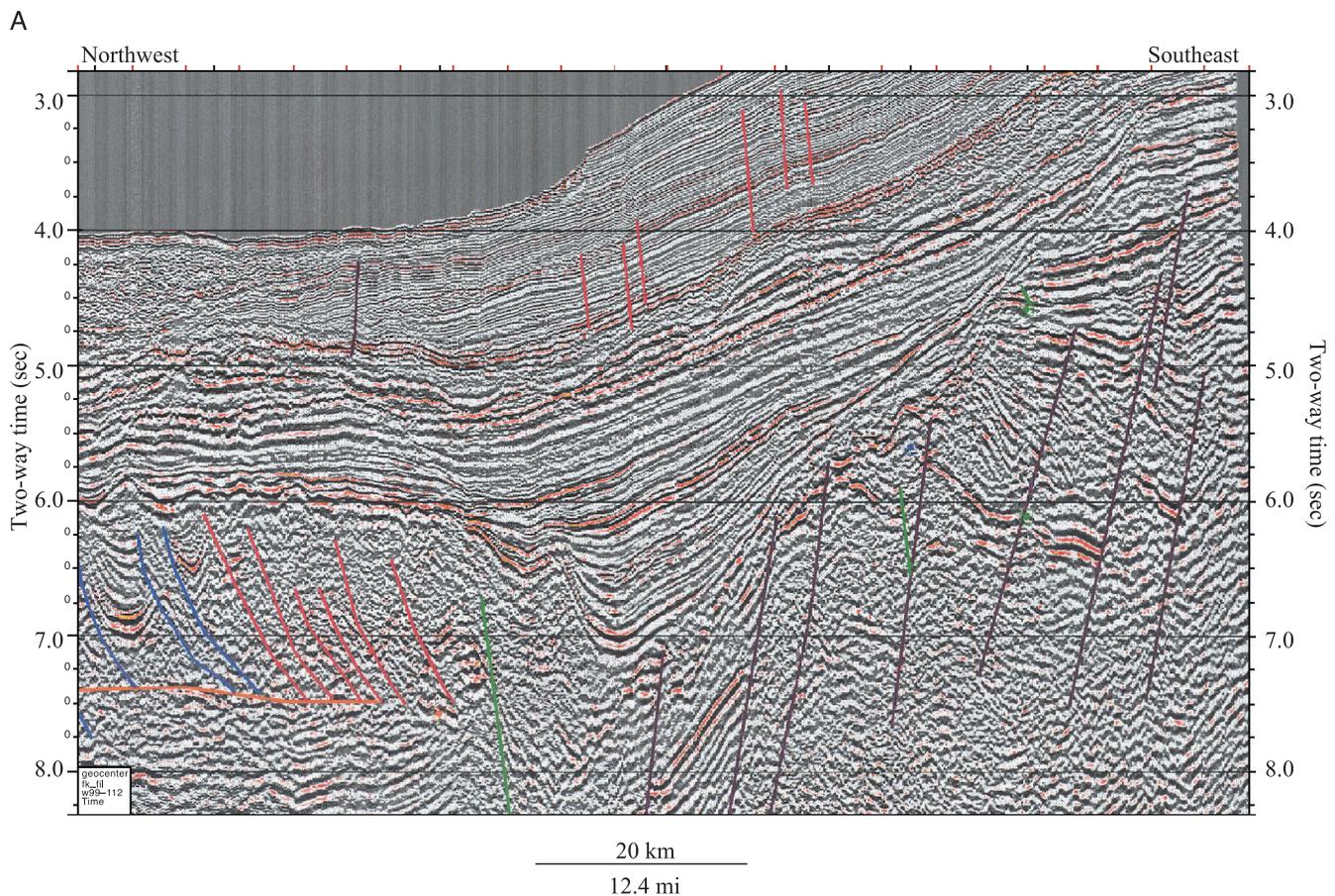
A

Figure 23. (A) Uninterpreted migrated time section (seismic Line 2) across the west Suriname submarine canyon (see Figures 7 and 22 for location). (B) Interpreted migrated time section showing infilling of the canyon by Cenomanian-Turonian turbidites and submarine fans, probably derived from the area surrounding the Galibi Offshore-1 well. Seismic reflectors were correlated to biostratigraphic data from the Demerara A2-1 and Galibi Offshore-1 wells. Note the double onlap nature of seismic reflectors in the canyon, indicating preexisting paleobathymetric relief in the canyon. UK = Upper Cretaceous, LK = Lower Cretaceous.

Cooper et al., 1995; Guerrero and Sarmiento, 1996; Vergara-S., 1997b; Villamil, 1998) created an orographic barrier along northwestern South America (Figures 26 and 29). This caused high amounts of precipitation and subsequent delta progradation from eastern Colombia into the Maracaibo and Barinas-Apure Basins (Erlich et al., 1999b). The late Maastrichtian temperature rise (Barrera and Savin, 1999; Frakes, 1999) continued this depositional pattern of delta progradation and infilling of the basins, with eventual establishment of estuarine and coastal mangrove environments (Pocknall et al., 1997).

Eastern Venezuela, Trinidad, and Suriname

As in western Venezuela, increased wind-driven upwelling in eastern Venezuela and Trinidad was not accompanied by the deposition and preservation of

large amounts of organic matter. In fact, the TOC content of upper San Antonio, San Juan, and Naparima Hill Formation rocks also is low (about 1%) and decreases into the Campanian (Alberdi and Lafargue, 1993; Requejo et al., 1994; Erlich et al., 1999b). Disruption of the organic-matter preservation cycle was most likely a result of the influx of oxygenated Antarctic Intermediate Waters (AAIW), which eventually replaced the low-oxygen shelf/slope water mass (Erlich et al., 1999b, 2000).

Increased fluvial runoff in eastern Venezuela, Trinidad, and Suriname caused delta progradation across the previously marine shelves (Figures 25 and 26; Prieto, 1987; Di Croce, 1995; Erikson and Pindell, 1998; Di Croce et al., 1999). Shelf- to shallow-marine sandstones of the Campanian-Maastrichtian San Juan Formation of eastern Venezuela were overlain by prodelta shales of the Maastrichtian-Paleocene Vidoño Formation.
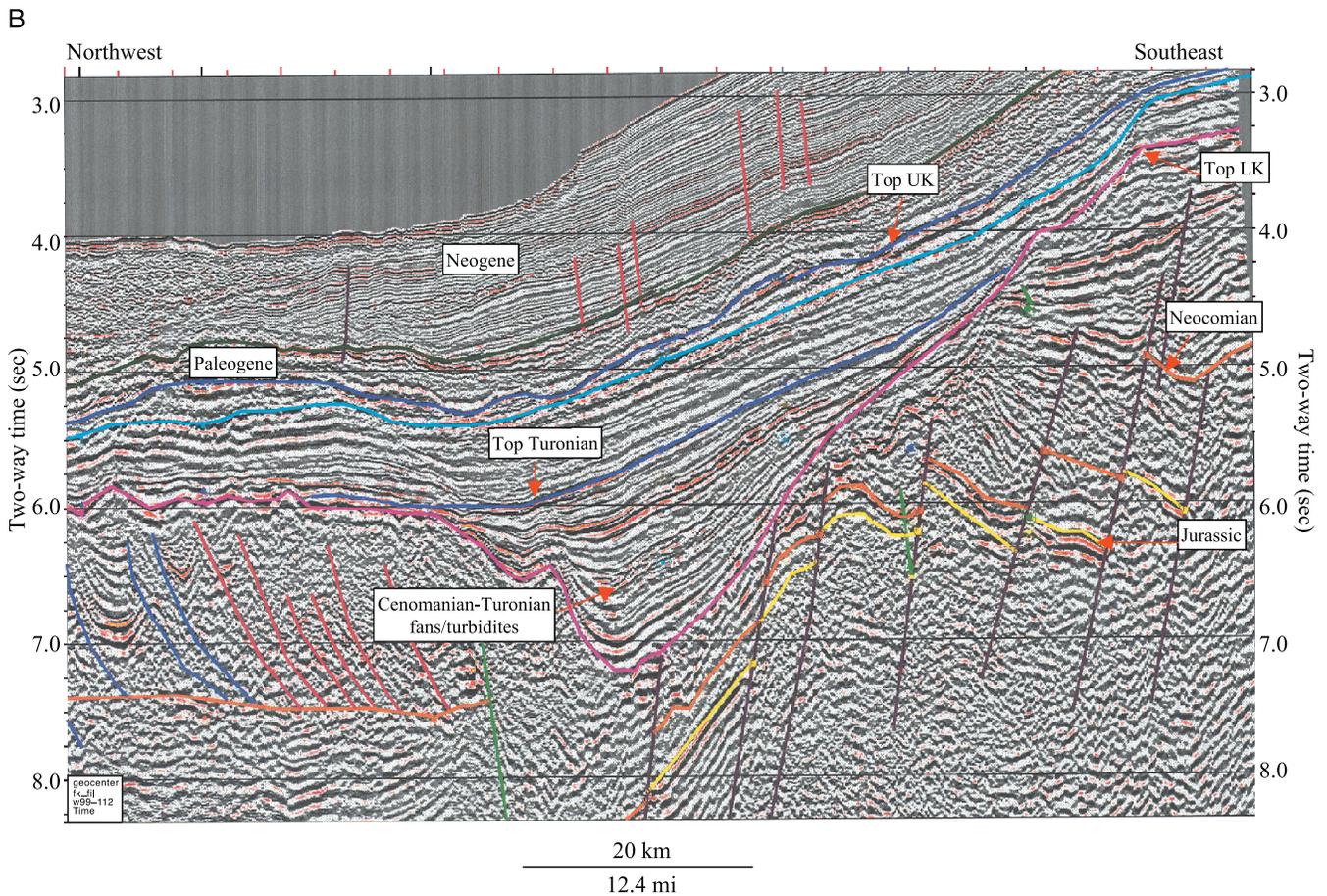
B

Figure 23. (cont.).

The extensive drainage systems that transported large amounts of siliciclastic sediments into deep-water depositional environments in Trinidad apparently shifted to the southeast from their Albian-Cenomanian locations or ceased altogether (Sanchez, 2001; Figure 19). Low TOC limestones and cherts of the upper Naparima Hill Formation were overlain by low TOC Guayaguayare Formation siltstones and shales and marked the end of Cretaceous sedimentation in central and southern Trinidad.

Mid- and bottom-water oxygen levels increased and the preservation of organic matter decreased in the Guyana-Suriname Basin following the Turonian and Coniacian. As in eastern Venezuela and Trinidad, this change reflects the ventilation of the previously stagnant water mass with AAIW, plus more frequent episodes of siliciclastic dilution. Submarine fan and turbidite deposition of the upper New Amsterdam Formation was common along the shelf/slope area during the Santonian-Campanian but was diminished during the Maastrichtian (Figures 25 and 26).

Why Did Source Rock Deposition Cease in Northern South America?

While there is no simple answer to the question of why source rock deposition ceased in northern South America, we can demonstrate that local modulation of regional- and global-scale climatic and oceanographic changes was the dominant cause. Three key global events had an important impact on late Cretaceous climate:

1) The establishment of intermediate- and deep-water longitudinal circulation between the South Atlantic and the North Atlantic/Tethys (Wonders, 1980; Erlich et al., 1996; Hay and DeConto, 1999; Premoli Silva and Sliter, 1999). This provided a new, better-oxygenated water mass to the Atlantic and Tethys, thus altering organic-matter preservation patterns across northern South America.
2) Milankovitch-driven variations in sea-surface temperature (Dingle and Lavelle, 1998; Barrera and Savin, 1999; Frakes, 1999; Upchurch et al., 1999). Sea-surface temperature generally cooled from
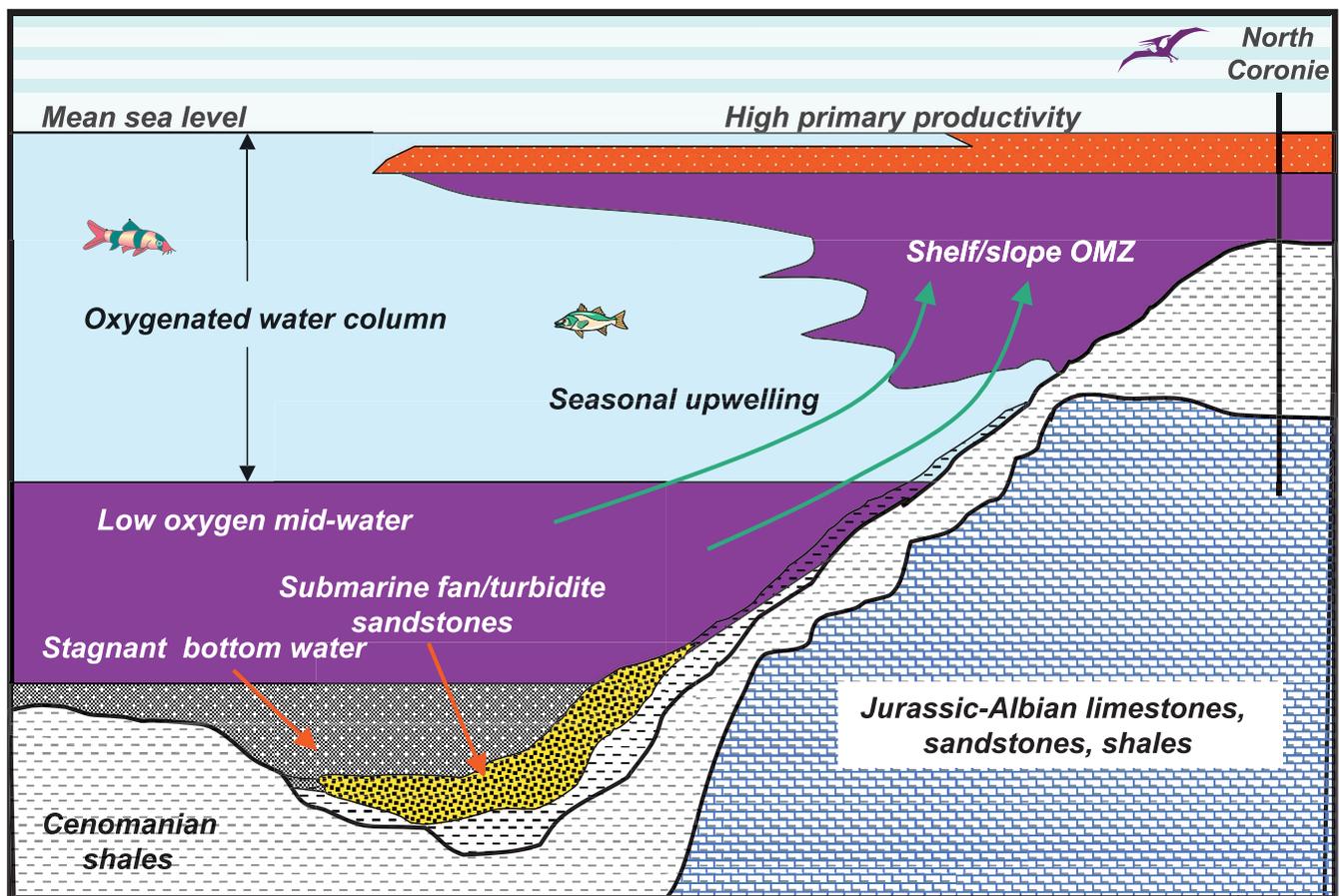
Figure 24. Albian-Turonian depositional model of the offshore western Suriname area. Bottom waters entrained in the submarine canyon (lower gray stippled pattern) could not be ventilated except during the deposition of submarine fans (yellow stippled pattern), in a manner similar to the Trinidad ''wet'' season model. Strong seasonal upwelling along the shelf allowed for the development of a shelf marginal OMZ (upper violet area) and the preservation of deposited organic matter. This may account for the deposition of organic carbon-rich sediments across wide range of paleobathymetries but also may infer a ''bypass zone'' along the middle slope where organic carbon–rich sediments may be thin or absent.

the late Campanian–late Maastrichtian, with rapid temperature increases in the late Santonian and late Maastrichtian. This resulted in higher land-sea temperature gradients (Poulsen et al., 1999) and higher seasonal wind stress.

3) Fluctuations in volcanogenic CO_2 (Barron and Washington, 1985; Crowley, 1991; Huber et al., 1995; Dingle and Lavelle, 1998; Barrera and Savin, 1999; Frakes, 1999; Poulsen et al., 1999) impacted global temperatures through variations in albedo, radiant heat, and PCO_2 of the oceans.

One direct result of these events was intensification of seasonal wet/dry cycles in northeastern South America. Rainfall patterns changed dramatically and changed depositional patterns accordingly. Long periods of seasonal aridity that were common in northwestern South America during the late Cenomanian–late Santonian were eliminated by the progradation

of large delta systems (Figures 25 and 26). Shelf areas that had been sites of infrequent freshwater input were infilled rapidly by siliciclastic sediments, further disrupting organic-matter preservation.

The global variables discussed previously influenced depositional, climatic, and oceanographic patterns in northern South America in a direct way, but were nonetheless modified by local variations in tectonics, bathymetry, and topography. For example, it is arguable whether the regional change in rainfall patterns observed in the lithologic record of northeastern South America would have been duplicated in northwestern South America without uplift of the Central Cordillera of Colombia. The creation of a local orographic barrier to the easterly trade winds undoubtedly helped focus rainfall on the eastern side of the uplift, thus providing the transport mechanism for the deltaic sediments that infilled the Llanos, Maracaibo, and Barinas-Apure Basins
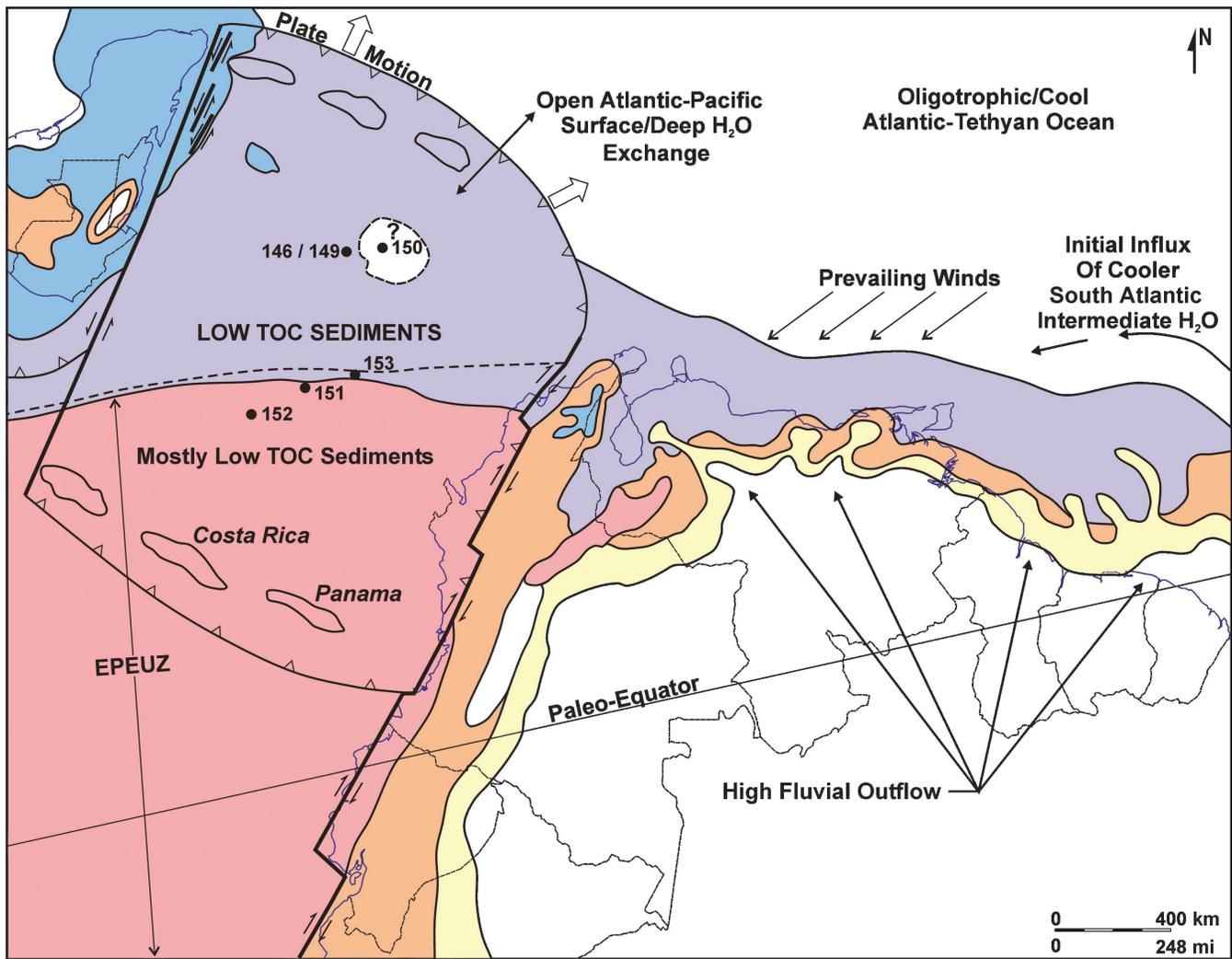
Figure 25. Late Santonian–early Maastrichtian paleogeography of the study area. See Figures 5 and 9 for color codes for depositional environments; pink = siliceous shales and cherts. A major increase in precipitation across northern South America led to greater deposition of siliciclastic sediments in previously restricted environments. The resulting dilution and oxygenation helped to diminish the organic carbon content of sediments deposited during this interval. Open circulation between the Atlantic and Pacific allowed stagnant central Caribbean bottom waters to be flushed and ventilated.

(Figure 29). Accompanying foreland subsidence of the Maracaibo Basin also may have sufficiently lowered paleobathymetric barriers in the northern part of the basin to allow previously ponded bottom waters to be vented north into the Atlantic (Erlich et al., 1999a, 2000).

Increased wind stress brought on by higher land-sea temperature gradients (Kruijs and Barron, 1990; Poulsen et al., 1999) and cooling global climate also increased the frequency and intensity of seasonal coastal upwelling. However, this was not a common regional phenomenon after the Santonian. Upwelling was therefore confined primarily to northwestern South America as a result of the specific paleobathymetric configuration of the Llanos, Maracaibo, and Barinas-Apure Basins. Catastrophic overturn of

stagnant, nutrient-laden water masses occurred primarily during dry cycles and facilitated the primary productivity responsible for the vast chert and phosphorite deposits of the Colombian and Venezuelan Andes. This intense upwelling also aided ventilation of previously stagnant bottom waters.

CONCLUSIONS

Recent access to previously proprietary well and seismic data, plus incorporation of preexisting datasets, has revealed several common factors that governed the onset, maintenance, and eventual termination of source rock depositional systems across northern South America. Global factors such as changes in sea-surface temperature (caused by Milankovitch or
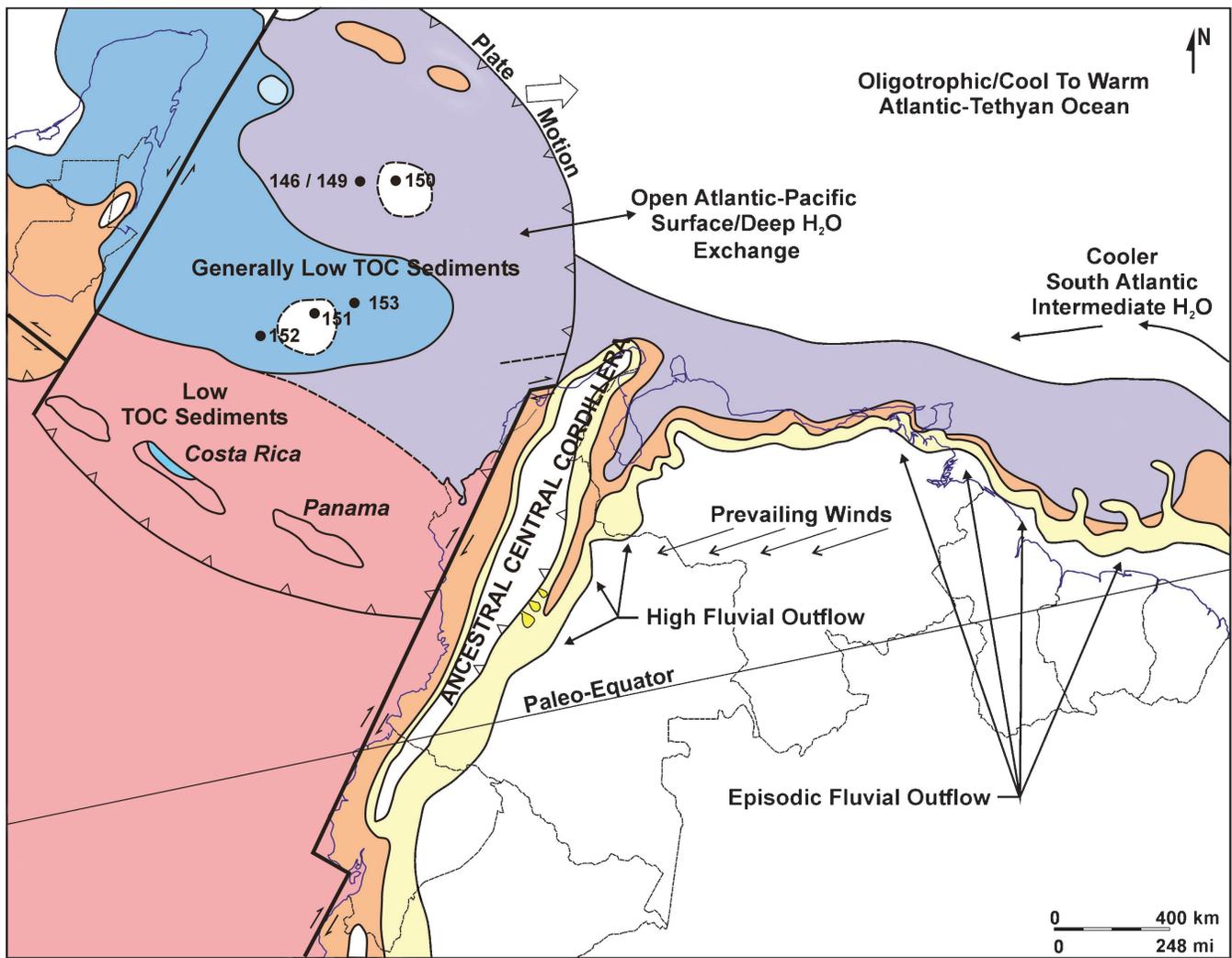
Figure 26. Late Maastrichtian paleogeography of the study area. See Figures 5 and 9 for color codes for depositional environments; pink = siliceous shales and cherts. Uplift of the Central Cordillera of Colombia provided an orographic barrier to the easterly trade winds and caused massive delta progradation into the Maracaibo, Llanos, and Barinas-Apure Basins. Formation of the Maracaibo foreland basin allowed stagnant Maracaibo Basin waters to be vented north into the open Atlantic.

other variables), formation of new intermediate- and bottom-water masses, and elevated eustatic sea levels provided the background conditions necessary to drive certain areas toward organic carbon accumulation and preservation. However, local modifications of these global events controlled where, when, and for how long organic matter accumulated in each basin.

Costa Rica/Central Caribbean

The presence of low-oxygen, saline bottom waters during the Late Cretaceous enhanced the impact of regional upwelling along the EPEUZ, increasing primary productivity in the surface water column. Primary productivity was very high and dominated by

siliceous marine organisms (radiolaria and diatoms). However, the formation of bathymetric barriers along the proto-Greater Antilles and Costa Rica/Panama island arcs prevented exchange and ventilation of low-oxygen bottom waters and increased the preservation of organic matter at the sediment-water interface. Termination of these conditions occurred primarily as a result of the influx of oxygenated AAIW from the South Atlantic.

Colombia and Western Venezuela

Initial flooding of the Maraca carbonate platform of western Venezuela and equivalent units in Colombia, plus the onset of arid climatic conditions, helped form a local high-salinity bottom-water mass
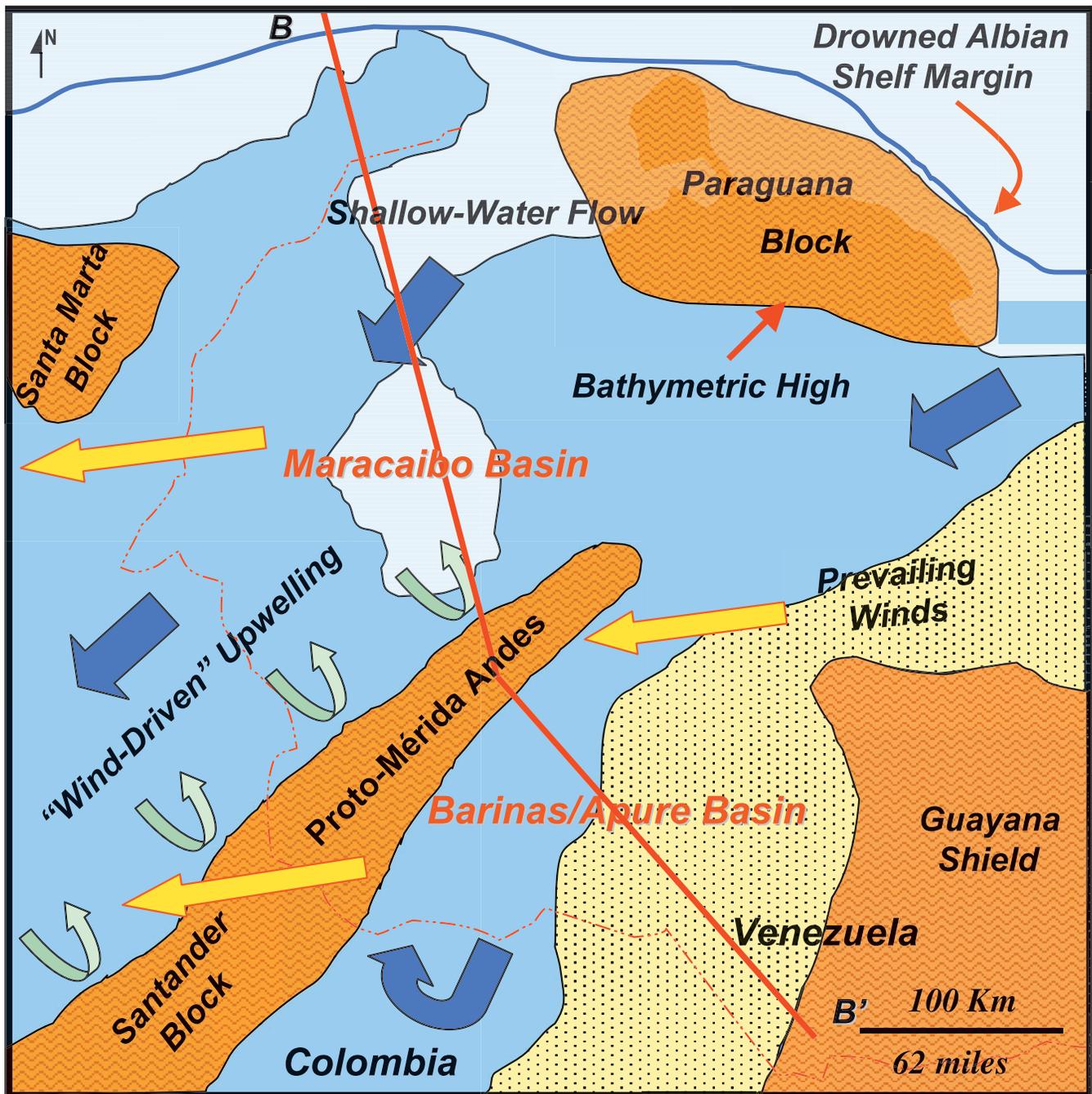
Figure 27. Late Santonian–early Maastrichtian paleogeography of western Venezuela. Silica- and phosphate-rich sediments were deposited along the proto-Mérida Andes as a result of wind-driven upwelling. Nearshore marine siliciclastic sediments (yellow stippled pattern) were common along the margins of the Guayana Shield. Line B-B′ is Figure 28.

in the Maracaibo, Barinas-Apure and Middle Magdalena Basins. Primary productivity was only moderate and was dominated by planktonic foraminifera. Paleobathymetric barriers surrounding the Maracaibo, Barinas-Apure and Magdalena Basins and elevated eustatic sea levels prevented ventilation of low-oxygen bottom waters until the late Santonian.

The onset of strong seasonal upwelling helped to ventilate stagnant bottom waters through catastrophic overturn, while increased precipitation (caused by formation of the Central Cordillera of Colombia) caused delta progradation into the basins. Delta progradation into the Upper and Middle Magdalena Basins filled accommodation space, terminated marine
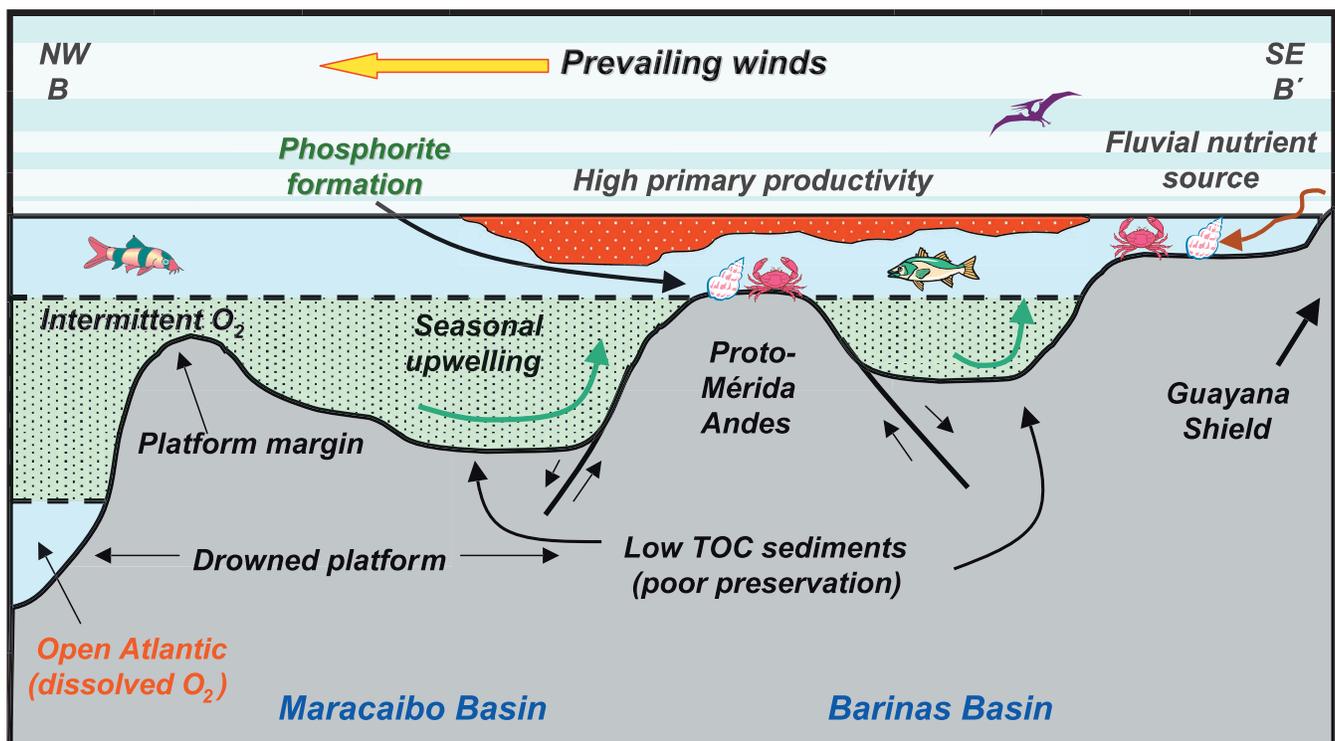
Figure 28. Late Santonian–early Maastrichtian depositional model for the Maracaibo and Barinas-Apure Basins. Strong seasonal upwelling caused deposition of siliceous and phosphatic sediments along the proto-Mérida Andes paleo-bathymetric high. Even though high primary productivity was common in the surface water column (red stippled pattern), the upper 50 m were probably well oxygenated. However, mid and bottom waters probably still were oxygenated only intermittently (green stippled pattern).

deposition, and forced a slightly earlier termination to source rock deposition. Foreland subsidence of the Maracaibo Basin breached the older paleobathymetric barriers and eventually vented the previously ponded Maracaibo Basin bottom water north into the Atlantic.

Eastern Venezuela, Trinidad, and Suriname

Eustatic sea level rise helped to pond shelf waters south of the El Cantil shelf margin. Nutrient flux was governed by seasonal upwelling and episodic fluvial outflow, which extended seaward of the drowned El Cantil shelf margin and into the upper slope. Slope and basin-floor submarine fan deposition helped briefly to introduce oxygenated waters into deep-water settings; however, low-oxygen conditions returned rapidly following these events. An exception to this probably occurred in bathymetrically restricted submarine canyons, which were common along the Suriname margin and possibly along the Trinidad margin as well.

Ventilation of the entrained shelf-water mass in eastern Venezuela and the stratified slope-water mass in Trinidad began in the late Santonian. Stronger seasonal upwelling, more frequent fluvial outflow, and the mixing of AAIW helped reduce the preservation potential of organic matter at the sediment-water interface. Delta progradation gradually infilled shelfal environments, and stagnant water masses in submarine canyons were eventually ventilated by mixing with oxygenated AAIW, thus ending source rock deposition across the region.
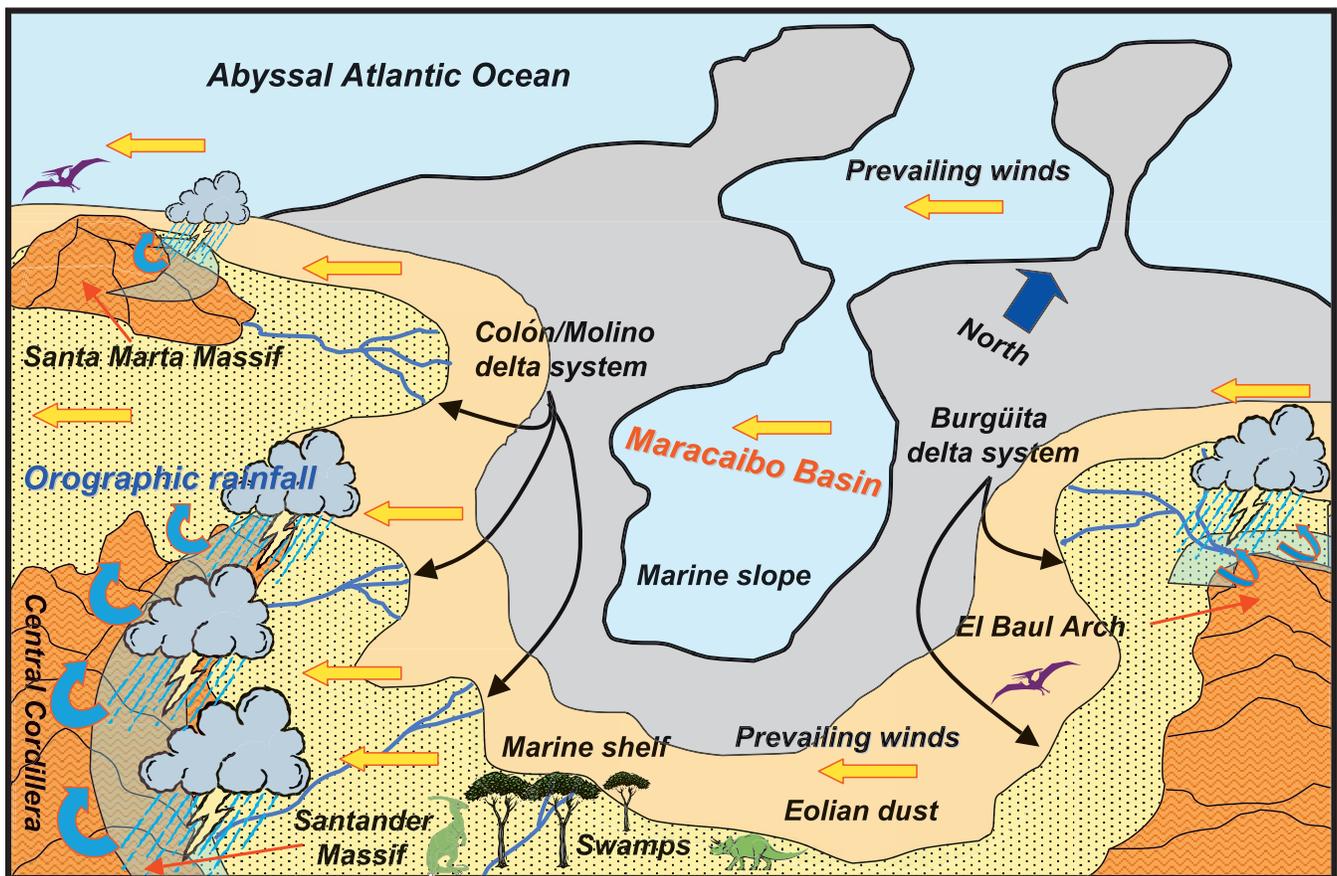
Figure 29. Maastrichtian ''weather map'' for western Venezuela. This cartoon portrays the likely impact of orographic barriers (orange-colored Central Cordillera, Santa Marta Massif, northern El Baul Arch) on regional rainfall patterns (green shading). The presence of large amounts of deltaic rocks (yellow stippled pattern) and palynological evidence of extensive swamps suggests this highly generalized model may be valid for most of the Maastrichtian.

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