Cenozoic Kinematics and Dynamics of Oblique Collision Between two Convergent Plate Margins: The Caribbean-South America Collision in Eastern Venezuela, Trinidad and Barbados

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Abstract

Numerous structural, tectonic, and geometric aspects of the Eastern South Caribbean Plate Boundary Zone are assessed or reassessed in the light of seismic reflection data, field studies from 2000-2007, heavy mineral analysis, updated interpretation of seismic tomography, seismicity, GPS data, and refined plate kinematic constraints for the Cenozoic. We show that the Cretaceous passive margin of northern South America was transformed to a north-facing, slowly convergent margin in the Late Maastrichtian, and that the collision between the Caribbean and South America was a collision of two convergent margins above an intervening, “doubly subducting” Proto-Caribbean oceanic lithosphere. The new assessments are iteratively integrated to create semi-quantitative palinspastic reconstructions for 5, 10, 25, 31 and 42 Ma, on which paleogeographies are developed. The origin of key sandstone units are considered, due to their importance as major reservoirs, as well as the implications of the kinematic and dynamic modeling for structural timing. The primary collision between the two plates was completed by 10 Ma, with subsequent motion being essentially E-W strike slip, the deformations of which are driven mainly in a bow-wave model of transcurrent simple shear.
Introduction

We present an updated synthesis of the tectonic processes and stages of history that have shaped Eastern Venezuela and Trinidad during Cenozoic time. Throughout our analysis we seek to emphasise three primary points. The first is that regional syntheses such as this one must be conducted in, as far as possible, a quantitative palinspastic reference frame that retrogressively retracts deformations backwards through time. This requirement is in addition to the definition of a rigorous but more regional plate kinematic framework. Second, in contrast to the common perception of an ongoing transpressive collision between the Caribbean and South America in the eastern South Caribbean Plate Boundary Zone (ESCPBZ), the last 10 million years of evolution at this boundary have occurred under a regime of E-W dextral shear. It was only prior to 10 Ma (end Middle Miocene) that these two plates underwent dextral oblique collision. Third, the collision prior to 10 Ma took place between two active margins rather than an arc and a passive margin, because northern South America had already been converted to an actively convergent margin before the Caribbean Plate began to collide with it.

We start with a summary of new perspectives on various aspects of the ESCPBZ. The new perspectives are afforded largely on the basis of large volumes of (1) seismic data courtesy of Petrotrin, BPTT, Venture, the Trinidad and Tobago Ministry of Energy and Energy Industries; (2) copious amounts of field work in parallel with the seismic interpretation; (3) heavy mineral analyses of over 150 field and core samples from Eastern Venezuela, Trinidad, and Barbados; (4) extensive thin section analysis of field and core samples; and (5) gravity modeling of various key cross sections. The new perspectives allow us to identify the important tectonic processes and elements of tectonic history within the plate boundary zone. It is seen that a “bow-wave” model built around E-W shear is a highly satisfactory way in which to view regional development since 10 Ma. The analysis also lets us develop a reconstruction for the end of the oblique Caribbean-South America collision at about 12 Ma from which the transcurrent phase subsequently took over.

We then review and expand upon the arguments in favour of the development of a “Proto-Caribbean” subduction zone along northern South America prior to, and unrelated to, the arrival of the Caribbean Plate from the west. An important part of this is a comprehensive examination and interpretation of the mantle seismic tomography of Van der Hilst (1990). This analysis in turn helps to establish a refined definition of regional plate kinematics, in which we abandon the Cayman Trough as the primary yardstick for assessing Caribbean-American relative motion rate, although it remains critical for understanding the general azimuth of motion. For rate, we employ instead the kinematic requirements of the migrating Caribbean foredeep basin along northern South America, which give a fairly steady South America-Caribbean displacement rate of 18 to 24 mm/yr back to the Late Paleocene. This plate kinematic section establishes that both the Caribbean and South American plates were convergently active margins at the time of their mutual collision, such that the collision was a “prism-prism” or “trench-trench” collision. General concepts of such a collision are noted, and aspects of regional geology are identified which support the concepts.
Next, we employ the 12 Ma palinspastic reconstruction derived earlier in order to assess the structural geometries and processes of the Early and Middle Miocene orogeny associated with the Caribbean-South America collision in the ESCPBZ. Assessment of this orogeny simply cannot be achieved with any paleogeographic rigour without first removing some 240 km of subsequent E-W strike slip offset from the orogen. Identification and understanding of the primary structural elements of the orogen in palinspastic coordinates in turn allows us to propose a Late Oligocene reconstruction for the margin which retracts the bulk of deformations from the Serranía Oriental and Trinidad.

The Late Oligocene palinspastic reconstruction in conjunction with the regional plate kinematics allows us to construct paleogeographic maps showing sandstone distributions and to identify tectonic processes for northern South America at times prior to the “orogenic” phases of the ESBPBZ. In particular, various sandstone units, which are important due to their hydrocarbon reservoir capacity, are related to those processes and highlighted by the reconstructions. The provenance and causes of deposition of these sandstones could not have been so rigorously identified had we not first completed the iterative procedures of all the above.

**Perspectives on today’s Eastern South Caribbean Plate Boundary Zone**

The eastern South Caribbean Plate Boundary Zone (ESCPBZ; Figs. 1A,B) is commonly perceived as a site of ongoing dextral oblique collision or transpression involving a component of N-S contraction (e.g., Speed, 1985). This misperception is caused by the recognition of widespread SE-directed folding and thrusting across the region (e.g., Case and Holcombe, 1980; Hung, 2005), as well as by the ongoing rapid subsidence in the large, asymmetric Maturín-Southern Basin foredeep (e.g., Di Croce et al., 1999). However, the perception is not strictly valid, because the relative motion between the Caribbean and South American plates in the ESCPBZ has an azimuth of 085° (N85E), meaning dextral slip, and is occurring at 20 mm/yr. The 085° azimuth derives from the style of young structural development (Robertson and Burke, 1989; Algar and Pindell, 1993), analysis of seismicity (Deng and Sykes, 1995), and GPS motion studies (Perez et al., 2001; Saleh et al., 2004).

One way to explain this misperception is to invoke a dextral simple shear model on the entire region (e.g., Robertson and Burke, 1989). Such a model predicts that the axis of maximum horizontal compression is NW-SE, thereby explaining SE-directed convergent structures. This model certainly holds merit for much of the regional structure, but it appears not to explain three important observations:

The first is the magnitude of the development of the Maturín-Southern Basin foredeep, because dextral shear, on its own, does not provide a progressive increase in tectonic load large enough to drive the observed subsidence (Fig. 2; Jacomé et al., 2003a,b).

The second is the drastic change in structural style at about 10 to 12 Ma noted by Algar and Pindell (1993) and Pindell et al. (1998). The simple shear model, on its own, does not explain why the predominant deformation style should change from SE-ward compression to E-ward extension at 10 Ma in various areas such as the Gulf of Paria or the Maturín Basin. These authors showed that the 085° azimuth satisfies structural
Figure 1. A) Generalised structure map of the Southern Caribbean, including deep features such as the Proto-Caribbean Subduction Zone and the subducted Caribbean slab beneath Central Venezuela; B) Features relating to Caribbean-South America interaction, and the southern Caribbean Plate Boundary Zone, developed within the Caribbean “orogenic float”. The background is Sandwell and Smith free-air gravity.
Figure 2. Cross-section of the Maturín foreland basin, through El Furrial, modified from Jacomé et al., 2003b. Note that Middle Miocene thrust structures are buried by Late Miocene and younger sediments. Only very minor post-10 Ma shortening can be seen in the section, and yet there is over 4.5 km of accommodation space developed since that time, more than during the Middle Miocene imbrication of Serranía Cretaceous strata.

Figure 3. Selected seismic lines modified slightly from Ysaccis (1997). A) N-S line extending from Araya to La Blanquilla Basin showing compressional structures within upper layer of Caribbean Plate developed in the Caribbean “orogenic float” prior to ca. 10 Ma. B) Similar pre-10 Ma structures immediately north of Margarita and the western end of the La Blanquilla Basin. C) Close to the Bocas High, Northern Range metasediment is present on the south end of this line. Original seismic in this area locally shows pronounced south-dipping reflectors within the Patao (Tobago Terrane) metavolcanics and close to the contact with the Northern Range, suggesting that many thrusts in this area are north-vergent, not south-vergent as suggested here, and that Caribbean basement beneath the basal detachment to these thrusts may wedge underneath the Northern Range. This event is dated by the pre-10 Ma thrusts and appears to post-date the south-vergent high-level emplacement of the leading edge of the Caribbean Nappes over Araya-Paria. D) Apparent cumulative west to east extension on right-stepping pull-aparts along the NCFZ, off the north coast of Araya-Paria, can be used to estimate the maximum slip on the NCFZ. Including young basins as far east as Tobago, we conclude that probably not more than ca. 25 km dextral slip occurred on the NCFZ since 10 Ma, and larger measured offsets on older structures are probably older than 10 Ma. There are no through-going lineaments along this fault zone, in contrast to the very sharply defined El Pilar-Caroni-Guaico-Scorpion Fault trend.
development back to about 10 Ma only, prior to which the Caribbean and South America were undergoing a much more compressional collision (see Fig. 18A, developed below).

The third is the emplacement of allochthonous Caribbean rocks, such as the Villa de Cura Complex of the Caribbean Mountains and the basalts drilled in the Gulf of Barcelona (Ysaccis, 1997), up to 100 km south of what is commonly perceived as the main Caribbean-South American shear zone (i.e., the Morón-El Pilar fault system). It is difficult to imagine the emplacement of these bodies, involving up to 100 km of lateral displacement from the fault zone, as petals of a positive flower structure.

From the above, a two stage evolution appears to be required, and 10 Ma seems to mark the transition from a more convergent phase of evolution to a more transcurrent one. In the following sections, we will characterise the present ESCPBZ and construct the bow wave model for tectonic development over the last 10 m.y., and restore the post-10 Ma deformations to reconstruct the orogen at the end of the convergent phase.

Aspects of the tectonics of the Eastern South Caribbean Plate Boundary Zone

Aspect 1

The trace of the southeastern edge of crystalline Caribbean crust is curvilinear, trending E-W along the El Pilar Fault but curving around to N-S at Barbados (Fig. 1). As we shall see, this is critical for understanding the regional deformation history since 10 Ma.

Aspect 2

Seismic data north of Trinidad and Araya-Paria Peninsulas suggest that structures originally formed during early to Middle Miocene oblique compression have been subject only to relatively minor transpressional or transtensional reactivation since 10 Ma (Fig. 3; Ysaccis, 1997; Robertson and Burke, 1989). Seismic lines show thrusts with northward structural vergence within what is usually mapped as Patao-Tobago Terrane volcanic arc. Some lines also show what appear to be south-dipping thrusts very close to the edge of the Northern Range, and limited well data suggest that some of the highest level rocks drilled off the north coast have affinity with Northern Range rocks or the Sans Souci and Toco Formations than with true Tobago Terrane (primitive island arc) and may be remnants of the proposed “Proto-Caribbean Accretionary Prism”. These thrusts must merge at a detachment several kilometres deep and thus Caribbean crust below this detachment probably underthrust the Northern Range during the Middle Miocene (Fig. 4). This is no longer a simple thrust relationship except in relatively small areas, but has been modified by low magnitude dextral shear north of Trinidad since 10 Ma. There does not seem to be any significant through-going, large offset, shear zone that could act as the principal plate boundary. A summation of the apparent offsets on transtensional and transpressional structures along the North Coast Fault Zone leads us to propose no more than about 25 km dextral offset between Tobago and the Northern Range, increasing west to perhaps 50 km north of Araya (GPS
Figure 4. A) Location map, and lithospheric-scale cross-sections through B) Cumaná (Serranía Oriental, Venezuela) and C) Port of Spain (Northern Range, Trinidad), showing the interpreted wedging of Caribbean forearc lithosphere under the Araya-Paria-Northern Range Terrane at a depth of ca. 10-20 km. This is accommodated in part by backthrusting of the upper most Caribbean crust and associated sediments and in part by south-vergent thrusting of the Cretaceous and possibly Jurassic strata of the former passive margin, with slices of basement also possibly present within the northern part of this thrust belt. The key feature of these sections is that there is not a steep lithospheric scale strike-slip fault zone separating Caribbean lithosphere in the north from South American lithosphere in the south. We show Caribbean crust overthrusting South American basement beneath the underthrust wedge and extending 100-150 km north of the surface trace of the El Pilar Fault, consistent with tomographic data. This deep “flap” of South America is limited in the north by the former Proto-Caribbean Subduction Zone, and continues up dip to the east to emerge at the trench east of Tobago. The strike-slip faults, such as the North Coast Fault Zone (NCFZ), the El Pilar (ELP) and Central Range Fault (CRF), which cut the thrust belt that had developed by 10 Ma, are inferred to root into the north-deepening basal detachment of the thrust belt at depths of ca. 20 km under the Central Range, 25-30 km under the Gulf of Paria, and perhaps 40 km under the El Pilar Fault near Cumaná. During Middle Miocene orogeny, the bivergent “orogenic float” structural style developed, but since 10 Ma, Caribbean-South America motion has largely been accommodated by strike-slip on the El Pilar Fault and Point Radix-Darien Ridge Fault, and by reactivation of compressional features only on the south side of this strike-slip belt. Middle Miocene compressional structures within the Caribbean have largely been dormant since 10 Ma (see seismic line examples in Fig. 3).
data from Perez et al., 2001 and seismic lines from Ysaccis, 1997). Furthermore, offsets on Late Pleistocene to Recent sediments along the NCFZ are small to non-existent, indicating that the structure has not been active for perhaps 1 Ma or more, as also indicated by the GPS data. East of El Pilar Village near the El Pilar Fault in the Serranía Oriental, the Carupano and Tobago platform crust likely continues beneath the Northern Range to about the trace of the El Pilar Fault. West of El Pilar Village it does as well, but there it also is present on the south side of the El Pilar Fault, and probably at two different structural levels (see Aspects 13 and 14). In summary, the Northern offshore area does not seem to have been a strongly transcurrent part of the plate boundary zone since 10 Ma, implying that most relative motion since that time has passed farther south, through onshore Trinidad.

Aspect 3

The active El Pilar Fault, which appears to accommodate most Caribbean-South America motion in Venezuela is commonly shown as continuing along the line of the “Arima Fault” at the southern foot of the Northern Range. Both transtensional and transpressional models have been proposed for this fault, but neither is supported by seismic lines. Marine seismic data east of the Northern Range (“North Basin” area) in the area where the Arima Fault is commonly presumed to exist show that no such fault exists there. Instead, the Northern Range rocks continue SE-ward beneath a Late Miocene SE-dipping unconformity onlapped NW-wards by latest Miocene-Pleistocene strata. Thus, the strike-slip displacement on the El Pilar Fault cannot track along the foot of the Northern Range. However, Caroni Basin onshore seismic data do show a continuous approximately E-W zone of stratal disruption along the line of the Caroni and Guaico Rivers (Figs. 5 and 6), rather than on the northern edge of the Northern Basin. This zone shows transtensional graben structures were it trends slightly SE and pop-up structures where it trends slightly NE. Faults along this line break all reflectors to the surface, and separate slightly incised Pleistocene and older strata to the south, from still subsiding, swampy river valleys to the north. We propose that this disrupted zone overlies the eastward continuation of the El Pilar Fault across northern Trinidad, and we call this the Caroni Fault Zone. Offshore to the east, its continuation is seen in a narrow graben which swings SSE from the El Pilar Fault near the Dragon’s Mouth and intersects the coast about 5 km south of the Caroni River delta. In the eastern offshore, the Caroni Fault passes south of the “North Basin” homocline and merges with active fault traces trending 065° along the north side of the Central Range. Overall, the proposed Caroni Fault is more laterally continuous, narrow, through-going and younger a lineament than the North Coast Fault Zone.

Aspect 4

GPS data (Saleh et al., 2004) show that effectively all Caribbean-South America relative motion (20 mm/yr) is occurring south of the Northern Range today, through central Trinidad (Fig. 7). About 75% of it (15 mm/yr) appears to be distributed along the Central Range and probably the Point Radix Fault Zone, while a
Figure 5. Map showing main displacement loci during post-10 Ma transcurrent phase, and position of Caroni seismic line (Fig. 6). The trace of the newly-defined Caroni Fault Zone across northern Trinidad, from Piarco to Guaico is shown. In Mid-Miocene time, Caribbean crust (green) had abutted against SoAm crust, an outer wedge of which (red) was caught up between the plates during thrusting. Late Miocene shear on the blue faults stretched this wedge in the northern Gulf of Paria, forming that basin, and controlling Manzanilla deposition. These faults are still active, but were joined in Pliocene (yellow faults) by deep deformation jumping south and west into San Juan Graben and Southern Range. Los Bajos Fault was active in both phases, but it is unclear where Late Miocene strain on it was accommodated eastward. Central Range activity now steals most displacement formerly on Point Radix-Darien Ridge. San Francisco Fault may be involved in this later phase. Also shown is the location of a semi-balanced strike-line (Fig. 9) through the Gulf of Paria from which east-west extension can be estimated.

Figure 6. Example seismic line across the Caroni Basin near Piarco Airport, showing still active structures along the proposed “Caroni Fault”. Similar transtensional graben or transpressional pop-ups are found in a continuous through-going fault zone from the Caroni Swamp to the Guaico River and Oropuche Swamp. The structures define the northern boundary of the mapped, incised Talparo and older strata on the geological map of Trinidad, and is narrower and more continuous than the North Coast Fault Zone. Furthermore, the fault zone merges offshore with the very young “Scorpion” Fault which runs just north of Angostura. Off the east coast there is no sign of the trace of the Arima Fault along the line most commonly drawn (e.g. Robertson and Burke, 1989; Saunders et al., 1997) and thus we infer that this lineament, with the Central Range Fault and Darien Ridge Fault farther south, is in fact the locus of much of the strike-slip between the Caribbean Plate and South America, and that the North Coast Fault Zone has been less significant, at least since 10 Ma.
pre-10 Ma thrust stack, e.g., Brighton, with Nariva Fm on backside

Manzanilla (pink) in “half graben”, cut in Plio-Pleistocene by South Boundary Fault after significant transtensional opening, growth recorded by Springvale and younger (yellow).

Figure 7. GPS vectors for Caribbean motion relative to South America. Red vectors come from Perez et al. (2001) and black vectors from Weber et al. (2001) and Saleh et al. (2004). Note that in the Trinidad region CA-SA motion is uniformly towards ca. 085° at 20-21 mm/yr. In Trinidad, these magnitudes of eastward motion continue as far south as the Central Range Fault, indicating that the Northern Range is effectively riding passively with (and probably on) the Caribbean Plate. North of Carupano Village perhaps as much as 25% of the relative plate motion is occurring on the North Coast Fault Zone. Thus, there must be a southward step in plate motion between here and the Northern Range, possibly through the area of the Dragon’s Mouth, which appears to be undergoing east-west extension, leading to subsidence and drowning of coastal valleys in northwesternmost Trinidad (e.g., Diego Margin and Tucker Valley).

Figure 8. Schematic cross-section of the Gulf of Paria low angle detachment basin, showing the South Boundary Fault Zone reactivating a formerly slightly extensional (ca. 5 km) strike-slip (up to 50 km) fault. Also shown is a location map of the major through-going strike-slip zones in the Gulf of Paria.

From Flinch et al., 1999.
minor amount occurs along the Southern Range or even farther south in submarine extensional faults of the Columbus Channel. However, seismic data as well as the general paucity of basement-depth seismicity in central Trinidad suggest that the active fault zones dip north and pass beneath the Northern Range, and are not high angle faults into deep central Trinidadian basement (Fig. 4). The actual “basement-level, or petrologic, plate boundary” lies beneath the Northern Range.

Aspect 5

The E-W trending strike slip fault zones of the ESCPBZ were initiated at about 10 Ma within a pre-existing Middle Miocene compressional orogen with SW-NE-trending structures which formed primarily during oblique Caribbean-South American collision. These include the Morón, El Pilar, Caroni (see below), South Boundary, Point Radix (see below), and Los Bajos (SE-trending but motion was eastward; see below) faults. Sedimentation (e.g., La Pica, Morichito, Cruse, Manzanilla Formations) in the transtensional basins controlled by these faults (Cariaco and Gulf of Paria basins) and overlying the earlier compressional orogeny began at about 10 Ma close to the Middle to Late Miocene boundary (Erlich and Barrett, 1990; Algar and Pindell, 1993; Babb and Mann, 1999). In addition, after widespread Middle Miocene uplift and erosion across the Tobago and Carupano platforms, subsidence and sedimentation were renewed there in the Late Miocene as well (Bellizzia, 1985; Yssacis, 1997).

Aspect 6

The Gulf of Paria is an extensional basin which formed at the site of a right step splaying off the dextral El Pilar Fault. Seismic data in the Gulf of Paria Basin (northern part of the geographic Gulf of Paria) show a Late Miocene to Recent N-ward collapsing, rotational half-graben geometry that is bisected by an E-W high-angle transcurrent fault zone (Fig. 8), the South Boundary Fault (referred to erroneously by some authors as the Warm Springs Fault), which runs close to the southern edge of Blocks 1ab. The basin on the whole is a low-angle extensional detachment basin within the pre-existing Serranía-Nariva thrust belt, the unroofed footwall of which is the northern flank of the E-W trending North Marine Ridge. The “hanging “wall” is now a series of NW-SE trending ridges (e.g., Avocado, Domoil, Gulf Highs) in the northern half of the basin that are buried by Late Miocene and younger basin fill strata, and that have been extended E-W during basin extension to form the intervening troughs between the ridges. Thus, the basin has undergone three-dimensional strain, extending eastward while collapsing northward. Eastward extension is far larger (up to 70 km; Fig. 9) than northward detachment (~5 km), such that actual fault plane motion directions were toward azimuth 080°-085°. The detachment surfaces formed entirely within the pre-existing Middle Miocene thrust pile, the lowest thrust-sheet of which appears to be a slice of South American basement (see Fig. 4) overlain by 2-3 km of Neocomian evaporite (post-rift Yucatán Platform type, not rift-related) and younger Cretaceous strata. There may be a pre-evaporite marine (Upper Jurassic) section as well (Pindell and Erikson, 1994), but this has not been reached by
Figure 9. Strike-line in the Gulf of Paria (modified from Flinch et al., 1999, location shown on Fig. 5) shows strong west to east extension of Cretaceous carbonates with low angle normal faults cutting through the Couva evaporates and ultimately rooting into the basal detachment of the older Middle Miocene Fold-Thrust Belt. We have taken a number of approaches to estimating the extension, using offsets of seismic markers across faults (line-length balancing) and the approach shown here (area balancing). If we outline the area on the section occupied by Cretaceous carbonates we can restore these to a reasonable estimate of their pre-extension thickness. This in turn yields an extension estimate for this line of about 50 km. Using all these approaches, we have estimated a total extension between the San Juan Graben, in the eastern Serranía, and the Caroni Basin, in Trinidad, of about 70 km.
wells drilled to date. The basement slice in interpreted to have been involved in the Middle Miocene thrusting, and is displaced SE-ward by about 40-50 km (i.e., we infer that it drove the shortening of Cretaceous strata from the Brighton area to the south coast), such that it is not a classic “thick-skinned” style of deformation; rather, it is a thin-skinned basement-involved thrust deformation. This parautochthonous slice sits above the northward-dipping autochthonous South American footwall and subjacent to the allochthonous migrating Caribbean crust, which is situated in turn beneath the Northern Range metasediments. Thus, the basement slice has been sheared between the two stronger, more intact plates since 10 Ma, which is probably why it has been extended E-W so much in the Gulf of Paria Basin. The slice probably continues eastward (although broken) into the western part of the Caroni Basin, and westward back towards the Urica Fault. Beneath the Serranía, it is probably the same basement slice as has been proposed to be present in the hanging wall of the Pirital Thrust (Roure et al., 2003).

Extensional detachment faults controlling Late Miocene strata within the Gulf of Paria low angle detachment basin reach westward to the NW-trending coastline along the northwestern Gulf of Paria. However, the westernmost “head” of extensional detachment faulting jumped westward in the middle Pliocene (~2-3 Ma) to at least the San Juan Graben of the Serranía Oriental as shown by seismic, and probably (i.e., no proof from seismic) to the San Francisco Fault. This younger system of faults cuts through the entire Serranía Oriental thrust pile southward to the Middle Miocene deformation toe. This is farther south than the Late Miocene-Early Pliocene boundary of the basin; both these fault zones tie directly into the diapir trend of the eastern Maturín Basin, which is the western part of the transfer zone that continues into the Pedernales-Southern Range trend. Eastward extension on this younger system is on the order of 5 km, and this strain has been carried eastward along the Pedernales-Southern Range trend all the way to Galeota (or the western Columbus Channel normal faults). The effect of the shift was to incorporate more of the Middle Miocene thrust pile (i.e., all of it) into the zone of eastward collapse; the former (Late Miocene-Early Pliocene) footwall of the detachment basin now (since 2 or 3 Ma) lies in the hanging wall. In contrast, transtensional dismemberment of the previously mentioned basement slice appears to have controlled the position of Late Miocene-Early Pliocene basin development.

Aspect 7

The Los Bajos Fault Zone has a deep expression and history that has not been fully appreciated in the past (Fig. 10). The Los Bajos Fault sensu-stricto is a high angle, dextral transcurrent fault zone with up to 11 km offset (Wilson, 1968). However, the anastomosing faults in the fault zone project downwards to the trailing tip of a hanging wall above a NW-SE trending, NE-dipping low angle detachment fault between the Brighton (hanging wall keel) and Soldado Highs (top of footwall). The shallow, relatively steep, faults do not pass through this detachment surface. This detachment occurs within the Middle Miocene thrust pile only and may have originated as a dextral, east-dipping, lateral ramp. Judging by offset of the 10 Ma unconformity on the hanging wall relative to that on the footwall, the hanging wall has undergone a net normal throw of about 5 km since 10 Ma. The
Figure 10. Synthesis of the geometry and history of the Los Bajos Fault Zone. This “typical section” derives from seismic lines offshore Point Fortin. The fault as commonly mapped is at the upper level only, an anastomosing set of dextral, mainly transpressive faults cutting to surface with a collective offset of 10 to 11 km (Wilson, 1968). But a more significant, deeper control underlies this upper level within, and probably cutting through, the Cretaceous-involved Middle Miocene thrustbelt. The precursor to the fault is an east-dipping lateral ramp separating the Soldado and Brighton Thrust stacks, and SW Peninsula from the structurally higher imbricate stack in the Moruga-Guayaguayare area. During the Late Miocene this lateral ramp was reactivated as a down to the east extensional fault (“Soldado Breakaway”), which bounded a Manzanilla (possibly even Lengua?) depocenter on the NE side of the Soldado Main Field and which reached the surface close to the crest of the Main Field (clearly delineated by drilling, with almost all Main Field wells drilled in the footwall of the fault). Subsequent SE-directed thrusting on the east side of the breakaway (forming the Rock Dome thrust culmination) reactivated this detachment, but faulting splayed vertically off the detachment at the edge of the more competent Cretaceous units in its hanging wall (which can be traced on seismic up-dip towards Brighton) rather than cutting at a shallow angle through the incompetent Cruse and Springvale. As a result, the “neotectonic” Los Bajos Fault is seen as a more or less vertical fault zone, with positive flower structures indicating an overall slight transpressive inversion, that can only be traced to base of the Late Miocene section. What has not previously be recognised is that the undulations in the “10 Ma unconformity surface” into which the Los Bajos Fault appears to root are in fact the trace of a Manzanilla-aged half-graben and associated breakaway fault, and not the result of compressional deformation. Thus, there is no deeper vertical expression of the Los Bajos Fault and the strike-slip roots east into the base of the Rock Dome thrust sheet. Seismic data in the Soldado area also indicate that Los Bajos offset predates the base Talparo unconformity in the North Field area, placing important constraints on the age of the Rock Dome Thrust, and also explaining why the Los Bajos Fault cannot be traced through the area of thick Talparo NW of North Field to link with the South Boundary Fault; it does link, but only at a sub-Talparo level.
azimuth of motion since 2 or 3 Ma is parallel to the surface trace of the fault, and the strike-slip displacement runs along the low-angle detachment at depth and then cuts upward at a high angle toward the surface. From 10 Ma to about 3 Ma, however, the only provable displacement was the above-noted extension, whose azimuth we estimate was toward about 080° in order to cohere with regional structural development of that period. The SEward directed component of motion along the fault since 3 Ma has been fed into the shortening accumulated at the Rock Dome fold/thrust and, to a lesser degree, the tightening of the Moruga fold/thrust to the south of Rock Dome. This model can help explain the termination towards the northwest of the shallow Los Bajos Fault; SW-NE trending folds appear to link to a similar trending fault to the SW, very close to the surface trace of the Late Miocene low-angle detachment fault. Furthermore, the apparent disappearance of the Los Bajos Fault towards the NW is also in part explained by its being overlapped by the basal Talparo (Pleistocene) of the Gulf of Paria, indicating that it may be largely inactive since ?Middle Pleistocene time; thus is does not cut through the thicker Talparo section in the that area.

Aspect 8

Between San Fernando and Point Radix, the geological map of Trinidad (Kugler, 1996) shows an apparent dextral, en-echelon, displacement of structures. De Verteuil and Eggerton (2000) called this zone the Point Radix Fault, and pointed out that the trend continues eastward offshore to define the southern edge of the Darien Ridge. The supposed Rio Claro “Boulder Beds” (Saunders, 1974, stratigraphic chart, in Kugler, 1996) occur directly along this trend, but Liska (1988) studied these in a 30 m trench cut for a gas pipeline and determined that the “bouldery appearance” was in fact a tectonic melange (fault breccia) with numerous vertical faults running E-W. Since then, Saunders et al. (1997) accordingly have removed the “Rio Claro Boulder Beds” from the stratigraphic lexicon included with their map, acknowledging that the bouldery texture was produced tectonically. Smaller apparently dextral offsets are seen in the alignment of slivers of Lizard Springs on the north side of Dunmore Hill and in the abrupt E-W strike changes in Cipero Formation strata between Debe and St. Croix. The tectonic rupturing of the section is testament to the existence of the Point Radix fault zone. In addition, our seismic mapping in the Southern Basin seismic data set has shown this entire belt to be completely disrupted, no coherent reflectors being correlatable from N to S across it. The zone does, however, dip to the north, and presumably ties into the detachments beneath the Central Range and eventually into those beneath the Northern Range. To the east in the offshore, this trend marks a primary structural boundary defining the Darien Ridge, and recently one or more mud volcanoes leading to intermittent island formation have erupted along it (see http://www.gstt.org/Geology/radix/Radix%20event%202007.htm). To the west, the Point Radix Fault ties into the South Boundary Fault of the Gulf of Paria Basin, which cuts upward through young section from the primary trace of E-W displacement through that basin. Balancing of E-W seismic sections across the Gulf of Paria (see Fig. 9) suggests that total post-10 Ma extension is as large as 70 km. Realignment of the two known sandy portions of the Nariva Formation (i.e., those at Brighton and Nariva Hill) requires a similarly large
displacement (De Verteuil and Eggertson, 2000). The South Boundary Fault is the primary transfer zone for carrying this motion eastward as the basin opened (southerly step from El Pilar Fault), but the Central Range and the eastward component on the Los Bajos Fault have carried some of this as well. We roughly estimate that the post-10 Ma offsets on these 3 systems are: Los Bajos, 10 km; Central Range, 10-20 km; Point Radix Fault, 40-50 km. Bear in mind, however, that due to the transfer nature of these three faults, displacement along them will vary with location as extensional and compressional faults splay off of them.

Aspect 9

If we accept that the Caribbean-South American displacement rate has been 20 mm/yr since 10 Ma, and that all of the E-W transcurrent shear zones (El Pilar, Caroni, Point Radix, Southern Range, Los Bajos, and Central Range) are 10 Ma or less in age, then the total offset on the various fault zones should sum to 200 km. Therefore, in addition to the respective ca. 10, 20, and 50 km proposed for the Los Bajos Fault Zone, Central Range, and Point Radix Fault Zone (see above), we need to identify the positions of another ca. 120 km of displacement. The available options are the Southern Range, the Caroni Fault, faults in the northern offshore (NCFZ, or perhaps through the northern parts of the Northern Range as no E-W faults younger than 10 Ma occur in the offshore between Galera Point and the Caroni Fault). Seismic lines across the Southern Range west of the Los Bajos Fault show a simple fault propagation fold with limited (<5 km) shortening, and the paucity of surface breaks along the trend by strike slip faults suggests that such strike slip displacement is also less than 5 km. These deformations are very young (<3 Ma). We estimate no more than ca. 25 km on the North Coast Fault Zone, and that perhaps as much as 30 km can be accounted for as distributed simple shear (manifested in, for example, the young shortening within the Central Range and Southern Basin). This places the bulk of excess motion since 10 Ma on the Caroni Fault, approximately 70 km. If the internal parts of the Northern Range have been dormant and riding passively on the Caribbean fringe since 10 Ma, we may need to reduce our estimate for the NCFZ and increase our estimate for the Caroni Fault and/or the Central Range Fault. The proposed offset on the Caroni Fault is sufficient to bring the end Middle Miocene unconformity in the “North Basin” of the eastern offshore, back to the north side of the same unconformity across the Caroni Basin onshore, and also to pull the toe of what appears to be a “basement wedge” (in our view, a fragment of the Proto-Caribbean hanging wall ridge) back to align with the leading edge of the inferred basement wedge under the Gulf of Paria, before it was stretched west to east (locations of basement wedges shown in Fig. 5).

If one prefers to increase the general simple shear value, then motion on the Caroni can be reduced accordingly. We note that the Arima Fault is primarily a down to the south normal fault, accommodating the vertical component of motion of the blocks stretching west to east in the Gulf of Paria, and strike slip does not reach into the offshore at the eastern end of the Northern Range. However, a small component of strike slip motion on the Arima could step southward at unidentified places in the Caroni (Northern) Basin to the Caroni Fault, in particular through the swampy, low ground where the Toco Main Road crosses the Oropuche River.
Finally, it must be greatly emphasised that all the motions mentioned here are with respect to section beneath the 10 Ma unconformity. This is because the unconformity also serves as a detachment horizon on which the post-10 Ma section commonly slumps eastward, especially south of Point Radix Fault. In places, such as along the Darien Ridge, the section above the 10 Ma unconformity in the growth fault province to the south, driven largely by gravity and delta progradation, is moving east at about the same rate as the section north of the Point Radix Fault, thereby masking the fact that the northern flank is moving east relative to the sub-10 Ma section of the southern side of the fault.

**Aspect 10**

In the eastern offshore, the continent-ocean crustal boundary or transition, at the foot of the continental slope, is easier to recognise on seismic than those at most margins. It is also relatively clear on Bouguer gravity anomaly maps (but not quite so clear on free-air anomaly maps, which are dominated by the effects of bathymetric gradient. The location is shown on Fig. 1A) as a pronounced gradient stepping up to the northeast. It trends NW and passes under the Darien Ridge at about 10.7°N/-60.2°W. This margin is a former transform fault where the Bahamas basement pulled away from the Demerara High, and migrated sinistrally relative to South America during the Jurassic and Early Cretaceous; the plate motions for this event are very well constrained by Central Atlantic magnetic anomalies. It is kinematically unlikely for the COB trend to step substantially to the right at the Darien Ridge, because such a step would be require compression during Bahamas migration. Thus, the COB most likely projects and continues beneath the Darien Ridge on the same trend, passing between Galera Point and Tobago. The Late Cretaceous shelf edge on the Guyana-Suriname margin sits updip and about 75 km to the west of the COB and can be traced NW towards Galeota. This raises an issue with the occurrence of the Cretaceous (Naparima Hill Formation source rocks) outer neritic and/or upper bathyal facies in the offshore Angostura-Emerald area (Emerald-1 well files, courtesy of Petrotrin), which lies immediately above the COB trend. Here, it is at least 50 km to the east of where we would expect it based on projections of the Late Cretaceous shelf edge from data on the Suriname-Guyana margin, keeping it approximately parallel to the continent-ocean transition. If the shelf edge and slope swings towards the NW as shown by Erlich et al. (2003), then the shear required to bring the Cretaceous in the Angostura area to its present position may be as high as 75 km or more. How did that stratigraphic package get there if the area is floored ultimately by transitional crust (highly attenuated continent, with strong oceanic crust influence)? We submit that the entire offshore Central Range trend, which lies north of the Point Radix Fault and Darien Ridge, has migrated laterally from farther west of the COB, where normal-thickness continental crust away from the COB once supported outer shelf-upper bathyal paleo-water depths, to its position close to the COB as a function of the post-10 Ma strike slip history. The top Cretaceous structure map of Boettcher et al. (2003) shows this very nicely. However, because the Point Radix Fault dips north, roots into the basal detachment of an essentially thin-skinned orogen, and ties into the true plate boundary beneath the Northern Range, the offshore platform section (1) has been detached from its...
original continental foundation, and (2) is allochthonous (detached) with respect to the transitional crust it now sits on while continuing to transpress eastwards. This serves to reactivate Middle Miocene thrusts in the pile, and also to inflate the Darien Ridge by structural shortening of previously undeformed section. This low angle detached transpressional foldbelt has overridden and accreted fresh source rocks at depth since 10 Ma, suggesting the possibility of two phases of hydrocarbon maturation within the thrust pile, one of Middle Miocene age and the second of Late Miocene and younger age.

Aspect 11

To the southeast of Trinidad, the southern limit of the supra-Middle Miocene growth fault province is defined by a scallop shaped set of transtensional gravitational collapse structures (location shown on Fig. 1B), informally called the “Escalera fault zone” by British Petroleum Trinidad and Tobago and not strictly related to the Caribbean plate boundary zone. Instead, it is much more due more to gravity-driven tectonics within the prograding Orinoco Delta. The more E-W fault segments in the “Escalera fault zone” are dextral lateral ramps or transfer zones between the collapsing hanging walls and the southern, more stable portion of the shelf and slope. The total extension across E-W stratigraphic dip is significant, on the order of 40 km (Gibson et al., 2004). This motion must carry eastward along a lateral ramp connecting the Escalera transtensional growth fault limit to the transpressional southern end of the Barbados prism. Very few seismic lines exist with which to map the details of this process, but limited data do show that it occurs, as it must, and that the two features are in fact connected along a diffuse E-W line. The trend of folds and thrusts at the southern end of the prism curves into E-W parallelism with the transfer zone by processes beyond the scope of this paper, but which probably involve fault drag (along the transfer zone) and the imposition of the near north to south tectonic strain on the extending hanging walls of the gravity-driven normal faults.

We suspect that dextral motion on the Point Radix-Darien Ridge shear zone certainly facilitates the gravitational collapse in the Columbus Channel, by dextral drag rotating and opening growth faults further, or by pulling hanging wall stratigraphic section which continues up and over the Darien Ridge from the south towards the east with the ongoing dextral shear, thereby tectonically enhancing gravity-driven growth fault offsets. Locally, gravity-driven growth faulting is able to extend eastwards slightly faster than the dextral motion to the north of the Darren Ridge, and this is manifested in the E-trending or ENE-trending normal faults seen east of Diamond and Emerald, close to the very abrupt transition between shelf and extremely steep slope (built structurally, not by a prograding delta slope).

Overall, the Columbus Channel can best be described as a thin-skinned pull-apart basin with a complex mix of tectonic and gravity (delta progradation) stresses driving the deformation, as suggested by Pindell and Kennan (2001) and by Gibson et al. (2004).
Seismic tomography (Van der Hilst, 1990) allows us to define where and how far the Caribbean Plate projects southward beneath northern South America. Briefly, Caribbean lithosphere now projects at a low dip angle to underlie all of the Maracaibo region, the Barinas Basin, the Caribbean Mountains, and the northern fringe of the Guarico Basin (shown on Fig. 1A). Beneath the Gulf of Barcelona, the Caribbean lithosphere rises toward Margarita where it emerges at the surface along the Orchila-Margarita fault zone, a dextral lateral ramp allowing the Aruba-Orchila islands to thrust NW-ward onto the Caribbean Plate interior (Dewey and Pindell, 1985; 1986). The subducted portion of the Caribbean Plate is continuous with the plate at the surface (the subduction trace is the South Caribbean Foldbelt/Orchila-Margarita fault zone) and, being unbroken, must have the same kinematics relative to South America. Therefore, the present position of the leading edge of the subducted Caribbean crust was achieved by motion toward 085° since 10 to 12 Ma. This west to east motion is, in fact, responsible for the intensification of the northern Andean orogeny; the entire Santa Marta-Maracaibo-Falcón region is riding eastward at a significant portion of the full Caribbean-South America displacement rate (Trenkamp et al., 2002) due to basal traction of this region’s lithosphere on the underlying Caribbean Plate. Hence, the Mérida Andes are a strong zone of dextral transpression where most Caribbean-South America seismicity now occurs. In addition, the high relief of the Caribbean Mountains is also caused by the motion of the Caribbean Plate beneath them. However, this uplift appears to have more to do with volume increase beneath the mountains by the progressive eastward emplacement of the Caribbean slab than to basal traction: only the portion of the mountains north of La Victoria Fault is moving eastward at any appreciable rate, suggesting that the crustal sliver between the Morón and La Victoria faults does in fact feel some basal shear stress.

In the Gulf of Barcelona, at least 4 wells have penetrated Pliocene-?-Late Miocene section and entered Cretaceous basaltic volcanic basement south of the Cariaco Basin/El Pilar Fault shear system (Ysaccis, 1997). These rocks are likely the eastward continuation of the Villa de Cura allochthon, although they appear to comprise less metamorphosed rocks similar to the Tiara volcanics, a cover section upon the Villa de Cura high-pressure, low temperature (HPLT) rocks (location shown on Figs. 1A,B).

A dense wedge of resumably mafic (oceanic), rock likely occurs deep beneath the northern Serranía del Interior Oriental, south of El Pilar Fault, as shown by gravity modeling (Passalacqua et al., 1995). The stratigraphy of the Cretaceous passive margin in this area is not what we would expect were it underlain by oceanic crust, and regional geology does not support the existence of South American ophiolites of pre-Cretaceous age. Therefore, we propose the wedge is a piece of Caribbean forearc, emplaced during the Middle Miocene orogeny involving the collision of the Caribbean Plate with the Serranía Oriental. The wedge helps to
resolve the space problem identified by Hung (2005). The location of the deep wedge is shown on Figure 1A, and a cross-section view is shown on Figure 4B.

**Tectonic history since 10 Ma**

The above aspects of the ESCPBZ may now be used to outline the history of development since the end of the Middle Miocene. We set the development within the kinematic history of Figure 18 (see later section, below), which shows the change from SE-ward Middle Miocene oblique convergence to more or less E-W (085°) transcurrent at about 10 Ma. If the present-day plate motion rate of 20 mm/yr can be extended back to 10 Ma, total displacement should be 200 km since that time. This fits well with the rate of advance of Caribbean foredeep basins (Pindell et al, 1991; see also Fig. 17, below), and it also realigns the following four features which we believe have been offset by the Morón-El Pilar Fault since 10 Ma: (1) Cretaceous basaltic “primitive island arc” volcanic rocks of the Gulf of Barcelona and those of the Bocas High and the Patao High (Ysaccis, 1997); (2) the Orchila-Margarita and the Urica lateral ramp transfer zones; (3) the juxtaposition of Araya Peninsula with the eastern end of the Cordillera de la Costa of the Caribbean Mountains (i.e., 200 km neatly closes the Cariaco Basin); and (4) the SE edge of Caribbean crust (Tobago Terrane) and the deep, dense wedge beneath the Serranía Oriental. In addition, we note that the 085° azimuth cannot be employed for distances greater than about 200-240 km, because larger values begin to overlap the basement of the Carupano Platform and Margarita with that in the Caribbean Mountains, the latter of which are thought to be essentially in place since 10 Ma (i.e., La Victoria Fault has only small, probably <<30 km, offset, and has slipped during Quaternary time at <3 mm/yr; Schubert, 1981; Audemard, 2000; Perez et al., 2001).

Using the fault offsets and movement directions discussed above, with 200 km of total motion between the Caribbean and South America since 10 Ma, we can draw the 10 Ma palinspastic reconstruction of Figure 11. Because we believe the Caribbean crust has reached southward to the El Pilar Fault since the Middle Miocene (Fig. 1A), the Araya-Paria and Northern Range restore westward along with the Caribbean Plate and realign with the Cordillera de la Costa. These ranges east of the Cariaco Basin ride essentially passively on the edge of Caribbean crust, which is why GPS studies show they move at or nearly at the full Caribbean velocity. The 10 Ma reconstruction is supported by the realignment of the blind toe of the Tobago Terrane with the deep, dense wedge beneath the Serranía Oriental, which together defined the leading edge of the Caribbean crystalline crust until the 10 Ma onset of faulting on the El Pilar Fault. Thus, in Venezuela, the majority of relative plate motion since 10 Ma has occurred on the El Pilar Fault, with only minor motions on fault splays and bulk shear strain occurring to the north or south of that fault.

Where the El Pilar Fault enters the northern Gulf of Paria, some (about 70 km) of the total El Pilar displacement has stepped southward across the basin to the northern flank of the North Marine Ridge and South Boundary Fault, producing the Gulf of Paria Basin (dextral pull-apart soling into a low-angle detachment at the base of the thrust wedge). From there, about 10 km (eastward component) of this 70 km has splayed southward...
Figure 11. Simple palinspastic reconstruction of the SE Caribbean PBZ for 10 Ma, assuming 20 mm/yr displacement rate at today’s azimuth of motion back to 10 Ma, at the time of transition from oblique collision to E-W transcurrent. Note the realignment of the blind toes of Caribbean forearc crust at Tobago and the Barcelona Volcanic Wedge. Faults primarily active before and after 10 Ma are shown in blue and black, respectively.

Figure 12. 5 Ma Palinspastic Reconstruction suitable for plotting shallow horizons, above the base Late Miocene unconformity. Thus, this map restores the 5 Ma and younger extension in the Orinoco Delta sediments of the Southern Basin. Because this extension detaches above the unconformity over the Middle Miocene orogen, the underlying rocks (Karamat and older formations, including Cretaceous) would be positioned somewhat farther to the east for any given present-day latitude and longitude. Therefore, the apparent offset on the Point Radix Fault would appear to be larger for Cretaceous rocks than for early Late Miocene rocks. The effect of extension in the Southern Basin and offshore Columbus Basin thus acts to reduce the apparent offset we can see today on the Point Radix-Darien Ridge Faults, because the hanging walls of extensional faults (rooted below Cruse) to the south may be moving to the east almost as fast as the north side of the Darien Ridge, rooted at the base of the fold-thrust belt.
again along the Los Bajos Fault, while some 60 km has headed east toward San Fernando. Between 10 Ma and mid-Pliocene, motion continued eastward along the Point Radix-Darien Ridge fault zone, passing around both the northern and southern flanks of the San Fernando mega-fault sliver, of which San Fernando Hill is a part. But since mid-Pliocene, a component of this eastward motion (~10-20 km) has splayed northwards along the Central Range, leaving a total of some 40-50 km along the eastward continuation of the Point Radix Fault. The 5 Ma reconstruction of Figure 12 accounts for the fault offsets noted above, and also restores the extension in the Gros Morne and Mayaro Formations (developed within the Orinoco Delta) and therefore the grid in the Southern Basin is appropriate for plotting paleofacies for late in the deposition of the Cruse Formation. The reconstruction pre-dates the Central Range uplift and displacement, as well as the renewed shortening on the Southern Range and the Pliocene-Pleistocene offset on the Los Bajos Fault.

Finally, also in the mid-Pliocene, along with the onset of the Central Range, the locus of low-angle extensional detachment jumped westwards to the San Juan Graben, where about 5 km of eastward collapse has occurred, with perhaps a smaller amount of additional extension reaching the San Francisco Fault (Fig. 5). The E-W transfer zone for this expanded zone of detachment (now comprising the entire Middle Miocene thrust pile down to its sole thrust and as far south as its toe) is the Late Pliocene-Recent Eastern Maturín diapir belt/Pedernales-Southern Range trend, which is a growing fold above a thrust telescoping from beneath the Middle Miocene deformation toe (Fig. 2).

**The bow-wave orogenic model since 10 Ma in the ESCPBZ**

The Gulf of Paria Basin, and to a lesser extent the San Juan Graben, are places where the original Middle Miocene thrust belt has been broken by a combination of dextral tectonic shear and gravitational collapse of the thrust belt toward the Atlantic since 10 Ma. These developments have produced very little N-S contraction (<5 km west of Los Bajos Fault). The post-10 Ma phase of history is distinctly different from the Early and Middle Miocene compressional orogeny. In contrast, however, structural development in eastern Trinidad and in the eastern offshore has remained more compressional. Even though extensional detachment faults have developed there, the detachments have themselves been folded quite strongly since their Pliocene formation. There appears to be an increase in post-10 Ma N-S contraction in the eastward direction.

To explain this observation, we apply a “bow-wave” model to the post-10 Ma transcurrent phase in the ESCPBZ. Because the southeastern limit of Caribbean crystalline crust is curvilinear (Aspect 1, above), veering from N-S beneath Barbados to E-W in the Caroni Basin and westward, this analogy is highly applicable. Along the “bow of the boat”, which is presently everywhere east of Port-of Spain, transpression occurs, like the waves generated by a boat. Along the flank of the boat, which is presently west of Port of Spain, N-S convergence is minimal or non-existent. This principle can be extended back in time, the migration of the boundary point between transpression and near-perfect strike slip will match the migration rate of the Caribbean relative to South America (Fig. 13). This point was situated 200 km west from Port of Spain at 10 Ma, placing it directly at...
A. Eastward advance of Caribbean Plate

Caribbean motion at 085° relative to SoAm

N. Range @ 10 Ma

first Paria Basin fault to form?

denotes migrating point between trancurrent shear zone to W and transpressive zone to SE.

B. Effective S-ward advance of Carib forearc, and progressive increase in accommodation space for Trinidad foredeep.

Figure 13. “Bow-Wave” model of orogenic shortening. A) Map of the displacement history of the curvilinear leading edge of the Caribbean Plate, as well as its trailing flank, since 10 Ma, showing the apparent S-ward advance of the position of the Caribbean crust along the profile, but not of its material particles (which move west to east), relative to Trinidad. B) The progressive increase in tectonic accommodation space (i.e., foredeep basin) above South America (employing a flexural profile) that is required to accommodate the eastward motion, and the effective southward motion of the Caribbean Plate, which of course thickens towards the west, towards the axis of the volcanic arc. Coloured wedges track the position of the leading edge of the Caribbean Plate along the profile, which apparently moves south. This model shows that southward shortening can be driven along the “bow” of the “Caribbean boat” (i.e., SE Trinidad and the eastern offshore at present) in the absence of actual N-S convergence. It also shows that shortening will not occur along the “sides” of the boat. It is instructive to keep in mind that the effective southward shortening can only occur if strike slip is active. The strike slip component, as shown earlier, has occurred since the Late Miocene through Trinidad largely at the Point Radix and Caroni faults, and since the Pliocene on the Central Range fault zone and “Southern Anticline” en-echelon culminations as well.

Figure 14. Motion history of North America relative to two points on South America since magnetic anomaly 34 (Early Campanian). Results of two data sets for each point are shown, those of Pindell et al. (1988) to the right and the updated results of Müller et al. (1999) to the left in order to show how well constrained and reproducible this relative motion history is. Actual path of the points might be best represented by the pink smoothed lines. Heavy black dots on the two pink curves show the amount of convergence which had accumulated between the Americas at the time when the Caribbean Plate began to collide with the South American margin at each point, which was about 100 km for both. The remaining convergence accumulated after Caribbean-South America collision was underway, below the developing suture zone of those two plates.
the NW corner of the Gulf of Paria Basin. Thus, the transpressional bow always lay ahead of the Gulf of Paria, and the growing Gulf of Paria Basin was always protected from N-S compression because it la to the west of the boundary point.

Another observation that is explained by this model is the progressive development (loading) of the Maturín-Southern Basin foredeep basin. The Caribbean Plate, which has not converged with South America since 10 Ma, nevertheless has moved eastward into a position where it increasingly loads the foreland basin, albeit laterally. The lateral loading has steadily increased in both the Maturín and the Southern foredeep sub-basins because the thickness of the Caribbean forearc lithosphere increases from about 20 km below Tobago, near the edge of the Caribbean plate, to about 100 below Margarita. This effective thickening of the plate in north-south cross section must be accommodated by an associated increase in downward flexure of South American basement and, hence, foredeep accommodation space.

The small amount of N-S shortening that is observed since the ?middle Pliocene west of the Los Bajos Fault (i.e., western Southern Range, Maturín diapir trend/Pedernales, Pirital Fault) is likely the result of 5 to 10 km of eastward reactivation of the deepest Middle Miocene thrust plane. Such a thrust likely dips toward about 330°-340°; thus, eastward reactivation would be transpressional with the potential to drive up to 5 km of young N-S transpressive shortening on certain structures such as Pirital Thrust and the diapir trends/Southern Range. The Pliocene activation of the Central Range Fault Zone, trending at 070°, may also relate to this process, or relate to the Trinidadian allochthons north of Point Radix Fault ramping up over the NW dipping basement surface of the Jurassic Trinidad re-entrant (Pindell et al., 1998).

This minor, late transpressional reactivation might have involved the Añaco Thrust which lies outside the Serranía Oriental re-entrant, west of the Urica Fault, and which is an inverted normal fault along the southern flank of the Espino Graben, itself a low-angle detachment basin with a N-dipping detachment plane. Inversion of the Añaco Fault is commonly thought to have occurred during Late Miocene deposition of the Freites Formation as marked by Freites onlap (Banks and Driver, 1957). However, GPS results (Perez et al., 2001) show that the El Baúl Massif may presently be moving east (Fig. 7) by perhaps 3 mm/yr relative to the South American base station, which lies near the Orinoco River at Canoa, to the southeast of the Añaco Thrust. Because we are aware of no other structure in the interior plains that could accommodate the eastward motion of the El Baúl High to the east, we speculate that the eastward motion of El Baúl is driving the Añaco inversion, such that it may still be active. And because El Baúl resides on the hanging wall of the 070°-trending Jurassic Espino Graben (geometrically, a half-graben), we consider that the half graben may be inverting as a whole. Inversion on this huge scale likely relates to the crust reaching all the way west to the basement-involved Mérida Andes and/or basal traction of the underthrust Caribbean Plate against the South American lithosphere south of Caracas. A dextral transfer zone extending from near the Colombian border to Añaco is suspected. We wonder if the intersection of such a trend with the southern end of the Urica Fault Zone might account for the apparent complexity in that area.
Whether or not this late reactivation represents the onset of a third phase, acknowledging and understanding the details of the oblique collision and subsequent transurrence in the SE Caribbean is paramount for hydrocarbon exploration, affecting interpretations of structural timing and style, maturation mechanisms and timing, and the relationship between sedimentation (provenance) and tectonics (driving causes). Further, individual components of various petroleum systems in the region have been amalgamated by the juxtaposition of terranes of quite different origin. Trinidad is not a place that can be neatly summarised by only local models of evolution; the bigger picture involving Venezuela and Barbados as well as a detailed understanding of Caribbean kinematics is absolutely required.

**Perspectives on the nature of the South American margin prior to 10 Ma**

Enormous effort by the collective geological community has been devoted to the description and characterisation of the Caribbean-South American plate boundary zone (Figs. 1A,B). Less but still considerable effort has gone into understanding the history of the Caribbean-South American plate collision, and still less effort has gone into trying to understand the nature of the South American margin prior to Caribbean collision. Was it a passive margin as the Caribbean progressively collided with it from the west, as many have come to believe, or was it already active during the Caribbean’s collision? If active, how so? Understanding the answer to this question is important for understanding the history of the collision itself and the structure of today’s plate boundary zone, as well as for better understanding the paleo-environments and distribution of source and reservoir rocks in various petroleum systems along the margin.

Prior to the advent of plate tectonic theory, workers envisioned an end-Cretaceous-Eocene northern marginal high that provided detritus with an orogenic signature to various clastic depocenters such as the Scotland Formation in Barbados (e.g., Senn, 1940). With the advent of plate tectonics, but prior to accurate plate kinematic control, came the idea that arc-continent collision caused tectonism and metamorphism in the Caribbean Mountains and Margarita of Late Cretaceous age, followed by some thin-skinned thrusting or gravity sliding in the Guarico foreland basin in the Paleogene (e.g., Maresch, 1974). With (1) the definition of accurate circum-Caribbean plate kinematics as allowed by early SEASAT and GEOSAT data, and (2) the realisation that northern South America’s foreland basin subsidence history is Tertiary, not Cretaceous, and youngs diachronously eastward (Pindell, 1985), came the realisation that the predominantly Cretaceous metamorphic and igneous rocks must be Pacific-derived allochthons that were not emplaced onto the margin until the Paleogene, and that the northern South American shelf was passive at least until the Maastrichtian and possibly to the time of Caribbean collision, facing onto the Proto-Caribbean Seaway, an arm of the Atlantic (Pindell, 1985; Dewey and Pindell, 1986; Pindell et al. 1988). But the arc-passive margin collision model was always hostage to one major problem: N-S convergence between North and South America since the Maastrichtian was significant (i.e., hundreds of km; Pindell et al., 1988) and this convergence began before the arrival of the Caribbean allochthons in Venezuela and Trinidad.
Thus, suspicion of a “pre-Caribbean-arrival” convergent boundary between the North and South American plates, somewhere in the Proto-Caribbean Seaway, clouded our confidence in the margin remaining passive until the time of Caribbean collision (i.e., during the Paleogene). It was not until the first seismic tomographic work in the Caribbean (Van der Hilst, 1990) that the geological community gained good evidence that the South American continental lithosphere has been severed from the Proto-Caribbean or Atlantic lithosphere. Driven by the suspicion of convergence since the Maastrichtian, Pindell et al. (1991) honoured the Cenozoic inter-American convergence by proposing that the northern South American Cretaceous passive margin was converted in the Late Maastrichtian-Paleocene to a south-dipping “Proto-Caribbean” subduction zone along the toe of the continental margin. This development had nothing to do with the Caribbean Plate, which lay to the northwest of the Guajira Peninsula in the Maastrichtian. Further, it was suggested that this Proto-Caribbean structure drove N-vergent accretion of South American continental slope and rise strata to South America’s northern edge (e.g., Caracas Group, Paria, and Northern Range strata), prior to the eastwardly diachronous collision of the Caribbean Plate, and associated emplacement of the Cretaceous allochthons, with Venezuela and Trinidad. In such a model, the term “trench-trench collision” is a more accurate description of Caribbean-South American interaction during Cenozoic time than is “arc-passive margin collision”, although convergence at the Proto-Caribbean thrustbelt or subduction zone has been too small for a magmatic arc to develop on South America.

Evidence for the Proto-Caribbean subduction zone

Evidence for the Proto-Caribbean subduction zone is geologically subtle in the onshore, but defining the Paleogene existence of the plate boundary (Pindell et al., 2006) is critical for understanding the origin and distribution of Paleogene reservoir clastics and burial/unroofing histories of Cretaceous source rocks, and thus deserves our full attention. Evidence for the Proto-Caribbean subduction zone/thrustbelt includes the following items.

- Atlantic plate kinematic history (Fig. 14) requires about 100 km of North America-South America convergence to have already occurred at the longitude of western Venezuela in the Middle Eocene when the Caribbean Plate collided with South America there, as well as at the longitude of Eastern Venezuela in the Middle Miocene when the Caribbean Plate collided there (Pindell et al., 1988; Müller et al., 1999). This shortening presumably had a pre-Caribbean-arrival geological expression, either within or at the margins of the Proto-Caribbean Seaway. We will see that the expression is greatest along the South American margin.

- Mantle seismic tomography in the Caribbean and northern South America area (Van der Hilst, 1990) shows a westward dipping subducted Proto-Caribbean (Atlantic) slab beneath the Caribbean Plate (Fig. 15, E-W sections), but this same slab also dips south and is overthrust by and severed from the northern edge of South American continental lithosphere (Fig. 15, N-S sections). This suggests subduction of Proto-Caribbean lithosphere beneath northern South America. Further, because N-S contraction between the Americas began
Figure 15. Our working interpretation of the Caribbean mantle seismic tomography as compiled by Van der Hilst (1990). Figure 15A) Location map of: main Caribbean region plate/block boundaries and features (black lines); reconstructed Maastrichtian paleoposition of South America and its continent-ocean boundary (COB) and the initial position, relative to North America, of the Proto-Caribbean subduction zone (blue; after Pindell et al., 1988; 1991; 1998); and transect positions A-G and 1-7 of the seismic tomographic profiles of Van der Hilst (1990). Ticks on profiles are at 100 km spacing. The Proto-Caribbean Trench extends into the Atlantic from under the Barbados Prism out to about the location of magnetic anomaly 30 (Maastrichtian). The obducted Caribbean terranes along northern South America are shown in grey, comprising: the Ruma (in Guajira), the Lara (in Falcón), the Villa de Cura (in central Venezuela), the “Barcelona Volcanics” (in Gulf of Barcelona), the Manicuare (western Araya), and the Copey/Toco/Sans Souci of Araya-Northern Range), which collectively represent the leading subduction complex of the Caribbean Plate. The Oca, Mérida, El Pilar, and Urica faults now offset this west-to-east diachronously emplaced belt whose basal thrust is the location of most Caribbean-South American displacement. RCMFZ is the Roques Canyon-Margarita Fault Zone, which was a dextral lateral ramp in the Middle Miocene allowing NW-ward backthrusting of the ABC island terrane above Caribbean Plate (Dewey and Pindell, 1985).
Figure 15B) Our interpretations of the raw N-S seismic tomographic profiles in Van der Hilst (1990), profiles A-G shown on Part A. South Caribbean Foldbelt is at km 800 on profile C; Morón Fault is km 550 on profile C; Villa de Cura Klippe is at km 500 on profile C; Cariaco Trough is at km 550 on profile D; Barcelona Wedge is at km 500 on profile D; Paraguaná Block is at km 600 on profile B; Lara Nappes are at km 500 on profile B; Guajira Block is at km 700 on profile A; Lara Nappes are at km 500 on profile A; Bahamas overthrust crust is at km 1550 on profiles A, B, C and D, and Proto-Caribbean slab is seen to be increasingly detached from Bahamas westward; Caribbean crust underthrusts SoAm on profiles A, B and C, abuts it on profile D, and SoAm underthrusts Caribbean on profiles E, and F (i.e., polarity change); Proto-Caribbean lithosphere is seen fingering by N-S extension in the downdip direction on profiles A, B and C (gaps shown by double headed arrows), but the total line length matches the Maastrichtian trace at the Earth’s surface (Part E); in profile E, two interpretations of slab dip are permissible due to poor data resolution. The temptation to interpret SoAm as dipping northwards down to 600 km in profile E is shown to be incorrect by the apparent gap in the slab on profile D. Seismicity is shown in dots, and supports the seismic tomographically imaged slabs. Oca Fault seismicity lies at about km 600 on profile G.
Figure 15C) Our interpretations of E-W seismic tomographic profiles from Van der Hilst (1990), profiles 1-7 shown on Part A. Caribbean overthrusts Proto-Caribbean (Atlantic) in profiles A-E; total subducted lithosphere is greater than 1500 km, recording a minimum Caribbean-Atlantic convergence (larger than the Eocene-Recent 1000 km offset recorded by Cayman Trough); in profile F, Caribbean overthrusts SoAm, and SoAm in turn has overthrust the upper reaches of the Proto-Caribbean slab. On 7, the Maracaibo slab of Caribbean lithosphere is seen dipping southwards from the South Caribbean Foldbelt, although no magmatic arc has formed due to this very slow subduction and offscraping of hydrous upper crust at the trench. Seismicity is shown in dots, and supports the seismic tomographically imaged slabs. Seismicity between km 800-950 on profile 7 is related to Mérida Andes transpression.
Figure 15D) Interpretation of the subsurface structure of the Proto-Caribbean or Atlantic, Caribbean, and South American subducted slabs. The Caribbean or “Maracaibo” slab is attached to and descends from the Caribbean Plate at the South Caribbean Foldbelt and Roques Canyon-Margarita fault zone (Van der Hilst, 1990). The Proto-Caribbean slab descends from the Puerto Rico-Lesser Antilles trench, but is torn from South American lithosphere such that it has underthrust South America. Further, the Proto-Caribbean lithosphere has a large slab gap beneath the western Venezuelan and Bonaire basins (tips out near 12N/65W), such that the portion beneath South America and beneath the Maracaibo Slab projects and dips southwestward from the SE Caribbean area. Relative to the mantle, the Caribbean (Maracaibo) slab is nearly stationary, but the Proto-Caribbean slab is attached to the Americas and thus is migrating west. This westward movement is likely associated with development of the large tear, as well as with the broad “S-shaped fold” that has developed in ENE-WSW cross section of the dangling finger beneath South America. Beneath Hispaniola and western Puerto Rico, the Proto-Caribbean slab is seen detaching from the Bahamas, perhaps due to slab drop off after the arc terranes collided with the Bahamas.
Figure 15E) Cross-sectional reconstructions of Proto-Caribbean Seaway for the Maastrichtian, using N-S cross sections B and C from Figures 15A and 15B. Heavy black uncoloured shapes are present day geometries and positions of: the Bahamas slab, two foundered pieces of Proto-Caribbean slab, and South America, as interpreted in Figure 15B. Red shapes are the Proto-Caribbean slab reconstructed to establish the slab’s line length prior to slab tearing and fingering. The blue shapes are equivalent to the red shapes, but have been rotated back to the earth’s surface about the subduction zone’s pivot point at the Greater Antilles-Bahamas suture (heavy black spot). The green shape is where the northern edge of South American continental crust was located in the Maastrichtian. The heavy dashed blue line is the proposed position and geometry of the Proto-Caribbean subduction zone when it first formed in the Late Maastrichtian, prior to the entry from the Pacific of the Caribbean Plate. Note the nearly perfect match between the extents of Proto-Caribbean lithosphere when returned to the earth’s surface, and the former positions of the South American continental crust, prior to Cenozoic northward convergence with North America. This greatly strengthens the interpretation that the tomographically imaged structures at 450 to 600 km beneath present day northern South America is in fact Proto-Caribbean crust, because if it were not, then a 500 wide lithospheric gap would have existed at the earth’s surface in N-S cross section in Late Cretaceous and Paleogene time. In addition, the foundered finger of Proto-Caribbean crust beneath South America in these two sections does merge with the main Proto-Caribbean slab eastwards (Figure 15D).
Figure 15F) Oblique section (see Figure 15D for line location) from Central Venezuela (10N/67W) to near Barbados (13N/58W), situated on the hanging wall of the Proto-Caribbean subduction zone. Intra-plate deformations within the Caribbean Plate, including obduction of Villa de Cura, occur within tectonic float above a detachment at perhaps 10 km depth. Deep Caribbean lithosphere is continuous from Lesser Antilles Arc to the Maracaibo Slab along this profile. Caribbean lithosphere dips westward from the surface at Margarita to beneath Central Venezuela, passing through a lithospheric, southward scissoring tear fault beneath the surface Urica fault zone, and beneath a zone of upper level orogenic float between the Urica zone and the Orchila Canyon-Margarita lateral ramp that was associated with mainly Middle Miocene NW-ward backthrusting toward the South Caribbean foldbelt. This passage through the Urica tear is how the polarity of Caribbean-South America collision changes to the west and east of the Gulf of Barcelona (see Figure 15B). The NW-ward backthrusting became largely inactive after 10 Ma, after which Caribbean motion became eastward and the Morón-El Pilar fault zone has allowed nearly E-W relative plate motion along the heavy pink highlighted fault.
before the arrival of the Caribbean Plate along northern South America, it is likely that this subduction of Proto-Caribbean lithosphere occurred ahead of the leading edge of the Caribbean Plate at a north-facing “Proto-Caribbean subduction zone” along northern South America. A closer look at the N-S tomographic cross sections reveals that the Proto-Caribbean slab: (1) has a westward widening wedge-shaped tear within it which helps to account for the Proto-Caribbean slab projecting several km underneath South American continental crust, and (2) has been severed from the lithosphere beneath the Bahamas (North America) by a small amount relative to the severing from South America. Due to the regional southward dip component of the Proto-Caribbean lithosphere and the rapid Middle Eocene uplift and erosion of the Greater Antilles Arc and the Bahamas foreland, we judge that the dislocation from the North American lithosphere is likely due to Eocene and younger gravitational slab drop off with attendant isostatic rebound of the orogen. Thus, south-dipping subduction of Proto-Caribbean lithosphere was probably established beneath northern South America earlier, and it was there that inter-American convergence was first established.

- ENE of Barbados on the Atlantic floor, a paired basement ridge/trough (south side/north side, respectively) with an attendant free-air gravity signature projects ENE into the Atlantic from beneath the Barbados accretionary ridge (Fig. 16). We interpret this feature as the eastward continuation of the N-facing Proto-Caribbean subduction zone’s hanging wall (ridge) and trench (trough), not yet overthrust in this area by Caribbean lithosphere or Barbados Prism (Pindell et al., 2006). This ridge/trough pair extends eastward to at least the position of western Atlantic magnetic anomaly 30 (Late Maastrichtian), which is the age when convergence between the Americas began. Therefore, the Proto-Caribbean subduction zone may have initiated simply as a third arm extending from a triple junction where it adjoined the Maastrichtian mid-Atlantic spreading center.

- Paleogene uplift and erosion of section along the northern South American shelf (Hedberg, 1950) was interpreted as being due to the eastward migration and passage of the Caribbean forebulge by Dewey and Pindell (1986) and Pindell et al. (1988; 1991). It is certainly true that the drowning of this forebulge unconformity is diachronous, mapped by the onlap of the unconformity (basal foredeep unconformity). However, this does not mean that the onset of erosion was eastwards diachronous. It may in fact be that uplift occurred along the entire margin due to the onset of Proto-Caribbean subduction (i.e., hanging wall uplift), and that the unconformity persisted until the erosional surface was loaded by the advancing Caribbean Plate. Furthermore, the presence of well-rounded Turonian and Albian blocks in the Late Eocene-earliest Oligocene Plaisance Conglomerate in the Central Trinidad suggests that erosion of section may have been deeper than expected by peripheral bulge uplift alone (i.e., 200 m), again pointing to the possibility of hanging wall uplift. Further, seismic records in Central Venezuela (e.g., PDVSA 1995 bid round pamphlets) show normal fault offsets at the basal foredeep unconformity that are often larger (up to 500 m) than those predicted by lithospheric forebulge flexure. This erosion and faulting may better be related to the conversion of the Cretaceous passive margin to the “Proto-Caribbean” subduction zone (Pindell and Kennan, 2001).
Figure 16. Free air gravity image of the eastern Caribbean region, showing the projection (negative gravity trough) of the Proto-Caribbean Trench eastward from beneath the Barbados Ridge out to about western Atlantic magnetic anomaly 30 (Maastrichtian), and the corresponding parallel gravity high immediately to the south. This trough exceeds (is more negative) than the signature of the southward crustal boundary of the Caribbean-Atlantic interface, suggesting it is at least as important as a tectonic crustal feature. Magnetic anomalies in the Trough are dashed due to uncertainty during the original identification, possibly due to crustal deformations in the area. The main gravity trough lies at a 30° angle to regional fracture zones, and is thus not related to seafloor spreading. Difference in trend in the magnetic anomalies north and south of the trough could suggest either a slightly different kinematic origin of the two sets of anomalies, or relative motion (rotation) between the two sets since their formation, or both. The Cenozoic rotation between the Americas shown in Figure 14 accounts for some of the difference. Inset: structure contours to basement, after Speed et al. (1984), highlighting the Proto-Caribbean Trench and Ridge pair of structures. Note that basement relief is up to 4 km across the pair.

Figure 17. West-to-east progression of initial collision between the Caribbean Plate (subduction complex) and the South American craton. See text for details and abbreviations.
Local occurrences of extensional faulting in the basement and/or the passive margin section may owe their origin to gravitational relaxation of hanging wall elements toward the free face of the new trench.

- Fission track cooling ages in apatite grains from the Barranquín Formation of the Serranía Oriental are mostly Miocene, but some are as old as Eocene (Perez et al., 2001; Locke and Garver, 2005). These authors speculate an Eocene onset of uplift in the Serranía Oriental, which pre-dates the Oligocene encroachment of the Caribbean foredeep in that area, and may relate, if not due to partial annealing, to the hanging wall uplift noted above.

- Post-orogenic cooling of the “Caribbean Series” metasediments through 350°C, as shown by Ar-Ar dating of first foliation micas, was underway in the Caracas Group by 42 Ma (Middle Eocene), and in the Paria Peninsula and Northern Range by about 26 Ma (Oligocene) (Sisson et al., 2005; Foland et al., 1992). A zircon fission track age of 29 Ma from Paria Peninsula (Cruz et al., 2004; in press) suggests that uplift and cooling locally may have begun even earlier there. These ages predate the time of Caribbean collision at these places as judged from initial foredeep development across strike (Oligocene in Guarico Basin; mainly Miocene in Maturín Basin), suggesting that metamorphism in these ranges was underway prior to the arrival of the Caribbean Plate. We suggest that an actively thickening orogenic pile of former continental slope and rise strata existed along the Proto-Caribbean trench as the Caribbean prism and forearc collided diachronously with it. Thus, the thermal conditions for metamorphism may have been largely established in this thickening pile by the onset of the prism-prism collision, but the younger collision may ultimately be responsible for many of the structural features preserved today, including the onset of progressive cooling at the times noted above.

- Speed (2002, and many earlier papers) built a comprehensive model for the depositional and deformational history of the Scotland District, Barbados, employing a single SE-migrating Caribbean trench in which Eocene-earliest Miocene pelagic strata of the forearc basin overthrust, in the Miocene, Eocene-?Oligocene fine to coarse grained clastic accretionary prism strata that originally lay on the Proto-Caribbean (Atlantic) seafloor. However, there are several apparent inadequacies in this model, some of which are: 1) fold and thrusts trend 070°±20°, not 010°±20° as Caribbean migration models predict; 2) much of the Scotland District deformation is NW-vergent, as opposed to ESE-vergent, as expected, thereby requiring special structural dynamics or backthrusting during initial accretion to explain; and 3) there is no gradation in lithology or composition between the Oceanics (pelagic forearc) and Basal Complex (clastic prism) strata, except for some radiolarites in the lower Basal Complex that could, but do not appear to, relate to the Oceanics; this raises doubt over whether the two units were ever adjacent enough to form parts of the same forearc-subduction complex. In contrast, a prism-prism collision model appears to explain the geology of the Barbados Ridge better; such a model is the subject of ongoing work by us. Much of the Basal Complex may pertain to the Proto-Caribbean Prism, rather than the Caribbean Prism, whereas the Oceanics very probably correspond to the Caribbean forearc/upper prism. If so, the observed N-vergence with fold-thrust trend 070°
in the Basal Complex is precisely that predicted for the Proto-Caribbean prism along northern South America, prior to Caribbean arrival. In addition, this model allows us to predict where and when where the two prisms collided; by backtracking the migration path of Barbados Island as part of the Caribbean Plate (ignoring relatively minor deformations around the island), it is seen that the flow line for Barbados crosses the trace of the Proto-Caribbean trench at about latitude 13.5° and longitude 62°, in the Middle Miocene. This is exactly the time argued by Speed for the backwedging of the Basal Complex beneath the Oceanic Complex, as constrained by the ages of involved and overlapping strata. Speed also concluded that the juxtaposition of the Oceanic and the Basal complexes was E-directed, in keeping with collision of two pre-existing prisms being driven by Caribbean migration. Finally, the backwedging of Basal Complex material into the Tobago Trough forearc strata (Torrini and Speed, 1989) would be seen in this model as the Caribbean crystalline forearc wedging beneath or into the pre-existing Proto-Caribbean Prism. Since this Middle Miocene tectonic juxtaposition and accretion of Proto-Caribbean Prism to the leading edge of the Caribbean Plate, the two prisms have moved eastwards by some 200-300 km relative to South America as a composite accretionary prism terrane.

The above seven lines of evidence provide a broad basis supporting the existence of a Proto-Caribbean subduction zone or convergent boundary situated ahead of the Caribbean Plate during its diachronous collision along northern South America. In the next section, we will examine Caribbean-South American kinematics so that comprehensive paleogeographic maps can be presented thereafter.

**Caribbean-American Cenozoic plate kinematics: Cayman Trough magnetic anomalies compared to diachronous Caribbean foredeep history in South America**

Constraining the rate and azimuth of Caribbean relative motion with the Americas as the latter drift west in the mantle reference frame is prerequisite to understanding the Cenozoic history of plate interactions between the respective plate margins. In this section, we show that models for the Cayman Trough’s opening history vary drastically in rate through time and thus are less firmly known than the history of Caribbean foredeep advance in northern South America. Thus, we suggest that the latter be used as a more accurate yardstick for assessing the rate of Cenozoic Caribbean-American displacement.

**Opening of the Cayman Trough**

Marine seismic, dredging, and heat flow data (Rosencrantz et al., 1988) indicate a Tertiary, probably Eocene to Present (opening is ongoing) age for the Cayman Trough. Mann and Burke (1984) suggested 1,200 km as the total offset along the trough, whereas Pindell and Barrett (1990) pointed out that some of the trough’s morphology was produced by stretching of arc crust at the trough ends such that the lateral offset was somewhat less than the trough’s total length; they suggested 900 km of seafloor spreading plus another 150 km of syn-rift extension. Rosencrantz (1995) inferred that 1,040 km of the Trough’s length is oceanic, Leroy et al. (2000)
suggested at least 900 km of oceanic crust, while Ten Brink et al. (2002) interpreted a length of about 812 km of oceanic crust. These workers presume the existence of mappable magnetic anomalies. Finally, Sykes et al. (1982) showed that a significant amount of slip is occurring along the SE margin of the trough (Jamaican flank), such that the actual strike slip offset along the Cayman Trough is larger than the E-W extension required to produce the trough itself. This point was amplified by Rosencrantz in 1993 while pointing out that Cayman Trough opening does not perfectly record North America-Caribbean relative motion, because the latter is larger.

Several authors have attempted to establish the Caribbean-North America Cenozoic displacement rate by mapping the N-S trending magnetic anomalies in the Cayman Trough as geomagnetic polarity reversals (MacDonald and Holcombe, 1978; Rosencrantz, et al. 1988; Rosencrantz, 1995; Leroy et al., 2000). Table 1 shows three of the more recent efforts, each presumably using the best data available but with little agreement. Reasons for the disagreement are probably four-fold: 1, to a lack of trustworthy data; 2, tectonic deformations such as transform drag and block faulting may have disrupted the original magnetic signal from the trough’s basement; 3, plate accretion (spreading) may have fed off-axis faults as well as the central spreading axis, thereby disrupting the original magnetic pattern; and 4, ridge jumps have probably occurred (Rosencrantz et al., 1988), thereby introducing model dependence in the interpretation of spreading.

Given the inconsistencies in Table 1 and the four very plausible possible causes for those inconsistencies noted above, Caribbean-American kinematic history might be constrained better by mapping the migration of Caribbean foredeep development along northern South America, which records the advance of the Caribbean tectonic load during the oblique collision of those two plates (Pindell, 1985; Dewey and Pindell, 1986; Pindell et al., 1988; 1991). In this paper, we review the foredeep migration analysis with more rigour than previously done, and propose a Caribbean-South America migration history that can then be compared to Caribbean-North America migration histories derived from the Cayman Trough.

Migration of the Caribbean foredeep in northern South America

Figure 17 shows the history of impingement (initial collision as a function of position as indicated by foreland subsidence history) of the Caribbean forearc/subduction complex relative to South America, shown as numbers (Ma) in the green squares. South America is shown in its Present position (gray) and also in its Maastrichtian configuration relative to North America (blue; after Pindell et al., 1998) to highlight its former NE-SW orientation during most of this collision, which was more head-on than is often thought. Formations identified by Pindell et al. (1988; 1991) denoting onset of foreland subsidence and that define the long-term Caribbean-South America migration are: Molino Formation in Cesar Basin, Late Maastrichtian-Early Paleocene; Marcelina Formation in western Maracaibo Basin, Late Paleocene to Early Eocene; Misoa-Pauji Formations in central and eastern Maracaibo Basin, Early to early Late Eocene; Paguey Formation in northern Barinas Basin, Late Eocene to Early Oligocene; Roblecito Formation in the Guarico Basin, Middle Oligocene to earliest Miocene; Areo and Carapita Formations in the Serranía Oriental/Maturín Basin, Early to Middle
Miocene; Upper Cipero Formation in the Southern Trinidad Basin, Middle Miocene. Foredeep development clearly migrates east through time and is controlled by Caribbean advance until 10 Ma, when Caribbean azimuth changed to E-W (Algar and Pindell, 1993). Note also that WNW-ESE diachroneity within a given formation, such as the Roblecito Formation, has long been recognised (e.g., Gonzalez de Juana et al., 1980). Heavy black line marks the southern reach of Caribbean forearc obductions on this reconstruction (prior to Neogene Andean offsetting), and green heavy lines mark the position of the Caribbean forearc associated with the initial obductions at the indicated times, in Ma. The actual displacement distances between successive paleopositions of the forearc must be measured parallel to the ESE Caribbean relative displacement azimuth, due to the collision’s obliquity. RCMFZ is Roques Canyon-Margarita fault zone. Note that today’s high-angle strike slip faults (grey lines) of the margin (e.g., El Pilar, Oca, Boconó, Morón Faults etc) formed late in the Caribbean-South America collision, after obduction of the allochthons and onset of underthrusting (backthrusting) at the South Caribbean Foldbelt; thus, they only record a minor amount of the overall relative motion (<200 km) and cut across the obducted thrustbelts (e.g., Lara Nappes). The bulk of plate displacement occurs at the base of the allochthons and thus is not directly measurable by fault piercing points (Pindell, 1985; Dewey and Pindell, 1986; Pindell and Barrett, 1990).

Using Figure 17 as a template for assessing Caribbean-South America displacement rate, we now assess Caribbean-South America kinematics more fully. In Figure 18A, Tertiary motion of the Caribbean forearc (Tobago, red line) and Caribbean Plate (La Blanquilla Island, purple) are shown relative to South America. The Tobago path dashed where dependent on the model for opening of the Grenada Basin; here, we employ a N-S opening model, e.g., Pindell and Barrett (1990) or Pindell and Kennan (2001). The change in Caribbean-South America (or Carib-SoAm) azimuth (purple line) at about 46 Ma relates to Caribbean motion becoming more E-W after the Middle Eocene Antilles-Bahamas collision. Because the northern Caribbean boundary (with North America) is essentially transcurrent, the S-ward component of Carib-SoAm motion (purple) from 46 Ma onward is largely due to the convergence between North America (NoAm) and SoAm (Müller et al., 1999; Fig. 14). The inset in Figure 18A directly compares the two flowlines (Blanquilla and Tobago), highlighting the effect of Grenada Basin opening and also of Middle Miocene intra-arc backthrusting in the Caroico-Margarita-Carupano platform areas (about 50 km toward NW, which brought the forearc/Tobago closer again to the plate interior/La Blanquilla) (Ysaccis, 1997; Clark, 2004). Figure 18B shows vector triangles loosely describing the poorly known kinematics of the intra-arc Grenada Basin opening (N-S opening model is employed here): Caribbean (C) and Tobago (T) move independently relative to SoAm (S), the difference being that the Grenada Basin opened in the N-S direction due to rollback of Proto-Caribbean lithosphere ahead of the arc (Pindell et al., 2005). For Grenada Basin opening models with more NW-SE extension (e.g., Bird et al., 1999), the azimuthal variation from the Carib-SoAm curve would be less drastic, but Tobago would still migrate faster (restore farther to the NW back in time) in the Paleogene to account for the basin opening. Figure 18C then plots Tertiary motion rate as derived from Figure 18A. Tobago of course moved faster than the Caribbean during intra-arc spreading, but slower during intra-arc backthrusting. Carib-SoAm rate has averaged about 18-24 mm/yr since
Figure 18. A, Tertiary motion of the Caribbean forearc (Tobago, red line) and Caribbean Plate (La Blanquilla Island, purple), relative to South America. B, vector triangles showing the kinematics of the Grenada Basin opening employed here: Caribbean (C) and Tobago (T) move independently relative to SoAm, the difference being Grenada Basin opening N-S. C, Tertiary motion rates for the Caribbean Plate and Tobago relative to South America. See text for discussion.
Eocene. This rate is similar to that of coeval Atlantic seafloor spreading (20-30 mm/yr; Klitgord and Schouten, 1986), indicating that Africa and the Caribbean lie in a similar reference frame (which is close to that of the mantle; Müller et al., 1999; Dewey and Pindell, 2006) while the Americas drift westward.

Comparison of Table 1 with Figure 18C reveals significant discrepancies between the two approaches to assessing Caribbean-American relative motion, although this is not a strict comparison because Table 1 portrays Carib-NoAm motion while Figure 18C portrays Caribbean-South America (Carib-SoAm) motion. However, NoAm/SoAm motion is essentially N-S for Cenozoic time, so the rough comparison roughly holds. In our opinion, the analysis deriving from the migrating Caribbean foredeep is more rigorous, as Table 1 demonstrates a degree of non-reproducibility in the analysis of Cayman Trough spreading. It would be interesting to explore if a viable interpretation of Cayman Trough magnetics could be made that closely matches the foredeep analysis as a hypothetical guide. Such a step may be wishful thinking, however, given that we do not know how much, and when or how often, northern Caribbean slip might have bypassed the mid-Cayman spreading center to pass along the Jamaican flank of the trough. We reiterate that the Cayman Trough only records a minimum of the total Carib-NoAm relative motion.

**Implications of regional kinematics: the generic prism-prism collision model**

From the above, the Caribbean-South America diachronous collision took place at a trench-trench-trench (actually, trench-trench-thrustbelt) triple junction where the Proto-Caribbean slab was concurrently subducted beneath both the Caribbean and South American hanging walls (Figs. 19A-C). Prior to the arrival of the Caribbean at any given point along South America, the Paleogene development of the Proto-Caribbean subduction zone/thrustbelt caused progressive shallowing and significant regional erosion of the South American hanging wall margin as it was thrust northwards over the Proto-Caribbean lithosphere (Figs. 19B). This thrusting may have imparted a minor (<3°) southward tilt upon the Serranía del Interior depositional surface. Judging from the surface geological map pattern, few thrusts could have been active within the Serranía hanging wall during this phase, but the Zorro Thrust near El Pilar village (northern Serranía) is one possibility, with an ?Eocene breccia/conglomerate under Aptian-Albian El Cantil limestone (Vierbuchen, 1984). Uplift of the South American hanging wall was then reversed as the Caribbean Plate arrived and drove foredeep subsidence from the WNW diachronously, due to the loading effect of the Caribbean lithosphere on first the Proto-Caribbean lithosphere at the Proto-Caribbean trench and then on the South American lithosphere itself, once the Proto-Caribbean trench had been crossed by Caribbean lithosphere (Figs. 19C). Thus, although Proto-Caribbean hanging wall uplift may have started synchronously along northern South America, the culmination of uplift and the onset of Caribbean load-induced subsidence on South America was predicted to young eastward with the migration of the Caribbean Plate (Pindell et al., 1991). In the eastern Serranía Oriental, the hanging wall uplift culminated in the latest Eocene to earliest Oligocene, producing such redeposited detritus (transported to slope facies) as the Plaisance Conglomerate of Trinidad. But the uplift was likely epeirogenic over the whole of the

<table>
<thead>
<tr>
<th>Mag. Anom./Ma interval</th>
<th>timespan</th>
<th>distance opened</th>
<th>km/my</th>
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<tr>
<td>Rosencrantz <em>et al.</em> (1988)</td>
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<tr>
<td>0-5, 0-10 Ma</td>
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<td>6-13, 19-34 Ma</td>
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<td>321 km</td>
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<td>13-20, 34-42 Ma</td>
<td>8 my</td>
<td>266 km</td>
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<td>total oceanic opening: 860 km since 42 Ma</td>
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<td>Rosencrantz (1995)</td>
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<td>0-5, 0-10 Ma</td>
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<td>6-13, 19-34 Ma</td>
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<td>263 km</td>
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<td>13-20, 34-42 Ma</td>
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<td>375 km</td>
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<td>total oceanic opening: 1040 km since 42 Ma</td>
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<td>Leroy <em>et al.</em> (2000)</td>
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<td>20-22, 42-49 Ma</td>
<td>7 my</td>
<td>100 km</td>
<td>14.0</td>
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<td></td>
<td></td>
<td></td>
<td>total oceanic opening: 900 km since 49 Ma</td>
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Figure 19. Generic model for the collision of two convergent margins above an intervening oceanic lithosphere. A) Map of the present case. Note that only the Caribbean hanging wall was volcanically active because convergence beneath the South American hanging wall was so slow. Concerning the Proto-Caribbean Trench, the Alaskan subduction zone is an analogue although directions (N and S) are reversed. From Guajira to either the Bohordal transfer zone or the Guyana paleo-transform, the trench hanging wall was continental, as in the southern Alaskan segment, but eastward the hanging wall was oceanic, as in the Aleutians. It is not clear whether the crust between the Bohordal and Guyana transfer zones was oceanic or thinned continental. Peripheral bulges will lie outboard of both trenches and migrate through the Proto-Caribbean (Atlantic) lithosphere until they merge due to plate convergence. B) Once merged, the forebulges will no longer migrate, and then they must be overridden by the advancing forearcs. This has the effect of driving the intervening lithosphere downwards into the mantle, but this in turn can only be achieved as a result being loaded by the forearcs. Thus, both forearcs will actively be uplifted, on a scale of 1 to 2 km depending on rates and other factors which we will not go into here, prior to actual contact between the two forearcs. If the forearcs were shallower than the amount of forearc uplift, subaerial unconformity will result. This was certainly the case for the South American margin, as shown by the Late Eocene-earliest Oligocene unconformity (zig-zag line) and production of sandstone and shale sequences east of Urica Fault with only a clean, continental mineral signature and no sign of detritus from the Caribbean Plate (applies to Vidoño, Caratas, Los Jabillos, Chaudière, Lizard Springs, Pointe-a-Pierre, Navet, Plaisance “unit” (latter of which is no longer seen as part of San Fernando Formation), and the San Fernando Formations of eastern Venezuela and Trinidad (Tectonic Analysis Ltd, 2005; 2007). C) Once the two forearcs began to collide, the Caribbean remained on top and overthrust the South American crust. This is the stage that drove much of the Guarico-Maturín-Southern Basin syn-collisional foredeep subsidence (La Pascua/Roblecito, Carapita/Chapopotol, and Upper Cipero/Herrera Formations). Concerning the Tobago portion of the Caribbean side of the collision, Pliocene rests on Albian and zircons in Albian rocks cooled through 220°C by 103 Ma and apatites cooled through ~100°C at about 45 Ma (Snoke et al., 2001). The Early to Middle Eocene cooling relates to the low-angle detachment opening of the Grenada Basin (Margarita and Tobago were parts of the footwall according to Pindell et al., 2005), thereby explaining the lack of Upper Cretaceous rocks on Tobago, but the end Eocene forearc uplift by the mechanism of Figure 19B, followed by collisional uplift as in the mechanism of Figure 19B, kept any sediment from accumulating on the surface of the Tobago High until the Late Miocene (Pliocene on the island itself).
Serranía, and the resulting angular discordances of only 2 or 3 degrees are not readily observable in today’s deformed field sections.

In addition, South American hanging wall uplift is predicted to have produced a Cenozoic paleobathymetric ridge projecting and plunging ENE from the northern flank of the Serranía del Interior out to about 15°N/53°W in the Atlantic, passing under the present position of Barbados (shown schematically in Fig. 19A). We believe that today’s expression of this is shown in Figure 16, inset. The seafloor expression of this submarine ridge and its adjacent trough was buried by sedimentation only in the Middle or Late Miocene, and thus the ridge separated the Paleogene clastic dispersal pattern from South America into 2 realms. The first is a deep water “Proto-Caribbean” realm, which included the Tiburón Rise, whose complex heavy mineral signature reflects Eocene-Oligocene orogenesis between the Caribbean and South America in western and Central Venezuela (eg., Barbados field samples, Tiburón ODP cores). The second is a “Guyana-Trinidad-Eastern Venezuela” realm on the backside (south) of this Proto-Caribbean ridge, which remained entirely cratonic and mineralogically mature until the Upper Oligocene onset of the Naricual and Nariva formations, marking the closure of the Proto-Caribbean Trough at the longitude of the East Venezuelan Basin, such that orogenic minerals finally breached the barrier and reached into Trinidad (Tectonic Analysis, 2005; 2007). East of Barbados, this buried Atlantic basement ridge, with about 3 km of relief at the basement level, is also at least partly responsible for Barbados’ present, uniquely subaerial exposure on the E-wardly migrating Barbados Ridge; the island is presently passing over the Proto-Caribbean basement ridge.

**Late Oligocene-Middle Miocene orogeny in the ESCPBZ**

Having unraveled the palinspastic effects of the last 10 m.y. of tectonic evolution, defined the regional plate kinematics, and established the case for the existence of the Proto-Caribbean subduction zone, we now focus our attention on the Late Oligocene to end Middle Miocene orogeny in Trinidad and, to a lesser extent, in Eastern Venezuela and Barbados Ridge. The orogeny, culminating at about 10-12 Ma in Eastern Venezuela and Trinidad, was dominated by ESE-directed folding and thrusting driven by the approach of the Caribbean Plate from the northwest. This orogeny reached the Columbus Channel, and was detached at or near to the base of the post-rift stratigraphic section in Central Trinidad; it appears to involve older rock toward the north. Restoring the gross deformations produced in the orogeny will provide a Late Oligocene, pre-orogenic palinspastic reconstruction which may be used to assess earlier Paleogene development of the Caribbean-South America plate boundary.

**Figure 20** shows an outline tectonic elements map of the Trinidad region based on our own mapping of an extensive seismic database (Gulf of Paria, onshore and eastern offshore areas) supplemented where necessary by published maps (e.g. Robertson and Burke, 1989; Babb and Mann, 1999; Flinch *et al.*, 1999; Boettcher *et al.*, 2003). Trinidad is clearly a complex geological collage with a polyphase geological history and structural elements that are continuously inherited and reused. Present-day structure is typical of strike-slip-dominated
Figure 20. Map of principal present day structural elements of Trinidad, based upon extensive seismic mapping.
deformation, and comprises several discrete through-going linear fault zones which bound overlapping and anastomosing zones of extensional (releasing bend or pull-apart) and compressional (restraining bend) structures (see earlier discussion of various aspects of the ESCPBZ). However, much of the terrane through which these fault zones pass comprises deformed orogen from the Late Oligocene-Middle Miocene stage of development.

**Figure 4B** shows a cross-section across the map of **Figure 20** through Port of Spain at full lithosphere scale, based on seismic data (approximately depth-converted), patterns of earthquake activity, and seismic tomography (Van der Hilst, 1990). We are confident this is a substantial improvement over most cross-sections published to date, and that it coherently illustrates relationships between distinct elements of Trinidadian structure. The most important point is that South American continental lithosphere, although dipping NW, can be traced at least 150 km north of Trinidad (as proposed by Speed, 1985), reaching the Grenada Arc, and is overridden by the Caribbean Plate. There is no indication of a lithospheric-scale vertical strike-slip tear below about 30-50 km. Thus, South America does not end at the El Pilar or North Coast Faults (as implied by the maps of, eg., Robertson and Burke, 1989). The deep seismicity of the “Paria Cluster” is part of a continuous Benioff Zone which can be traced updip to the east where it emerges at the toe of the Barbados Prism. Thus, we show the Caribbean Plate apparently over-thrusting the South American Plate above a detachment which shallows from about 50 km beneath the North Coast Fault Zone, and is continuous with the basal detachments at about 30 km beneath the Gulf of Paria, and about 15 km beneath the Southern Basin (see below). The Caribbean is now moving approximately normal to this cross-section but because the Caribbean Plate thickens from east to west, it is continually depressing the northern feather edge of South American lithosphere, and this continues to drive subsidence in the absence of strong north to south compression (see “bow-wave model”, above). It is also apparent that the East Venezuela-Trinidadian orogen is essentially a bivergent orogenic float developed above this Benioff Zone, involving north-directed thrusting of the upper level of the southern edge of the Caribbean Plate, as a response to its impinging on South America, and south-directed thrusting of the sedimentary cover of South America. Oblique strain within this float prior to about 10 Ma is partitioned between dextral strike-slip and apparently compressional deformations and the degree and type of partitioning varies through time controlled by factors such as changing relative plate motions and variations in pre-existing structure and stratigraphy of the South American margin.

**Figure 21** shows a closer view of this cross-section. Note that all the major strike-slip lineaments in Trinidad root into the detachment above South American lithosphere. None are associated with seismicity deeper than ca. 30 km (Sobiesiak *et al.*, 2002), and all earthquakes with dextral focal plane solutions are relatively shallow. This rooting enables the strike-slip faults to move across the detachment surface towards the north or south, and thus none are fixed with respect to South America, in contrast to the more traditional view of, for example, Robertson and Burke (1989). The structure of the Southern Basin (see below) clearly roots to the base of a more or less layer-cake post-rift stratigraphic section. Towards the north, beneath the Gulf of Paria, we speculate that a sliver of basement (note that “thin-skinned” but “basement-involved” are not mutually exclusive) may play a role in elevating the Early Cretaceous stratigraphy drilled in the Couva Marine area. This
Figure 21. Close-up cross-section (see Fig. 4C) showing “oblique-thin-skinned” character of the Trinidadian Orogen.

Figure 22. Example seismic line-drawing through the Mokatika area (location on Figure 25). Note 1) Upper deck structure is initially pre-Late Miocene; 2) Evidence of “relaxation” before and during Manzanilla; 3) Likely location of Central Range Dextral Fault is “clear”; 4) Plio-Pleistocene folding near Central Range Fault; 5) Deeper structure shows stacked horses detaching near base Cretaceous, truncated by Darien Ridge so age relative to young strata not so clear.
sliver may either represent southward ramping of the detachment from a mid-crustal level (brittle ductile transition) to more or less the base of the post-rift section, or may be a former low angle extensional horse formed during Jurassic separation of Yucatán and South America.

Note that we show the leading edge of Caribbean forearc crust wedged between the metasediments of the Northern Range and the proposed basement sliver to the south. This is based on observations to the west (Serranía Oriental and Central) and east (Tobago area) but can only be inferred for onshore Trinidad. We infer the wedging to be of Middle Miocene age and believe that it played a significant role in the Middle Miocene unroofing and cooling of the Northern Range.

**Seismic mapping of dismembered Middle Miocene structures in Trinidad**

**Figure 22** is an interpretation of a seismic line in the Mokatika area in the eastern Central Range offshore, showing the major structural elements of the Middle Miocene and younger deformations. Cretaceous strata are elevated at least 12 km (or about 10s TWTT) above the regional level of Cretaceous to the south. This elevation is achieved through imbrication of horses of passive margin strata approximately 2s thick. The horses shown in this figure were clearly in place prior to the erosion of the base Late Miocene (ca. 10 Ma) unconformity. The uppermost horse (above bold black thrust) corresponds to the rocks of the Central Range and Angostura areas, and appears to tip up to the south into intense imbrication of Nariva shales. Deeper horses correspond to rocks found in the Southern Basin and beneath the Nariva Fold-Thrust Belt onshore. Note that the projection of the Central Range Fault from Manzanilla Point is clear on this line, but it does not appear to be neotectonically active; it does not break the seafloor or cut very young reflectors. The youngest surface breaks are along the “Scorpion Fault” indicating that the active shearing (Prentice et al., 2001) we see along the onshore Central Range Fault (CRF) steps north through Block 2ab (where there are young synclines comprising sediment of Plio-Pleistocene age) or (less likely) steps south towards the Darien Ridge Fault on one of several E-W-trending transtensional faults (see below). We do not explore this issue further in this paper, but it appears that the magnitude of oblique shortening in the Central Range between Pointe-a-Pierre and Angostura thus places a constraint on the magnitude of strike-slip on the Central Range onshore (perhaps 10-15 km, matching the apparent offset on E-W-trending pre-Central Range faults north and south of today’s Central Range Fault).

Timing of structuring is constrained by the relationships of imbricated strata to major unconformities (Figs. 22 & 23). In the immediate Angostura area, high-quality seismic appears to show initial imbrication before ca. 30 Ma, and the entire width of the section was deformed prior to erosion of the ca. 10 Ma base Late Miocene unconformity. Syn-depositional folding of Late Miocene and Pliocene strata is evident indicating further tightening of folds related to the Cretaceous horses beneath.

Both figures also show the presence of numerous minor normal faults within the growth sections of Late Miocene and Pliocene strata which hint at three-dimensional strain. These young compression and extensional features overlap in time and cannot be neatly separated into discrete phases.
Cross-section A-A’

Topaz interpreted as backthrust wedge driven by reactivation of underlying Emerald Thrust...

Upper NFTB?  Mt Harris Allochthon?

Angostura Anticline (Thick lowstand wedge sands)

Lateral ramps of Mid-Miocene age were reactivated from 10-5 Ma as transtensional normal faults before being refolded after 5 Ma.

Deepest apparently normal fault underlies Emerald and its footwall and appears to trend W-E, surfacing south of Kitchener (“N. Darien Fault?”).

Speculative interpretation of clinoform type wedge suggests approaching outer shelf - now in Emerald area? - to north, but south of paleoposition of Angostura sands.

Below here, there are further Southern Basin-like repeats of Cret. stratigraphy, detached on ?Couva.

Figure 23. Semi-schematic cross-section, based on seismic data, through Topaz-Emerald area (location on Figure 25). In this view, it is very hard to tell whether north-dipping faults which cut the deep undrilled stratigraphy are true thrust faults or oblique views through NE-dipping normal faults or lateral ramps.

Cross-section B-B’

WSW

Manzanilla in triangular depocentres above transtensional ramps

Emerald-Amber fold-thrust structure

Major E-W fault truncates Angostura Trend

ESE faults truncated by SE-dipping normal faults after 3-5 Ma

Southern Basin type imbricates of Cretaceous, detached on ?Couva. Basal detachment at ca. 10s TWTT

Major lateral ramp reactivated as later normal fault. Appears to trend E-W and pass south of Kitchener-Spitfire.

Figure 24. Strike-line through Emerald area (location on Figure 25) showing apparent W-E extension of the Miocene thrust belt. Emerald and other structures terminate against a middle Miocene ESE-trending lateral ramp (heavy blue line). Ramps have apparent dextral offset of up to 15-25 km, and significant apparent extension. Some ramps were reactivated since 10 Ma as extensional faults, bounding Manzanilla basins - smaller extension, almost no strike-slip. Distinctive structural and stratigraphic features that allow us to restore middle Miocene dextral offsets.
A further significant problem can only be resolved when strike-lines are also interpreted, and when structures are mapped more fully in three-dimensions. In general, the quality of seismic imaging within the imbricated Cretaceous is poor. Although the generally imbricated structural character is clear, it is not always obvious whether we are seeing more or less across-strike views of thrust faults or oblique views of lateral ramps. Mapping of the faults shown in black on Figure 23 in particular suggest that these may be significant lateral ramps on which dextral strike-slip displacement oblique to the line may exceed the apparent thrust shortening. There are also locations where the top of Cretaceous in some of the syncline cores appears to have dropped lower than its expected level, indicating the possibility of cryptic extensional faulting.

**Figure 24** is a line-drawing of a 2D seismic strike-line through the Emerald and Amber areas showing apparent E-W extension of the Middle Miocene imbricate stack. Several of the faults identified on Figures 4 and 5 are clearly seen to be east-dipping apparent normal faults. As with dip-lines, a simple interpretation may mislead. For instance, although the normal faults may appear to sole out at the same level as some of the thrusts, in three-dimensions they are found to dip moderately to steeply to the northeast, while the thrust dip generally steeply to the northwest. The complex three-dimensional structure also suggests that some, if not many, of the reflectors in these lines are side-swipes coming from out of the plane of the section and should not be over-interpreted.

The apparently normal faults clearly bound Late Miocene (Manzanilla-equivalent) depocenters. However, a map view (Fig. 25) shows that these apparently normal faults also appear to coincide with lateral ramps which trend more or less E-W in the Mokatika-Angostura-Emerald area. Offsets on these ramps can be estimated from terminations and offsets of distinctive architectural elements of the Middle Miocene orogen such as the Topaz Anticline and the Emerald Imbricate Antiformal Stack. These offsets are generally about 10 km, but reach ca. 25 km on the major E-W trending fault in Block 3b, immediately east of the Amber well. The age of the strike-slip offset is constrained to mostly pre-Late Miocene because onlap edges of Late Miocene strata onto the 10 Ma unconformity are hardly offset across lateral ramps which show large offsets of Middle Miocene structures.

Thus, it is clear that substantial eastward-lengthening of the Middle Miocene orogen was also occurring at the same time as, or just after, initial thrusting and that the normal faults which bound Late Miocene depocenters reused these pre-existing lateral ramps, without significant further strike-slip offset.

A reconstruction of the configuration of the Middle Miocene orogen at its culmination must thus attempt to estimate the extent of tightening of older structures during the Late Miocene to Recent, and restore the effects of Late Miocene extension which formed the Manzanilla depocenters. Reconstruction of the margin prior to the Middle Miocene deformation requires not only estimation of cross-strike shortening but also assessment of the cumulative offsets on the numerous E-W-trending lateral ramps.

In our view, the Point Radix-Darien Ridge Fault is not simply another one of these east-west trending lateral ramps, although it may have originated as one. A substantial (up to 50 km) eastward motion of the blocks on the north side of the fault is required during the Late Miocene opening of the Gulf of Paria, and must match...
Figure 25. Sketch map showing the relationship between Mokatika Arch, Emerald Imbricate Stack and Topaz Anticline, showing significant apparent dextral offsets between Middle Miocene structures. Lateral ramps were reactivated as extensional faults during Manzanilla deposition, subsequently overprinted by renewed tightening of underlying structures. Cross sections are Figures 22-24.
the measured extension in the Gulf of Paria. The measured offset across the fault today will be substantially smaller, because the rocks of the Southern Basin has also moved some distance to the southeast during subsequent oblique shortening.

One important, and disturbing to some, conclusion that should be pointed out here is that the evidence for material moving in and out of the plane of any long cross-section through Trinidad is substantial. Only relatively short sections, drawn between major lateral ramps and limited by the major through-going strike-slip faults can even be approximately balanced. Any long cross-section (i.e. extending from the Caribbean Plate to the Guayana Shield) that is rigorously balanced along its full length will inherently have error and have potentially negative predictive value.

**Geometry and age of structures in the Southern Basin, Trinidad**

Our work on the Southern Basin focussed on structures at top Cretaceous level, on the geometric relationship between deeper strata and the Late Miocene and younger normal-faulted package above, and on the relationship of Miocene foredeep and wedge-top fill to pre-Lengua-Cruse structures. Our maps are based on a detailed interpretation of all available seismic and well data in the Southern Basin, integrated with 2D and 3D data from the Soldado area, the Columbus Channel and limited Venezuelan data. **Figures 26 and 28** show some examples of seismic structural styles in the basin.

**Figure 26A** is a composite line running from the eastern Central Range through Guayaguayare and into the Columbus Channel. The broadly imbricate structural style is clear, particularly in the shallow Nariva Fold-Thrust Belt, which detaches above Cretaceous strata south of the Central Range. Deep Cretaceous structure is generally poorly imaged except in the Mayaro area and the major strike-slip zones are only seen as “no data zones” across which no sensible seismic ties can be made. Oblique strike-lines across the Point Radix Fault indicate a steep northward dip on that fault. Cretaceous culminations are present in the Lizard and Guayaguayare areas where they are truncated beneath Late Miocene Cruse and younger strata. The Central Range itself appears to comprise thrust sheets of Cretaceous which overlie Southern Basin type Cretaceous (drilled in the Esmeralda well, west of this line) which drive the Nariva Fold-Thrust Belt. These Cretaceous sheets are overlain by tightly deformed Paleogene rocks in the Mt. Harris area, which may detach above the Cretaceous and derive from yet farther north. These upper Paleogene rocks appear on this and other seismic lines nearby to be unconformably overlain by Brasso, at least on the north flank of the Central Range. The apparent southward dip of the basal detachment of the Nariva Fold-Thrust Belt close to the Central Range is probably a pull-up due to higher velocity rocks shallow in the section. At present, the south flank of the Central Range is bounded by the Central Range Fault, and a further lineament with slivers of Paleogene faulted against Brasso (the Bocono Hill-Fishing Pond Lineament) lies close to the north side of the range. Seismic continuity across these is poor, and we suggest that strike-slip on both of these faults has disrupted a once more continuous fold-thrust belt.
Figure 26. Onshore seismic examples of structural styles. Data are computer filtered from original seismic provided by Petrotrin & BPTT. Simplified from Tectonic Analysis, 2007 (seismic interpretations done with Bruce Eggertson).
The stratigraphic template for any interpretation and structural cross-section can be seen offshore to the south, where there is a northward thickening wedge at least 3 seconds (ca. 4-5 km?) of Cretaceous strata, which have been drilled in Venezuelan waters and include Barranquín-equivalent strata at their base. This sediment pile includes several more or less competent units (Barranquin sands and limestones, unproven by drilling in Trinidad, Naparima Hill argillites, Paleogene marls, Middle Miocene) and several shale-prone incompetent units (Cuche, Guayaguayare, Nariva shales) and resulting in ramp-flat-ramp thrust trajectories. We can thus estimate “regional” top and base Cretaceous underneath Trinidad (ca. 7-10s) and see that Cretaceous has been lifted at least 3-4s above regional across onshore Trinidad.

Figure 26B is a composite line running from San Fernando into the central Columbus Channel. Here, the convergence of the Central Range and Point Radix Faults has reduced the width of the Nariva Fold-Thrust Belt to less than 10 km, and the combined strike-slip offsets on these faults has juxtaposed the relatively hinterlandward rocks of the Gulf of Paria and Caroni Basins with the relatively forelandward rocks of the Southern Basin. The three characteristic cross-sectional structural domains of the Southern Basin are especially clear:

- Imbricates of Cretaceous strata which ramp from a deep (ca. 8-10s) detachment with local flats in Albian Cuch shales and possibly Nariva shales, repeating the Cretaceous and locally placing Gautier and Naparima Hill strata above Middle Miocene Retrench (Marac-1 well),
- Imbricated Early and Middle Miocene strata (Penal-Barrackpore Fold-Thrust Belt) which lie entirely above the Cretaceous imbricates and,
- Late Miocene and younger strata above folded extensional detachments in the Ortoire Syncline.

Of particular note on this line is the Rock Dome Thrust which repeats the Cretaceous with about 10 km overlap. Mapping of the detachments at the base of the Cruse on this and adjacent lines shows the base Cruse and top Cretaceous more or less parallel, suggesting that this Cretaceous thrust sheet, at least, was emplaced only relatively recently.

Offshore seismic lines are not deep enough to constrain the Cretaceous section, but E-W lines in the Columbus Channel do constrain the offshore depth the detachment for Cruse-Mayaro-aged listric faults.

Figure 26C shows an example of a line to the west of the Los Bajos Fault. Here the structure is apparently simpler than to the east. The Cruse and younger section is apparently parallel-bedded and was deposited updip from the extensional breakaways so typical farther east. Cretaceous structure at depth is hypothetical and largely based on analogues in the El Furrial area (Duerto and McClay, 2002 and Jacomé et al., 2003a,b).

The Southern Anticline here is interpreted as cored by mobile mud and, as at El Furrial, the tent-like anticline with dips up to 60-70° on each limb is thought to be offset from, and south of, the nearest deeper Cretaceous culmination. Field evidence shows that mudflows have been erupting along this trend since Lengua time and through Cruse and this too points to the existence of a deeper pre-existing Cretaceous culmination.
which overthrusts overpressured Miocene mudstones. In this section, the regional level of Cretaceous strata in the Columbus Channel is constrained by Venezuelan seismic lines (e.g. di Croce et al., 1999); top Cretaceous shallows from about 7.5s (ca. 12 km?) at the south coast to about 6s (ca. 7.5 km?) off Punta Pescadore. The Cretaceous culminations shown are in part constrained by poorly imaged patches of high-amplitudes comparable to drilled Cretaceous east of the Los Bajos Fault and appear to be uplifted about 2s or ca. 3.5 km above “regional”.

Cross-sections based on the seismic data indicate that about 1.5-3s of Cretaceous strata are present in each thrust slice. The Cuche shale (Middle to Upper Albian in the Southern Basin) or base Gautier (mainly Cenomanian sandstones) acts as an intermediate detachment level, and the deeper, thicker parts of the thrust slices may contain a section comparable to the Barranquín sandstones outcropping in Venezuela, and drilled south of the Columbus Channel (Orinoco and Guarao wells, see di Croce et al., 1999). We speculate that the deep detachment level is equivalent to the Couva evaporites drilled in the Gulf of Paria and that no rift phase stratigraphy is involved in Central and Southern Trinidad thrusting. The abrupt southern termination of Cretaceous culminations, and the fact that thrusting did not propagate farther south since the Late Miocene, suggests a fundamental stratigraphic control on thrusting, possibly the southern pinchout or fault truncation of an evaporite.

A top Cretaceous form map (Fig. 27) shows multiple, en-echelon, doubly-plunging culminations, including the Rock Dome, Moruga, Guayaguayare and, possibly, Galeota structures. The relationship of these structures to the Late Miocene and younger section demonstrates that they must have been uplifted prior to deposition of the Cruse Formation (see below). The angularity between Cretaceous and Cruse is particularly clear on a seismic line through the Moruga area (Fig. 28) which also shows triangular north-thickening wedges of imbricated Cenozoic strata between the Cretaceous highs. Internal unconformities within the Herrera, Karamat and Lengua indicate that the Penal-Barrackpore-Balata imbricate stacks of Cenozoic strata are slightly older than the deeper Cretaceous culminations. The en-echelon geometry of the Cretaceous culminations suggests that they may be synchronous, and may have formed in a dextral transpressive setting.

Mapping the Cretaceous structures also provides an insight into the nature and origin of the Los Bajos Fault. There are no known analogues to the Moruga and Guayaguayare culminations on the west side of the fault, suggesting that the Los Bajos originated as a dextral lateral ramp during Middle Miocene thrusting. This is supported by mapping in the Soldado area, where there is a Cretaceous-cored antiformal stack with an apparent >20 km offset across the Los Bajos Fault from a similar thrust stack in the Brighton area. These antiformal stacks are cored by Cretaceous thrust sheets which appear to drive Retrench-Herrera-Karamat imbrication to the south prior to 10 Ma. They continued to tighten during Cruse time, separating the Cruse and Manzanilla basins. They could not have formed entirely since 10 Ma because there appears to be significantly more shortening at Cretaceous level than in Cruse and younger rocks. Much of this offset must have occurred when the Moruga and Guayaguayare culminations were forming, and fits well with our estimates of pre-Cruse shortening either side of the fault. Our mapping of young structures supports the ca. 10 km Pleistocene offset of the Skinner Fault...
Figure 27. Structure form map of Southern Trinidad showing en-echelon culminations at top Cretaceous level. Structures involving Cretaceous deep section were mapped in detail in Southern Basin from all available seismic, controlled by 68 Cretaceous and Paleocene-Eocene well penetrations. Note the overlapping, en-echelon fault bend or fault propagation folds east of the Los Bajos Fault, which has its origin as a Middle Miocene lateral ramp. Most culminations are “old”, but refolded, with the exception of the Rock Dome culmination which formed only since the Late Pliocene. There has been no southward propagation since the beginning of the Late Miocene, and source kitchens were compartmentalised by that time.

Figure 28. Part of line 140 shows angular unconformity of end Middle Miocene age reused as extensional detachment. Location shown on inset of Figure 26. Simplified from Tectonic Analysis, 2007 (seismic interpretations done with Bruce Eggertson).
commonly considered as the type offset marker for the fault. It matches our shortening estimate for the Rock Dome thrust slice, which appears to be the only Cretaceous thrust slice that entirely post-dates the Cruse, and for which there is no equivalent on the west side of the Los Bajos Fault, and it also matches the offset between the Santa Flora Fault and the Papure Syncline Fault which we propose to be segments of a once continuous Cruse-Forest-aged growth fault.

On all these seismic lines (Figs. 26 and 28), the “10 Ma unconformity surface” at the base of the Cruse has been re-used as the basal detachment for younger gravity-driven listric normal faults which generally dip to the east. The overall thickness of the Cruse-Forest-Mayaro section deposited within this normal fault belt remains fairly constant (about 8000’) from the axis of the Erin-Siparia Syncline and into the Columbus Channel, suggesting that the base Cruse was not perched higher onshore than in the Columbus Channel. Thus, we can use the base Cruse surface as a structural datum. Furthermore, this surface is the only reliable structural datum or paleo-horizontal (or approximately so) that can be used to restore cross-sections to a pre-Cruse state in this area and understand the origin of the Cretaceous culminations.

The very steep dips recorded in the Cruse and Forest strata on the flanks of the southern anticline do not represent limb dips of the deeper structures and are generally not coaxial with those deeper structures. The steep dips result from the superimposition of two distinct tilts with different orientations. Late Miocene growth fault bounded sediment wedges generally roll back towards the west, and the steepest bedding in these wedges had a more or less N-S strike and perhaps 30°-45° westward dip. These wedges were then refolded when the Cretaceous cored culminations were reactivated from the Late Pliocene to Recent. The refolding pattern is spectacularly clear on the geological map (Kugler, 1996; Saunders et al., 1997) of the south coast (especially between Negra Pt. and Moruga Bay, and between Canari Bay and the St. Hilaire River) and Lizard Springs, Salt Spring areas.

The only paleo-horizontal in the Cruse-Mayaro section are to be expected downdip from, or east of, rollover sections, but these are hard to identify because we typically find the next downdip listric fault and an associated rollover sediment wedge. The post-growth overlap section (Upper Forest and younger formations in the west and Palmiste and younger formations in the east) can be used locally as a paleo-horizontal but only shows that significant reactivation of the Cretaceous culminations occurred during Late Pliocene and younger time. The available well and seismic data does not allow us clearly pick the exact equivalents of onshore formations in the Columbus Channel, so flattening on these young surfaces is subject to some error. In contrast, the seismic and well data do allow us to pick with confidence the surface into which the rollover faults detach both onshore and in the Columbus Channel.

Figure 29 shows an attempt to map these folded normal faults, and is based on the entire Southern Basin Consortium seismic dataset and some older data where quality is good, together with well data. The refolding of normal faults which sole into base-Cruse or Lengua is particularly clear around the Rock Dome culmination and we can also trace several of the major faults on strike-lines in the Columbus Channel into the faults which bound the tilted growth sections on the south coast. This remapping of growth faults and our attempts to tie sections...
Figure 29. Folded normal faults, onshore and offshore southern Trinidad. Cruse-Mayaro growth faults reflect eastward growth of Orinoco Delta and bury older structures, but are folded above Middle Miocene culminations retightened during Plio-Pleistocene, resulting in complex outcrop patterns in Late Miocene and younger growth strata. In general shallow structure is a poor indicator of structure at depth. The stratigraphy in the Late Miocene and Pliocene compartments is not a good fit to layercake stratigraphy. This new (ish) paradigm may offer opportunities in young sandstone fairways.

What would the orogen look like if we remove estimated Late Miocene and younger deformation?

Figure 30. Palinspastic reconstruction for 12 Ma, close to the end of Middle Miocene orogeny. Distorted latitude-longitude grids account for cumulative deformation and the resulting map is analogous to a restoration of a balanced structural cross-section. Restoring even Late Miocene and younger deformation dramatically distorts the shape of Trinidad (paleoshape shown in heavy blue lines). To make this map we used relatively conservative shortening and shear estimates south of El Pilar, Caroni Fault. Northern Range position is more model constrained; e.g. is unroofing driven by Caribbean wedging? is there a match between Caracas-Araya-Paria. The map provides a geographic framework for plotting and reconstructing Middle Miocene deformation.
across growth faults revealed some significant miscorrelations or misnaming of Formations across Trinidad and resulted in a sketch attempt to modify the geological map as shown in Figure 29. In particular, it seems clear that:

- What is picked as “Cruse” is often rotated growth section (upper slope facies”) and what is picked as “Forest” is often the topset to these growth wedges, is usually parallel-layered on seismic (but with small scale foresets).
- These young consistently from west to east, and the “Forest” in the Catshill area appears to be younger than “type Forest” and ties to Lower Morne L’enfer reflectors to the west.
- The Gros Morne is a growth section approximately equivalent to the Forest and Lower Morne L’enfer Silt farther west and the Mayaro is a growth section approximately equivalent to the slightly younger Lower Morne L’enfer sandstone.
- The Lower and Upper Forest Clays are slightly older (albeit still within the P. Margaritae biozone) than the Lawai Clay and St. Hilaire Silt in the southeast, and the Palmiste Clay appears to tie better with the Lot 7 Silt reflector than with either Forest Clay.
- The poorly-dated Morne L’enfer may thus be slightly older than thought, given that the Palmiste Clay lies at the top of the P. Margaritae biozone.
- The Erin onshore may also be slightly older than usually considered. This is consistent with the observations from Soldado area seismic that “Erin” is folded and truncated by the base Talparo unconformity.

The basic constraint on these proposed ties is the requirement to make all apparently normal growth faults on seismic have net normal displacement however small, whereas the correlation scheme used on the Saunders et al. (1997) revision of the geological map of Trinidad results in some growth faults having to have reverse offset. Kugler’s original 1959 geological map (republished in 1996) better represents the geology of the Siparia-Ortoire Syncline (for instance, there is no culmination where they syncline crosses the Moruga Road), albeit mapping lithofacies (the growth vs topset distinction noted above) rather than chronostratigraphy.

Flattening on the “10 Ma unconformity surface” datum reveals that Late Cretaceous or Paleocene strata were exposed immediately below the surface at latest Middle Miocene time in the Lizard Springs and Moruga-Guayaguayare areas (Figs. 26a & 28). The synclines between culminations preserve imbricated sections of Eocene (Navet or San Fernando) through Middle Miocene (Retrench-Herrera-Karamat-Lengua) strata. This wedge of pre-Cruse Cenozoic sediment reaches a maximum thickness of about 8000’ thinning to zero over the Cretaceous anticlines. The thinning is too abrupt to be the southern pinchout of a foreland basin and this thick section is generally absent in the hanging walls of Cruse-aged normal faults. If it had been present, the Cruse-Mayaro section would have to double in thickness in these areas, to about 16000’, which it does not. Thus, the culminations must be late Middle Miocene in age. Only the Rock Dome thrust slice, in which Cretaceous through Cruse-aged strata are more or less parallel to each other, was emplaced later, during Late Pliocene or Early Pleistocene time.

Pindell and Kennan, SE Caribbean, Trinidad & Venezuela, for GCSSEPM 2007
We have not constructed rigorously balanced cross-sections of the Southern Basin and Nariva Fold-Thrust Belt, because of uncertainties in true shortening direction, motion of material through sections, and time-depth conversion. Semi-balanced cross-sections indicate that we can assess the uplift of the folded base Cruse growth faults above regional and also the uplift of Cretaceous above regional. A simple excess area calculation on the latter suggests \( \text{ca. 45-55 km} \) apparent total shortening required to uplift the Cretaceous to its present level, assuming that only more or less layer-cake post-rift stratigraphy is involved, and that perhaps 50% of this occurred before 10 Ma and 50% since the Late Pliocene. The overall shortening direction was approximately towards the southeast, with perhaps a minor dextral component.

**Late Middle Miocene reconstruction of the orogen**

Using semi-balanced cross-sections, excess-area calculations, estimated extension in the Gulf of Paria, correlation of piercing points across strike-slip faults, such as offset Nariva sand fairways (De Verteuil and Eggertson, 2000) and offset older faults, and regional assessments of the position of the Caribbean Plate at 12 Ma, we have built a palinspastic latitude-longitude grid (Fig. 30) which reasonably captures the shape change of the Trinidad area since that time. Note the contrast between 12 Ma and present shapes of Trinidad.

Overall apparent shortening as measured between Piarco Airport and Galeota Point is approximately 85 km, but this is composed of about 40-50 km true southeastward shortening and about 50 km of dextral strike-slip. Piarco restores to about 110 km west of its present position. Although this cumulative apparent strike-slip total appears worryingly large to some, the process of building this map is analogous to balancing and restoring a cross-section; the strain is distributed across numerous faults. The largest single offset proposed is across the South Boundary Fault which bounds the Gulf of Paria extensional basin. Approximately 70 km of eastward extension must be balanced by dextral offset, which (when we account for other strains) reaches a maximum of \( \text{ca. 50 km} \) somewhere northwest of Soldado, but the displacement drops to the east and is probably not more than \( \text{ca. 30 km} \) anywhere along the trace of the Point Radix and Darien Ridge Faults between San Fernando and Block 2ab. This matches the maximum allowable offset of Cretaceous facies belts (Tony Ramlackhansingh, pers. comm., 2007). The Angostura area restores to about 125 km WNW of its present position at 12 Ma and Tobago restores 240 km west of its present position.

The position of the Northern Range is more model dependent than the restoration for areas south of the El Pilar and Caroni Faults. Features along the North Coast Fault Zone suggest not more than about 25-40 km of dextral offset since 12 Ma, and GPS data indicate it is now inactive, requiring a dextral offset across the Caroni Fault of about 70 km. There are a few direct offset markers: a possible basement slice accreted to the leading edge of true Caribbean igneous crust in the Tobago area restores to the northeast edge of a basement wedge (see Fig. 21) thought to underlie the Gulf of Paria; the tilted base Late Miocene unconformity in the “North Basin” offshore restores to a paleoposition north of a similar surface in the Caroni Basin; the slope sediments of the Northern Range restore close to the Serranía Oriental shelf stratigraphy with which plausible correlations have...
been proposed (e.g., Algar, 1998); the restoration also closes the Late Miocene Gulf of Cariaco pull-apart basin and restores the west end of the Araya Peninsula against the Caracas Group basement of central Venezuela.

A paleogeographic map (Fig. 31) drawn on the Figure 30 base shows the Caribbean Arc north of present day Margarita, separated from the emergent orogen by the Caracolito-Tobago forearc basin. By this time, underthrusting of the Caribbean forearc beneath the former Proto-Caribbean Prism of the Araya-Paria-Northern Range block was complete and southward thrusting of this block had imbricated Cretaceous strata as Brighton and the culminations in the Southern Basin were about to form. The emergent orogen is limited in the north by the backthrusts which formed as Caribbean crust wedged under the Araya-Paria-Northern Range block. To the south, the Guarico Fold-Thrust Belt, Northern Serranía Oriental, Northern Range, Caroni Basin and Central Range are uplifting and eroding.

The Nariva Fold-Thrust Belt has already shortened and is starting to be uplifted above deeper Cretaceous thrust sheets. The Brasso Formation was deposited in a wedge-top setting above the Central Range Thrusts and Nariva Fold-Thrust Belt and comprises relatively shallow water (shelfal) silts and limestones. To the south, the Nariva thrusts drive imbrication of the Late Middle Miocene Retrench-Herrera sandstones and shales which we interpret as largely axial-fed turbidites carried down the axis of the Caribbean foredeep, and containing a substantial component of high-grade metamorphic minerals derived from the Villa de Cura area in Central Venezuela.

There are also more proximal facies derived from the mountain front, such as the Morichito Conglomerate of the Serranía Oriental and Herrera cobble conglomerates found at Galfa Point on Trinidad’s south coast. Some of the Herrera sands may also be derived from areas of the South American margin uplifted on the crest of the Caribbean forebulge (the equivalent Oficina Formation onlaps bare Guayana Shield or Cretaceous rocks on the south side of the Maturín Basin). During the interval 10-12 Ma, the Cretaceous culminations of the Southern Basin began to form. On the crests of some of these, Tamana-like limestones may have been deposited, and we suggest this is a more plausible origin for “olistoliths” such as the Morne Diablo Quarry limestone than derivation from the Central Range (some 100 km to the northwest at this time).

A semi-schematic cross-section (Fig. 32) can now be drawn across the orogen (in this case, though the eastern Central Range and Brighton areas) which puts end Middle Miocene structural elements in the correct order, without the juxtapositions of hinterlandward and forelandward elements (and some elements missing entirely) that we have on any present day cross-section. We highlight:

- Caribbean forearc basement overthrusting South American basement and wedging beneath a largely eroded Proto-Caribbean Accretionary Prism which had previously been overthrust by an entirely eroded Caribbean Accretionary Prism.
- The Northern Range, interpreted as part of the highest Caribbean allochthons above South American basement. Timing constraints on deformation and uplift indicate that at the same time as it was being underthrust by Caribbean crust (ca. 23-20 Ma) it was also driving thrusting of Paleogene sediments in the
Figure 31. Palinspastic reconstruction and paleogeography for 12 Ma, close to the end of Middle Miocene orogeny showing the geometry of the orogen before Late Miocene and younger strike-slip-dominated deformation. Distorted latitude-longitude grids account for cumulative deformation and the resulting map is analogous to a restoration of a balanced structural cross-section. Restoring even Late Miocene and younger deformation dramatically distorts the shape of Trinidad (paleoshape shown in heavy blue lines). By this time, substantial areas of the former foreland basin had been incorporated into the orogen. Proximal fine through coarse-grained clastic and carbonate facies accumulated on the north side of the foreland basin, deposited in shallower water conditions than in the axial trough to the south. Proximal sands were sourced from nearby pre-Miocene outcrops, including reworked foreland basin sediment. Significant W-E extension in the orogen is indicated by thick carbonate and clastic sediments (Brasso Formation) deposited in a wedgetop setting in waterdepths far less than the sediment thickness. True basement subsidence is indicated by continued foredeep subsidence beyond the deformation front, and additional accommodation space resulted from thinning of the allochthons. With the end of SE-directed relative plate motion we see continued subsidence driven by the distant but encroaching load of the Caribbean Plate but not, in most areas, by active continued foreland shortening. As a result, Orinoco Delta sediments, although of the same origin as older foredeep axis sediments, are able to overstep and bury the active thrust front.
Figure 32. Cartoon cross-section showing the configuration of the orogen before young strike-slip, at the end of Caribbean oblique convergence. Abbreviations: N.R. = Northern Range; B.S? = Basement slice?; COU. = Couva-Cuche in Paria, at or near uplifted detachment?; C.R. = Ancestral Central Range; C.T.T.S. = Deep Central Trinidad Thrust Stack (Brighton?, deep Emerald?); HER. = Imbricated Herrera-Karamat foredeep and piggyback fill; S.B.T.S. = Southern Basin Thrust Stack (detached at base “Barranquin”).
Central Trinidad Trough (now in upper part of Central Range). Top to the west, shearing within S1 cleavage in the Northern Range may possibly relate to early partitioning of strain between dextral strike-slip and southeastward shortening, and this dextral shear may have surfaced in the vicinity of the North Coast Fault Zone.

- The basal detachment of the Northern Range is interpreted to be folded up and over a sheet of South American basement under the Gulf of Paria, and may lie at the same Couva evaporite level proposed for the Southern Basin. Ramps from this higher detachment drove imbrication of high-level Paleogene strata in the Central Range (Mt. Harris area) above less tightly deformed Cretaceous, and then thrust Cretaceous rocks (Central Range Cuche) south towards the Nariva Fold-Thrust Belt.

- The Nariva Fold-Thrust Belt appears to comprise an upper allochthon (reaches the Nariva Thrust as mapped by Kugler), probably driven by the Paleogene thrust sheets in the upper Central Range, and a lower imbricate stack driven by the Central Range Cretaceous thrust sheets. Both detach at about Middle Oligocene level. Because early exploration onshore was focused on Nariva sands, there are few wells which test the possibility of subthrust Angostura sand beneath this imbricate stack.

- At the culmination of Northern Range exhumation, the leading edge of the Caribbean reached far enough south to entrain a slice of South American basement at its leading edge. Thrusts rising from the leading edge of this slice include the Pirital Thrust in Venezuela. In Trinidad, we propose that this basement slice underlies the elevated Couva in the Gulf of Paria, and that it forms the cores of the NW-SE-trending structural highs which formed during Late Miocene pull-apart formation. This coupling appears to coincide with the deepening of the detachment below the Nariva Fold-Thrust Belt into the Cretaceous, resulting in imbrication of the Upper Cretaceous in the Brighton area, and in the uplift and erosion of the top of the Nariva Fold-Thrust Belt (note that the NFTB is placed north of the Brighton imbricates in this section, a result of restoring ca. 50 km dextral motion on the Point Radix Fault). These Cretaceous thrust slices in turn ramp up to drive imbrication of the Retrench-Herrera-Karamat Middle Miocene sandstones in the Penal-Barrackpore and Balata trends.

- The deepest and southernmost imbricates detach on base Cretaceous (Couva evaporites?), deform the previously imbricate Middle Miocene strata, and bring Cretaceous to the surface by ca. 10 Ma along the Moruga and Guayaguayare culminations.

- Only after the time represented by this section did the El Pilar Fault and South Boundary Fault become active, dissecting the orogen.

**Late Oligocene, pre-orogenic, reconstruction of the orogen**

Reconstruction of the Trinidadian margin early in the history of Caribbean thrusting is rather more difficult. Shortening estimates based on cross-sections are only minima, because almost all the structures formed
between 25 Ma and 12 Ma are relatively high-level. Hanging wall cut-offs are almost entirely eroded in, for example, Angostura area and the Nariva Fold-Thrust Belt. However, we can establish some reasonable shortening and strike-slip estimates:

- As for the 12 Ma reconstruction, we can use an area balance to crudely estimate NW-SE-directed shortening in the Southern Basin, this time flattening top Cretaceous. Approximately 30 km shortening between the Brighton through Guayaguayare Cretaceous slices is sufficient to elevate the Cretaceous to its estimated position at 12 Ma, locally eroded at the base Cruse unconformity.

- The southernmost thrusts in the Cretaceous appear to be blind (fault propagation folds) but the Brighton imbricates ramp up and imbricate Middle Miocene strata; we estimate total shortening at about 20 km between San Fernando and Penal based on seismic data, comparison of present structured thickness and pre-thrust stratigraphic thickness, and published sections.

- At least 5-6 imbricate slices are present in the Nariva fold thrust belt, resulting in a structured thickness of Nariva of about 12000’ compared to a likely stratigraphic maximum thickness of between 2000’ and 4000’ (assuming no repetition in the type Nariva Hill section, which appears to be the south flank of a relatively simple syncline on seismic). Given the width of the belt, this would suggest an absolute minimum shortening of 25 km, without accounting for any erosion of hanging wall cutoffs.

- Shortening within the upper levels of the Central Range is hard to estimate. However, sub-Brasso bedding within the Paleogene of the Mt. Harris area is typically steeply-dipping and tightly chevron-folded over the ca. 10 km width of the outcrop, and so ca. 20 km shortening and overthrusting detached above Cretaceous could reasonably be hidden within this area.

- In the Angostura area offshore short semi-balanced cross-sections can be drawn more or less normal to fold axes and in the areas between the major E-W-trending lateral ramps (see Fig. 25) and these too suggest some tens of kilometres of shortening in these areas, truncated to the north by the Central Range and Scorpion Faults, and to the south by the Darien Ridge Fault.

- We noted above that the lateral ramps in the Angostura area appear to show dextral offsets of 10-25 km of apparently similar structural elements from one structural corridor to the next, and the relationships of these faults to Late Miocene and younger strata indicate that these offsets largely happened during or immediately after thrusting, allowing the orogen to lengthen from west to east. Thus, we must also restore these offsets when making a 25 Ma palinspastic latitude-longitude grid.

- We estimate that the Caribbean forearc has wedged perhaps 20 km underneath the Northern Range in Trinidad, and this process seems to have started at about 25-20 Ma. Thus, we must also pull the Northern Range to a position about 20 km SE of its position shown on the 12 Ma map.

The position of the Caribbean Plate provides the ultimate boundary condition for a 25 Ma reconstruction. Super-regional features such as the rate of foredeep migration and timing of deformation along
the Northern Caribbean margin constrain its position and a palinspastic grid must restore the Northern Range far enough to the northwest to be influenced by the Caribbean forearc at this time.

**Figure 33** shows the result of the iterative process required to build a satisfactory palinspastic grid from these estimates. Note that the paleoshape of Trinidad is elongated substantially farther towards the northwest than on **Figure 30**. Again, although this may at first sight appear a rather extreme reconstruction of the paleoshape of Trinidad, it is simply the cumulative result of restoring a large number of relatively small strains such as thrusting, extension and generally conservative dextral strike-slip offset estimates.

The key features of this restoration (**Fig. 33**) are:

- Cretaceous shelfal rocks all restore to the southwest side of the estimated Early Cretaceous shelf edge (projected from Guyana-Suriname, parallel to, but inboard of, the Guyana Transform continent-ocean boundary).

- Cretaceous shelf rocks in the footwall of the Central Range and deep beneath the thrust sheets at Angostura define a minimum position of a northwest-facing Cretaceous shelf-slope break and the Angostura area restores into the axis of a newly-defined “Central Trinidad Trough” (CRT), indicating about 80-100 km of southeastward thrusting of the Angostura between 25 Ma and 12 Ma, consistent with the estimates above.

- The SW flank of the CRT is defined by the Bohordal escarpment, which limits the Serranía Oriental Cretaceous shelf, and its NW flank is defined by the Proto-Caribbean Ridge and the Proto-Caribbean Trench.

- The northern edge of the Caroni Basin (Piarco area) is restored to the south side of the Proto-Caribbean Ridge, but no rocks of this age are preserved in this area. The Cuche of the Caroni Basin may underlie a significant thrust detachment and may belong farther southeast on a Cretaceous palinspastic reconstruction, close to the southeastern edge of the trough.

- The Northern Range is restored about 120 km to the northwest of its 12 Ma position. The 40 km excess relative to the Central Trinidad Trough is probably accounted for by internal Northern Range strain and by overthrusting onto rocks of the Central Range Trend. The Northern Range is thus shown immediately ahead of the Caribbean forearc (Tobago Terrane) at this time.

- Similarly, the Araya-Paria Terrane is restored to the northwest and rotated slightly counterclockwise to match total shortening estimates (at least 80 km) in the Serranía Oriental (**Roure et al.**, 1993; 2003).

**Paleogene Caribbean-South America interactions**

Looking back to the pre-Late Oligocene, the pre-orogenic stage of **Figure 19B** is applicable to the Eocene Eastern Venezuela and Trinidad, while the syn-collisional stage of **Figure 19C** is applicable to the Eocene of Central Venezuela (Caribbean Mountains and the Guarico Basin). And concerning western Venezuela, establishment of the Proto-Caribbean subduction zone likely provided additional first order controls.
Figure 33. 25 Ma palinspastic reconstruction, showing the geometry of the orogen before Early and Middle Miocene deformation. Note that the distortion in the shape of Trinidad indicates that apparent N-S facies changes in present-day geographic coordinates are in fact NW-SE facies changes along, not across, the margin. One important effect of the distortion is to place the northern depocenter (Central Trinidad Trough) adjacent to the Serranía Oriental, such that Paleogene sands can be derived from the west or southwest without crossing Southern Trinidad, where carbonates prevailed, and large Early Cretaceous clasts (such as in the Plaisance conglomerate) can derive from the NE-facing Bohordal slope, or the north-facing Central Range slope through incision of bypass surfaces with little Late Cretaceous or Paleogene cover. The map hints strongly at a point source for sediment from what we refer to as the “Espino-Maturín River” and that the sediment source and paleoflow orientation may in fact be orthogonal to the apparent fining direction across Trinidad.
on deposition there as well, but these will be harder to identify because the effects of Caribbean-South America collision are more coeval with those of initial Proto-Caribbean hanging wall uplift, and the two may have mutually interfered in as yet unclear ways. However, it is tempting to speculate such things as the intra-Paleocene top Guasare-base Misoa unconformity (Zambrano et al., 1971) representing the hanging wall uplift stage, and the down-dip continuation of the Misoa depositional system being at least partly if not entirely to the ENE along the coeval Guarico Trough (in which the Guarico Formation was deposited), between the Shield to the south and the “Caracas Group Prism high” to the north.

Concerning the syn-collisional stage of Figure 19C, our Miocene discussion above allows us to generalise the Caribbean-South America collision as encapsulating the following steps at any given location east of the Uricula Fault:

- The Caribbean Prism overthrust the Proto-Caribbean Prism. In Venezuela, the Caribbean Prism is represented by the Manicuare and Copey Formations and Gulf of Barcelona volcanics. In Trinidad, we believe it is represented by the ?Toco and ?Galera Formations and the Sans Souci volcanics of the Northern Range. In Barbados, we believe it comprises the Oceanic Complex and the northerly parts of the Basal Complex. The Proto-Caribbean Prism is represented by the Guinimita, Carupano, and Tunapui Formations of Araya-Paria, the Maraval, Maracas, Chancellor, and Rio Seco of the Northern Range, and much, but not all, of the “Basal Complex” (Speed, 2002) of Barbados.

- When the Caribbean crystalline forearc reached the overthrust Proto-Caribbean prism, the forearc did not also overthrust the Proto-Caribbean prism (being too rigid and dense) but rather wedged under or into it, thus driving a wedge of Proto-Caribbean prism and overlying Caribbean prism onto the Caribbean forearc basement. SE-vergent thrusting on the SE flank of the Proto-Caribbean prism began as a result, carrying both prisms onto the South American shelf/autochthon and leading to imbrication thereof.

- When the Caribbean forearc basement encountered South American basement, the former overthrust the latter, causing wedges of Caribbean forearc to be emplaced above South American basement but beneath the Proto-Caribbean prism and, in the Serranía del Interior at least, beneath outer shelf strata as well (see Passalacqua et al., 1995 for evidence of a deep, dense wedge of Caribbean lithology south of El Pilar Fault and beneath the Barranquín Formation of the NW Serranía Oriental). In addition, large wedges or former Jurassic rift blocks of outer South American basement were likely imbricated subjacent to the obducted Caribbean forearc bodies, thereby elevating the outer portions of the margin relative to inner ones. For example, the Lower Cretaceous carbonates and evaporites of the northern Gulf of Paria Basin likely overlie southwardly emplaced continental basement (thin skinned but basement involved), thrust ahead of a blind wedge of Caribbean forearc beneath the Araya-Northern Range Terrane. The Gulf of Paria Cretaceous is far shallower, structurally, than the autochthonous Cretaceous of Southern Trinidad, and a tectonic elevation of it is required.
West of the Urica Fault, the equivalent rock units to those noted in step (1) above are: the Villa de Cura Complex and the Early Eocene Garrapata and Middle Eocene Los Cajones Formations of central Venezuela (Caribbean Prism and syn-collisional detritus); much of the Caracas Group, *i.e.*, the meta-sedimentary Las Brisas, Mercedes, and other sections that were once part of the Mesozoic passive margin sequence along northern Venezuela (Proto-Caribbean Prism). In addition, the margin west of the Urica Fault has a fundamental difference to that to the east, namely that Caribbean lithosphere presently underthrusts (is subducted beneath) South American basement (*Figs. 15B,D,F*). That is, west of the Urica Fault, there was a fourth step in the marginal evolution during collision with the Caribbean. The backthrusting seen within the Caribbean lithosphere at the South Caribbean foldbelt and Bonaire Basin is tied into this subduction process; the upper level of the lithosphere (including the Aruba-Orchila Ridge) is imbricated above the lower Caribbean lithosphere, and it is the lower lithosphere only which underthrusts South America as a result. This last stage of shortening was necessary in the west (extending from Orchila to southern Panama) in order to allow the Caribbean collision to progress to closure by 10 Ma in Eastern Venezuela and Trinidad. Many hundreds of km of Caribbean lithosphere stripped of its upper level now underlies NW South America (Van der Hilst and Mann, 1994; *Fig. 15D*), and the upper level is accreted into the San Jacinto and Sinú foldbelts of Colombia and the South Caribbean Foldbelt north of the Aruba-Bonaire-Curacao (or ABC) islands. This stage of development has not occurred east of the Urica Fault, where Caribbean lithosphere still overlies the South American basement, thereby driving load subsidence manifested as the greater East Venezuelan Basin. However, with the E-W Caribbean-South America motion since 10 Ma, the subducted slab is migrating eastward and progressively expanding the scissoring on the Urica Fault at the South American basement level (*Fig. 15F*).

Concerning paleogeography, the 25 Ma palinspastic reconstruction of *Figure 33* provides a robust framework for plotting 25 Ma paleogeographic and paleotectonic elements (*Fig. 34*). An important aspect of *Figure 34* is that although the foredeep axis was ENE in orientation, the foredeep fill was supplied primarily along-axis rather than north to south. Most of Trinidad was distal to the ensuing orogeny, either as supra-forebulge (Lower Cipero Formation) or outer foredeep basin (early, southerly Nariva), whereas Eastern Venezuela comprised the coarser, shallower, inner foredeep basin (Areo, Naricual *sensu stricto* Formations). East of the Urica Fault, the Gulf of Barcelona volcanics (Ysaccis, 1997), Manicuare schists and Copey metavolcanics comprise outer Caribbean forearc or basal Caribbean prism rocks thrust onto (and over) the rocks of the Araya Peninsula, which were reaching peak metamorphism at about this time. The main Caribbean forearc (*e.g.*, Patao, Tobago Terranes) did not thrust so high, and broke away from this outer forearc/prism wedge and started to underthrust, uplift and cool the Araya-Paria-Northern Range Terrane, driving deeper-rooted southeastward thrusting in the northern Serranía Oriental.

In Central Venezuela, the Caribbean subduction complex (Villa de Cura HPLT rocks, Tiara volcanics) had overthrust the Proto-Caribbean Prism (Caracas Group) and outer margin, thereby driving the low-angle emplacement of the Garrapata-Los Cajones belt syn-collisional detritus, and subjacent imbrication of the Guarico fold-thrust belt immediately to the south (note: we do not recognise the Garrapata and Los Cajones units...
Figure 34. Palinspastic paleogeographic map for 25 Ma, Late Oligocene, see text for discussion.
as members of the Guarico, as was originally mapped). Uplift of this belt diverted the axis of the Caribbean foredeep into the Serranía Oriental and shut off coarse Eocene clastic sedimentation previously supplied to the Barbados area to the north (see below). Axially-fed sands with a characteristic high-pressure metamorphic heavy mineral signature appear for the first time in the Upper Roblecito, Carapita and Nariva Formations of the foredeep basin. In the Central Range Trend, the mineralogically immature Nariva overlies mature, 2+ Ga zircon-bearing sandstones of the Angostura Formation which almost certainly derived from South America (Meyers, 2007 Geological Society of Trinidad and Tobago conference). In what is now Central Trinidad, the Nariva appears to be shelfal or perhaps uppermost slope (based on lithofacies); the Nariva basin was shallowest toward the northwest (adjacent to the orogen and toward Venezuela), and deepened from west to east. It appears that the Caribbean forebulge was situated in southern Trinidad at this time, and that forebulge passage and advance of the foredeep is indicated by the Silty Cipero burying a widespread latest Eocene or earliest Oligocene erosional unconformity over much of the western Southern Basin south of the Point Radix Fault. Southern Trinidad lay sufficiently southeast of the point source of clastics in the axis of the Caribbean foredeep that Nariva-aged facies are typically marly (i.e., Lower Cipero Formation) with clean-water planktic rather than turbid-water benthic foraminifera. True Nariva facies are largely restricted to the Central Trinidad Trough and may have onlapped southward up the former slope, almost but not quite reaching the Eocene-Early Oligocene shelf-slope break, allowing Cipero Marls to be deposited in upper slope to outer shelf water depths in southern Trinidad. Early and Middle Miocene thrusting emplaced the Nariva southeastward over the former Cretaceous shelf edge ahead of slices of Cretaceous rocks derived from the northern or central portions of the Central Range Trend.

Most, if not all, of the tectonic deformation driven by the Caribbean Plate prior to 25 Ma was located northwest of the Serranía Oriental and Central Trinidad Trough, and thus we use the same basic palinspastic latitude-longitude grid to plot our older paleogeographic maps of the region. Figure 35 shows the paleogeography at 31 Ma (Early Oligocene), and Figure 36 at 42 Ma (Middle Eocene), with the Caribbean Plate shown progressively farther west back in time. At 42 Ma, the Proto-Caribbean Trench and associated basement ridge and Proto-Caribbean accretionary prism of Central Venezuela had not yet been overridden by the Caribbean Prism/Plate anywhere east of Golfo de Triste.

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Figure 35. Palinspastic paleogeographic map for 31 Ma, Early Oligocene, capturing the end of sedimentation in the Central Trinidad Trough and the onset of sedimentation at the leading edge of the SE-migrating Caribbean foredeep in the Serranía. Leading up to this time, a significant area of subaerial exposure had developed in the NE Serranía and sediment eroded from this surface was deposited directly over the Bohordal shelf edge into the Central Trinidad Trough, or transported via tributaries of our proposed Espino-Maturín River and discharged into the Trough at a point source upstream of the restored position of the Plaisance Conglomerate. The onset of Caribbean foredeep subsidence drowned this non-angular unconformity beneath the Los Jabillos sandstone, which youngs from possible latest Eocene (but probably Early Oligocene) in the NW Serranía to Late Oligocene or Early Miocene (where it should be called “Merecure” unit) in the El Furrial area. South of its onlap edge there must have been a subtle flexural forebulge which helped to constrain the drainage products of the Espino-Maturín River to the foredeep. The Plaisance conglomerate and Angostura sandstones, which were abruptly buried by shales, represent the culmination of the Espino-Maturín drainage and the uplift of its drainage basin on the crest of the forebulge. The ensuing shaley sedimentation is the eastern distal and entirely submarine equivalent to the onlap seen in the Serranía.
Figure 36. Palinspastic paleogeographic map for 42 Ma, Middle Eocene, showing the depositional context for the mineralogically sub-mature Early and Middle Eocene Scotland sands of Barbados. At least the Chalky Mount and Bissex Hill sections of the Scotland sands were likely deposited in the Proto-Caribbean accretionary prism, but the finer grained sections (Walker’s, Morgan Lewis members) may have been originally situated on the Proto-Caribbean basin plain somewhat to the WNW, both about 600-700 km downstream of the onshore end of the Caribbean foredeep axis (Pindell and Frampton, 2007). We postulate that the coarser Scotland conglomerate fractions containing Upper Cretaceous mudstones and carbonates may derive from the Proto-Caribbean hanging wall or prism, shed northward to merge with the trench-axis sandstone fairway. It is possible that closer to the Caribbean foredeep axis, the Proto-Caribbean Trench axis was overfilled such that a sediment-confining trench morphology was limited and easily bypassed. Transport of fine-grained, glaucophane-bearing clastic sediment over these distances is proven by the sands drilled on the Tiburón Rise, located even farther to the NE than our proposed location for the Scotland sands. The map also shows the interpreted setting for the Pointe-a-Pierre (sensu lato, age may be a little older) sandstones in Trinidad. We infer that the role of the Proto-Caribbean Ridge was only to act as a bathymetric barrier between the immature Proto-Caribbean (i.e. Scotland) and mature Central Trinidadian (i.e. Chaudière, Pointe-a-Pierre, Charuma) clastic domains. We infer a southwestern sediment source for the mature Pointe-a-Pierre continental sandstones, possibly from a river which passed through the Quiriquire area, where the “Caratas Formation” is virtually identical in subsurface. Every characteristic of these sands, including heavy mineral content, points to a mature, shelf-stored, recycled or shield sediment source; nothing supports a northern origin. Objections to a cratonic source due to the occurrence of rare staurolite grains in Pointe-a-Pierre sands are entirely unfounded, as staurolite does occur in distributary systems on South America. Note that the finer grained facies of southern Trinidad are inferred to have been deposited in slightly shallower conditions, sheltered from the point sediment source feeding the Central Trinidad Trough. As such, the apparent north to south fining is interpreted as a lateral, not down-dip, fining.
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