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Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved

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ABSTRACT

Eight points of recurring controversy regarding the primary foundations of models of Gulf of Mexico and Caribbean tectonic evolution are identified and examined. The eight points are controversial mainly because of the disconnect between different scales of thinking by different workers, a common but unfortunate problem in the geological profession. Large-scale thinkers often are unaware of local geological detail, and local-scale workers fail to appreciate the level of evolutionary precision and constraint provided by regional tectonics and plate kinematics. The eight controversies are: (1) the degree of freedom in the Gulf-Caribbean kinematic framework that is allowed by Atlantic opening parameters; (2) the existence of a South Bahamas-Guyana Transform, and the role of this structure in Cuban, Bahamian, Trinidadian, and Guyanese evolution; (3) the anticlockwise rotation of the Yucatán Block during the opening of the Gulf of Mexico; (4) the Pacific origin of the Caribbean oceanic crust; (5) the Aptian age and plate boundary geometry of the onset of west-dipping subduction of Proto-Caribbean beneath Caribbean lithospheres; (6) the origin and causal mechanism of the Caribbean Large Igneous Province…not Galapagos!; (7) the number and origin of magmatic arcs in the northern Caribbean; and (8) the origin of Paleogene "flysch" deposits along northern South America: the Proto-Caribbean subduction zone. Here we show that there are viable marriages between the larger and finer scale data sets that define working and testable elements of the region's evolution. In our opinion, these marriages are geologically accurate and suggest that they should form discrete elements that can and be integrated into regional models of Gulf and Caribbean evolution. We also call upon different facets of the geological community to collaborate and integrate diverse data sets more openly, in the hopes of improving general understanding and limiting the publication of unnecessary papers which only serve to spread geological uncertainty.

KEYWORDS **Gulf of Mexico. Caribbean. Tectonic evolution. Proto-Caribbean. Pacific origin.**

INTRODUCTION

In recent years, the geological community has seen the re-emergence of some former controversies regarding the evolution of the Gulf of Mexico-Caribbean region. In part this reflects a change in academic research emphasis, with a reduction in the recognition of the importance of robust regional plate tectonic reconstructions and the degree of accuracy that these reconstructions have, and thus the constraints they can place on evolutionary models at the sub-regional and local scales in the Caribbean. From the 1970s to the early 1990s many of these controversial issues had been largely sorted out. The situation may also partly reflect the involvement of new or younger workers who were not actively involved in much of the older work, for whom there is a tendency to “start again” with regional models rather than to acknowledge and assimilate the vast wealth of historical progress. In this paper, we identify eight of these controversies, outline local data and regional analyses to show that viable marriages of the two scales can in fact be made, and suggest that the integrated solutions to the controversies comprise essential elements of any regional evolutionary synthesis of the Caribbean region.

CONTROVERSY 1, PRECISION LEVELS OF ATLANTIC RECONSTRUCTIONS AND THE GULF/CARIBBEAN FRAMEWORK

Marine magnetic anomalies (shiptrack data) and fracture zone traces (Seasat and Geosat altimetry data), have now been mapped in the Central, Equatorial, and South Atlantic oceans to a level of detail that allows reconstruction of the relative paleopositions of the circum-Atlantic continents to accuracies of better than 50 km error for most anomalies (Klitgord and Schouten, 1986; Pindell et al., 1988; Müller et al., 1997, 1999). This, combined with ever-improving accuracies of the ages of the magnetic anomalies (Gradstein and Ogg, 1996; Gradstein et al., 2005), allows very little freedom for proposing changes to the geometric framework that the Atlantic opening history provides on Gulf of Mexico and Caribbean evolution. Figure 1 shows an updated relative motion history for North and South America derived from finite difference solutions of the three-plate circuit North America-Africa-South America (Ladd, 1976; Pindell et al., 1988) , along with estimated error bars (ellipses) for Triassic to Present.

For anomalies 34 and younger, the errors are small and due mainly to the 20 km or so width of fracture zones, within which we do not exactly know where the paleo-transform faults lie. Estimated error ellipses are somewhat larger for the pre-Aptian portion of the flowpath, because for pre-Aptian time the flowpath is dependent upon the less accurate Aptian and older continental reconstruction employed for the Equatorial Atlantic. However, recent satellite altimetry (and resulting gravity anomaly maps) data provide sufficiently accurate definition of Equatorial Atlantic fracture zones and their intersections with the South American and African margins that we can now reconstruct the syn-rift configuration of that oceanic tract with greater accuracy (~50 km freedom) than we could previously. Figure 2 shows two stages of this reconstruction which: (1) bring opposing continental crusts together along the flow lines indicated by fracture zones, (2) require the independent rotation of the Sao Luis block to close the Marajó Basin and to avoid continental overlap along the middle portion of the reconstruction (following Pindell, 1985a); (3) realign the Guinea and Demerara plateaux which together had formed the southeastern part of the Middle Jurassic-Aptian Central Atlantic continental margin prior to Equatorial Atlantic break-up; and (4) accord with the Early Aptian as the time of initial Equatorial Atlantic rifting as confidently indicated by the fills of the Equatorial Atlantic rift basins and margins (Ojeda, 1982; Marqués de Almeida et al., 1996; Mascle et al., 1995). The pre-rift Equatorial Atlantic reconstruction of Fig. 2B and others like it (Pindell, 1985a) are far tighter than the classic reconstruction of Bullard et al. (1965), thereby requiring the existence of two or more plates in Early Cretaceous Africa (Dewey and Burke, 1974; Pindell and Dewey, 1982).

Regarding the Gulf of Mexico/Caribbean region, Fig. 2B defines an assembly of northern Africa and northern South America that in turn can be progressively reconstructed with North America by closing Early Cretaceous–Jurassic portions of the Central Atlantic spreading fabric. This is how we must define the pre-Aptian relative positions of North and South America (Ladd, 1976); in order to do this we are forced to accept the assumption that no significant motions occurred along the reconstructed Equatorial Atlantic rifted margins prior to the time represented by our Fig. 2B reconstruction. But how valid is this assumption, and what error limits can be placed on it?

Pre-Aptian ages on basalts from the Equatorial Atlantic margins have been reported from K-Ar age dating efforts (Mizusaki et al., 2002; Ojeda, 1982), suggesting the possibility of some “creaking and groaning”, particularly in and south of the “Amazon Rift”, prior to eventual Aptian breakup. Judging from reconstructions of Pangea that adhere kinematically to Atlantic closure flowlines (Pindell and Kennan, 2001a), such early motions (which we presume if they happened at all would have been extensional along both the future Equatorial rift and transform trends) would affect the initial relationship between North and South America mainly in an ENE-

WSW direction. To our knowledge there is no record of pre-Aptian marine deposition along the Equatorial Atlantic margins south of the reconstructed composite Demerara-Guinea Plateau, indicating to us that such possible early motions were relatively minor. If pre-Aptian extensional movement between these two margins was as much as, say, 30 km, then the total effect on the Pangean reconstruction in the Gulf of Mexico area after closure would be to shift northern South America about 50 km to the ENE relative to North America. This potential adjustment is far too small to allow for any significant difference in the initial relationships between crustal blocks in the Gulf of Mexico/Yucatán/Bahamas area, but it might lead to slightly different local structural models for certain rift zones and to small adjustments in the amount of syn-rift stretching or block rotation. If this degree of minor intra-plate deformation did occur in the Equatorial Atlantic, there is no way other than to date every extrusive basalt along the margin to ascertain if the 30-50 km shift in the reconstruction occurred throughout Late Jurassic-Neocomian time, or if it occurred as a more discrete episode at some point within that timespan, such as

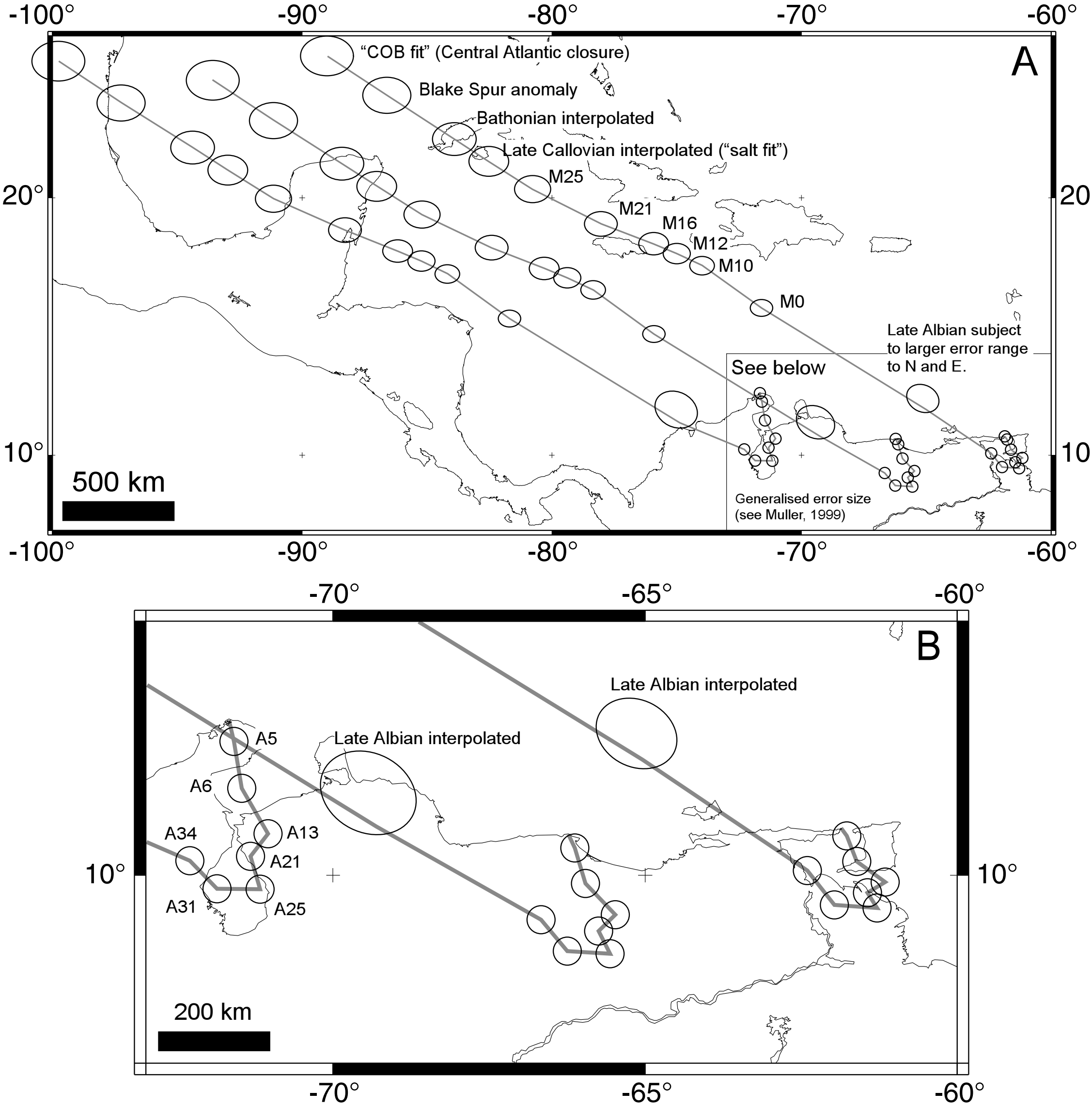

FIGURE 1 | **Relative motion history for North and South America from initial opening of the Central Atlantic Ocean through to the present. The lower map shows an enlargement for Late Cretaceous to the present. Sources include Pindell et al. (1988), Müller et al. (1999) and minor revisions (Tectonic Analysis Ltd., unpublished calculations) to the Aptian-Albian fit between Africa and South America. Estimated error ellipses are semi-schematic and show the general range of variation between various plate-kinematic models published over the last 20 years. Error ellipses for the Late Cretaceous through recent schematically represent the error ranges calculated by Müller et al. (1999). The error ellipse for Late Albian time (100 Ma) is larger and skewed to the northeast, reflecting uncertainties in the early opening history of the Equatorial Atlantic. This figure and others below were prepared with the aid of the Generic Mapping Tools package (Wessel and Smith, 1991).**

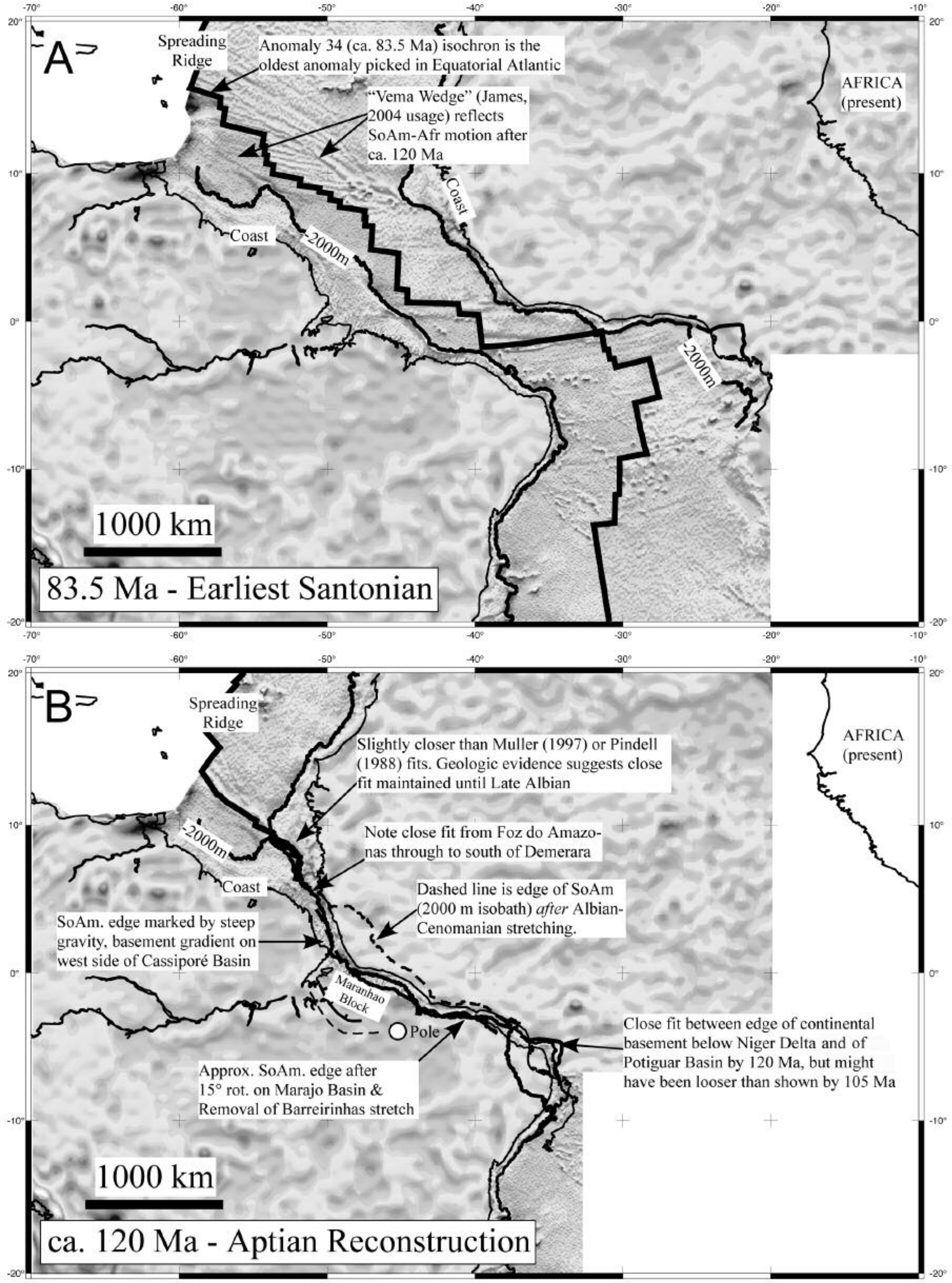

FIGURE 2 | **A) 83.5 Ma Campanian reconstruction has restored Africa relative to a fixed South America, using flowlines and magnetic anomalies in the Equatorial Atlantic. No older magnetic anomalies are identified in the region, indicating that initial opening occurred at or after earliest Aptian time. B) A ca. 120 Ma Aptian reconstruction closes the Equatorial Atlantic, initially following flowlines defined by pre-Campanian fracture zones,and finally matching South American continental edges between Demerara and Potiguar and African continental edges between Guinea and the Niger Delta. Geologic evidence points to a diachronous opening history after the time represented on this map, with rifting and separation starting in the south in the early Aptian propagating northward and reaching the Demerara-Guinea area by about middle Albian time. The rotation pole parameters for the Equatorial Atlantic fit are Longitude: 325.22, Latitude: 51.79, Age: 120.4 Ma, Angle: 51.68.**

just prior to Aptian breakup. Hence, we are forced to accept a 50 km or so error limit in the pre-Aptian relative paleopositions of North and South America (Fig. 1).

Concerning the age of initial significant rifting in the Equatorial Atlantic margins, the stratigraphy of the marginal basins suggests Early Aptian rifting (red beds) followed by Late Aptian marine inundation. However, if rifting was either greatly protracted or essentially instantaneous, then this estimate may be in error by a few million years, leaving a possible range from Barremian to "middle" Aptian. This age range does not affect pre-Barremian circum-Atlantic reconstructions, nor does it affect the flowpaths of North and South America. However, it could affect the amount of separation between South America and northern Africa along those flow lines for the Barremian-Santonian period, by perhaps a few tens of km. Again, this degree of freedom is far too small to allow for significantly different viewpoints in the origin of large blocks and plates in the overall Gulf of Mexico/Caribbean system.

A related, and more significant, aspect of Equatorial Atlantic opening history is the rate at which it opened during the Mid-Cretaceous Quiet Period (time between anomalies M0-34; 119-84 Ma). Although we can define the flow path (azimuth) very well between these two continents for this interval, the rate of opening during the interval may have been (1) linear (Pindell et al., 1988), (2) slower early on and faster later on, (3) faster early on and slower later on, or (4) more variable throughout, with pulses and lulls. A slower rate of Equatorial Atlantic opening early on would have created a larger marine gap within the Proto-Caribbean Seaway earlier, as the slower Equatorial rate would have to be accompanied by a faster opening rate in the Proto-Caribbean. This option was employed to a maximum by Pindell (1993), in which the Late Albian North-South America reconstruction is nearly the same as the anomaly 34 reconstruction in order to maximize the Proto-Caribbean gap prior to the relative eastward migration of the Caribbean Plate from the Pacific. Similarly, a more rapid initial rate of Equatorial Atlantic opening, but with a later time of onset of opening (suggested by data from ODP Leg 207, Erbacher et al., 2004) has the same result. However, the maximum employment of this option (Pindell, 1993) is probably incorrect, because models of Late Cretaceous tectonic interactions between the Great Caribbean Arc and North America and South America, respectively, are most compelling within a framework of continued divergence between the Americas until the Early Campanian (Pindell and Kennan, 2001; Controversy 5, below). Given that we must adhere to Atlantic flow lines defined by fracture zone trends, the Late Albian (~100 Ma) position between North and South America could have been about 300 km different (allowing in turn a Proto-Caribbean that is 300 km wider in the NW-SE direction) than a Late Albian reconstruction that assumes (1) linear spreading rates in the Equatorial and Central Atlantic during the Cretaceous Quiet Period, and (2) an Early Aptian onset of spreading in the Equatorial Atlantic. If continents take time to accelerate during rifting (on the order of 10 m.y.?), then such a kinematic model for the Equatorial Atlantic (and thus the Proto-Caribbean) is perhaps warranted.

In summary, the freedom for each magnetic anomaly's reconstruction, even those during the Cretaceous Quiet Period, is sufficiently small that significant changes to the regional kinematic framework (flowpath shown in Fig. 1) cannot be made without violating mapped oceanic spreading fabrics or currently accepted models of Equatorial Atlantic continental break-up.

CONTROVERSY 2, THE SOUTH BAHAMAS-GUYANA TRANSFORM MARGINAL OFFSET: TEMPLATE FOR ASPECTS OF TRINIDADIAN AND CUBAN EVOLUTION

An important derivative of the Atlantic opening history is that the southwestern limit of thinned continental crust beneath the Grand Banks portion of the Bahamas (Ladd and Sheridan, 1987), but not the southeastern Bahamas (Uchhupi et al., 1971), must form the conjugate [transform] marginal offset to the northeast limit of the continental crust along the Guyana margin, and vice-versa (Fig. 3). Further, Fig. 3 indicates that this marginal offset limiting the Bahamian continental crust should be situated now beneath the allochthonous arc-related rocks of Cuba, approximately along central Cuba's southwestern offshore shelf. Such a position is supported by sharp gravity and bathymetric gradients, which may pertain to more than just the boundary between the Yucatán [intra-arc] Basin (Rosencrantz, 1990) and the Cuban allochthonous terranes. The allochthonous terranes were emplaced in the Paleogene, and comprise the parallochthonous belts of the Remedios and Camajuani zones, the accretionary Placetas Zone, and the allochthonous northern ophiolites (suture zone) and the obducted arc and subduction zone-related complexes (i.e., Escambray, Mabujina, Cretaceous arc volcanics) of central Cuba between Havana and the Cauto Basin. In the Jurassic, the Bahamian continental crust including that now beneath Cuba filled the space to the northeast of the Guyana Escarpment and to the northwest of the reconstructed Guinea-Demerara Plateau of the Equatorial Atlantic (Pindell, 1985a). The position of the boundary between rifted continental crust and oceanic volcanic crust at the foot of the Guyana Escarpment is well-constrained (unpublished oil industry seismic and gravity data; Boettcher et al., 2003), and hence we can use the Atlantic kinematics to infer the approximate position of the Bahamian marginal offset, within the error limits of Fig. 1, even though it is now hidden beneath the Cuban thrust belt. Concerning the southeastern Bahamas (i.e., Caicos, Inagua and eastwards), gravity, seismic reflection, and seismic refraction data suggest that the basement is of probable oceanic or hot-spot origin, formed in relation to Atlantic seafloor spreading, such that this crust need not fit into Jurassic continental reconstructions. We suspect that the Oriente Province of Cuba, southeast of Cauto Basin, does not have Bahamian continental crust beneath it, and possesses a more typical arc-type crust. However, the metamorphosed carbonates beneath the Purial volcanic complex of Oriente (Iturralde-Vinent, 1994, this volume) may suggest that at least atolls or other shallow carbonate banks existed in the Proto-Caribbean Seaway as the Cuban arc approached the Bahamas.

Two important points can be drawn from Fig. 3. The first is that the allochthonous Cuban forearc/prism thrust imbricates have been obducted onto the southern edge of the Great Bahamas Bank by 150-200 km. This overthrusting is only the last increment (Eocene age) of a much larger demonstrable shortening in excess of 450 km (Hempton and Barros, 1993). The second point is that the Darien Ridge in the Trinidadian eastern offshore, which bears Cretaceous-Middle Miocene shelf strata in the subsurface (Boettcher et al., 2003), must have migrated eastward across the NW projection of the Guyana Escarpment marginal offset during Late Miocene and younger dextral strike-slip motion along the Point Radix-Darien and Central Range fault trends (Pindell and Kennan, 2001b). This Late Miocene-Recent eastward migration must closely match the amount and timing of E-W extension in the Gulf of Paria low-angle detachment basin to the west, and exceeds 80 km. This type of "lateral obduction" of a terrane from one basement to another along strike has only rarely been recognized in thrust belts of the world, because only rarely is the strike-slip component of motion measurable in thrust belts.

Figure 3 has further implications for the Yucatán-South America reconstruction. The existence of a "Trinidad re-entrant" along the northern South American margin of the Proto-Caribbean Seaway has been considered for some time (Pindell and Erikson, 1994; Pindell et al., 1998). Such a re-entrant should have a corresponding salient or promontory of thinned continental crust on the northwestern side of the Proto-Caribbean Seaway, and more specifically along the northeastern flank of the Yucatán Block. The Isle of Youth sits in precisely that position in our reconstruction; although comprised at the surface of metamorphosed material belonging to the allochthonous Cuban thrustbelt, the Isle of Youth surface material may have been thrust in the Paleocene-Eocene onto a salient of thinned Yucatán continental basement

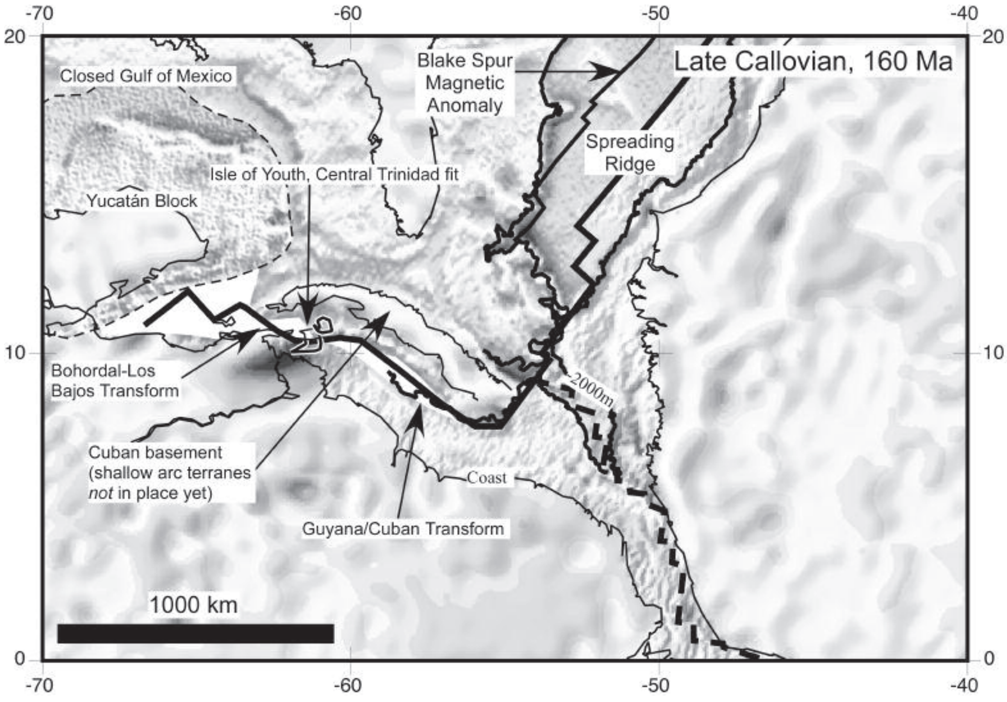

FIGURE 3 | **Reconstruction of North America, South America and Africa at approximately the time of last salt deposition in the Gulf of Mexico Basin ("salt fit"). This map rotates the gravity data for all three continents, and demonstrates the tight fit between the Western Bahamas and the Guyana Margin, the absence of the not-yet-formed Eastern Bahamas (avoids overlap with Demerara-Guinea) and the striking conjugate fit between an "Isle of Youth Promontory" and the "North Trinidad Embayment". The map also shows a clockwise rotation of Yucatán which is addressed further below.**

that is the counterpart to Trinidad's re-entrant. Figure 3 explicitly matches the gravity maps of North America and South America to demonstrate this possibility, namely that a deep continental salient supports the Isle of Youth's high structural position, and that this salient filled the Trinidad re-entrant during Middle Jurassic and earlier time.

CONTROVERSY 3, ANTI-CLOCKWISE ROTATION OF YUCATÁN DURING THE OPENING OF THE GULF OF MEXICO

Accepting the Atlantic closure assemblies (Figs. 2 and 3), the only viable origin for the Yucatán Block relative to North America in the reconstruction of western Pangea is in the position of the northern Gulf of Mexico, and rotated clockwise relative to the present by some 40° to 50°. This initial position places a first-order constraint on the evolution of the Gulf of Mexico, namely that anti-clockwise rotation was involved as Yucatán Block rotated away from the US Gulf Coast to its present position. That migration occurred in two stages; the first was Late Triassic-Oxfordian syn-rift continental extension during which about 10-15° of Yucatán's total rotation occurred about a pole east of North and South Carolina, followed by the Late Jurassic-Valanginian drift stage of oceanic spreading in the deep central Gulf about a southeastwardly migrating pole along the Florida Straits during which the remaining 30-35° of Yucatán's rotation occurred (Pindell and Dewey, 1982; Pindell, 1985a; Pindell and Kennan, 2001a).

In addition, the anti-clockwise rotation of Yucatán is also indicated by five further arguments:

1. Paleomagnetic studies in the Maya Mountains (Steiner et al., 2005) and the Chiapas Massif (Molina-Garza et al., 1992) portions of the Yucatán Block suggest anti-clockwise rotation of basement rocks on the order of 30° to 40° since the Triassic.

2. An Oxfordian reconstruction of North America and Yucatán at the end of continental stretching and the onset of seafloor spreading nicely realigns the rift fabric of the Georgia Embayment with gravity and magnetic trends that we interpret as basement rift structures in the northeastern Campeche Platform subsurface (Figs. 4A and 4B). These two sets of features are not parallel unless Yucatán is rotated by 30° to 40°. The rift structure shown onshore Yucatán Peninsula by the Exxon Tectonic Map of the World (1985), and which is claimed by James (2004) to align with the Georgia Embayment rifts and therefore to disprove Yucatán rotation, lies at a significant angle to what we believe is the true rift orientation beneath the Campeche Platform which lay closer to Florida than did onshore Yucatán Peninsula. Further, the onshore Yucatán rift structure of the Exxon map lies parallel to the rift fabric of onshore central Venezuela (Ostos et al., 2005) to which it lies closest, only when Yucatán has been rotated by some 30° (Fig. 4B). We consider that these latter two rifts relate more to the Proto-Caribbean rift zone than to the Gulf of Mexico rift zone.

3. The basement fabric in the deep, eastern, oceanic part of the Gulf of Mexico comprises a high-density extensional fault pattern (faults trending NW-SE, with SW-NE extensional direction) crossed sub-orthogonally by arcuate volcanic highs and troughs (Peel et al., 2001; Stephens, 2001). We have little doubt that this fabric is a typical seafloor spreading fabric, recording NE-SW rotational divergence between Yucatán and North America, with leaky transforms (the volcanic ridges) lying roughly concentrically around Yucatán's pole of rotation to the southeast (Fig. 4A). In addition, a central NW-SE trending trough with small lateral offsets exists within this fabric, which may in fact be the trace of the extinct spreading ridge, or "axial valley". A present-day analogue for this type of strongly rotational spreading (with a proximal pole of rotation) lies offshore southern Mexico, in the area referred to as the "Carolina Plate" (Klitgord and Mammerickx, 1982; Mammerickx and Klitgord, 1982) and renamed "Rivera Plate" (Bird, 2003).

4. It is becoming increasingly clear as gravity, magnetic, and seismic data improve and are progressively released (Fig. 5) that the very narrow, post-salt, Late Jurassic (as opposed to Middle Jurassic) eastern Mexican margin (Tuxpan-Veracruz margin) is a fracture zone margin along which Yucatán/Chiapas Massif and the central Gulf of Mexico spreading center migrated southwards (Pindell, 1985a; Martön and Buffler, 1994; Pindell and Kennan, 2001a; Miranda et al., 2003). This margin is a "Stage 2" structure of Pindell and Kennan (2001a) that developed within the earlier stretched crust (NW-SE directed low angle detachment faulting of "Stage 1") between Yucatán and Northern Mexico.

5. Accepting the eastern Mexican margin (Tuxpan-Veracruz) as roughly parallel to the azimuth of Yucatán-North America paleo-motion, regional cross sections (Miranda et al., 2003) show that a greater total amount of total N-S displacement has occurred in the western Gulf (~1100 km) than in the eastern Gulf (600 km), which is explained and required by the rotation of the Yucatán Block relative to North America.

The above five arguments support and collectively require the anti-clockwise rotation of Yucatán during the rotational opening of the Gulf of Mexico. Models for the Gulf that do not rotate Yucatán conflict with all six of these arguments while providing a unique explanation for none that we are aware of.

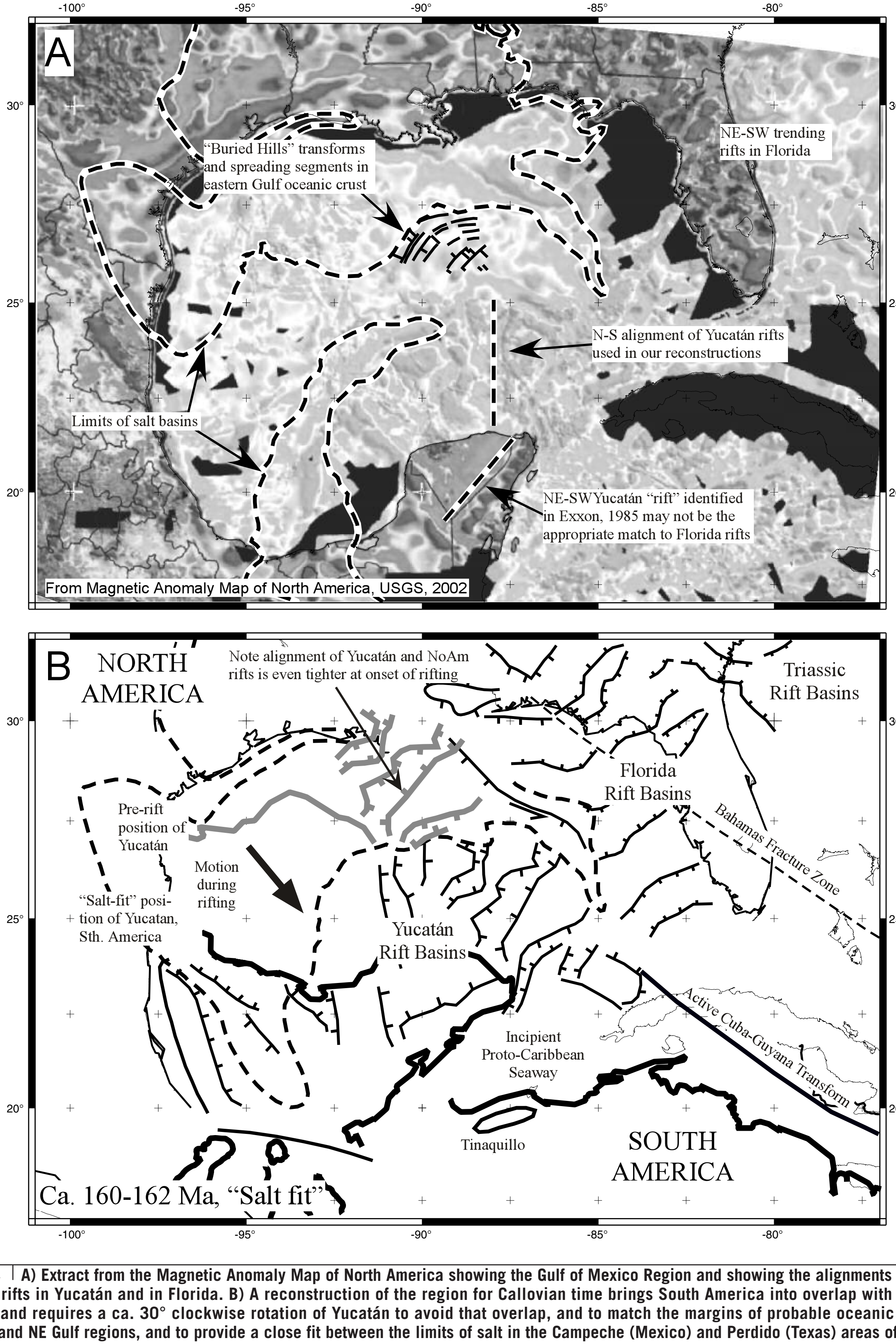

FIGURE 4 **A) Extract from the Magnetic Anomaly Map of North America showing the Gulf of Mexico Region and showing the alignments identified as Jurassic rifts in Yucatán and in Florida. B) A reconstruction of the region for Callovian time brings South America into overlap with present-day Yucatán and requires a ca. 30° clockwise rotation of Yucatán to avoid that overlap, and to match the margins of probable oceanic crust in the Yucatán and NE Gulf regions, and to provide a close fit between the limits of salt in the Campeche (Mexico) and Perdido (Texas) areas of the western Gulf. Note the excellent match between formerly N-S trending rifts in Yucatán and the NE-SW trending rifts of Florida. These initiated in the early Jurassic (position shown in grey) and ceased stretching with the onset of ocean crust formation in the Gulf of Mexico during the Oxfordian.**

CONTROVERSY 4, PACIFIC ORIGIN OF CARIBEAN OCEANIC CRUST

Pindell (1985b), Burke (1988), and Pindell and Barrett (1990) showed that the vast majority of Caribbean geology and basin histories can be explained by large relative displacement between the Americas and a single, long-lived west-dipping subduction zone anchored in the mantle with the Great Caribbean Arc behind it, calling on changes in arc style through time such as flattening of slabs, opening of backarc basins, axis-parallel extension, etc. to explain Caribbean geology at the sub-regional scale. Other models employ multiple and transient subduction zones and arcs, collisions, terminations of subduction, etc. to explain geology at the sub-regional level (Kerr et al., 1999), while still other models are highly fixist (James, 2004), both of which we believe are unrealistic and fraught with violations of basic geology and/or plate kinematic history.

Pindell's (1990, 1993) original six arguments for a Pacific origin of the Caribbean oceanic crust still stand firm. These are:

1. The Cayman Trough indicates at least 1100 km of east-west Caribbean-American displacement since the Eocene.

2. The apparently continuous Albian-Eocene period of Great Caribbean Arc magmatism, prior to the opening of Cayman Trough, indicates additional westward dipping subduction and therefore relative motion with the Americas back to the Albian, such that the total displacement is far greater than the 1100 km shown by the Cayman Trough.

3. The geometric impossibility of a pre-Aptian Caribbean Plate fitting between the Americas in Aptian time due to lack of space in the Atlantic opening history.

4. Lack of tuffs in the Cretaceous autochthonous sections of Yucatán, the Bahamas, and northern South America, requiring significant spatial separation between the Caribbean Cretaceous active arcs and the Proto-Caribbean passive margins during Cretaceous time.

5. The Paleocene-Eocene magmatic arcs of western Mexico (in Cordillera Occidental) and the Chortís block are offset by more than 1000 km, and the inception of the younger arc of southern Mexico has migrated eastward since the Oligocene, in keeping with the migration of the Chortís block as part of the Caribbean Plate along the southern boundary of the North American Plate for Cenozoic time.

6. The Late Cretaceous merging of Caribbean (Pacific) and Proto-Caribbean (Tethyan) faunal provinces as a function of the insertion of the Caribbean Plate between the Americas.

We may now augment these original arguments by additional arguments as a result of new data sets and better levels of regional geological understanding.

The first additional argument is provided by van der Hilst's (1990) seismic tomographic data (Fig. 6). In all the E-W tomographic profiles across the Lesser Antilles Subduction Zone, the Atlantic slab is clearly visible dipping west beneath the Caribbean lithosphere from the trench to at least, and possibly farther than, the Beata Ridge, representing a minimum of 1500 km of subduction

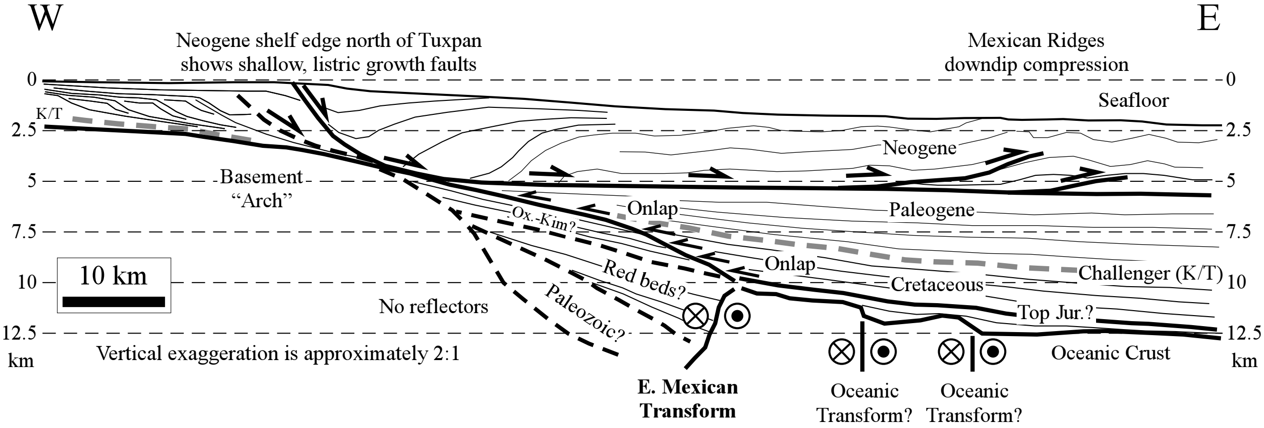

FIGURE 5 **Line drawing of an-E-W seismic line across the eastern Mexican (Tampico) margin (after Miranda et al., 2003). Note the narrow width of the margin, and how rapidly basement steps eastward down to oceanic basement in the Gulf. Heavy black lines are inferred positions of transform faults which became fracture zones once the central Gulf spreading center had passed by this portion of the margin. Our modeling suggests that the westernmost fracture zone is where most dextral transcurrent displacement took place. Most subsidence occurred after passage of the ridge (during the fracture zone stage), thus there is no strong disruption of beds above the basement fault zone. The oldest known marine sediment along this margin appears to be Oxfordian, in keeping with this margin being a "Stage 2" structure (oceanic spreading stage) of Pindell and Kennan (2001a).**

of Atlantic crust beneath the Caribbean Plate, and hence of east-west Caribbean-American displacement. The imaged subducted Atlantic slab could only have arrived in this position beneath the Caribbean Plate by westward (relative to the Caribbean) subduction at the Lesser Antilles Trench; it could not have arrived there by an alternative movement from north or south, because the surrounding continents were ever-present, as is well-documented from the Atlantic kinematic history (Fig. 1). The seismic tomography cannot be explained by any means other than by at least 1500 km of roughly west-east relative motion between the Caribbean and Atlantic lithospheres. This period of subduction is recorded largely by the Eocene to Recent volcanism of the Lesser Antilles Arc. Furthermore, roughly 1100 km of east-west relative motion is recorded by the Cenozoic Cayman Trough pull-apart basin (Pindell and Dewey, 1982; Mann and Burke, 1984; Rosencrantz et al., 1988), providing an alternative yardstick for much, but not all, of the motion indicated by the seismic tomography. This suggests that the very deepest levels of the slab seen in the tomography (400 km or more) were subducted before the Cayman Trough began to open, probably in the early Paleogene. We see no reason to suspect any break in Caribbean-American relative motion in the Eocene, as was once suggested by Pindell and Dewey (1982); in contrast, motion has probably been continuous with perhaps small variations in rate since the Aptian-Albian.

In addition, van der Hilst's tomography also demonstrates the existence of a large area of subducted Caribbean slab beneath Colombia (van der Hilst and Mann, 1994; also, the northeast edge of this slab is visible in line B of Fig. 6). This subducted slab underlies Colombia far too deeply to have arrived there by subduction from the north, because there has not been enough convergence between North and South American to account for this much subduction lithosphere (Fig. 1). Thus the slab must derive from the west, in which case the amount of Caribbean subduction beneath Colombia that is visible in tomography approaches 1000 km. This is yet another direct measurement of a minimum of 1000 km of east-west Caribbean-American displacement; the reason that this slab has only been subducted by 1000 km or so is that the subduction zone along western Colombia was only initiated in the Maastrichtian (Pindell, 1993).

A second new argument pertains to the dynamic behaviour of arc systems. Dewey (1980) classified arcs as compressional, neutral, or extensional depending on their tectonic style at any given time. Subduction rate has little effect on arc/hanging wall tectonic style; more important is the motion of the hanging wall relative to the trench position, which usually has a tendency to "roll back" away from the arc at very slow rates due to slab subsidence and negative buoyancy forces (typically <10 mm/yr). Disregarding arc-parallel strains in the following discussion, neutral arcs are those where the forearc hanging wall moves trenchward at approximately the roll back velocity (not the subduction velocity) of the downgoing plate, and thus there is no driver for extension or compression in the arc itself. Arc morphology and topographic development remains moderate, volcanism is fairly continuous and of intermediate chemistry, and intra- or back-arc extension and compression are minimal. In contrast, extensional arcs are those whose forearcs do not keep pace with trench roll back velocity, and the arc collapses gravitationally in order for the forearc to "maintain contact" with the downgoing slab, as in the Marianas system. This is achieved by extension in the intra-arc position, which when extreme becomes a back-arc position as extension leads to seafloor spreading between the active and remnant arcs. Morphology and topographic development is subdued and often submarine, and magmatic chemistry is often mafic. Compressional arcs are those whose forearcs migrate toward the trench and downgoing plate faster than the roll back velocity, such that the forearc is telescoped onto the upper part of the downgoing plate, thereby producing a flat slab subduction geometry, which in turn drives compression in and behind the arc (back-arc thrusting). These arcs often have explosive magmatic chemistries, high topography, large seismicity, basement rocks exposed at surface, back-arc thrust belts, strongly coupled Benioff Zones, and often flat subducting slabs, as in much of the Andean and North American Cordilleras. The reason that the Andean and North American Cordilleras have been compressional since at least the Aptian-Albian is that the American plates have been driven westward across the mantle reference frame faster than roll back of the Pacific and Nazca plates has been able to accommodate. This westward velocity is directly related to, but not uniquely caused by, seafloor spreading in the Atlantic: Africa moves much more slowly in the mantle reference frame than do the Americas; thus, as the Atlantic grows, the American arc systems behave compressionally.

Concerning the Caribbean, by all accounts the Lesser Antilles Arc has been essentially neutral since the Eocene opening of the Grenada intra-arc basin. As for the Costa Rican Arc, minor (<10 km) Quaternary intra-arc extension has occurred in the Lagos de Managua y Nicaragua Basin, and some backthrusting has developed locally at Limón Basin where the buoyant Cocos Ridge enters the trench, but on the whole this arc appears to have been more or less neutral back into Cretaceous time. The essential neutrality of these two arcs is important for assessing relative migration history of the Caribbean Plate: if the Caribbean crust were of intra-American (local) rather than of Pacific origin, and thus had not moved far relative to the Americas, then it, like the Americas, would have migrated westward across the mantle since the Cretaceous at nearly the same rate as the Americas. Thus, the Costa Rica Arc, like the North American and Andean cordilleras, would have behaved compressionally over this entire time. However, the fact that the Costa Rica Arc looks nothing like the Andes, and has not, in fact, behaved compressionally, indicates clearly that the Caribbean Plate has not moved westward over the mantle with the Americas. Because this arc has been neutral, large Caribbean-American displacement must have occurred. Seafloor spreading in the Atlantic

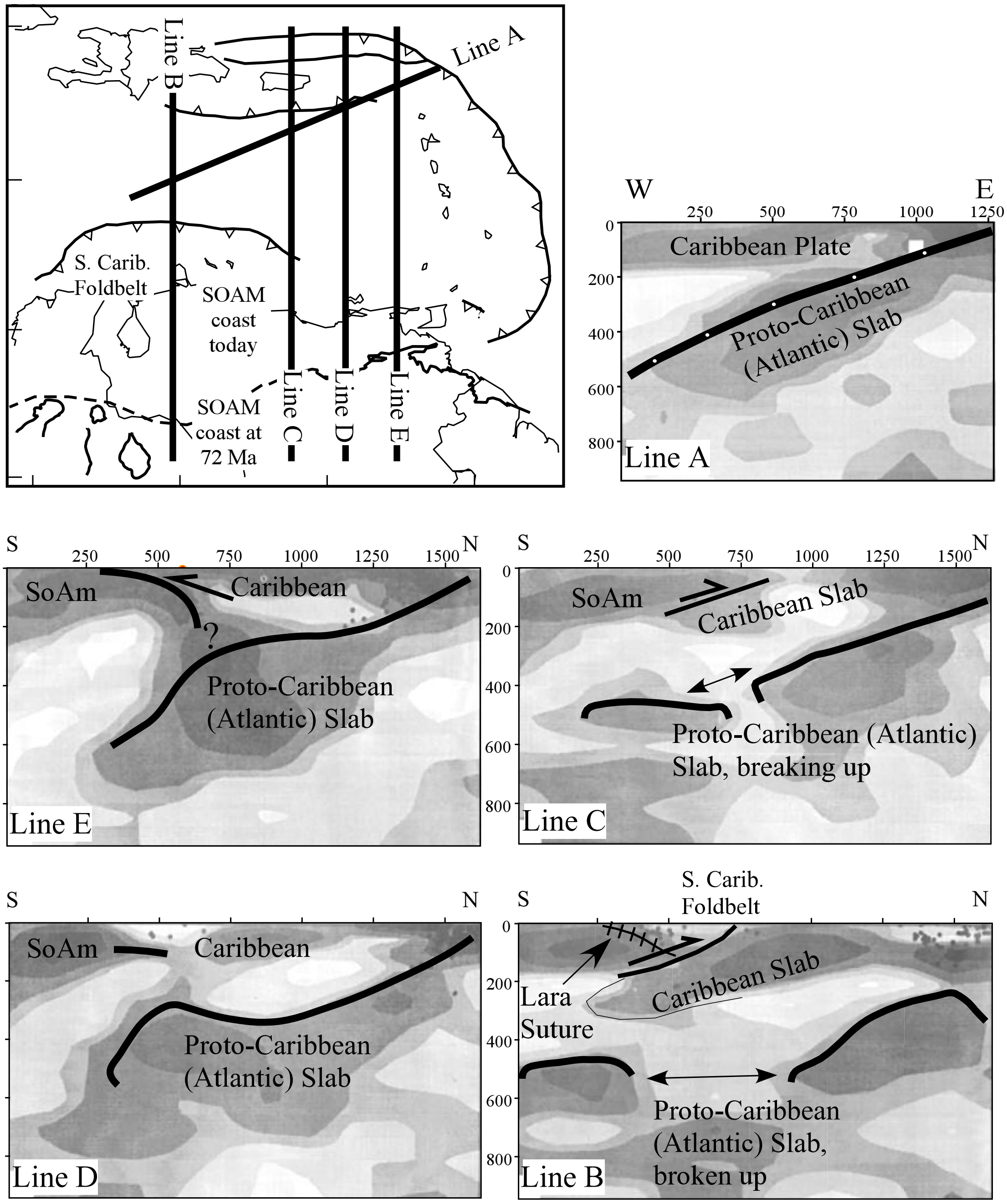

FIGURE 6 | **Location map and tomographic sections A, B, C, D, E (from van der Hilst, 1990, unpublished Ph.D thesis), and total post-72 Ma NA-SA convergence (blue v black in map; Pindell et al., 1988). Greater than 1500 km of Proto-Caribbean (Atlantic) crust has been consumed at Lesser Antilles trench (line A), Most NA-SA convergence was taken up at S-dipping Proto-Caribbean trench where Proto-Caribbean crust underthrust SA (see tomography), which was underway as the Caribbean Plate migrated from the west into each tomographic section. In addition, a westward-widening tear has developed in the subducted Proto-Caribbean slab (lines C, B), such that the slab beneath central and western Venezuela is no longer connected to the slab beneath the bulk of the Caribbean Plate.**

has been roughly matched by subduction at the Lesser Antilles, the proof of which is visible in the seismic tomography (Fig. 6, line A). Atlantic spreading rates have averaged about 2-3 cm/yr during the Cenozoic. If that is matched by Lesser Antillean subduction so that the Costa Rica Arc has remained essentially neutral, then Caribbean-American relative motion rate must also have been 2-3 cm/yr on average. This agrees well with Cayman Trough opening models (1100 km of opening since ~50 Ma). The Caribbean Plate thus sits roughly in the mantle reference frame as the Americas drift by to the west, as also shown independently by Müller et al. (1999). If this were not the case, then Costa Rica would look more like the basement-involved Andes thrust belt than the primarily volcanic chain that it is.

The third new argument for the Caribbean's Pacific origin is also a key argument for the Aptian onset of west-dipping subduction of Proto-Caribbean lithosphere beneath the Caribbean lithosphere (next section). The argument stems from age dating of high-pressure, low temperature (HP-LT) metamorphic suites and arc magmatic rocks in the Caribbean (Table 1 of Pindell et al., 2005, for a full review), and the spatial relationship of the HP-LT suites with their associated magmatic arc complexes. Several circum-Caribbean HP-LT metamorphic complexes occur on the outer, or eastern flank of the Great Caribbean Arc magmatic axis which began to form in the Aptian (125-113 Ma), requiring that west-dipping subduction dates back to Aptian. However, because the Aptian Atlantic reconstruction (Figs. 1, 7B, 11A) leaves no room for the Caribbean arcs to have formed with westward dipping subduction within the Proto-Caribbean realm, then the Great Caribbean Arc, as well as the entire Caribbean Plate behind (west of) it, must have lain west of Colombia and south of Yucatán/Chortís at 120 Ma. However, just how far out into the Pacific the arc lay at the onset of west-dipping subduction remains unconstrained. There was probably about 18 million years worth of west-dipping subduction prior to the onset of arc-continent interactions with southern Yucatán and the northern Andes (see earlier), during which perhaps some 350 to 700 km of subduction and relative motion are feasible depending on subduction rate. Such early subduction is well recorded by the widespread Albian to mid-Cretaceous plutons and volcanics low down in the Albian-Eocene “Antillean Cycle” of the Great Caribbean Arc.

CONTROVERSY 5, APTIAN AGE AND PLATE BOUNDARY GEOMETRY FOR THE ONSET OF WEST - DIPPING SUBDUCTION OF PROTO-CARIBBEAN BENEATH CARIBBEAN LITHOSPHERES

Pindell et al. (2005) outlined seven aspects of Caribbean geology that point to an Aptian (125-112 Ma) age for the onset of westward-dipping subduction beneath the Great Caribbean Arc, which may have involved arc polarity reversal. These are: 1) onset of HP-LT metamorphism in the Great Arc's forearc; 2) Aptian-Lower Albian hiatus in volcano-sedimentary history in the Great Arc; 3) development of a limestone platform upon parts of the Aptian-Lower Albian hiatus in the Great Arc; 4) shift in the positions of magmatic axes in parts of the Great Arc; 5) change in the magmatic chemistry from Primitive Island Arc (PIA) to calc-alkaline in the Great Arc; 6) emplacement of nappes in Hispaniola as a function of the arc polarity reversal that initiated the Great Arc; and 7) geometric simplicity of an Aptian as opposed to a Campanian arc polarity reversal of the Great Arc.

Although some of these arguments are not as comprehensively definitive as one would like, by all accounts the transformation of the west-facing Intra-American Arc (above an east-dipping subduction zone) to the east-facing Great Caribbean Arc (above a west-dipping subduction zone) was an Aptian event which therefore involved some form of arc polarity reversal. However, the mechanisms by which the reversal was achieved are unclear and very likely involved a several-million year intermediate phase of sinistral transcurrent motion along the arc. This transcurrent phase probably involved very strong arc-parallel stretching and intrusion of basaltic magmas in extensional settings along the arc, which is perhaps why the pre-Albian parts of the Great Arc are not continuous along the arc (Fig. 8). Also, the oceanic crust to the northeast of the arc in Aptian time would have satisfied the geochemical criteria for back-arc spreading, as this was the area of continued seafloor spreading in the Proto-Caribbean Seaway which lay on the hanging wall side of the Inter-American arc prior to its ultimate polarity reversal. By the time of the actual establishment of west-dipping subduction, the arc may have comprised a set of Early Cretaceous primitive island arc complexes separated by extensional “pull-aparts” and strung out between parallel sinistral transforms. That along the north side of the arc may effectively have been a Proto-Caribbean spreading transform, while that to the south of the arc may have been the former Inter-American trench whose relative motion had become transcurrent, much like the Puerto Rico and westernmost Aleutian trenches of today.

Refining the understanding of the Aptian arc polarity reversal is obviously an area deserving much more work. But it is clear that, apart from local events, at no other time in the Cretaceous was there such a profound collective change in depositional, magmatic, structural, and geochemical conditions along the entire arc's length. Further, the similarity of the observed Aptian-Albian changes in many of today's Great Arc fragments suggests that the

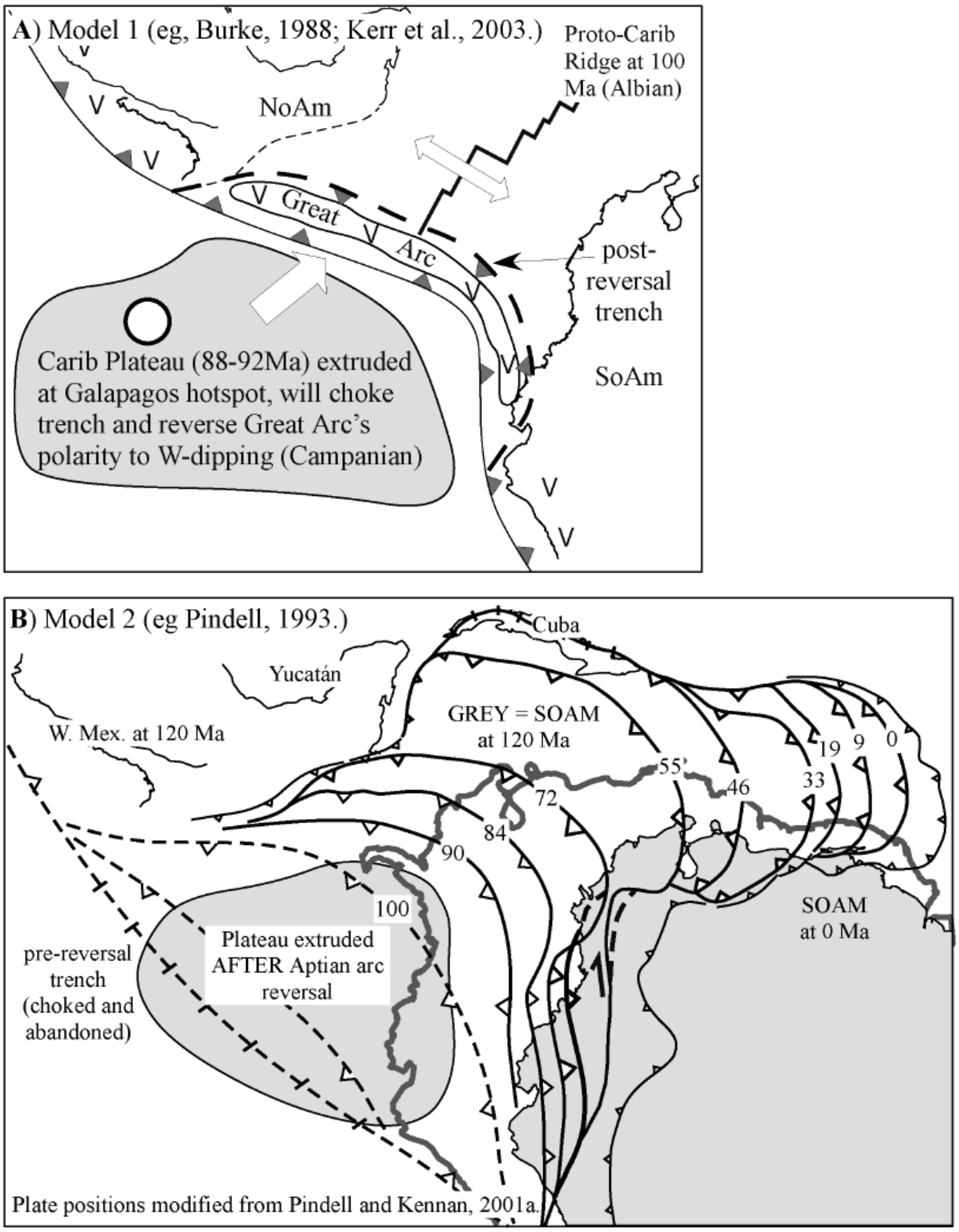

FIGURE 7 **Two contrasting popular models for the 92-88 Ma extrusion of the Caribbean Large Igneous Province (CLIP) onto pre-existing crust: A) Model (1) CLIP was extruded at Galapagos Hot Spot while Farallon Plate was in the Pacific and moving NE; CLIP then choked and reversed the Cordilleran Trench in the Campanian, such that the CLIP plateau then moved into the region between the Americas as part of the Caribbean Plate. In favour of Model 1: CLIP basalts show little sign of supra-subduction zone geochemical traits. Against Model 1: There is little evidence in Caribbean terranes for a Campanian orogenic episode that might be tied to arc reversal; magmatism is continuous through the Campanian in many arc fragments, and nearly all Caribbean HP-LT mineral suites on the north or east side of the arc are older than Campanian, such that they could not have formed if the west-dipping trench were only Campanian and younger. B) Model (2) CLIP was extruded onto Farallon crust after an Aptian reversal, such that extrusion occurred above the Great Arc Benioff Zone as the Caribbean Plate moved into the region between the Americas. It is important to note that seafloor spreading continued between the Americas (in the Proto-Caribbean Seaway) until about magnetic anomaly 34 (Campanian). Therefore, the active Proto-Caribbean spreading ridge must have been subducted beneath the Great Arc during the 120-84 Ma period. This period closely matches the age range of basalts associated with the CLIP, although most of them are about 92-88 Ma. In favour of Model 2: Polarity reversal of the Great Arc was probably as old as Aptian, based on (1) HP-LT mineral ages from northern, eastern and southern Caribbean forearc terranes ahead of the Great Arc's magmatic axis, (2) all Great Arc fragments record Aptian deformations or onset of metamorphism, and (3) the record of "Antillean Magmatism" in most of the arc's fragments begins in the Albian (establishment of W-dipping subduction) and shows little interruption in the Campanian. Against Model 2: Plateau basalts must have been extruded onto Caribbean Plate while west-dipping subduction beneath the plate was occurring, thereby potentially contradicting the geochemical traits for non-supra-subduction extrusion.**

fragments once lay much closer together and thus were susceptible to a common Aptian history. In the Aptian, the distance between the Americas was about 1000 km less than during the Late Cretaceous (Fig. 1), greatly facilitating this common history. The Great Arc's collective geologic record shows no similarly profound collective change in the Campanian, as might be expected had the onset of west-dipping subduction (subduction polarity reversal) been delayed until after the eruption of the Caribbean Large Igneous Province, as some authors have believed.

Insight into the geometry of the Aptian-Albian plate boundaries where the Proto-Caribbean Seaway met the Pacific may be gleaned from circum-Caribbean HP-LT metamorphic suites and their relationship with adjacent arc magmatic axes. According to structural and geochronological data, most of the broader Caribbean region's HP-LT metamorphic suites, which denote former Benioff Zones or deep parts of forearc settings, began acquiring their HP-LT metamorphic overprint in the Early Cretaceous (Pindell et al., 2005). This includes the complexes which clearly lie on the eastern flank of the former

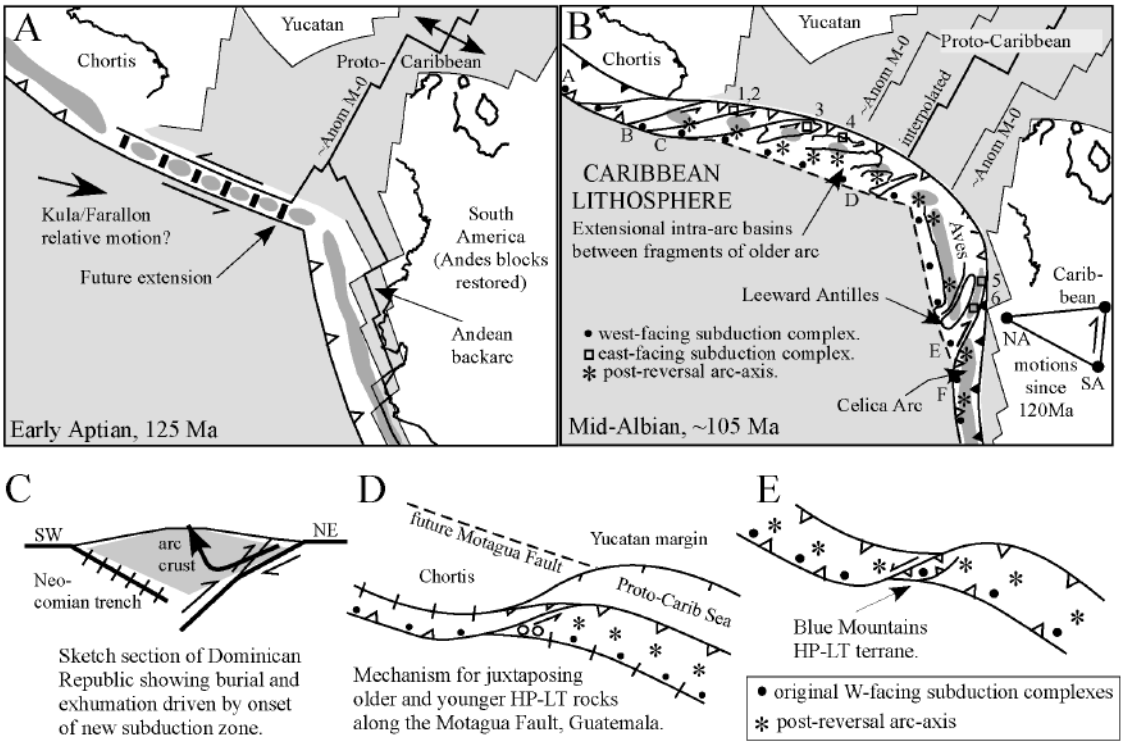

FIGURE 8 | **Depictions of possible paleogeography of the early Caribbean arc complexes, based on the framework provided by Pindell and Kennan (2001), some suggested local tectonic complexities in the early history of Great Arc. A) Pre-subduction-polarity-reversal time. We infer the existence of an Aleutian-like arc and show schematically several axis-parallel extension centers which enable arc-lengthening to match NA-SA drift. These separate "pods" of pre-existing Neocomian arc and may be partly-filled supra-subduction mafic magmatic rocks. Note that the primary shape of the northern and eastern margins or the Caribbean Plate is already established, requiring no little further plate-scale deformation. B) Post-subduction-polarity-reversal time. Extension centers (gray) have been lengthened, subduction polarity has been reversed, and the Great Arc's HP-LT forearc has been initiated. The Eastern Caribbean transcurrently migrates northward along the western edge of northern South America. The two sets of HP-LT and other subduction-related complexes (west- and east-facing) are schematically shown. The Costa-Rica-Panama Arc is not considered or shown here, although that subduction zone was probably active by Late Albian. Note: this model implies Caribbean-North America azimuth began to change from ESE (Aptian) to ENE by the Albian. This, in turn, was related to onset of Equatorial Atlantic opening, and to the acceleration of spreading in the Central and Southern Atlantic. One prediction of this model is that the deep, western flank of Aves Ridge was once an east-dipping subduction zone. Seismic records recently collected by the BOLIVAR program north of La Blanquilla (Clark et al., 2004) suggest that a deep, south- or east-dipping paleo-subduction zone is entirely possible. Abbreviations for subduction complexes: 1: Escambray, Cuba; 2: Cajalbana-Holguin, Cuba; 3: Purial, Cuba; 4: Río San Juan, Dom Republic; 5: Margarita; 6: Villa de Cura; A: Baja California; B: Motagua "south"; C: Blue Mts. Jamaica; D: Bermeja, P. Rico; E: Amaime/Jambalo, Colombia; F: Raspas, Ecuador. C) Relationships of the Aptian (Kesler et al., 2005) Maimon and Los Ranchos Formations of the Dominican Republic. Were they metamorphosed by imbrication of NE arc-flank strata as W-dipping subduction began, then exhumed by axis-parallel extension, and finally onlapped unconformably by Mid-Albian Hatillo shallow water limestone? D) Along the Motagua Fault Zone older (south) and younger (north) HP-LT rocks are juxtaposed. On the south side, a tail of originally west-facing HP rocks (larger, open circles) could have been sheared out and then emplaced on the southern Yucatán margin without an arc either ahead of or behind it. These rocks may then have been backthrust onto Chortis much later in the Tertiary as Chortis passed from west to east by transpressional movement along the Motagua Fault and so they need not be related to subduction on the north flank of the Chortis Block itself. E) Similarly, the Blue Mountains HP-LT terrane of Jamaica may have been juxtaposed with Late Cretaceous arc plutons (compare with Draper, 1986) to its west during cross-arc transpression? This suggests that the Jamaican HP-LT terrane may be the only such terrane in the northern Caribbean region associated with the pre reversal subduction zone otherwise preserved in Guatemala, Colombia and Ecuador.**

Great Caribbean Arc and which are allochthonous with respect to the continental footwalls which they overthrust, as well as those within the western North and South American Cordillera (e.g., those along the Romeral Fault of Colombia and in Baja California and Guatemala). Concerning the complexes on the east flank of the Great Arc, the Cuban forearc HP-LT examples lie north of the primary Cayman Ridge arc axis (see later), the two being separated by the Paleocene intra-arc Yucatán Basin; the Río San Juan, Puerto Plata, and Samaná HP-LT complexes lie northeast of Hispaniola's Central Cordilleran arc; and the Margarita-Villa de Cura forearc HP-LT trend lies southeast of the Leeward Antilles/Aves Ridge part of the Great Arc. HP-LT metamorphism requires active subduction (at least 15-20 km/Ma, Maresch and Gerya, 2003) as does the generation of the associated arcs. The period of magmatic activity in each of these portions of the Great Caribbean Arc dates back to at least the Albian, thus overlapping with the initiation of HP-LT metamorphism in their respective forearcs, and continues into the Paleogene, a period of some 60 my. This indicates that today's pieces of the Great Caribbean Arc, however they are reconstructed in detail back through time, underwent large relative displacements (subduction) with respect to their downgoing plate, amounting to 1000 or more km of west-dipping subduction for the Albian-Eocene period. If we look at Early Cretaceous paleopositions of the Americas for possible locations of the original trench settings where the HP-LT suites could have formed (e.g., 120 Ma reconstruction of Fig. 7B when the Bahamas, Yucatán, and northern South America were all passive margins along a very narrow Proto-Caribbean Sea), we see that the Early Cretaceous trench(es) must have lain along or outboard of the Cordilleran margin of the Americas.

This setting along the western flank of the Americas was obviously the site of the original Inter-American (Cordilleran) subduction zone which dipped eastward beneath the western flank of Pangea during the early Mesozoic and which, despite various terrane accretions/displacements and back-arc openings/closures, survives today along much of western North America and most of western South America. But, as pointed out above, the west-dipping Great Arc subduction zone must also have been initiated in this area as well. This second subduction zone has been responsible for the large scale Caribbean-American plate displacements because, being west-dipping, the Proto-Caribbean lithosphere between the Americas has been subducted into it, and it survives today as the Lesser Antilles subduction zone. This is how the concept of Aptian arc-polarity reversal of the Inter-American Arc was conceived (Pindell and Dewey, 1982); now, with our understanding of HP-LT metamorphism from the region, we may refine the geometries of the plate boundaries during and after the polarity reversal to better explain the regional geology.

Pindell and Tabbutt (1995) demonstrated an Aptian onset of compressive arc conditions from the western USA to northern Peru. They related the onset of backarc thrusting (Sevier Belt, Sierra Madre Oriental, and the closure of the Peruvian backarc) and an eastward shift in the magmatic axis in the Cordillera of continental North and South America to flattening of the Farallon/Kula slab. This was in turn attributed to an acceleration of Atlantic spreading and a westward acceleration of the Americas across the mantle, thereby throwing the hanging walls of the arc systems into compression. Where the Inter-American Arc was intra-oceanic across the Proto-Caribbean gap, they proposed that the backarc thrusting evolved more drastically into arc polarity reversal.

The HP-LT suites that formed at the west-dipping subduction zone should date back to within a few million years of the time of the polarity reversal and not older. We observe that the ages of the HP-LT suites that clearly lie along the east flank of the Great Caribbean Arc axis go back to but are not older than the Aptian. These include the Escambray, Cangre and Northern Serpentinite mélange complexes of Cuba (119–106 Ma; García-Casco et al., 2001, this volume; Maresch et al., 2003; Stanek et al., this volume), the Río San Juan Complex of Hispaniola (104–88 Ma; Lapierre et al., 1999; Krebs et al., 2003, 2005), La Rinconada unit of Margarita (110–86 Ma; Stöckhert et al., 1995), and the Villa de Cura Complex (96–80 Ma; Smith et al., 1999) and the Cordillera de la Costa (96 Ma, by analogy with Margarita; Avé Lallemant and Sisson, 1993; Smith et al., 1999) of Venezuela's Caribbean Mountains. Where it is possible to relate geochronologic data to metamorphic textures it appears that peak metamorphism was reached certainly in the Albian and possibly in the Aptian, with very substantial unroofing and cooling having already occurred before intrusion by plutonic magmas of Late Cenomanian to Santonian age (93-85 MA). Our interpretation of these data is that west-dipping subduction at the Great Caribbean Arc's trench began in the Aptian, and not before, and continued thereafter.

However, slightly older HP-LT ages, some of which are pre-Aptian, also occur within the "greater Caribbean" region. Such ages are found in the El Oro Terrane of Ecuador (132 Ma; Aspden et al., 1995) and the Amaime Terrane/Romeral Fault Zone of Colombia (113-126 Ma; Bourgois et al., 1982, 1987; McCourt et al., 1984). These we associate with the original west-facing forearc of the Inter-American Arc. Likewise, the Berméja Complex (ophiolite) of southwest Puerto Rico, with its Early Jurassic, Pacific derived red radiolarian ribbon cherts, may represent a shallower structural level of this Inter-American Arc's subduction zone that lies, as it would, along the southwestern flank of the Great Arc's magmatic axis. Blueschist metamorphism in Baja California is also associated with the east-dipping, west-facing Mexican portion of the Inter-American arc. The 115-95 Ma age of metamorphism (Baldwin and Harrison, 1989, 1992) may indicate enhanced rates of burial and exhumation coinciding with the increase in the rate of westward motion of the Americas across the mantle.

The cooling ages from many of the HP-LT suites (particularly as documented in the Escambray complex of Cuba, and on Margarita Island, Venezuela) generally indicate prolonged, progressive cooling and unroofing histories from the Aptian to at least 60 Ma, without evidence of Late Cretaceous reburial events, which would be expected by models of Late Cretaceous subduction polarity reversal or onset of west-dipping subduction (Burke, 1988; Hoernle et al., 2002; Kerr et al., 2003). In addition, the precise pressure-temperature-time paths obtained for blocks of high-pressure metamorphic rocks in subduction-zone mélanges of the Río San Juan Complex of the Dominican Republic (Krebs et al., 2003, 2005) document an active and continuous subduction-zone system in at least that part of the Great Arc from about 110 Ma to about 60 Ma.

Figure 8 shows stages of a model for the Aptian polarity reversal that incorporates transcurrent stretching of the arc as North America migrated westward due to Proto-Caribbean seafloor spreading in the Barremian-Early Aptian, leading eventually to ?Late Aptian reversal as both of the American plates accelerated westward at even greater rates. We propose two speculative features within this broader model. First, there must have been, both in the northwest and in the southeast, sinistral and dextral cross-arc transfer faults, respectively, that connected the former Inter-American Benioff Zone with the nascent Great Caribbean Arc Benioff Zone. If these were oblique, as shown, it is possible that the Great Arc had "tails" of Inter-American trench material at both ends which extended beyond the limits of the Great Caribbean Arc. We consider it possible that both the Romeral and the older Guatemalan (113-125 Ma; Harlow et al., 2004) HP-LT complexes are remnants of such tails, as neither has any Great Arc magmatic rocks ahead of or behind them. Such a model for the southern Motagua complex requires Cenozoic backthrusting of the complex onto the Chortis Block during sinistral shear along Motagua Fault. Likewise, the Blue Mountain (Jamaica) HP-LT complex may also be of Inter-American Benioff Zone origin, i.e., a piece of the Inter-American forearc that was sheared left-laterally into adjacency with the Great Caribbean Arc axis of central Jamaica. Unfortunately, the age of initial metamorphism is too poorly known to discern clearly the origin of this terrane.

Second, Kesler et al. (2005) report Aptian ages (111-114 or 118 Ma) for the PIA lavas of the Los Ranchos Formation of Dominican Republic. This unit must subsequently have been buried to greenschist metamorphic depths, and then exhumed back to the surface by late Lower Albian when the Hatillo limestone was deposited unconformably on it (Lebron and Perfit, 1993; Myczynski and Iturralde-Vinent, 2005). We consider it possible that this very rapid burial mechanism for the Los Ranchos was the onset of west-dipping subduction itself, or perhaps thrust faults associated with that onset, such that the Los Ranchos was taken down as part of a footwall to greenschist depths and then transferred to the hanging wall and exhumed to the surface, perhaps by axis parallel extension and/or strike slip faulting within the arc. If this suggestion is correct, it places a maximum age limit on the onset of west-dipping subduction in this location; the oldest age for peak HP-LT conditions (i.e., essentially the maximum burial stage) of 104 Ma from Río San Juan (Krebs et al., 2003, 2005) provides a minimum age in a nearby location.

CONTROVERSY 6, ORIGIN AND CAUSAL MECHANISMS OF THE CARIBBEAN LARGE IGNEOUS PROVINCE... NOT GALAPAGOS

While few now doubt an eastern Pacific origin for the Caribbean oceanic crust, controversy continues about the age and cause of inception of west-dipping subduction beneath the Great Caribbean Arc, and thus the onset of eastward Caribbean migration relative to the Americas. Concerning the age of inception, workers seem to be divided between the Aptian (e.g., this paper, Pindell, 1993; Pindell and Kennan, 2001a; Snoke et al., 2001) and the Campanian (Duncan and Hargraves, 1984; Burke, 1988; Kerr et al., 1998; Kerr and Tarney, 2005; Thompson et al., 2003). Because of this division in tectonic models, the accompanying models for the extrusion of the ? Aptian-Santonian Caribbean Large Igneous Province are necessarily entirely different as well.

Probably because the Campanian-inception models are older and more entrenched, there is a continuing presumption in the literature that the mid-Cretaceous Caribbean Large Igneous Province (CLIP) was extruded onto Pacific-derived Late Jurassic-Early Cretaceous Caribbean lithosphere as it passed over the Galapagos hot spot, and that this thickened crust then choked and reversed the polarity of a west-facing Intra-American Arc in the Campanian, after which the Caribbean lithosphere continued to migrate to its present position between the Americas (Fig. 7A). Further, the "Galapagos Plateau" concept appears to be perceived by some workers as an integral part of the general Pacific origin model for the

Caribbean (Kerr et al., 2003), such that if one does not accept this story, then the Pacific origin concept is doubted as well. But an important test for this model concerns the onset of west-dipping subduction; if the CLIP, the most common ages for which are 88-92 Ma, choked and drove the arc-polarity reversal from east- to west-dipping subduction, then the reversal must be younger than 88 Ma (hence, Campanian).

However, the age of circum-Caribbean HP-LT metamorphism discussed earlier, as well as several additional arguments reviewed in the next section, an Aptian age is far more likely for the inception of west-dipping subduction (Fig. 7B). In addition, the following points shed additional doubt on the "Galapagos Plateau" model.

First, the existence of the Galapagos hot spot as a distinct physical feature can only be dated by magnetic anomalies and ODP drilling back to the Early Miocene (Christie et al., 1992; Werner et al., 1999), requiring a leap of faith about whether it existed any earlier than this time. Cretaceous and early Tertiary rocks with geochemical similarities to those of the Galapagos islands are known from Costa Rica and Colombia (Hoernle et al., 2002, 2004), but there are few ages to demonstrate continuity of Galapagos volcanism during the interval 50-24 Ma.

Second, the stratigraphies of southern Yucatán and the northern Andes (northern Ecuador and Colombia) indicate Early Cretaceous non-volcanic, passive margin conditions, with more pronounced tectonic control on stratigraphy, but no magmatism, beginning in the Turonian. In northern Guatemala, foredeep drowning of a forebulge unconformity on the mid-Cretaceous (Cobán) shelf section began in the Turonian-Coniacian (~90 Ma, Campur Formation), following which an allochthonous forearc sliver was thrust northwards over the foredeep basin in the Maastrichtian (Rosenfeld, 1993). Along the western flank of the Central Cordillera of the northern Andes, allochthonous fragments of oceanic and magmatic arc complexes of the Cauca Valley and Western Cordillera were accreted diachronously northwards throughout the Late Cretaceous (Pindell et al., 2005). In parts of the southern and central Eastern Cordillera of Colombia, but not in Venezuela, the Turonian Villeta Formation contains thin bands of volcanic ash indicating proximity to an active volcanic arc (i.e., to the west of but not north of Colombia; Villamil and Pindell, 1998). Because there is no indication of Cretaceous magmatic intrusion in the autochthonous continental parts of either Colombia's Central Cordillera (the Antioquia Terrane has likely migrated north by several hundred km along the Palestina-Otú fault zone and is thus allochthonous) or in Mexico-northern Guatemala, then the arc responsible for these tectonic interactions was allochthonous with respect to the Americas, and was most likely the Great Caribbean Arc as required by Pacific origin Caribbean models. A Turonian onset of Caribbean-American interactions is entirely consistent with an Aptian onset of west-dipping subduction beneath the Great Caribbean Arc, which progressively brought the Americas closer to the Caribbean lithosphere thereafter. More importantly for the argument here is that if these tectonic interactions with the Americas were in fact Caribbean driven, as we firmly believe, then the paleoposition of Galapagos hot spot (assuming a hot spot reference frame) was some 1000 km west of the Caribbean lithosphere at the time the CLIP was extruded (~90 Ma) onto the Caribbean Plate (Fig. 9). Thus, a Galapagos origin for the CLIP is only possible if Galapagos hotspot has migrated some 1000 km in the mantle reference frame. Such large migration of hotspots is strongly doubted (Steinberger and O'Connell, 2000). Finally, unlike "Galapagos Plateau" models which require the Caribbean lithosphere at Galapagos at 90 Ma, a Pacific origin for the Caribbean that is 1000 km closer to the Americas in the mid-Cretaceous satisfies the Costa Rican paleomagnetic constraints of Meschede and Frisch (1998).

Third, it is not clear how a point-source like Galapagos hot spot might have affected an area as large as the CLIP, which is at least on the order of 1200 km by 2200 km and probably much greater if we include the subducted Caribbean lithosphere beneath northern South America (van der Hilst and Mann, 1994). However, at about the same time (Aptian through Cenomanian), the Ontong-Java Plateau was erupted over an area broadly similar to that of the Caribbean (ODP Leg 192, Mahoney et al., 2001), suggesting that numerous plumes may have collectively affected a large area of the Cretaceous Pacific Ocean. Thus, in the Caribbean case, it is conceivable that similar multiple vents produced the CLIP, but the bulk of the extrusion would have to have occurred more than 1000 km to the east of the eventual position of the hotspot as it later became concentrated to a point source. Paleomagnetic data only constrain the Caribbean Plateau to having formed at near Equatorial latitudes (Roperch et al., 1987; Acton et al., 2000), which cannot readily differentiate between the two models (Fig. 7). Some rocks once thought to have been part of the Caribbean Plateau, such as Gorgona in Colombia, have geochemical (Thompson et al., 2003; Kerr and Tarney, 2005) and paleomagnetic (Estrada, 1995; MacDonald et al., 1997) evidence indicating an origin farther south than shown in Fig. 7B.

Fourth, clastic erosional products of intermediate (arc) magmatism in the Costa Rica Arc are present in a deep borehole down to at least Cenomanian (97-93 Ma) levels in material considered as "Loma Chumico Formation" by Erlich et al. (1996). Calvo and Bolz (1994) and Calvo (2003) had assumed that because the Loma Chumico Fm is known to reach the Albian, then the sandstones were that old as well. However, Flores et al. (2005) showed that the sandstones are not actually in the Loma Chumico but rather in the Berrugate Fm for which sandstone is characteristic and the oldest faunal zonation known thusfar from field study is Turonian. We consider that Erlich's et al. (1996) Cenomanian sand-bearing level may also be from this formation. Accordingly, this implies an Albian age for the onset of subduction at the Costa Rica-Panamá Arc, as several million years of subduction are required for arc magmas to be generated. If so, then in order for the Galapagos hot spot to have driven basaltic volcanism on the interior of the Caribbean Plate at about 90 Ma, the hot spot would subsequently have had to migrate westward across the trace of the Costa Rican subduction zone/plate boundary to get to its present position west of the Caribbean Plate (Fig. 10), which we find highly unlikely.

Fifth, Thompson et al. (2003) build a case to suggest isotopic correlations between Caribbean Plateau basalts with those of the Galapagos islands. Their data and graphs do show overlap between Galapagos and Caribbean rocks on Hf/Nd cross-plots, but there is also a substantial overlap with generalized OIB (ocean island basalt) compositions, and both Galapagos and Caribbean rocks could lie on mixing lines between East Pacific Rise (EPR) MORB (depleted) and a more generalized Eastern Pacific mantle (enriched) end member. There is also wide variation within the Galapagos islands suggesting that more than one magma source may have contributed even to that small area. There is significant unexplained divergence in Sr isotope composition and also overlap with EPR Pb isotope composition. Although a difference from Iceland basalt composition is noted, we wonder how apparent the difference would be were Caribbean basalts compared to other Pacific plateau basalts, and if it is not more likely that both Galapagos and Caribbean volcanics draw on source regions deep below the same general area of the Eastern Pacific, and therefore possibly share broadly similar geochemical characteristics. We also wonder how great is the similarity to or difference from intra-oceanic and other possibly hotspot-related Cretaceous basalts in nearby areas of Mexico (Freydier et al., 2000; Ortiz-Hernández et al., 2003), the perimeter of the Gulf of Mexico (Byerly, 1991) and even Ecuador (Barragán et al., 1997; Barragán and Baby, 1999), all of which appear to have been in the hanging wall of subduction zones on the western side of the Americas, and therefore must have been very distant from the Galapagos hotspot at their time of eruption. Therefore, at present we see no necessarily unique association between Caribbean and Galapagos basalts.

For the above 5 reasons, we conclude that (1) the Caribbean lithosphere is highly unlikely to have been situated above the Galapagos hot spot, if the latter existed at all in the mid-Cretaceous; and (2) the Caribbean lithosphere had western (Costa Rica Arc) and eastern (Great Caribbean Arc) plate boundaries since the Albian, and therefore formed a "plate" in its own right when the Mid-Cretaceous CLIP was extruded. This in turn implies that parts of the rim of the Caribbean Plate lay above subduction zones when the CLIP was extruded, which is

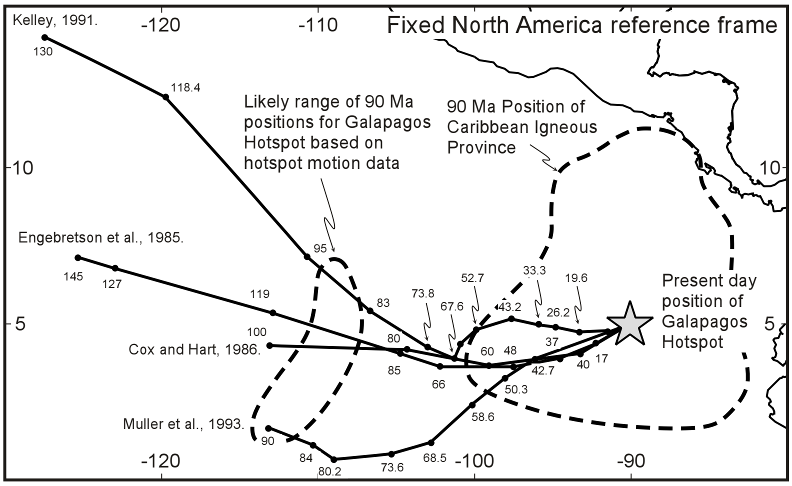

FIGURE 9 | **Comparison of the position of the Caribbean Plate at ca. 90 Ma (time of eruption of the Caribbean LIP) and the Galapagos Hotspot (four different plate motion models), both drawn in a fixed North America reference frame. At this time, the leading edge of the Caribbean Plate was already starting to interact with North and South America indicating that it lay at least 1000 km farther east than the Galapagos Hotspot at that time. Note that the fact that the Caribbean Plate appears to overlie the present position of the hotspot has lead to substantial confusion because some workers have not accounted for both inter-plate motions and plate motions with respect to hotspots.**

not commonly indicated in the geochemistry of CLIP samples. Therefore, we seek an alternative mechanism to the Galapagos hot spot for the origin of the CLIP basalts. Further, the mechanism must be able to account for the lack of evidence for supra-subduction basaltic extrusion.

In order to define guidelines for a new CLIP model, we review the mid-Cretaceous regional setting:

1) Seafloor spreading in the Proto-Caribbean began in the Late Jurassic, continued through the mid-Cretaceous, and had slowed dramatically by the Early Campanian (about 84 Ma). The extension direction was NW-SE. 2) The majority of CLIP basalts by both volume and regional extent appear to be about 88-92 Ma old, but the basalts range from the Albian to the Early Campanian (Donnelly et al., 1990). 3) Westward-dipping subduction beneath the Great Caribbean Arc and the Caribbean Plate behind it began in the Aptian. 4) Eastward-dipping subduction beneath the Costa Rica-Panamá Arc probably began in the Albian (about 100–110 Ma). 5) Early Cretaceous to Turonian passive margin conditions in southern Mexico and Yucatán Block suggest that the southwest end of the Proto-Caribbean spreading center was probably subducted at the Great Caribbean Arc during the mid-Cretaceous rather than being connected to the Cordilleran Trench along long sinistral transforms through those passive margin areas (Pindell and Dewey, 1982; Pindell and Barrett, 1990).

Perhaps the most significant aspect of this mid-Cretaceous Caribbean setting is that Proto-Caribbean seafloor spreading overlapped in time with the subduction of Proto-Caribbean seafloor at the Great Caribbean Arc from the Albian to the Early Campanian, which is precisely the age range of the CLIP basalts. Therefore, Pindell (2004) proposed: (1) that a slab window formed in the west-dipping, downgoing Proto-Caribbean lithosphere as the Proto-Caribbean spreading ridge was subducted beneath the Great Arc as the Caribbean lithosphere migrated into the widening inter-American gap in mid-Cretaceous time (Fig. 11); and (2) that the Proto-Caribbean (Atlantic) mantle spreading cell likely reached the base of Caribbean lithosphere through this slab gap, thereby providing a logical and perhaps testable cause for excess volcanism and crustal extension (NW-SE extension direction) in the Caribbean Plate as the CLIP was formed. Figure 12 integrates Cretaceous Caribbean-American interactions, the formation of HP-LT metamorphic suites, the Albian onset of the "Antillean Phase" of the Great Caribbean Arc's magmatic activity, and the development of the slab window whose areal size, if we consider slab rollback from the original slab window, could have reached the known extent of the CLIP by 90 Ma, which is the most common age of CLIP basalts. Thus, the vast majority of the CLIP basalts would not show supra-subduction geochemical characteristics.

Lapilli tuffs in CLIP exposures in southern Hispaniola and Aruba indicate at least local subaerial exposure during basaltic extrusion (Pindell, 1981; Wright and Wyld, 2005), as do fluvially-rounded clasts in Turonian strata on Aruba (Wright and Wyld, 2005). Mapped mid-Cretaceous Caribbean crustal extension (grabens) and CLIP volcanism (Diebold et al., 1999; Driscoll and Diebold, 1999) are reminiscent of the geology above other slab windows (e.g., Patagonia), but here that geology developed in oceanic crust. The mapped graben features in the Caribbean crust may be repositories for conglomeratic material like that on Aruba. Further, the slab window model (Pindell, 2004) may explain why certain batholiths (e.g., Aruba Batholith) are difficult to categorize as "arc" or "non-arc" related (White et al., 1999; Wright and Wyld, 2005), because slab windows can provide settings for both types of intrusion. Finally, the fact that the mapped extensional structures in the Caribbean crust (Diebold and Driscoll, 1999) are perpendicular to the mid-Cretaceous Proto-Caribbean separation direction suggests that the Proto-Caribbean spreading cell may have driven the Caribbean extension, and, if so, that the Caribbean Plate has not rotated very much since 90 Ma.

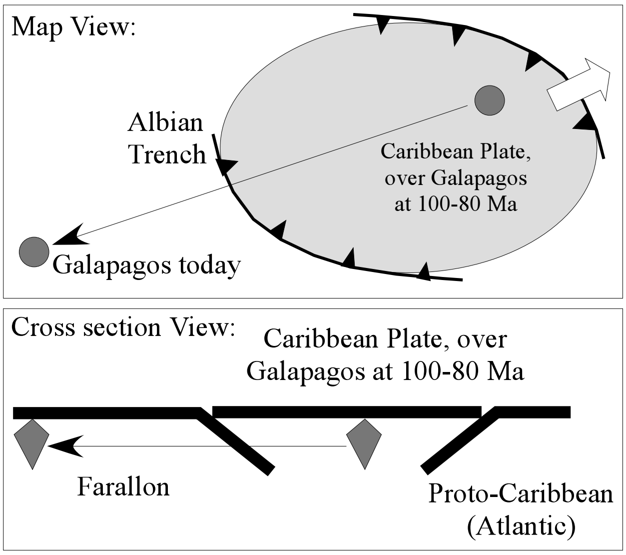

FIGURE 10 | **Cartoon showing how the Galapagos Hotspot would have to cross an active subduction zone if 1) the Costa Rica arc had become active by Albian time and 2) the same plume or hotspot was responsible for both the Caribbean LIP and the Miocene trace of the Galapagos Hotspot west of that arc.**

CONTROVERSY 7, DEVELOPMENT OF THE CUBAN SECTOR OF THE GREAT CARIBBEAN ARC

Subduction zones are among the largest geological structures on Earth. As such, they should not appear and disappear in evolutionary models in ad-hoc fashion to explain 2nd- or 3rd-order geological details for which other simpler mechanisms within a single arc system may exist. "Cross-sectional analysis" of tectonic development is particularly naïve, given that a single oblique strike slip fault across an arc or orogenic belt may produce a map pattern that gives the appearance of excessively complex (or simple) evolution in cross section. Palinspastic and, therefore, paleogeographic analysis must be conducted in three dimensions, i.e., in map view as well as in cross section, and evolutionary interpretation must entertain a wide range of possible mechanisms to explain a given set of geological observations.

The Cuban sub-region is a part of the Caribbean where the number of arcs and plate boundaries has been particularly controversial. Central Cuba comprises three primary elements: (1) the parautochthonous Bahamas Platform and northern Cuban flexural foreland along most of the northern coast (Meyerhoff and Hatten, 1968; Pardo, 1975; Pindell, 1985a), (2) the more allochthonous Cuban Southwestern terranes comprising thrust sheets of eastern or southern Yucatán margin shelf and slope strata (Pindell, 1985a; Iturralde-Vinent, 1994, 1998; Hutson et al., 1998), and (3) the highly allochthonous, Cretaceous arc-related rocks and the Cuban ophiolitic mélanges, which overlie the subthrust Bahamian terrane (Wassal, 1956; Somin and Millán, 1981). It is also necessary to distinguish the arc-related rocks of central Cuba from those of eastern Cuba (Oriente), which are separated by the Cauto Depression and which have quite different arc geologies and histories (Nagy et al., 1983; Cobiella et al., 1984; Iturralde-Vinent, 1996). Indeed, Oriente has a Paleocene to Eocene arc history (Nagy et al., 1983; Cobiella, 1988; Iturralde-Vinent, 1994, 1996), which is not present in central Cuba and may partly post-date the Great Arc's collision with the Bahamas; we will return to this possibly distinct arc further below.

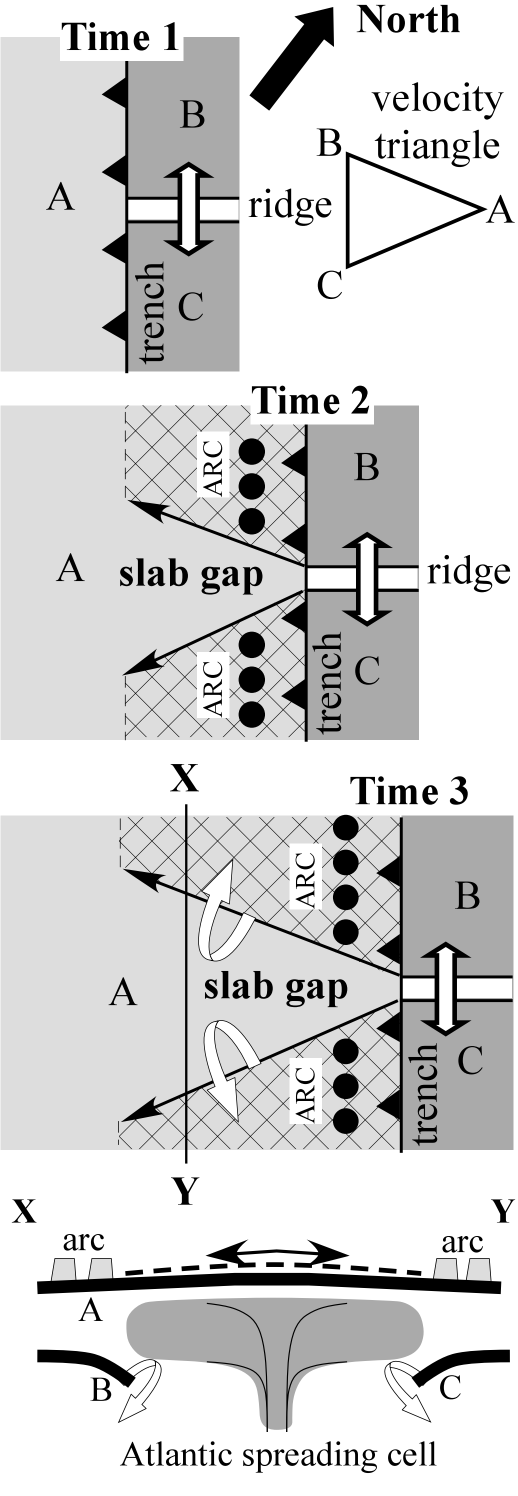

FIGURE 11 | **Simple conceptual model showing the geometry of slab-gap development as a pre-existing oceanic spreading center (in this case, within the Proto-Caribbean Seaway) is subducted. Plate separation continues beneath the arc but no new slab can form, so a window develops in the subducting slab which could allow the Atlantic convection cell to reach the base of and intrude the Caribbean lithosphere, despite the latter being surrounded by inward-dipping subduction zones. We would expect the resulting lavas to have the "oceanic plateau" geochemical signature observed. The size of the growing slab gap in the subducting plate depends on a) spreading rate at the subducted ridge; b) subduction rate at the trench and c) lateral motion of the spreading ridge along the trench. Rollback (white curved arrows) of the subducted slab flanks serves to enlarge the slab gap. There is always a narrow gap in the magmatic arc where there is no underlying subducting plate and basalts intruded into this gap and farther into the back-arc region where the slab gap is wider, may not show any supra-subduction geochemical characteristics. The Careen Hill Intrusive Suite northeast-trending sheeted dyke complexes (Rankin, 2002) and the Late Aptian–Early Albian Water Island Formation (Jolly and Lidiak, 2005; Lidiak and Jolly, 2005), both of the Virgin Islands, may fit such a setting and thus we have drawn the Proto-Caribbean Ridge subducting at that point along the Great Arc. For the velocity triangle, A = Caribbean Crust, B = North America and C = South America.**

One key point we wish to make about the Cuban sector of the Great Caribbean Arc is that the arc-related rocks west of the Cauto Tertiary Depression, including the intermediate arc magmatic rocks, the ophiolitic forearc rocks, the mélanges of the trench environment, and metamorphic rocks with arc affinities (Escambray, Isle of Youth) form a belt only about 100 km across strike that cannot be regarded as a complete "arc complex". This arc-related belt and its overlying Paleogene sediments are known as the Zaza Zone (Ducloz and Vuagnat, 1962; Hatten et al., 1988); the Zaza Zone comprises only the frontal half of the Great Caribbean Arc (Pindell and Barrett, 1990). The Zaza Zone occurs in thin (<10 km) sheets emplaced onto the southern flank of the Bahamas Platform crust in the Paleocene-early Upper Eocene (Iturralde-Vinent, 1998). The HP-LT rocks of the Escambray Mountains occur near the south coast of Cuba, south of and structurally beneath the Zaza Zone, but all of these rocks lie within only tens of kms from the northern ophiolitic mélange belt (Cuban Suture), and thus fit within the scale of a typical forearc setting, into and onto which some of the Great Arc's magmas were intruded and extruded. Escambray represents a tectonically-unroofed, deep level of the Great Arc's forearc, where passive margin strata had been subducted and subcreted in the Aptian-Albian judging from the age of HP-LT metamorphism (Stanek et al., this volume; García Casco et al., this volume). We interpret the last portion of Escambray's uplift history (Late Maastrichtian-Middle Eocene; Somin and Millán, 1981; Stanek, 2000) to pertain to isostatic rebound during the opening of the Yucatán [intra-arc] Basin (Fig. 15; Gealey, 1980; Pindell and Dewey, 1982; Rosencrantz, 1990), in which Cuba's southern margin served as the footwall to primary south-southeast-directed detachment faults (Pindell et al., 2005). The Cayman Ridge to the south of Yucatán Basin has a much thicker and more typical arc-like crustal architecture (Case et al., 1984; Rosencrantz, 1990) than the allochthonous arc rocks of Central Cuba, and has yielded mainly Paleocene intrusive ages on arc magmatic rocks collected by dredging (Perfit and Heezen, 1978; Lewis et al., 2005) and

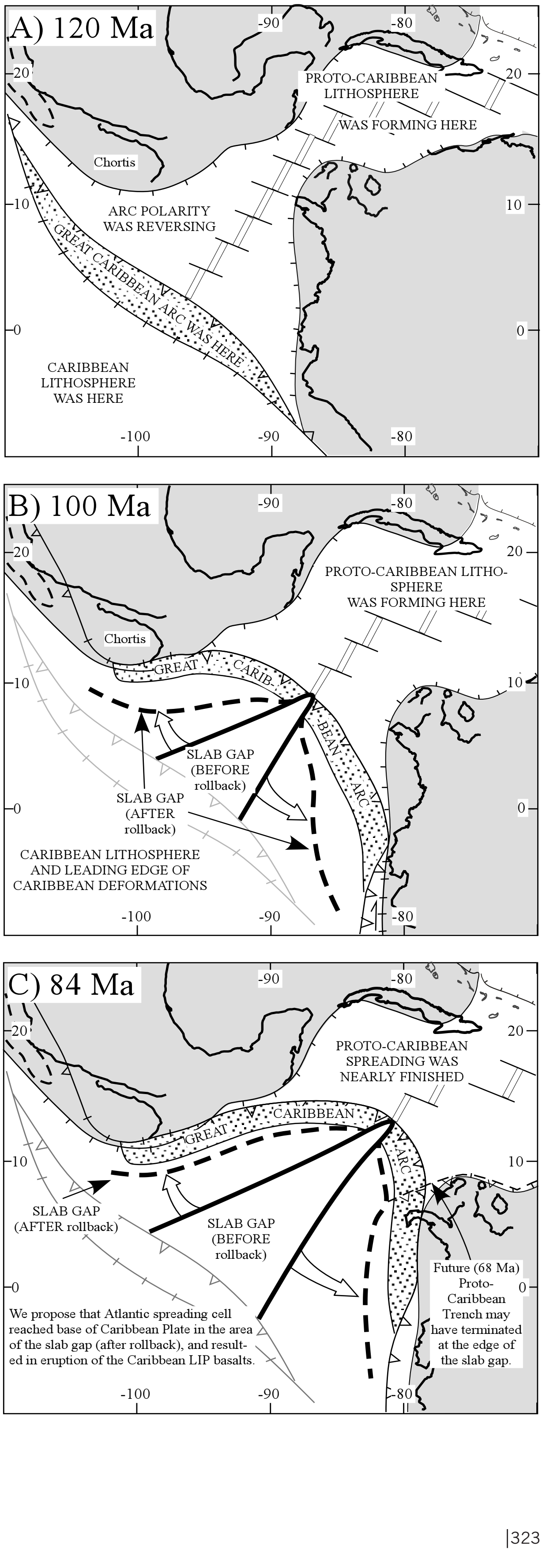

FIGURE 12 | **Three maps (note fixed North American reference frame) illustrating the application of the slab gap concept to the Caribbean region, showing the extent of the slab gap at A) 120 Ma, B) approximately 100 Ma and C) 84 Ma, after which little or no Proto-Caribbean ocean crust formation occurred, and after which no slab gap growth would happen. Westward dipping subduction had begun by about 120 Ma and the Caribbean started to migrate east with respect to the Americas. At the same time, subduction of the Atlantic (Proto-Caribbean) Ridge produced a slab gap in the downgoing plate. Eventually, the Atlantic (or Proto-Caribbean) convection cell was able to reach the base of the Caribbean Plate, leading to basaltic magmatism and extension therein. Rollback of the subducted flanks of the Proto-Caribbean lithosphere at depth could help enlarge the area of the slab gap, such that the gap approached the size of the Caribbean Plate itself by ca. 90 Ma. If this model is correct, then Mid-Cretaceous extension direction in the Caribbean Plate should roughly match the spreading direction between North America and South America, since the driving mechanism is the same. This appears to be the case, and thus it could be argued that the Caribbean Plate has not been rotated significantly since Mid-Cretaceous time. These three maps are modified from Pindell and Kennan (2001a) and Pindell et al. (2005).**

drilling (Sigurdsson et al., 1997). The two parts of the original arc were separated by latest Maastrichtian-Paleocene extension (as indicated by zircon fission track cooling ages; Stanek, 2000) and local seafloor spreading which probably continued into the Middle Eocene in the Yucatán Basin, prior to which they formed part of the western, magmatically active end of the Great Caribbean Arc. Extension in the Yucatán Basin, which tipped out into the coeval Cauto Basin (Pindell and Dewey, 1982), was NNW-directed with respect to the Cayman Ridge and Oriente, Cuba (Rosencrantz, 1990) but NNE-directed with respect to the Proto-Caribbean (Pindell and Barrett, 1990). The extension was probably driven by rapid rollback of the Jurassic Proto-Caribbean lithosphere ahead of the Cuban forearc (Fig. 15B; Pindell et al., 2005). Given the narrowness of the Zaza Zone after Yucatán Basin rifting, the Campanian cessation of volcanism in onshore central Cuba (Stanek and Cabrera, 1992; Rojas et al., 1995; Iturralde-Vinent, 1994, 1996) does not mean that subduction was terminated beneath the Zaza Zone at that time; it simply means that any Maastrichtian-Lower Eocene subduction-related volcanism associated with the last few hundred kilometers of the Zaza Zone's migration toward the Bahamas either did not occur (subduction too slow?) or occurred over a typical arc-trench gap of 150 km, which would have placed it south of central onshore Cuba as suggested by Pindell and Barrett (1990). In contrast, arc magmatism was not shut off in the Maastrichtian in the Oriente Province of Cuba, which was situated to the south and east of the Yucatán-Cauto intra-arc basin and hence remained part of the Great Caribbean Arc into the Paleogene (discussed later).

Now we will show how the geology of Cuba, the Yucatán Basin, and the Cayman Ridge relates to the Pacific-derived, Great Caribbean Arc story. Our first concern is the degree of allochthoneity of the Central Cuban forearc terrane (i.e., "Cretaceous volcano-plutonic complex" of some authors). Northward of the ophiolitic suture belt, Cuba consists of four belts of thrust-bounded "structural facies zones" (Pardo, 1975; Ducloz and Vuagnat, 1962; Meyerhoff and Hatten, 1968; Hatten et al., 1988). Current terminology for these are the Cayo Coco zone, the Remedios zone (both of the Bahamas platform edge), the Camajuani zone (southern Bahamas continental slope and rise), and the Placetas zone (deep water Proto-Caribbean facies). Hempton and Barros (1993), citing an unpublished internal oil company report by Hempton (1991), argued for a minimum of 450 km of shortening across these zones. The Cayo Coco, Remedios and Camajuani zones are parautochthonous to the Bahamas Platform, but the presence of detrital glaucophane and other forearc-derived minerals in the Turonian sediments within the Placetas and Camajuaní belts (Linares and Smagoulov, 1987) suggests that the Placetas Belt was already associated with, or proximal to, the trench ahead of the Cuban forearc at that time (Psczólkowski and Myczynski, 2003, for a different view). Thus, it is more than possible that the Placetas Belt, and especially its upper levels, is not a parautochthonous belt, but is instead more related to the arc and perhaps a remnant of the Cuban accretionary complex that is very far traveled.

The earliest parameter with which we can locate the Great Arc concerns the onset of southwest-dipping subduction. As outlined earlier, recent isotopic age determinations on HP-LT minerals in the Cuban and other parts of the Great Arc's forearc (see Pindell et al., 2005, for a summary and references) date the onset of southwest-dipping subduction as Aptian, when the position of this early arc must have been south of Yucatán and west of Colombia, and probably south of the Chortis Block as well (Figs. 7 and 8). Thus, the western end of the Great Arc would interact, from south to north, with the Jurassic and younger, essentially continuous and correlative, continental margin sections of Chortis, southern Yucatán, eastern Yucatán, and eventually the Bahamas (Fig. 13). Somin and Millán (1981), Iturralde-Vinent (1998), and Pszczolkowski (1999) have highlighted certain similarities in the sedimentary protoliths of parts of the Escambray, Isle of Youth, and Guaniguanico terranes of Cuba. Pindell (1985a) and Hutson et al. (1998) suggested a more southerly, eastern Yucatán origin for Guaniguanico. The metamorphic rocks at the surface on the Isle of Youth likely comprise a higher nappe than the Guaniguanico terrane, and thus are probably farther traveled. Escambray's correlative protoliths likely derive from eastern Chortis or Nicaragua Rise, because the initiation of HP-LT metamorphism there dates to a time when the arc was situated along Chortis (Fig. 13; Pindell et al., 2005).

The next parameters in time that constrain the position of the Great Arc relative to North America are: (1) the Turonian-Santonian unconformity in northern Guatemala (beneath the northward-onlapping Campur-Sepur Formation foredeep flysch) which we interpret as the passage of the Great Arc's peripheral bulge, and (2) the Campanian-Maastrichtian obduction of a forearc complex onto the southern margin of Yucatán which we interpret as the westward continuation of the Cuban forearc, possibly the original forearc north of Jamaica (Rosenfeld, 1993; Pindell and Dewey, 1982). We relate this forearc obduction to the Great Caribbean Arc because there is absolutely no evidence for Caribbean arc terranes lying farther north or east than this at that time. For example, the stratigraphies of Trinidad, Venezuela, northern Colombia, the Bahamas, and eastern Yucatán lack arc-related tuffs or volcaniclastic sands until well after the Campanian, even though the Caribbean islands were highly volcanic throughout the Upper Cretaceous: significant spatial separation is required. The appearance of tuffs and volcaniclastic sands in the Proto-Caribbean margins is a phenomenon that youngs eastward in accord with Caribbean-American migration (there are none in Trinidad, for example, until the Oligocene).

If the Placetas Belt was associated with the Cuban trench as early as the Turonian as indicated above, and if the arc arrived at southern Yucatán in the Campanian, then the depositional position of the Placetas Belt must have been south of Yucatán, some 1500 km SSW of its position today along the Bahamas. This gives a measure of the large, often under-appreciated degree of Cuban Arc allochthoneity, suggesting that the Cuban accretionary record has significant gaps in it because of structural effects and erosion.

From the above, the Cuban "arc" appears to have been situated near the Chortis Block at the mouth of the Proto-Caribbean Seaway in the Aptian, south of the Yucatán Block in the Turonian, adjacent to southern Yucatán in the Campanian-Maastrichtian (Rosenfeld, 1993), and along the Bahamas by the Middle Eocene. This represents a slow migration relative to North America of about 20-30 mm/yr, and suggests that many of central and western Cuba's geological relationships pertain to tectonic interactions between the arc and the margins of Chortís and Yucatán, rather than with just the Bahamas (Fig. 13). We consider that the Campanian "termination" of magmatism in central Cuba had nothing to do with the Bahamas as has commonly been perceived, and was instead closely tied to the opening of the Yucatán Basin; it was not so much a strict termination as a southward shift of the magmatic axis into the juvenile Yucatán [intra-arc] Basin and Cayman Ridge, with only an apparent termination in onshore Cuba. Granitoids of 62-66 Ma age have been dredged from the Cayman Ridge (Perfit and Heezen, 1978; Lewis et al., 2005), with probably a more complete arc assemblage (?Albian-Paleocene) at deeper levels. Figure 13 shows the migration history of the western Great Arc from a Pacific origin, highlighting where and how different varieties (mineralogies) and ages of flysch may have been incorporated into Cuba's geology.

Our second concern addresses the way in which metamorphic and geochemical data are interpreted in terms of arc history. Both these data sets are commonly cited as supporting relatively complex models involving multiple arcs and transient subduction zones. However, when considered within the paleogeographic framework for the evolution of the Proto-Caribbean Seaway and origin of the Caribbean Plate and its migration (Fig. 7), these data fit very well within the context of a single long-lived "Great Arc of the Caribbean". For example, it has been

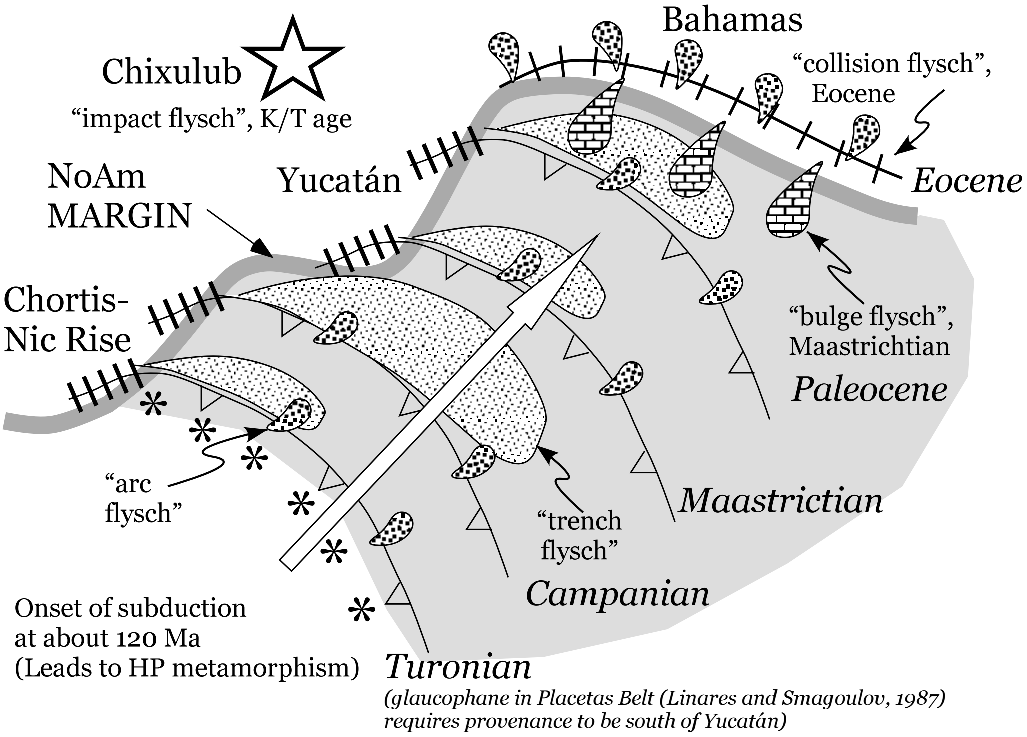

FIGURE 13 | **Flysch belts of Cuba appear to show a systematic trend from arc and subduction zone source (glaucophane and other minerals) during the Turonian, through a Yucatán source and then a Bahamas source as the trench at the leading edge of the Caribbean Plate migrated along the Yucatán margin before docking with the Bahamas during the Paleogene.**

noted that although geochronologic data indicate that HP-LT rocks in ophiolitic mélanges in Cuba formed approximately during the Aptian or early Albian, there are substantial differences in the details of their P-T-t history (García Casco et al., this volume). None of these data imply that they did not evolve in the same subduction zone, nor even in widely spatially separated parts of the same subduction zone. The complexities may in part depend on the precise nature of what was subducted at a given time and place, and also on the geologic accident of which part of the accretionary complex was exhumed. Recent computer models (Gerya et al., 2002) clearly show that it is possible to have very different P-T-t paths, including both clockwise and anticlockwise paths, in the same subduction zone.

Models like Fig. 7B have been criticized because they are thought not to adequately explain the wide variety of geochemistry found in lavas in Cuba and elsewhere in the Caribbean. In particular, Cuban volcanics show geochemical variations suggesting oceanic island arc through supra-subduction (sometimes referred to as "back-arc") origins (Kerr et al., 1999), in addition to rift, intra-oceanic and Bonin-type arc settings. Again, the published interpretations of these data illustrate the weakness of the two-dimensional, "cross-sectional" interpretation method because they do not take account of possible along-strike variations in the Great Arc, and too often they also ignore the very poor age constraints. In the case of Cuba, we note that some of the rocks interpreted as primitive-island-arc and back-arc pre-date our proposed onset of westward-dipping subduction (Kerr, et al., 1999). As such, we would expect PIA type rocks because "Pacific" plates were subducting eastward beneath the Inter-American Arc and causing melting of fertile mantle. That back-arc affinities are found in these pre-reversal rocks is also no surprise; effectively the Proto-Caribbean Seaway lay in a back-arc basin position east of the Inter-American subduction zone, albeit one in which the spreading center probably lay at a high angle to the trench. Also, given the subduction of at least 1000 km of Proto-Caribbean Seaway prior to docking of the Great Arc with the Bahamas in the early Paleogene, it should be no surprise that the ophiolitic mélanges at the northeastern edge of the Cuban allochthons also contain dismembered remains of intra-oceanic basalts representing Proto-Caribbean Seaway crust, but northeast of the influence of the pre-reversal, east-dipping subduction zone. Further, boninites in Cuba have been used to propose an entirely new arc, above a west-dipping subduction zone, and separated by a substantial back-arc basin from the Inter-American Arc (Kerr et al., 1999). However, this interpretation is based solely on blocks and boulders within the ophiolitic mélange, and has no age constraints. Boninites are thought to form at "hotter-than normal" subduction zones, possibly where ridge subduction occurs or where subduction initiates on pre-existing fracture zones. Both these possibilities are likely during the early stages of west-dipping subduction (Fig. 7B; see also Pindell et al., 2005 for more detail), so the presence of boninite remnants might be expected in the single arc model. Finally, the calc-alkaline arc rocks in western and central Cuba are, as integrated into the model (Fig. 7B), largely confined to the post-reversal arc (Albian–Campanian). Thus, it seems clear to us that the relatively simple subduction configuration shown in Fig. 7B can provide more than enough variation in initial conditions to explain the observed variations in both metamorphic and volcanic assemblages. Indeed, it is hard to imagine how the same initial conditions could exist along strike over distances of a thousand kilometers or more, a distance over which subsequent and significant variations exist today.

The next concern we address is the origin of the Paleogene arc magmatics of Oriente, Cuba (Lewis and Straczek, 1955; Cobiella, 1988; Iturralde-Vinent, 1994, 1996, 1998) which do not occur in central Cuba for the reasons stated above. The arc magmatics here comprise mainly Eocene volcanics and plutons of 46-60 Ma age (Cazañas et al., 1998; Rojas-Agramonte et al., 2004; Lewis et al., 2005). On the basis of differing age and geochemistry, Lewis et al. (2005) distinguish these from the dredged arc rocks of the Cayman Ridge (62-66 Ma) to the west, which had been thought by some to be the continuation of Oriente (Perfit and Heezen, 1978). Oriente Cuba's arc rocks have been associated with (1) the final stage of magmatism from southwest-dipping subduction during the Great Arc-Bahamas collision (Pindell and Barrett, 1990), or (2) a short-lived northward-dipping subduction zone, either in the Cayman Trough (Perfit and Heezen, 1978; Cobiella, 1988), or along the Peralta-Ocoa belt of Hispaniola (Sykes et al., 1982; Pindell and Draper, 1991; Iturralde-Vinent 1996, 1998). Pursuing the north-dipping option further, a satisfactory Eocene-Oligocene reconstruction of the Paleogene arc axes and flanking basins of Hispaniola's Central Cordillera and Oriente, Cuba can be made by retracting about 350 km of offset along the Oriente Fault/northern Hispaniolan faults (Pindell, 1985b; Pindell and Barrett, 1990; Erikson et al., 1990; Iturralde-Vinent and MacPhee, 1999). If Oriente's Paleogene arc magmatics are due to north-dipping subduction, then Hispaniola's Paleogene arc magmatics could be as well (Cobiella, 1988; Iturralde-Vinent, 1996, 1998). In Hispaniola, the Palma Picada lavas along the south flank of Cordillera Septentrional, the Loma Caballero and Los Banitos units, and unnamed ?Eocene dioritic stocks cutting the Maimon and Peralvillo formations all lie north of the Upper Cretaceous arc axis, and flank the Cibao Basin (Bowin, 1960). If these volcanics are the southeastward continuation of the Oriente arc volcanics ("Oriente-Cibao arc"), then the trench must have lain along the site of the San Juan Basin to the south of Hispaniola's Central Cordillera, and not along the Cayman Trench or Oriente Fault.

Figure 14 shows the approximate Eocene plate boundary configuration in relation to the reconstructed "Oriente-Cibao arc", highlighting the north-dipping thrustbelt and potential trench along the southern flank of the Central Cordillera (Sykes et al., 1982; "San Juan Restraining Bend" of Pindell and Barrett, 1990; Peralta Belt of Dolan et al., 1991; Peralta-Oca Belt of Iturralde-Vinent, 1996, 1998). We note that in order to induce arc magmatism under this restraining bend configuration, the Caribbean azimuth of motion must have been ENE relative to the intermittent arc axis by Paleocene time.

In the Cretaceous before this fault zone became active, Oriente's arc magmatic rocks can be fit nicely into the Albian-Maastrichtian "Great Arc" model. As for the Paleogene, the north-dipping subduction option (Fig. 14) is strengthened by seismological work that shows the existence of two interfering subducted slabs beneath Hispaniola (McCann et al., 1990). The significance of this model (Fig. 14) is that the Oriente-Hispaniolan portion of the Great Arc could have collided with the Bahamas somewhat earlier (Maastrichtian-Early Paleocene) than would be required if the Oriente-Cibao magmatism pertained to south-dipping subduction from the north (Eocene). Thus, the idea of the Cuba-Bahamas collision being eastwardly diachronous (Mann et al., 1995) would be invalid, and the Cuban collision may actually have been diachronous westward, where suturing was Middle to early Late Eocene. Further, the strong imbrication of the Purial ophiolites, the Cretaceous arc rocks, and the underlying metamorphosed carbonate strata of easternmost Cuba (Pushcharovsky et al., 1988; Inturralde-Vinent, 1994, this volume; García Casco et al., this volume) may be due to the Bahamian collision being particularly intense here, driven by true convergent plate motions rather than merely by subduction zone rollback as it was to the west of the Cauto Depression (see below). In this light, the San Juan Basin transpression can be viewed as backthrusting related to the Bahamian collision.

Our last point regarding the Cuban region addresses the concurrent Yucatán Basin intra-arc spreading and forearc collision with the Bahamas (Fig. 15). The feasibility of this process, where coupled large-scale extension and compression occur simultaneously, and which is also seen in the Appenines-Tyrrhenian Sea area and elsewhere (Rosenbaum et al., 2002; Mantovani et al., 2002), is not immediately apparent because it gives the appearance that compressive thrusting builds a positive topographic head ahead of a negative, actively extensional oceanic basin.

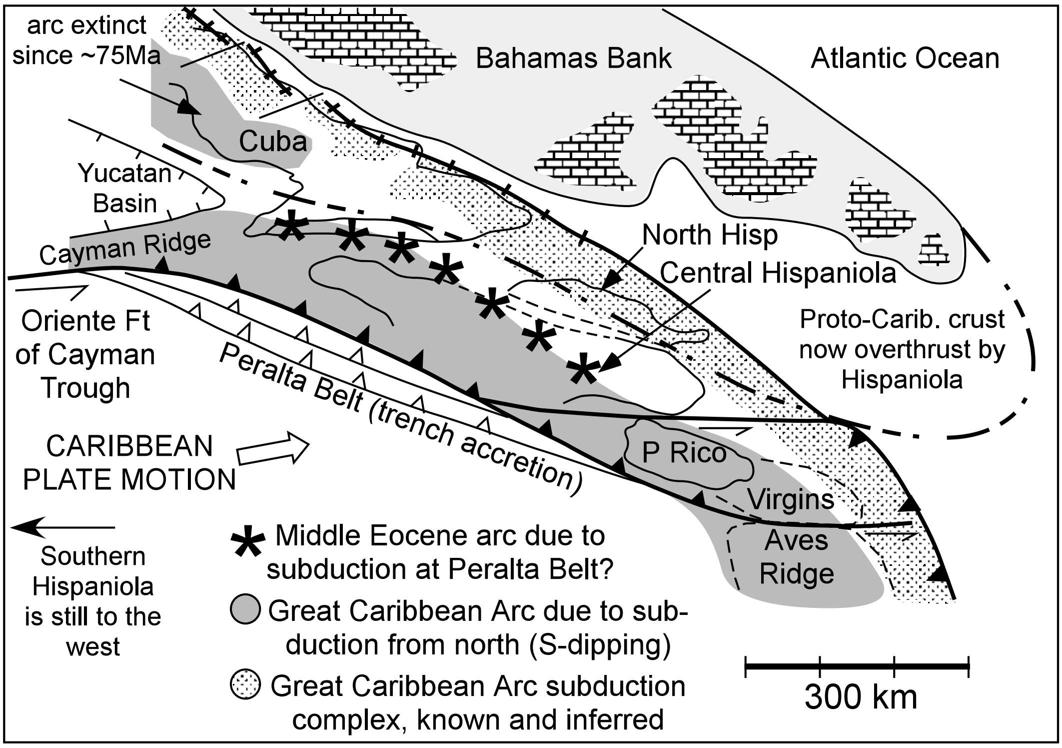

FIGURE 14 | **Flysch belts of Cuba appear to show a systematic trend from arc and subduction zone source (glaucophane and other minerals) during the Turonian, through a Yucatán source and then a Bahamas source as the trench at the leading edge of the Caribbean Plate migrated along the Yucatán margin before docking with the Bahamas during the Paleogene.**

However, this is only the appearance today. In reality, however, most of the uplift that forms the positive orogen relates the isostatic rebound of the thrustbelt and foredeep basin as the formerly subducting oceanic part of the slab drops off into the mantle as the continent chokes the Benioff Zone beneath the arc. In the case of Cuba, the subsidence history of the Bahamas (Paulus, 1972) shows accelerated creation of accommodation space in the Paleocene, marking the arrival of the allochthonous Cuban arc and thrustbelt (north-directed foredeep loading), followed by a strong Eocene erosional unconformity which matches the age of the post-orogenic unconformity onshore Cuba (Angstadt et al., 1985; Pardo, 1975). Because the Early Eocene flysch of the Cuban orogen is of deep water nature (Bralower and Iturralde-Vinent, 1997), the Paleogene structural shortening in the Cuban thrustbelt was largely a submarine process. Hence, intra-arc extension in the Yucatán Basin did not drive the emergence of the Cuban orogen, but was instead a passive response to Proto-Caribbean lithospheric rollback ahead of the slowly migrating arc terrane (Fig. 15B; Pindell et al., 2005). As the Bahamas approached the trench, they were loaded in the Paleocene but they ultimately choked the Benioff Zone by the Middle to Late Eocene. The strong and rapid Late Eocene uplift (Iturralde-Vinent and MacPhee, 1999) was then generated by isostatic rebound of the entire thrust belt and flanks of adjacent basins as the negative load of the subducted Proto-Caribbean slab was detached from the lithosphere beneath the Bahamas (Fig. 15C).

CONTROVERSY 8, ORIGIN OF PALEOGENE “FLYSCH” DEPOSITS ALONG NORTHERN SOUTH AMERICA: THE PROTO-CARIBBEAN SUBDUCTION ZONE

Several Paleogene units in Central and Eastern Venezuela and Trinidad comprise turbiditic sand, shale, and conglomerate which have long been considered as “flysch” or “wildflysch” in the sense of being indicative of orogenesis (Kugler, 1953). These include the Maastrichtian Galera Formation of the eastern Northern Range, Trinidad; the Paleocene-Lower Eocene Guarico Formation in central Venezuela (Beck, 1977); the Paleocene-Lower Eocene northwestern but not the southern Vidoño Formation of the Eastern Serranía (Hedberg, 1950); the probably Oligocene “Lecheria” (informal) beds north of Barcelona, Venezuela (either Los Jabillos or Naricual equivalent; Tectonic Analysis, unpublished data) the Maastrichtian-Lower Eocene Chaudiere and Pointe-a-Pierre Formations of the Central Range of Trinidad (Kugler, 1953); the Late Eocene/Early Oligocene Plaisance “Member” of the San Fernando Formation in the Central Range of Trinidad (Kugler, 1953); the Lower Oligocene Angostura Trend reservoir offshore eastern Trinidad (Taylor, 2005); and the Eocene (Speed, 1994) or Oligocene-Early Miocene (Baldwin et al., 1986) Scotland Formation of Barbados. Most of these units are turbiditic and carry conspicuous detrital mica, and the Plaisance, Angostura, Scotland and Lecheria units comprise olistostromal conglomerate and intra-formational slumps within them. These units generally lie north of time equivalent shallower-water shelf strata such as the Lizard Springs and Navet Formations of southern Trinidad and the southern Vidono and Caratas Formations of the southern Serranía which lack signs of “orogenesis”. This observation was central to the hypothesis (Kugler, 1953) of

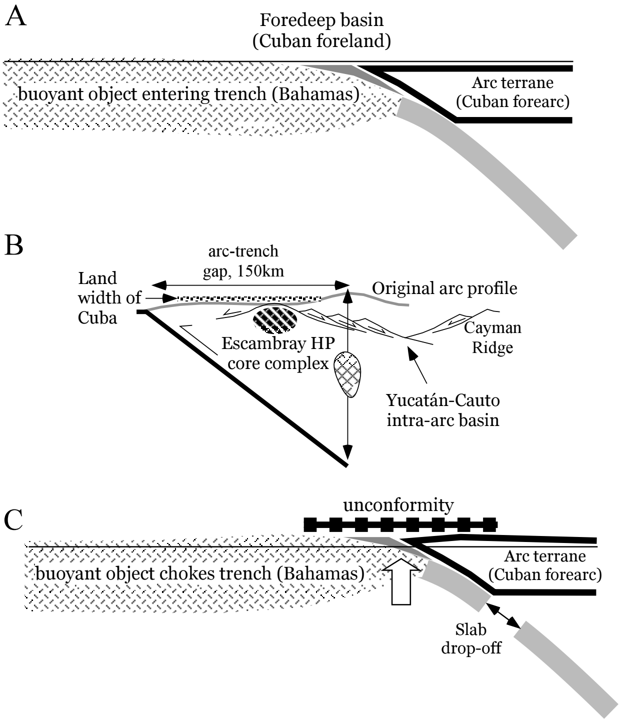

FIGURE 15 | **Paleogene mechanics of the Cuban portion of the Great Caribbean Arc. A) Rollback of Proto-Caribbean lithosphere drove intra-arc extension in Yucatán Basin (shown in B) until the Bahamas entered the trench and choked the Benioff Zone. During the subduction stage, negative buoyancy of the subducting slab drives rollback such that the forearc complex is sucked toward retreating trench line. As thicker crust of the Bahamas approaches the trench, the negative buoyancy and the load of the arc terrane generates accommodation space and hence the foredeep basin. Eventually, the buoyant material chokes trench, causing “collision”. B) Paleocene intra-arc extension in Yucatán basin, after Pindell et al. (2005). Cuban forearc terrane separates from Cayman Ridge remnant arc due to extensional stresses caused by Proto-Caribbean rollback ahead of Cuba. Escambray, Cangre, and Isle of Youth terranes are normal fault footwalls tectonically elevated by structural unroofing in Late Maastrichtian-Paleocene time (modified after Pindell et al., 2005). C) Slab break away mechanism for the creation of the Middle Eocene post-orogenic unconformity across Cuba and southern Bahamas, as a result of trench choking. As the Bahamas Platform resists subduction due to its positive buoyancy, the subducted slab undergoes extensional failure and drops off into the mantle. The removal of this negative buoyancy force allows isostatic rebound to occur, producing the “post-orogenic unconformity” over an area extending some 200-300 km in each direction from the trace of the suture zone.**

orogenesis to the north of the present day onshore. Furthermore, early workers looked to the Northern Range and Araya-Paria Peninsula metamorphic rocks as evidence for the Late Cretaceous orogeny responsible for provenance of these units.

The reason that this issue is now a point of Caribbean controversy is that the Caribbean-South America dextral oblique collision model (Pindell et al., 1988) cannot account for orogeny in these areas prior to the Oligocene, but the occurrence of "flysch" has been taken by some to indicate an in-situ origin for the Caribbean Plate. Thus, we need to examine the nature of these supposed "syn-orogenic" deposits and other regional relations to see if the presence of the Caribbean Plate is required. First of all, primary D1 deformation and metamorphism in the Northern Range, the Paria Peninsula, and probably the footwall of the allochthonous Cretaceous thrust sheets of the Araya Peninsula were probably Eocene-Middle Oligocene events (Pindell et al., 1991; Foland et al., 1992; Algar and Pindell, 1993), not Late Cretaceous as had been thought by earlier workers. Thus, the existence of a northern orogenic belt, especially one shedding mica, during deposition of most of the "flyschoid" units is suspect.

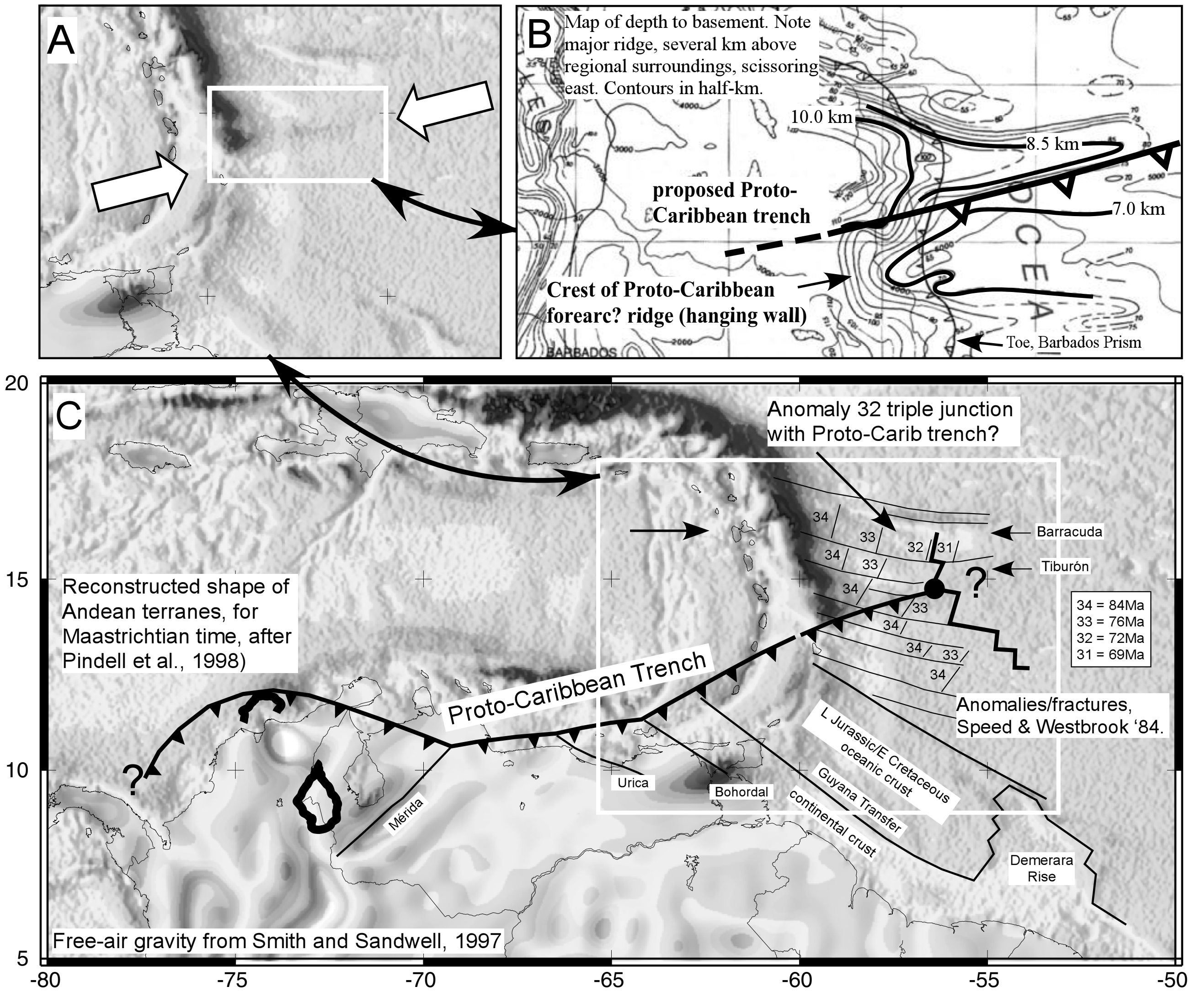

FIGURE 16 | **Aspects of the Proto-Caribbean subduction zone. A) The eastern end of the proposed Proto-Caribbean Trench can be seen on free-air gravity data (Smith and Sandwell, 1997), and on B) detailed basement maps of the Barbados region derived from reflection seismic data (modified from Speed et al., 1984). All but the E-ward projection of the Proto-Caribbean Trench (between arrows) has been subducted beneath the Caribbean. The projection is marked by a prominent basement offset: a southern basement ridge (hanging wall?) appears to be overthrusting a trough (footwall). Here, the crustal hanging wall and footwall have not yet cleared each other (~3 km offset only) across the E-wardly scissoring fault plane. NA-SA kinematics show convergence began around magnetic anomaly 31, and the proposed trench points directly to anomaly 31 in the western Atlantic, suggesting that a triple junction formed there then. It is not clear if the structure is still propagating: it may be one of several planes of weakness through the lithosphere where Cenozoic motions between NA and SA have been taken up.**

Second, deposits with very similar sedimentology to the aforementioned units have been well-accepted in passive margin settings at times of lowstand deposition when orogenesis was entirely lacking. Further, the mineralogies of the sands in the noted formations are generally void of volcanics, tuffs, basaltic or metamorphic rock fragments, or any other types of grains indicating the presence or collision of the Caribbean Plate in the area. Only the Scotland Formation of Barbados carries grains that are commonly associated with subduction or plate collision (very rare glaucophane), but whether or not this is pertinent to the present discussion depends on one's model for the origin of the Scotland Formation in the first place. If the Scotland was accreted to the Caribbean forearc early as part of a far traveled Caribbean accretionary prism, or if the age of the Scotand is Oligocene-Early Miocene rather than Eocene in a more in-situ depositional model with relatively late accretion to the Caribbean, then a Caribbean trench origin for the glaucophane is entirely consistent with a far-traveled (Pacific origin) Caribbean Plate. Concerning the mica in most of these formations, we have observed mica in cores from the sands of the Gautier, Navet and San Fernando units of southern Trinidad, which are almost certainly south-derived from the shield, and thus we do not believe there is any specific need to invoke a northerly or westerly source for the mica in the flyschoid units. Finally, we have been able to expand the mapped area of Late Eocene/earliest Oligocene erosional unconformity across much of southern Trinidad and the southern Serranía del Interior of Late Eocene age, thereby documenting a very proximal, southerly source (fluvially-bypassed correlative unconformity) for many of the noted (lowstand) units.

In summary, we know of no data whatsoever requiring spatial proximity of the Caribbean Plate with eastern Venezuela or Trinidad prior to the Middle Oligocene; from the geology of that region, the Pacific origin model with a Caribbean-South America displacement rate of about 20 mm/yr is entirely compatible if not required. Furthermore, the weakness of the "orogenesis" is well summarised by Hedberg (1950): *"the time from the Late Cretaceous to Late Eocene was one of widespread emergence accompanied by tectonic movements and pronounced changes in paleogeography…[however], in the Serranía del Interior [Oriental] there was at no time sufficient disturbance to create any strong angular relation between any of the several formations or sufficient erosion to break the normal sequence of formational units or even very markedly reduce individual formation thicknesses"*.

From the above, what did occur in this region in the Late Cretaceous-Paleogene? Our own extensive field and lab studies (Tectonic Analysis, 1990-2005 unpublished data) document widespread Paleogene erosion (unconformity) as well as widespread redeposition of clastic material (low stand wedges) in Eastern Venezuela and Trinidad. But the most severe aspect concerning "orogeny" we can yet point to is the presence of rounded Albian clasts up to 50 cm in size in the Late Eocene-?earliest Oligocene Plaisance unit of the Central Range of Trinidad, which, on the basis of lithology and fauna, we believe originated from Eastern Venezuela. We are still assessing if these clasts were necessarily eroded in a subaerial environment (Serranía del Interior) in the Late Eocene; if so, then the degree of epeiric (non-contractional) uplift must have exceeded 1000-1500 m in order to cut down to the Albian. But if we can satisfactorily accept a submarine mechanism for the rounding, then perhaps a canyon origin is feasible (outer shelf or slope slumping) that requires far less epeiric uplift. At present we prefer the former interpretation, suggesting fairly significant uplift.

Pindell et al. (1991) and Algar and Pindell (1993) explored two different drivers for Paleogene orogenesis in Eastern Venezuela and Trinidad. Pindell et al. (1991) employed the seismic tomography of van der Hilst (1990) to propose south-dipping subduction of Proto-Caribbean crust, which also accounted for the several hundred km of N-S convergence between North and South America since the Maastrichtian which had been documented from Atlantic kinematics by Pindell et al. (1988) and which has been reaffirmed by Müller et al. (1999; Fig. 1). Algar and Pindell's (1993) discussion of the origin of the Northern Range considered that "Proto-Caribbean subduction" model, but developed an alternative model of N-ward downslope gravitational contraction into the Caribbean foredeep as a means of driving Northern Range deformation. The deposition of the Paleogene clastic units could be fit into either model.

However, recent magnetic anomaly and fracture zone picking of the Atlantic basin (Müller et al., 1999) has corroborated the results of Pindell et al. (1988), i.e., that substantial convergence has occurred between North America and South America since the Maastrichtian (Fig. 1B). We continue to believe the effect of this convergence is visible in the seismic tomography (Figures 6D and 6E), namely the subduction of Proto-Caribbean lithosphere beneath northern South America prior to the arrival of the Caribbean Plate from the west. Müller's et al. (1999) corroboration, in conjunction with our field programs in Venezuela and Trinidad, has increased our confidence that a Proto-Caribbean subduction zone has existed along northern South America since the Late Maastrichtian. Further, we believe that the eastern continuation of this Proto-Caribbean trench can be seen in both gravity and basement structure contours where it emerges from the

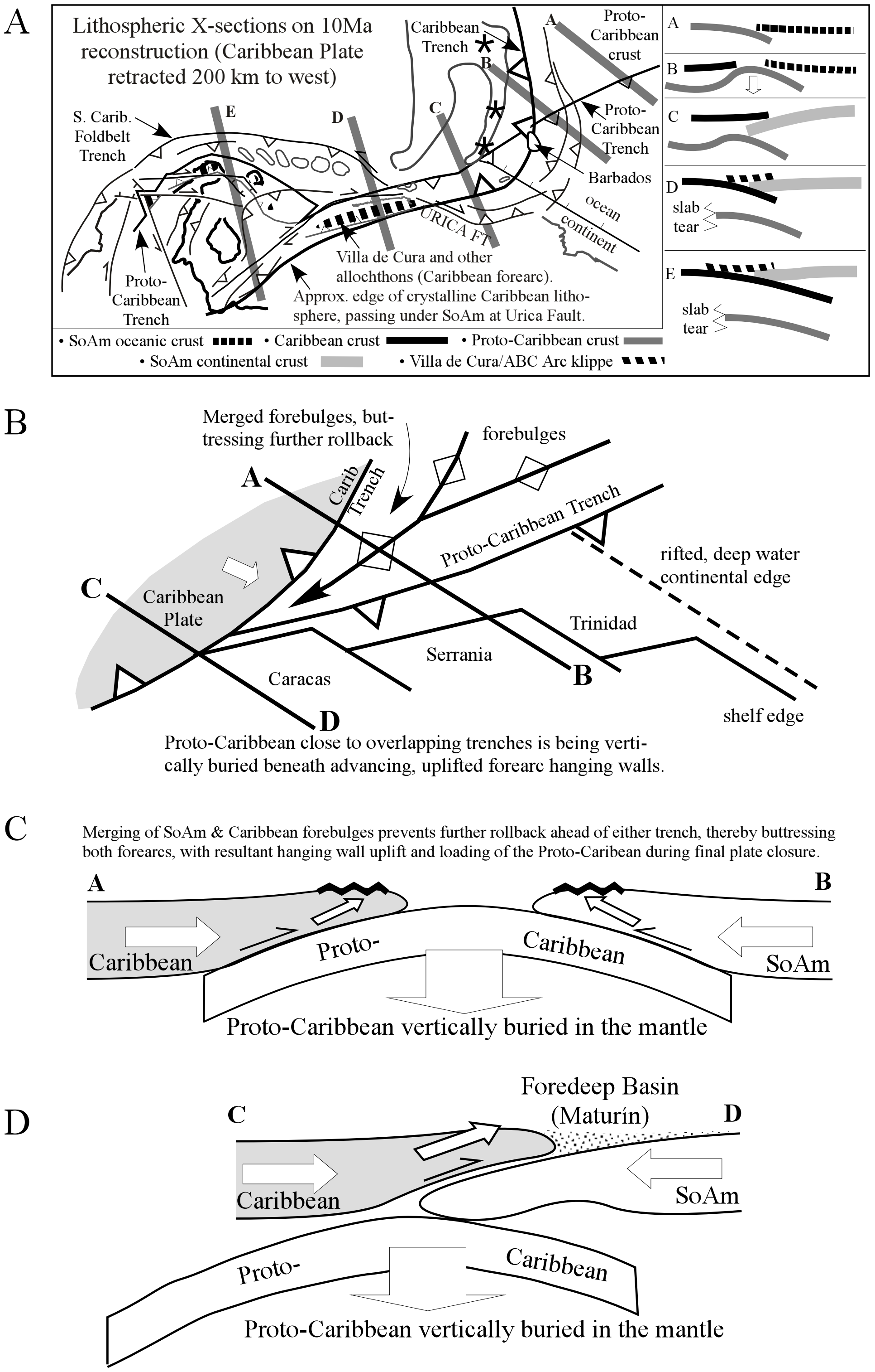

FIGURE 17 **A) History of plate interaction at any point along northern SoAm can be defined by examining N-S cross-sections moving westward on a Mid-Miocene reconstruction (before Morón-El Pilar-Radix Fault system cut across the orogen). In the Maracaibo region, all stages A-E have occurred, but east of Barbados only Stage A has occurred. B) If northern SoAm was a trench hanging wall before the Caribbean collided, then collision was a trench-trench collision, and Pindell's (1985b) arc-continent collision hypothesis in which a migrating forebulge drove diachronous unconformity along northern SoAm must be revised. The revision comprises the vertical burial of the intervening Proto-Caribbean lithosphere as the converging forearcs loaded it (forearcs were strongly uplifted as convergence continued once their forebulges had merged), followed by collision of the Caribbean and South American forearcs. Incision depths on the South American unconformity reached Albian, too deep to be explained by forebulge uplift, but comfortably in line with the expectations of hanging wall uplift. C) Hanging wall uplift mechanism as forearcs begin to merge, and D) south-directed foredeep loading of South American crust once the Proto-Caribbean crust no longer supports the forearcs.**

Barbados accretionary prism at about 14.5°N (Fig. 16), east of the Caribbean Plate.

We can use the seismic tomography to roughly define the existence and position of the Proto-Caribbean slab, as well as the South American hanging wall to this Proto-Caribbean trench which is now largely located beneath the more recently arrived Caribbean Plate. The Maastrichtian geometry of the Proto-Caribbean Seaway can then be restored by connecting at the surface the subducted elements of these lithospheres. We find that such a geometry, whereby the Americas are 400-500 km farther apart than at present, matches well the Maastrichtian relative position of the Americas as defined by Atlantic mag-

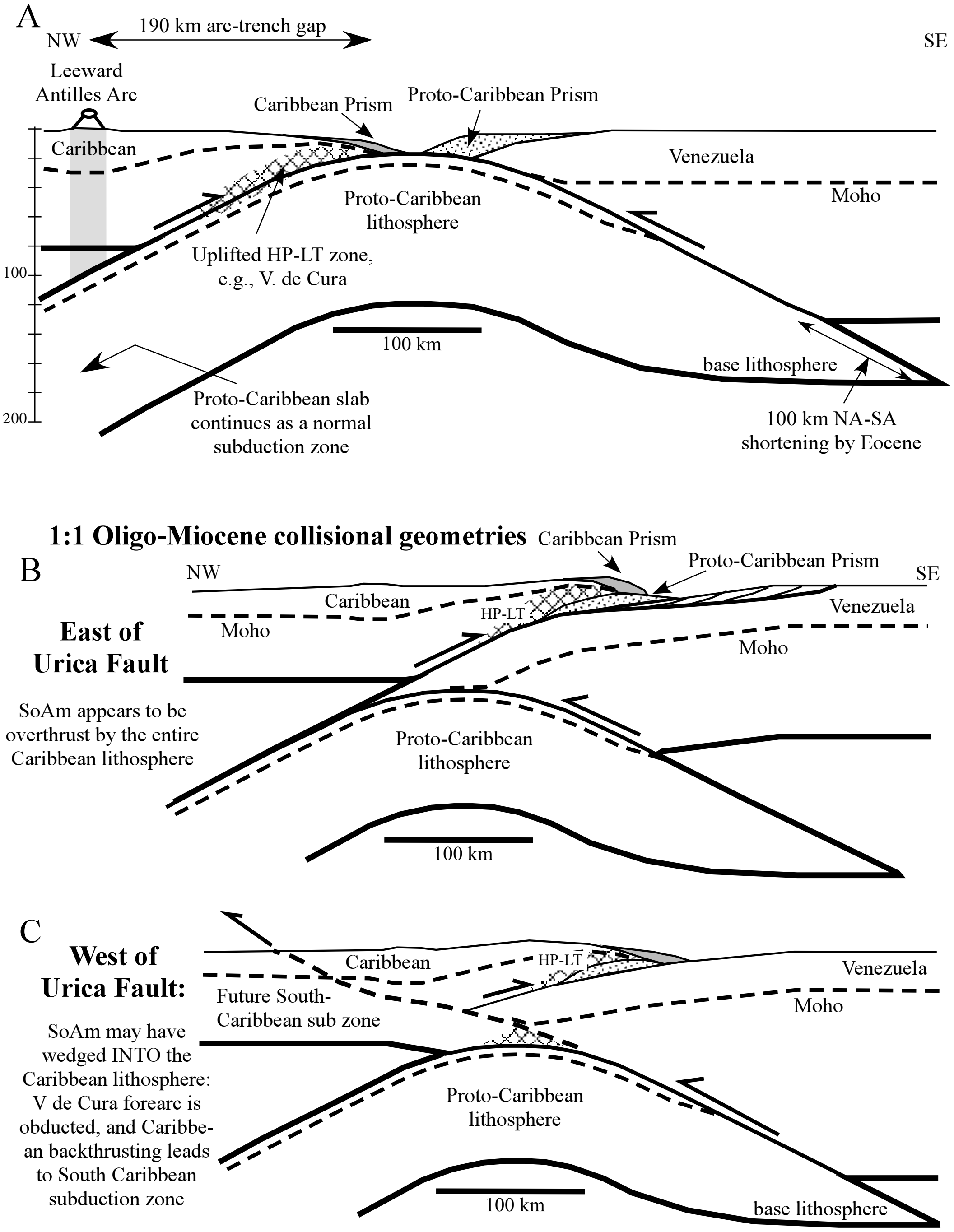

FIGURE 18 | **Lithospheric cross sections before (A) and during (B, C) the Caribbean-South American trench-trench collision to the west and east of the Urica Fault. The obduction of the Villa de Cura Belt and the Oligo-Miocene onset of subduction at the South Caribbean subduction zone may be due to the South American continental hanging wall slab effectively wedging into the Caribbean lithosphere (after Pindell, 2005).**

netics and fracture zones. Thus, it appears that the north-south contraction between the Americas has been taken up by slow, southward dipping, amagmatic subduction of Proto-Caribbean lithosphere beneath northern South America ahead of the Caribbean Plate.

As outlined earlier, the significance of Trinidad's Plaisance conglomerate seems to be that uplift of the easternmost Eastern Serranía was great enough (1500? m) by Late Eocene for the Albian level to have reached the erosional surface, after some 70 km of north-south contraction had occurred at the Proto-Caribbean trench (Pindell and Kennan, unpublished data). The disposition of litho-units on the geological map of the northeastern Serranía allows for such an unconformity, but does not require it because the mid-Miocene to Present erosion level is deeper than that in the Eocene. Figure 17A shows the history of trench-trench collision between the Caribbean and northern South America; Fig. 17B shows the instantaneous plate boundary configuration during trench-trench collision; and Figs. 17C and 17D, respectively, provide an eastwardly diachronous mechanism for strong (kilometric) hanging wall uplift/erosion (Late Eocene unconformity) followed by strong foredeep subsidence (Los Jabillos-Areo-Carapita in Venezuela, Lower Cipero-Nariva-Upper Cipero/Herrera in Trinidad) within that trench-trench collisional history (Pindell, 2004). If we were to examine Fig. 17A in more detail, we would see that a primary structural difference in the Venezuelan margin to the east and west of the Urica Fault is likely that the South American hanging wall has wedged into the Caribbean Plate to the west of the fault, whereas to the east it has not (Fig. 18; Vandecar et al., 2003). This mechanism can account for the obduction of the Villa de Cura Belt (Caribbean forearc) onto South American basement in Central Venezuela.

In Eastern Venezuela and Trinidad, this Proto-Caribbean subduction zone stage of development pre-dated the younger collision with the Caribbean Plate in that area. The Cenozoic evolution of northern South America must be viewed as a diachronous trench-trench collision model rather than as an arc-continent collision model. The merits of the trench-trench collision model are several: (1) it explains the clearly imaged Proto-Caribbean slab subducted beneath northern South America in the seismic tomography (Fig. 6); (2) it accounts for the 250-400 km (increasing from east to west) of Maastrichtian-Present convergence between North and South America (Fig. 1); (3) it provides a Paleogene template for epeiric uplift in which northern South America was the hanging wall to the Proto-Caribbean subduction zone far ahead of the Caribbean Plate, in which tectonically-driven Paleogene unconformities and flyschoid regressive depositional units can be placed (Fig. 17C), (4) it provides an ideal setting for pre-25 Ma, north-vergent deformation and metamorphism in the Araya-Paria Peninsula-Northern Range Terrane, which probably continues into the deep (Paleogene accretion) levels of parts of the Barbados Ridge east of the Northern Range, and which we believe represent the Proto-Caribbean accretionary prism; and (5) it provides a crustal template for understanding the structural difference to the east and west of the Urica Fault Zone (Fig. 18). Although no magmatic arc products are known to have formed during Proto-Caribbean subduction, probably because the amount and rate of Proto-Caribbean subduction was so small (about 400 km in the west and 250 km in the east over some 67 m.y.), the Caribbean-South America collision is better considered as a trench-trench collision than as an arc-continent collision.

DISCUSSION AND CONCLUSIONS

The Gulf of Mexico-Caribbean literature represents many decades of collective effort by hundreds of workers, and working models of Caribbean evolution represent the synthesis of all that effort with well-constrained regional plate kinematic history. We should take care to understand and embrace the merits of what has come before, trying to build upon that knowledge base and incorporating the results of new work into long-established concepts, rather than trying to make radical changes for the sake of impact. The literature is simply too mature for the proposal of ad-hoc regional or subregional models based on small, limited, or local data sets to mean anything significant. Concerning publications, the peer-review process needs to be tightened up: several recent attempts to build "new" Caribbean models violate so much basic geology, ignore so much geophysical and geochemical data, and/or show a lack of understanding of tectonic synthesis, that they cannot be taken seriously. Workers with expertise in certain fields of the geosciences need to team up with others from other fields in order to broaden their collective understanding of geology. Cross-pollenation and sharing of ideas, principles, respect for error limits, and the understanding of geologic processes is a wonderful way to make new progress while at the same time ensuring a firmer foundation beneath that progress.

While numerous unresolved aspects of Gulf or Mexico and Caribbean evolution remain that we have not gone into here, we hope the discussions herein help to put our eight identified points of recurrent, and in our opinion unfounded, controversy to rest. We summarise:

1. The known spreading fabrics of the Atlantic Oceans *do* place tight constraints on regional kinematics and models of Caribbean evolution, with errors often much smaller (< 50 km) than local uncertainties about displacements on particular faults.

2. The southern edge of the Grand Banks (Bahamas) block, which was overthrust by the Cuban forearc terrane in the Eocene, is the north side of the Guyana Escarpment transtensional fault zone, and there was a tight fit between the Grand Bank/Cuban autochthonous basement and northeast South America prior to the Late Jurassic.

3. The Yucatán Block did rotate anti-clockwise away from Florida and Texas as the Gulf opened, creating a tract of oceanic crust that is significantly wider in the western Gulf than in the east, leaving a fracture zone type margin along eastern Mexico, and separating into two parts what was a single Louann-Campeche salt basin prior to the Oxfordian.

4. The oceanic crust of the Caribbean Plate certainly is of Pacific origin, and that crust was situated relatively close to but west of Colombia by Aptian time.

5. The Caribbean large igneous province was not caused by the plate passing over the Galapagos hotspot, and we offer a model for the origin of much of the Caribbean LIP for the Caribbean community to consider that we believe is consistent with far more data than other models.

6. Southwest-dipping subduction was established in the Aptian (125-112 Ma) beneath the Great Arc of the Caribbean, but the details of this development remain sketchy; since then Caribbean-American displacement has been due mainly to the westward drift of the Americas past a Caribbean Plate that is nearly fixed in the mantle reference frame.

7. A single Great Caribbean Arc in which local events and tectonic processes occur within it, such as changes in slab dip, intra-arc spreading, and arc-parallel extension, can explain most of what we know about the Caribbean arc fragments and the history of the Caribbean Plate, although development of a transient Eastern Cuba-Hispaniola Arc to the northeast of the adjacent San Juan Restraining Bend during or following the Great Arc-Bahamas collision is proposed here for consideration.

8. A Paleogene, south-dipping Proto-Caribbean subduction zone did develop along northern South America prior to the progressive oblique collision of the Caribbean Plate along northern South America, and this subduction zone is largely responsible for the occurrence of tectonically-driven low-stand wedge (not strictly flysch) deposits in Eastern Venezuela, Trinidad, and possibly Barbados prior to the arrival of the Caribbean Plate in that area.

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