Kinematic Evolution of the Gulf of Mexico and Caribbean

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Abstract

We present a series of 14 updated tectonic reconstructions for the Gulf of Mexico and Caribbean region since the Jurassic, giving due attention to plate kinematic and palinspastic accuracy. Primary elements of the model are: 1) a re-evaluation of the Mesozoic break-up of Pangea, to better define the Proto-Caribbean passive margin elements, the geology and kinematics of the Mexican and Colombian intra-arc basins, and the nature of the early Great Caribbean Arc; 2) pre-Albian circum-Caribbean rock assemblages are reconstructed into a primitive, west-facing, Mexico-Antilles-Ecuador arc (initial roots of Great Caribbean Arc) during the early separation of North and South America; 3) the subduction zone responsible for Caribbean Cretaceous HP/LT metamorphic assemblages was initiated during an Aptian subduction polarity reversal of the early Great Arc; the reversal was triggered by a strong westward acceleration of the Americas relative to the mantle which threw the original arc into compression; 4) the same acceleration led to the Aptian-Albian onset of back-arc closure and "Sevier" orogenesis in Mexico, the western USA, and the northern Andes, making this a nearly hemispheric event which must have had an equally regional driver; 5) once the Great Caribbean

Arc became east-facing after the polarity reversal, continued westward drift of the Americas, relative to the mantle, caused subduction of Proto-Caribbean lithosphere (which belonged to the American plates) beneath the Pacific-derived Caribbean lithosphere, and further developed the Great Arc; 6) Jurassic-Lower Cretaceous, "Pacific-derived", Caribbean ophiolite bodies were probably dragged and stretched (arc-parallel) southeastward during the Late-Jurassic to Early Cretaceous along an [Aleutian-type] arc spanning the widening gap between Mexico and Ecuador, having originated from subduction accretion complexes in western Mexico; 7) a Kula-Farallon ridge segment is proposed to have generated at least part of the western Caribbean Plate in Aptian-Albian time, as part of the plate reorganisation associated with the polarity reversal; 8) B" plateau basalts may relate to excessive Kula-Farallon ridge eruptions or to now unknown hotspots east of that ridge, but not to the Galapagos hotspot; 9) a two-stage model for Maastricthian-early Eocene intra-arc spreading is developed for Yucatán Basin; 10) the opening mechanism of the Grenada intra-arc basin remains elusive, but a north-south component of extension is required to understand arc accretion history in western Venezuela; 11) Paleocene and younger underthrusting of Proto-Caribbean crust beneath the northern South American margin pre-dates the arrival from the west of the Caribbean Plate along the margin; 12) recognition of a late middle Miocene change in the Caribbean-North American azimuth from E to ENE, and the Caribbean-South American azimuth from ESE to E, resulted in wholesale changes in tectonic development in both the northeastern and southeastern Caribbean plate boundary zones.

Introduction

The Gulf of Mexico and Caribbean region has evolved largely within or adjacent to the area created by the separation of North America, South America and Africa since the Jurassic breakup of Pangea. Despite the excellent quality of plate kinematic data from this region, compared to many others, key aspects of the tectonic history remain subject to controversy. In this paper, we present an updated series of tectonic evolutionary maps, highlighting many of the model's implications across the region, and identifying some remaining problems needing further attention.

Kinematic and palinspastic aspects of the methodology for unravelling the tectonic evolution of Meso-America and northern South America were recently reviewed by Pindell *et al.* (2000a, b, c, d), and will only be briefly summarized here. Of primary importance are the motions of the North American, South American and African Plates: plate kinematic analysis of this region not only provides the geometric framework in which to develop paleogeographic evolution, but it also constrains the primary setting, style and timing of basement structure in the region's continental margins. We employ the Equatorial Atlantic reconstruction of Pindell (1985), the Jurassic-Campanian opening histories for the Central and South Atlantic oceans of Pindell *et al.* (1988), and the Campanian-Recent opening histories for the same of Müller *et al.* (1999). Also important is the restoration of pre-tectonic shapes of the continental blocks involved in the model. For instance, to achieve a satisfactory palinspastic reconstruction of the northern Andes, we retract 150km of dextral shear from Venezuela's Mérida Andes faults, 110km of sinistral shear from Colombia's Santa Marta Fault and 120km of dextral shear from Colombia's Oca fault zone (*e.g.*, Dewey and Pindell, 1985, 1986; Pindell *et al.*, 2000b), in addition to undoing Andean-aged shortening within the Eastern Cordillera and Perijá Range of Colombia and within the Mérida Andes of Venezuela. We also must restore the effects of intra-continental extension in the various continental margins such as those in the Gulf of Mexico (Pindell, 1985; Dunbar and Sawyer, 1987; Marton and Buffler, 1994); and northern South America (Pindell *et* *al.*, 1998). Finally, we must remove oceanic and island arc terranes accreted to the continental margins (*e.g.*, parts of Baja California, Amaime, Ruma and Villa de Cura terranes of Colombia and Venezuela, Piñon Terrane of Ecuador, etc).

A consensus of opinion is emerging for the earlier (Jurassic) and later (Cenozoic) parts of the tectonic evolution of Meso-America. It is now widely accepted that the Gulf of Mexico and Proto-Caribbean seaways opened by Jurassic-earliest Cretaceous counterclockwise rotation of Yucatán away from North and South America as those continents diverged (Pindell and Dewey, 1982; Pindell, 1985; Schouten and Klitgord, 1994; Marton and Buffler, 1994; Pindell *et al.*, 2000d) and that the Caribbean Plate has moved a large distance to the east relative to the Americas during Cenozoic time (Hess, 1953; Malfait and Dinkleman, 1972; Burke *et al.*, 1978; Pindell *et al.*, 1988). However, the Cretaceous portion of the history continues to be made obscure by two ongoing arguments that we consider erroneous: (1) that the B" [basaltic] seismic horizon of the Caribbean Plate was produced by the plate passing over the Galapagos hotspot in mid-Cretaceous time (Duncan and Hargraves, 1984), and (2) that the Caribbean crust derives from Proto-Caribbean crust that was originally generated by seafloor spreading between the Americas (James, 1990; Klitgord and Schouten, 1986; Meschede and Frisch, 1998).

This paper takes the intermediate position, arguing that the Caribbean crust is of Pacific (Pindell, 1990) rather than of Proto-Caribbean (intra-American) origin, but that it was not far enough west relative to North America during mid-Cretaceous time to have encountered the Galapagos hotspot. We also strengthen the case for Aptian-Albian subduction polarity reversal (Mattson, 1979; Pindell and Dewey, 1982; Pindell, 1993; Snoke *et al.*, 1991; Draper *et al.*, 1996) in the Great Caribbean Arc (Burke, 1988), and build an updated Gulf-Caribbean tectonic model in a series of plate reconstructions that will help to guide more local studies and provide hypotheses to test around the region. In particular, it is seen that Cordilleran geology and geological history from California to Peru are directly related to Gulf and Caribbean evolution. Farther east, the geology of Venezuela and Trinidad shows primary influences of Jurassic rift history, Paleogene convergence between North and South America, and Neogene interaction with the leading edge of the Caribbean Plate.

Pacific vs Intra-American Origin for the Caribbean Plate

Even though ongoing debate over whether the Caribbean Plate was derived from the Pacific or the intra-American (Proto-Caribbean) realm regards mainly the Early Cretaceous time interval, we start here by examining this question first because it directly affects how we might interpret the overall evolution of the entire region. Pindell (1990) outlined seven arguments for a Pacific origin of the Caribbean Plate, all of which remain valid. Here, we identify a number of additional implications in the two models, and show that only those from the Pacific model are supported by regional geology.

Pacific-origin models predict that:

1) the Antillean ("Great Caribbean ") arc originated along the western boundary of the Americas and has roots at least as old as Jurassic, recording eastward dipping subduction of ocean crust from the Pacific;
2) arc-polarity reversal occurred in the Great Caribbean Arc, which we argue is of Aptian-Early Albian age, such that a younger (Late Cretaceous-Paleogene) arc is built upon the older arc;
3) the Panama-Costa Rica arc nucleated on oceanic crust (not an older arc) in the mid-Cretaceous;

4) passive margin conditions persisted in northern South America (north of central Ecuador) until 80-90 Ma.

In contrast, Intra-American-origin models predict that:

1) the Panama-Costa Rica Arc is the oldest arc in the Caribbean, having at its roots the arc that had existed since at least the Jurassic in the western Americas;
2) the Greater Antilles Arc is post-Albian only, and is built on Jurassic and/or Cretaceous Proto-Caribbean oceanic crust without any older arc foundation;
3) Northern South America, including all of Colombia and western Venezuela, was close to the Antilles Arc and directly affected by Caribbean tectonics since the Albian;
4) the Caribbean Plate was generated by seafloor spreading between the Americas, the rate and direction of which can be determined from Atlantic magnetic anomalies (Pindell *et al.*, 1988).

In contrast to the predictions of intra-American models, Panama is clearly not the oldest arc in the Caribbean, having started no earlier than Albian time (Calvo and Bolz, 1994, Hauff *et al.*, 2000). In contrast, Cuba, Jamaica, Hispaniola, Puerto Rico/Virgin Islands, Tobago, Margarita, and parts of the Venezuelan.Colombian allochthons (the Great Caribbean Arc) all comprise primitive arc rocks of Early Cretaceous age, which are overlain and intruded by Albian and younger calc-alkaline arc rocks (Maurrasse *et al.*, 1990; Donnelly *et al.*, 1990; Lebron and Perfit, 1994; Pindell and Barrett, 1990 and references therein). Also, passive margin conditions were maintained in Colombia and western Venezuela until Campanian to Maastrichtian, rather than Albian, times (Villamil and Pindell, 1998). Further, the Proto-Caribbean Seaway was not large enough to hold the known surface area of the Caribbean Plate until the Campanian (Pindell *et al.*, 1988; Müller *et al.*, 1999) and, in addition, intra-American models do not account for the enormous area of Caribbean Plate which must have been subducted beneath Colombia and western Venezuela as indicated by seismic tomography (van der Hilst and Mann, 1994). Finally, seismic data (*e.g.* Driscoll and Diebold, 1999) argue against seafloor spreading in the Caribbean Plate as young as Campanian, indicating instead that widespread oceanic plateau basalts were built up on a pre-exisiting ocean floor from *ca.* 90 Ma. Limited age data from areas such as the Piñon Terrane in Ecuador (*e.g.* Reynaud *et al.*, 1999) indicate that this ocean floor is likely to be 125 Ma or older. From the above points, the predictions made by intra-American models are incompatible with well known regional geology and geophysical data. Furthermore, the original seven arguments for a Pacific origin cited by Pindell (1990), in addition to those noted above, can only be explained by a Pacific origin for the Caribbean Plate. Therefore, we begin our series of reconstructions below working from this basic premise.

Early Motions Of Pacific Plates And Caribbean Evolution

Interaction between the Americas, which have roughly drifted westwards across the mantle from Africa since the break up of Pangea, and the oceanic plate(s) of the Pacific *sensu lato* have determined much of the course of the tectonic evolution of western Meso-America and Latin America. Unfortunately, due to possible early Paleogene fault motions within Antarctica, assessments of the motions of Pacific realm plates can be treated with confidence only back to the Eocene, and with caution back to the Campanian. During and prior to the Cretaceous magnetic quiet period, control is very poor. Prior to then, only relative motions of the plates in a "hotspot reference frame" are available, and these are disputed because it is not clear if Pacific and Atlantic-Africa hotspots have been fixed with respect to each other (*e.g.* Tarduno and Cotrell, 1997). However, given largely north to south apparent motion of the hotspots in some recent models (Steinberger, 2000) several of the essential features of fixed hotspot models (such as Engebretson *et al.*, 1985, pers.comm., 1999; and Kelley, 1993) remain reasonably valid.

Overall, the Kula and Farallon plates interacted with North America with a sinistral component for Jurassic to ?Aptian time (~100-120 Ma), and with a dextral component thereafter. Regions of Jurassic-Early Cretaceous oceanic crust, part of which may have been the oceanic "basement" of the Caribbean Plate, may thus have moved southeastwards from a Boreal position (Montgomery, *et al.*, 1994) to arrive at the tropical (Tethyan) entrance to the intra-American gap by 120 Ma, after which time the change in relative motion in the hotspot reference frame would be consistent with models arguing for northeastward migration of Caribbean crust into the intra-American gap, after a polarity reversal from east-dipping to west-dipping subduction (see below).

To improve on this constraint we take a rather different approach. Interaction of the Caribbean Plate with northern South America and southern Yucatán from Late Cretaceous time has already been documented (Rosenfeld, 1993; Pindell *et al.*, 1988; Villamil and Pindell, 1998). In the absence of contradictory evidence, we judge that prior to this time the number and tectonic style of plate boundaries remained essentially similar back to at least 120 Ma. We have integrated this judgement with geological data (timing of arc activity and shut-off, onset of compression, *etc.*) from southern and western Mexico and from Peru, Ecuador and Colombia to predict the position of the leading and trailing edges of the Caribbean Plate back to the Aptian, at which time it lay entirely within the Pacific realm. The geological data also lead us to propose a fundamentally different, new model for the intra-oceanic plate boundaries that allowed the Caribbean Plate to become differentiated from its Pacific oceanic parents (see below).

The Plate Kinematic Model

We present our internally consistent, kinematically rigorous summary of the region's plate tectonic evolution in mainly diagrammatic form, presenting below only a brief outline which covers key points and arguments supporting our kinematic reconstructions and plate boundary arrangements. For more comprehensive coverage of the region's geology and aspects of its sub-regional tectonic evolution, he reader is directed to: Burke (1988), Dengo and Case (1990, and papers therein), Donovan and Jackson (1994, and papers therein), James (1990), Kennan (1999), Litherland *et al.* (1994), Mann (1999, and papers therein), Mann and Burke (1984), Marton and Buffler (1994), Pindell (1985; 1993), Pindell and Barrett (1990); Pindell and Drake (1988, and papers therein), Salfity (1994, and papers therein), Sedlock (1993), Villamil (2000).

Triassic-Jurassic

We start with an outline of the Jurassic rift history of Western Pangea. Figure 1 shows an Early Jurassic reconstruction of western Pangea, not long after the onset of continental rifting (Eagle Mills and other basins), immediately prior to the onset of ocean crust formation in the Central Atlantic. Note that restored positions of African and South American coastlines are shown, relative to a fixed North America. The close fit between the Demerara Plateau offshore Guyana and the Guinea Plateau prior to 120 Ma produces a match between the Guyana Fracture Zone and a conjugate margin defining the southern edge of Bahamian continental crust (now buried by the central Cuban "arc" assemblages which we consider to be the forearc of the Great Caribbean Arc). Northwest South America must have covered all of the present-day positions of southern and central Mexico; thus, the terranes of southern and central Mexico must have been displaced at this time to the northwest. Restoration of some 700 km of pre-Oxfordian motion on the "Sonora-Mojave Megashear" (Anderson and Schmidt, 1983) avoids the overlap, and is consistent with offset markers in that region and with paleomagnetic data (*e.g.* Böhnel, 1999).

The position of Yucatán prior to opening of the Gulf of Mexico overlaps the Gulf coast of Texas. Alternative Yucatán positions are not compatible with the regional geology and there is no other suitable candidate block to fill the void between the Texas continental margin and the pre-rift position of South America. The positions of other continental blocks are also constrained by the overlap. Chortis must have lain NW of Colombia and south of southwestern Mexico, and parts of Baja California may have lain to the west. Continental basement fragments of Cuba (Isle of Pines, Escambray), including possible Late Jurassic HP/LT rocks that may be correlative to those in Baja-California, probably lay south of Chortis Block at this time. Quartz-sandstones from these areas, now metamorphosed, are similar in age to the Agua Fria sandstones in Guatemala (Gordon and Young, 1993) and may derive from the early Chortis shelf margin. To the south, Isla Margarita may have lain at the northern end of the continental-cored Andean Arc and in the Cretaceous back-arc (see also Fig. 8 below). The continental overlap problem of western Africa and southern Florida-western Bahamas (Fig. 2; Pindell, 1985) is avoided by retracting both a considerable amount of intra-continental extension and transform shear along the Bahamas Fracture Zone. Sinistral motion on this fracture zone appears to at least partially step across the Tampa Embayment "pull-apart" basin (note gravity signature of this basin in Klitgord *et al.*, 1984) to the Florida Escarpment Fault. Early rifting between Colombia and Mexico provided the pathway for the marine incursion signalled by the Huayacocotla Fm of Eastern Mexico.

As the Atlantic opened and rifting progressed in the Gulf (in Bathonian time, Fig. 3), we employ about 18° of anticlockwise rotation of Yucatán about the pole of rotation, prior to the

Oxfordian. This also affected the northeast Gulf, indicated by basins opening behind the rotating Wiggins and Middle Grounds Arches. The rotation away from Texas was complemented to the south by clockwise rotation of Yucatán away from Venezuela. Although poorly exposed, a number of indicators support the existence of a Jurassic marine margin in northern South America (Pindell and Erikson, 1994). During ongoing ESE-shearing within Mexico, the Chiapas Massif moved into a position offshore East Mexico, and the Chuacús Block started to converge with the Chiapas Massif. Note that this model infers only modest dextral offset between Chiapas Massif and Yucatán during the Early Jurassic along faults which lie below the Chiapas Foldbelt –we expect no large offset transform in this area. The continuation of the Mojave-Sonora Megashear, prior to 158Ma, is inferred to pass south of the Chiapas Massif, forming the early boundary with the Chuacus terrane of Guatemala.

By Early Oxfordian, (158 Ma; Fig. 4), South America had moved far enough away from North America for Yucatán to have rotated into a position that neatly reconstructs known salt occurrences from the northern (Louann) and southern (Campeche) Gulf. A second evaporite basin, with significantly lesser amounts of salt, can be reconstructed in the composite Bahamas, Takatu, Paria, Guinea Plateau region. By this time, crustal stretching had reached the point where ocean crust began to form in the early, evaporite-bearing Gulf and Proto-Caribbean Basins. MORB-type pillow basalts are known from western Cuba (Pszczolkowski, 1999) and ocean crust underlies the central Gulf of Mexico (Marton and Buffler, 1999).

A fundamental change in kinematic pattern occurred at this time. Moving Yucatán from its Oxfordian to its final position relative to North America involved a southward propagating rift in the eastern Gulf (Pindell, 1985; Marton and Buffler, 1994), and about 30° of rotation about a pole between Florida and Yucatán (Marton and Buffler, 1994). Yucatán was now bounded on the west by the East Mexican Transform which cut west of Chiapas Massif and south towards the Cuicateco terane of the Tehuentepec region. The pole of rotation inferred for Yucatán indicates that this transform would pass through the region occupied by the present day Veracruz Basin, and is possibly buried beneath the Veracruz and Cordoba Massif thrust fronts. The model indicates that oceanic crust should be present to the east of the transform, with correspondingly higher early heat flow than the slightly stretched continental crust to the west of the transform. The transform is obscured by the young Tuxtla volcanics and passes to the west of the Chiapas Massif; we expect no major transform to lie on its east side.

Narrow, NNW-SSE trending troughs within the Sierra Madre Oriental of Mexico are probably transtensional basins adjacent to the main transform (with strain partitioning). At about this time back-arc spreading also propagated into central Mexico, which we suggest was oriented more or less north-south. Such an orientation for Late Jurassic crustal motions in Mexico, parallel to those of Yucatán relative to Mexico, is supported by the lack of observed convergent deformation. There is no evidence of collision of southern and central Mexican blocks with Yucatán which would have resulted had motions within Mexico remained SE-directed; rather, the widespread occurrence of shale and carbonate at this time in southern Mexico (Salvador, 1991) argues for fairly regional subsidence. It also allows us to suggest a highly extended backarc region, as indicated by ophiolites and deep-water sediments along the western Sierra Madre Oriental, while later avoiding the need for overly large Cretaceous shortening values in the Laramide Orogeny. Thus, Mexico's basement probably has a N-S extensional grain, while later shortening in Sierra Madre Oriental was E-W.

By Tithonian (Fig. 5), seafloor spreading in the central Gulf was forming a tectonic grain that was different to that created during the earlier rifting. In the east, the long sinistral transform between the Bahamas and Guyana margins was probably thrown into transpression (Erikson and Pindell, 1998) as suggested by a kink in Atlantic fracture zones (Klitgord and Schouten, 1988). To the south, the Colombian Marginal Seaway (Pindell and Erikson, 1994) continued to widen. Rifting was probably also underway along the Andean back-arc basin of Ecuador and Peru. The widening gap between Mexico and Ecuador was bridged by a west-facing arc system that probably underwent strong arc-parallel stretching and terrane migration from west of Chortis and Mexico. These terranes probably possessed the Jurassic/Early Cretaceous ophiolites of Pacific affinity now found in Hispaniola, La Desirade, and Puerto Rico (Montgomery *et al.*, 1994).

Early Cretaceous

Only by the Early Cretaceous, ~130 Ma (Fig. 6), had North America pulled sufficiently far away from South America for Yucatán to occupy its final position. Initially, the Gulf of Mexico spreading center may have been genetically related to that farther south, but by 130 Ma it had become detached from the deep mantle flow that presumably still accommodated spreading in the Proto-Caribbean. The end of Yucatán's rotation may have allowed a single, slightly re-organised Proto-Caribbean ridge system to connect the Colombian/Andean backarc with the Atlantic ridge system. Matching the end of spreading in the Gulf, backarc extension in Mexico seems to have slowed or halted, as no younger faulting is known in the Sabinas or Parras basins from this time. Note also that we interpret the Cuicateco Terrane, floored by or at least possessing oceanic crust, to lie immediately west of Chiapas, where the stretching in the Mexican backarc, which locally produced basalt floored basins, meets the northwestern corner of the Colombian Marginal Seaway.

Figure 7 (~120Ma, Aptian), is the first map to identify Caribbean crust in the Pacific realm. At approximately 120 Ma, a reversal of subduction direction between the Americas occurred, as interpreted from thermochronological data from metamorphic rocks (Maresch *et al.*, 1999; Stanek *et al.*, 2000), stratigraphic changes in the Antilles (Fig. 8), and correlation with Sevier orogenesis and onset of backarc closure in the adjacent Mexican and Andean backarc basins. This nearly hemispheric event was caused by the documentable acceleration of spreading in the Atlantic (Klitgord and Schouten, 1988; Pindell *et al.*, 1988, Pindell, 1993), and a corresponding onset of convergent arc behavior (in the sense of Dewey, 1980, where the overriding plate advances toward the trench faster than the trench can roll back, and hence overthrusts it with "compressional behavior") at the Cordilleran arc system from Peru to Canada (Cobbing *et al.* 1981; Pindell, 1993; Sedlock, 1993). The timing of the polarity reversal is constrained to the Aptian, and the effects include a dramatic switch from primitive to calc-alkaline island arc magmas (Donnelly *et al.*, 1990; Lebron and Perfit, 1994), orogeny in Hispaniola (Draper *et al.*, 1996) and Tobago (Snoke et al., 1991), and establishment of a new east-facing subduction zone in which most of the Caribbean's HP/LT metamorphic suites were generated (*e.g.*, Escambray, Purial, Puerto Plata, Rio San Juan, Margarita, Villa de Cura, *etc.*).

The idea that the polarity reversal was driven by the arrival of the buoyant Caribbean Plate along the arc (*e.g.*, Burke, 1988) requires that the reversal occurred later, because the age of the B" material associated with Caribbean crustal thickening is generally 30m.y. younger (Diebold and Driscoll, 1999) than the age invoked here. We discount such a younger age for the reversal, based on: (1) the Aptian age of gross changes in Caribbean arcs (Fig. 8; and lack thereof for later Cretaceous times), (2) the fact that Caribbean HP/LT metamorphic assemblages along the east side of the Great Caribbean Arc range in age from Aptian through Late Cretaceous (hence, east-facing trench must have existed by end of Aptian), and (3) clear stratigraphic indications of Caribbean-American interactions starting by Cenomanian time (as discussed below; hence, the reversal must pre-date the Cenomanian in order for Caribbean terranes to be able to approach the American margins).

The development of intra-oceanic arc systems extending from Costa Rica (Calvo and Bolz, 1994) to Ecuador (Lapièrre *et al.*, 2000) indicates that the Caribbean Plate became separated from the Farallon Plate by perhaps 120 Ma and from then probably moved more slowly NE or E relative to North America. Pacific models for the Caribbean have usually assumed that the Caribbean Plate was first isolated on the west by inception of a proto-Costa Rica-Panama arc and that this arc extended from Mexico in the north to Peru in the south. However, the shape of such an arc would need to become excessively convex farther back in time, when the Caribbean lay far out in the Pacific relative to North America (Fig. 9). At the same time, most models for Pacific spreading history (*e.g.* Engebretson *et al.*, 1985) recognise, from at least 84 Ma, the presence of a Farallon-Kula spreading center in the eastern Pacific, often shown intersecting the trench somewhere off western Mexico. By analogy with the development of the Cocos Plate during the Miocene (Wortel and Cloetingh, 1981), we suggest that this arrangement was probably inherently mechanically unstable. We speculate that the northwestern boundary of the Caribbean Plate may have been an early Kula-Caribbean spreading center (analogous to the spreading centers between Cocos and Nazca Plates) while the southwestern boundary was a sinistrally transpressional trench that evolved from an unstable ridge-ridge-transform triple junction (Fig. 9). We suggest that the Aptian polarity reversal and plate reorganisation noted here may be a general phenomenon which occurs in widening oceanic gaps between two separating continents: we note that a similar history must also have occurred in the Scotia Sea area between southern South America and Antarctica.

The early Costa-Rica-Panama plate boundary may initially have used a pre-existing transform fabric which became compressional because the new Caribbean Plate did not move NE-wards as fast as the Farallon Plate did. At about 120 Ma this boundary of the Caribbean Plate intersected the South American Trench in central Peru. Subduction and arc activity continued to the south but shut off in northern Peru. We infer that the Piñon Terrane (currently in Western Ecuador) was part of the southern Caribbean consistent with paleomagnetic data and the presence of island arc volcanics. Not far to the west lay the basement of present-day central America (shown as heavy dashed lines in Fig. 7). We infer that the Sechura and Talara Blocks of northern Peru lay at least 200 km south of their present positions and also that the Antioquia Block of Colombia lay in the area occupied by present-day western Ecuador. By this time, the Andean back-arc had also reached its maximum width. An arc founded on continental crust lay to the west (Chaucha Terrane, Litherland *et al.*, 1994) currently separated by an ophiolite belt (late-Jurassic to early Cretaceous ages) from the Eastern Cordillera.

Unfortunately, it is nearly impossible to use accurate Pacific or Farallon motions with respect to the Americas to refine this basic model. Engebretson's (1985) or Müller's (1993) fixed hotspot models both have significant problems. Neither are consistent (DiVenere and Kent, 1999) with plate-circuit models, (*e.g.* Stock and Molnar, 1988). Palaeomagnetic data and inconsistent traces and modelling of deep mantle convection (*e.g.* Steinberger 2000) show that hotspots can and do move. Plate-circuit models unfortunately are also not particularly reliable past 43 Ma because the magnitude of rifting, not accounted for in plate circuit models, now known between east and west Antarctica is not clear (Cande *et al.*, 2000).

By 100 Ma (Fig. 10), relative eastward advance of Caribbean Plate was driving closure of the Andean back-arc – indicated by early deformation in Peru (Cobbing *et al.*, 1981), onset of uplift and unroofing in the Eastern Cordillera of Ecuador (Litherland *et al.*, 1994), coarse clastic sedimentation in adjacent basins (*e.g.* Berrones *et al.*, 1993) and overthrusting of the Amaime Terrane (interpreted here as Early Cretaceous back-arc basalts) onto the Antioquia Batholith in Colombia. To the north, central Cuba had started to migrate east with respect to Chortis, and poorly characterised Aptian-Albian deformation is also known in southwesternmost Mexico. Continental and adjacent ocean crust close to the northern end of the Andean back-arc may have been overridden by the NE-migrating (relative to North America) Caribbean Plate, creating HP/LT metamorphic terranes now found in Margarita (Stöckhert, *et al.*, 1995; Maresch *et al.*, 1999). Continued rapid separation of the Americas resulted in more or less head-on subduction in the NE Caribbean while dextral strike-slip dominates over compression in Ecuador and Colombia (see vector inset on Fig. 10). Almost all of the convergence between the Caribbean Plate and South America can be accounted for by the onset of shortening and back-arc closure in the Andes. Note that the area of Caribbean crust which *will* be subducted remains almost unchanged from 120 Ma to 84 Ma (based on tomography data of van der Hilst, 1990, which shows a slab only large enough for Tertiary Caribbean subduction beneath South America). In our revised western boundary area, in Costa Rica, an unstable triple junction has started to break up and ridge-related pillow basalts may underlie earliest true arc in Costa Rica (Fig. 9). To the north of Costa Rica, we show the Kula-Caribbean spreading center intersecting with the Chortis Block and note that this is consistent with an absence of arc volcanism in that area persisting through the Cretaceous.

By Campanian time (Fig. 11, 84Ma), the rate of spreading in the Proto-Caribbean had started to drop dramatically (Pindell *et al.*, 1988), and this resulted in the South America-Caribbean boundary becoming more compressive. This triggered a significant increase in cooling rates (due to uplift) throughout the Central Cordillera of Colombia and Ecuador and accretion of oceanic terranes to the Ecuadorian Andes. In Mexico, highly oblique motion between Kula Plate and Mexico triggered initial northward migration of Baja California (Sedlock *et al.*, 1993). The Chortis Block probably started to migrate east as indicated by onset of uplift and cooling in SW Mexican granitoids (Schaaf *et al.*, 1995) and the onset of uplift and deposition of continental clastic sediments in southern Mexico (Meneses-Rocha *et al.*, 1994). Subduction may have accelerated at the Costa Rica-Panama Arc, initiating significant arc volcanism. This arc now started to move towards Mexico and Chortis as the Caribbean migrated NE. In contrast to models showing a trench connecting with Chortis, the present model involves subducting young oceanic crust which may explain why there is no sign of an accreted arc of late Cretaceous age in Southern Mexico. We also note that palaeomagnetic data on the oldest tested rocks from this interval (Acton *et al.*, 2000) indicates that the newly erupted Caribbean Plateau Basalts (see below) in the vicinity of the Hess Escarpment lay 10-15° south of their present latitudes. This is consistent with the position for the plate as shown in our map but is not consistent with intra-American (*e.g.* Meschede and Frisch, 1998) models where this portion of the Caribbean would lie much closer to Chortis.

From *ca.* 90 Ma through to *ca.* 70 Ma hotspot volcanism occurred sporadically around the Caribbean. The suggestion by Duncan and Hargraves (1984) that the Caribbean B" basalt horizon was emplaced as a result of the plate passing over Galapagos hotspot in mid-Cretaceous time does not appear to be possible. Caribbean-American interactions had begun by Cenomanian time: in southern Yucatán we note the effects of forebulge uplift ahead of the Caribbean Plate by Cenomanian time (Coban A/B unconformity; Meneses-Rocha, pers. comm., 2000), and evidence for roughly 100Ma Andean interactions were noted above. Thus, by 100Ma, the Caribbean Plate lay close to the western margins of the Americas. The position of the Galapagos Hotspot (assuming it is representative of the hotspot reference frame) relative to North America (Fig. 12) has been calculated according to several recent models. Note that the largest uncertainties between the models are N-S rather than E-W. Also models for mobile hotspots also indicate N-S wander. Thus, we feel confident in asserting that the Galapagos Hotspot, if it even existed at this time (90 Ma would be unusually long-lived), was always well west of the Caribbean Plate: we cannot reconcile the Caribbean Plate supposedly lying in two places at one time. Cretaceous hotspot volcanism does, however, appear to have been highly widespread. Mid-Cretaceous hotspot volcanics are known from the subsurfaces of Texas, possibly from Mexico, the Amazon Basin, and the Oriente Basin of Ecuador. It may be possible that another (now subducted and extinct) hotspot was present in the paleo-Caribbean area (of Fig. 11) that we can no longer recognize.

By Maastrichtian time (Fig. 13, 72 Ma), the position of the Caribbean Plate is well-constrained in the north by development of the Sepur foredeep basin and accretion of the Santa Cruz and other ophiolites (fragments of proto-Caribbean origin, part of the leading edge of the Caribbean Plate on the NE side of the arc; Rosenfeld, 1993). Its position in the south is also well-constrained at this time by the overthrusting known to affect the Guajira Peninsula of NW Colombia (Ruma Metamorphic Belt, Case *et al.*, 1990). Note that in all the Cretaceous maps, we have restored Tertiary displacements between the fragments of the Greater Antilles (Eastern Cuba, Hispaniola, Puerto Rico, Aves Ridge; Pindell and Barrett, 1990), which we suggest is necessary for the Caribbean Plate to have passed neatly through the Yucatán-Guajira "bottleneck" at this time.

The leading edge of the Caribbean Plate came through the Yucatán-Guajira gap as Proto-Caribbean crust continued to enter the Great Arc trench. Volcanism occurred in much of the arc but was dormant in central Cuba, possibly because the subduction angle of the stretched? Yucatán margins was too low, or because the volcanic axis shifted farther south of present-day central Cuba (*i.e.*, rocks of central Cuba are mainly from the forearc). NE-directed motion between Chortis and the Caribbean Plate produced NE-directed subduction (contrast area of Caribbean Plate shown on Figs. 13 and 14) beneath central Chortis and arc volcanism which extended as far east as Jamaica. NE-motion of the Caribbean also drove pull-apart formation farther east, extending and rotating Jamaican blocks before or during the accretion of the Blue Mountains blueschists (possible fragment of Caribbean Plate, too young to be part of the Proto-Caribbean crust).

If we reconcile our calculated Caribbean Plate positions with one of a number of possible Pacific plate motion models (Engebretson *et al.*, 1985) we are required to reorganize the orientation of the Kula-Caribbean spreading center at this time. One result of this (also seen in other plate motion models) is that subduction became more head-on in Mexico, driving final closure of the Mexican back-arc basin and causing deformation to propagate as far east as the rear of the Sierra Madre Oriental.

Similarly in Colombia, enhanced (initiation of?) subduction of Caribbean Plate beneath Colombia resulted in NE-migration and uplift of the Antioquia Block, shedding sediments into the Upper and Middle Magdalena basins. Northward migration of a Caribbean/Andean peripheral bulge (Villamil and Pindell, 1998) in the interior foredeep mirrors the NE-migration of Andean deformation, reaching the César/western Maracaibo area by Maastrichtian (Molina Formation in Cesar Basin marks the arrival of the foredeep, and Maastrichtian N-S extensional faults in western Maracaibo mark the bulge; Pindell and Kennan, personal observation of Ecopetrol seismic data). To the south, the plate reconstruction allows us to approximate the position where the Panama trench intersected the Colombia trench. Clearly, the northward motion of the Caribbean Plate relative to the Americas (until its middle Eocene collision with the Bahamas), will be matched by the northward migration of the Panama-Colombia Triple Junction. By Maastrichtian, the triple junction had already migrated past Peru and lay opposite Ecuador, reaching southern Colombia by Paleocene and the latitude of the Upper Magdalena Basin by middle Eocene, where, due to the Bahamian collision and termination of further northward motion, it remained for the rest of the Tertiary.

This migration history has several implications for accreted volcanic arc terranes in Ecuador. First, it is consistent with the formation of intra-oceanic island arc assemblages forming on the Caribbean Plate close to South America, but being accreted no later than middle Eocene time. These terranes may include Piñon as shown on these maps, or Piñon may have been stranded farther south until Eocene time (where it could be the source of distinctive sediments in coastal basins of northern Peru; Pecora *et al.*, 1999) and later migrated north due to oblique subduction of the Farallon Plate. Second, it is possible to explain the accretion of arc terranes of Ecuador in simple terms of northward migration of a single major plate boundary (Panama Trench) and its associated triple junction.

Cenozoic

By Paleocene (Fig. 14, 56 Ma), subduction of Proto-Caribbean crust beneath the former passive margin of northern South America had begun (Pindell *et al.*, 1991; 1998; Pindell and Kennan, this volume). Subduction at this trench accommodated slow Cenozoic convergence between North and South America, and produced uplift of the northern Serranía del Interior

Oriental which in turn was the source of clastic sediments of orogenic character in northern Trinidad.

Also in the Paleocene, the portion of the Great Arc which had fit through the Guajira-Yucatán bottleneck found itself able to expand into the larger Proto-Caribbean oceanic basin; the result was the creation of the Yucatán and Grenada backarc basins, which let the Arc expand to maintain contact with the continental margins (Pindell and Barrett, 1990). As the northwestern portion of the Great Arc migrated to the northeast past the southeast Yucatán promontory, NW-directed roll-back of Jurassic Proto-Caribbean crust east of Yucatán drove northwestward stretching in the arc, which rifted at about the arc/forearc boundary. This produced a three-plate system of North America, Caribbean Arc (Cayman Ridge-Cuban Oriente Province), and a portion of the Great Arc's forearc (central Cuba). We suggest that this stretching is responsible for the dominant NE-SW trending extensional fabric of Yucatán Basin mapped by Rosencrantz (1990), that developed oceanic crust across much of Yucatán Basin. As the central Cuban forearc approached the Yucatán margin, that margin's sediments were accreted into the accretionary complex and are now seen in Sierra Guaniguanico Terrane of western Cuba.

In the latest Paleocene and early Eocene, accretion to Yucatán had been achieved, but now the remnant ocean to the north of central Cuba remained to be closed, and continued roll-back of the oceanic crust flanking the Bahamas, as attested to by increased subsidence rates in the Bahamas at this time, led to northward directed thrusting of the Cuban forearc and the Bahamian marginal sediments in early and middle Eocene time. We suggest that this latter period of roll-back was allowed by northward propagation of a tear at the ocean-continent interface in the Proto-Caribbean slab along eastern Yucatán, mimicked in the overriding plate as the "Eocene pull-apart basin" of Rosencrantz (1990). Finally, toward the end of the Bahamian collision, we presume that the south-dipping Proto-Caribbean slab dropped away, allowing rapid kilometric rebound of the Cuba-Bahamas collision zone, and creation of the middle Eocene unconformity across the orogen.

In the southeastern Caribbean Plate, extension was also initiated at this time in the area to become the Grenada Basin. Again, intra-arc rifting near the original boundary between the arc (Aves Ridge) and forearc (Tobago Terrane) probably reflects Proto-Caribbean southward slab roll-back towards the western Venezuelan margin, where the Lara Nappes were emplaced by middle Eocene time (Pindell *et al.*, 1998). Thus, the opening of the basin likely had a N-S component, but see Bird *et al.* (1999). In both the Cuban and Grenada cases, strike-slip was probably involved in creating the crustal break before or during the onset of basin opening, because both portions of the arc were quite oblique to migration direction. In the northeast Caribbean, where plate convergence was orthogonal to the arc, there was no such backarc basin formed at this time.

At the NW corner of the Caribbean Plate, the Costa Rica-Panama Arc (which did not exist farther north than shown) was accreted to the Chortis Block, but no farther northwest in Mexico (all accreted arc material has moved east with Chortis, or was subducted). In Mexico, convergent deformation was advancing into the Sierra Madre, and in the Tampico and Sabinas Basins the foredeep was overfilled with clastic sediment, the excess from which spilled into the western Gulf of Mexico.

In the middle Eocene (Fig. 15, 46 Ma), the Cuban suture zone was eroded deeply (rapid uplift), probably as a result of rebound as the Proto-Caribbean slab dropped off. Arc magmatism stopped in Oriente Province, Hispaniola, and Puerto Rico/Virgin Islands as a result of the collision. Continued North America-Caribbean relative motion began at this time to be taken up at the site of the sinistral Cayman Trough, whose faults can be traced eastward between terranes of southern and central Hispaniola, Puerto Rico and the Aves Ridge, eventually to merge at the Lesser Antilles trench (Pindell and Barrett, 1990; Erikson *et al.*, 1991). Eocene and later arc magmatism, however, developed in the new Lesser Antilles Arc after the Aves Ridge had become dormant, probably as the Benioff Zone was reorganised during the opening of the Grenada Basin (Pindell and Barrett, 1990; Bird, 1999). In our analysis, we adhere to the N-S opening model of Pindell and Barrett (1990) because it: (1) is suggested by the steep western margin of the basin, which appears to be a transform fault- rather than rift-escarpment, (2) is a predictable response to Proto-Caribbean slab roll-back, (3) allows the Dutch Antilles to be pulled out of the space currently occupied by the Basin. In short, we find it impossible to treat the Leeward Antilles arc (Aruba-Orchila island chain) as a southward extension of the Aves Ridge, because if this were the case, it would not be possible to fit the arc through the Yucatán-Guajira gap.

The Cuban collision and the development of the Cayman Trough allowed the Caribbean Plate to move in a more easterly direction with respect to South America. Thus, the Panama triple junction ceased its northward migration along the Colombian trench, remaining for the rest of the Tertiary fixed at a point west of the Upper Magdalena basin, where basement-involved deformations are well known for Eocene-Oligocene time (Butler and Schamel, 1988), analagous to the Limón Basin of present-day Costa Rica, where the buoyant Cocos Ridge (instead of the Panama Ridge) is subducting.

Finally, there is no more subduction beneath the Nicaragua Rise after early Eocene time (arc shuts off in Nicaragua Rise at this time), and the Chortis Block effectively starts to move as part of the Caribbean Plate. To the north, in Mexico, Sierra Madre Oriental thrusting had peaked and would shortly be followed by extensional collapse of that orogen.

In the early Oligocene (Fig. 16, 33 Ma), the westward drift of the Americas continues, now recorded by the opening of the Cayman Trough. In Hispaniola, sinistral transpression at a crustal scale began to cause sinistrally compressive imbrication of crustal slices, giving by Miocene time the island's ridge and valley morphology, although some faults there such as the Tavera fault zone in the southern Cibao Basin had local pull-aparts along them at the surface which received much coarse detritus. Dextral oblique and eastwardly diachronous arc collision was the rule along the Venezuelan margin, where the Caribbean forebulge, foredeep basin, and thrustfront migrated in a steady-state fashion from west to east. In western Venezuela, South America-Caribbean convergence is accommodated by the overriding of the Caribbean Plate by a hanging wall of continental crust and accreted terranes, producing flat slab subduction beneath Maracaibo Block. In Colombia, the buoyant Panamanian arc ridge began to enter and choke a specific portion of the Colombian trench, triggering southern Central Cordillera uplift, the adjacent Gualanday foredeep basin in the Upper Magdalena Valley, and sinistral tectonic escape of basement slivers comprising Panama to the northwest, thereby giving Panama its oroclinal shape. In Chortis, sinistral transpression along southern Mexico began to drive shortening in the Sierra de Chiapas at this time; some of the compression there was probably relieved by dextral shear on faults within Chortis, letting Chortis become longer in its E-W dimension. In southern Mexico, the Mexican trench-Motagua transform-Chortis trench triple junction migrated eastwards, allowing arc volcanism in southern Mexico to propagate eastward as Chortis moved farther and farther along the margin.

In the early Miocene (Fig. 17, 20 Ma), the developments of the Oligocene generally continued. The Cayman Trough is now longer, Hispaniola has been shortened (accretion of originally more separated slivers), the ongoing collision in Venezuela is now situated farther east in the Maturin Basin, the northern Andean terranes are now thrust well onto the underthrust flat slab Caribbean Plate, Panama continues to plow into Colombia, by now causing intense choking of the Colombian trench and the NE-ward tectonic escape of the Maracaibo Block, and shortening in Sierra de Chiapas is at a peak, with Chortis about to clear the Yucatán promontory. By this time, the Galapagos Ridge has been active for about 5 m.y., and it becomes possible to roughly estimate the position at which the Galapagos Ridge intersected the Panama trench. Trench-pull forces acting on the Farallon Plate at the Middle American and Colombian trenches may have been large enough to put the plate into tension (Wortel and Cloetingh, 1981; Wortel *et al.*, 1991).

In the late Miocene (Fig. 18, 9.5 Ma), some of the previous patterns were maintained, but others undergo fundamental changes. The Cayman Trough had lengthened still further, Hispaniola continued to be transpressed against the Bahamas, Chortis had rounded the Yucatán promontory and was in extension in order to maintain a fairly straight trench, Panama continued its choking of the Colombian trench, driving the northward escape of the northern Andes Blocks onto the Caribbean Plate, and the southern Mexican arc had propagated nearly to the Gulf of Tehuantepec. Despite the continuation of these aspects, the Caribbean Plate actually underwent a change in azimuth of motion relative to the Americas at this time, from roughly eastward to slightly north of east (~070°) relative to North America, and from about 105° to 085° relative to South America (Pindell *et al.*, 1998). This change has allowed, since the end of middle Miocene, the Puerto Rico Trench to remain in compression, and the southeastern Caribbean to become transtensional (see Pindell and Kennan, this volume).

Conclusions

Opening of the Gulf of Mexico occurred in two distinct phases. First, Early to Middle Jurassic stretching was direct WNW-ESE allowing Mexican terranes to migrate SSE along the Sonora-Mojave Megashear. Bahamas Platform moved SSE with respect to central Florida, opening Tampa Embayment. Salt deposition occurred during or towards the end of this interval. Second, during the Late Callovian-Oxfordian a fundamental kinematic reorganisation occurred. Yucatán rotation now occurred about a pole located in SW Florida. This defines the trace of the East Mexican Transform which passes beneath the thrust front of the Veracruz, Cordoba basins and east of the Tuxtla volcanics. This allowed Yucatán and Chiapas Massif to rotate towards their present position by *ca.* 130 Ma. Proto-Caribbean opening must occur at the same time, initiating passive margins of E. Yucatán and Cuba. The Venezuela-Trinidad passive margin is of the same age, and is now entirely buried beneath Caribbean Allochthons and the Serrania Thrust Belt. By 130 Ma South America was far enough from North America to allow Yucatán into its present position. The end of Gulf opening triggered a reorganisation of the spreading ridges in the Proto-Caribbean.

Pacific origin models for Caribbean evolution are entirely consistent with, and help us to understand, regional Caribbean geology, while intra-American models do not. In particular, Pacific models: accommodate the existence of the northern South American passive margin until Campanian times; explain why there are two differing periods and axes of arc magmatism in the Great Caribbean Arc; allow us to understand the eastward migration of arc-continent interactions starting along the Cordillera and progressing east to the Caribbean's present position relative to

the Americas; let us account for abnormally thick, B”-affected Caribbean crust as a Pacific phenomenon rather than one between the Americas which does not, mysteriously, affect the Caribbean margins; and allows the Caribbean Plate to be older than Campanian. Two basic tenets of our plate modelling through time have been: (1) not to change the shape of the Caribbean Plate in any way at any time, and (2) not to extract any crust out of trenches once it had been subducted. In practice, these two tenets are among the most constraining aspects of our modelling: given the plate kinematic framework provided by the former positions of North and South America, as well as our northern Andean palinspastic reconstruction, there is very little scope for changes in the positions of the Caribbean Plate after Campanian time. Also, our analysis indicates that the Galapagos Hotspot was not involved with Caribbean evolution.
Most HP/LT metamorphic assemblages in the Caribbean, with the exception of those in Jamaica (Draper, 1986; pers. comm, 2001), probably pertain to the Aptian onset of west-dipping subduction beneath the Great Caribbean Arc after arc polarity reversal, which subsequently allowed the Pacific-derived Caribbean Plate to enter the Proto-Caribbean realm during Late Cretaceous and Cenozoic times. We can only speculate at this point that westward acceleration of the Americas across the line of the early east-dipping trench triggered the initial reversal in subduction direction; however, given that it happened at about 120 Ma, it cannot have been due to collision of the buoyant 90Ma Caribbean Plateau.

We propose a radical new Aptian-Albian [constructional] plate boundary configuration for the western Caribbean that incorporates motions of the Farallon and Kula Plates, to demonstrate that viable alternatives exist to a simple Panama Trench connecting Mexico to Ecuador. This model provides a new alternative for understanding Caribbean B” basaltic extrusions; namely, that of an Iceland [excessive volcanism] model for B” volcanism at an active spreading ridge. We look forward to updated models for Pacific Plate and hotspot motions being able one day to test this hypothesis.

Campanian cessation of magmatism in central Cuba is likely due to shallowing of the subduction angle as the Great Arc approached the southern Yucatán margin. Also, we believe that the reason for the lack of volcanism in the central Cuban forearc terrane after Campanian is that it always lay ahead of the magmatic axis as the Yucatán backarc opened in Paleogene (it was too close to the trench).

We have built into this model the concept that Proto-Caribbean crust was subducted southwards beneath northern South America from Paleocene on (as proposed by Pindell *et al.*, 1991; 1998). Pindell and Kennan (this volume) explore this hypothesis in more detail, pointing out seismic tomographic, stratigraphic/sedimentological, and field-based lines of evidence, but this topic still needs more work and we look forward to learning more from others who may have data to bear on this issue.

The Yucatán and Grenada backarc basins formed in response to slab roll-back of Jurassic Proto-Caribbean lithosphere as the Great Arc was allowed to expand after having passed through the Yucatán-Guajira bottleneck. Grenada Basin must have had a N-S component of opening, and was therefore dextral as well, while the Yucatán Basin was sinistral and opened in two phases, the first to the northwest, and the second to the north-northeast.

Finally, although not hugely apparent at the scale of plate reconstructions presented here, there was a very clear change in the azimuth of Caribbean plate motion direction at about 10 to 12 Ma, and the structural configuration of both the northeast and the southeast Caribbean plate boundary zones have been strongly affected by this. Caribbean-North America relative motion changed from about 090° to 070°, whereas Caribbean-South America motion changed from 105° to 085° (Pindell and Kennan, this volume; 1998; Algar and Pindell, 1993; Weber *et al.*, in press).

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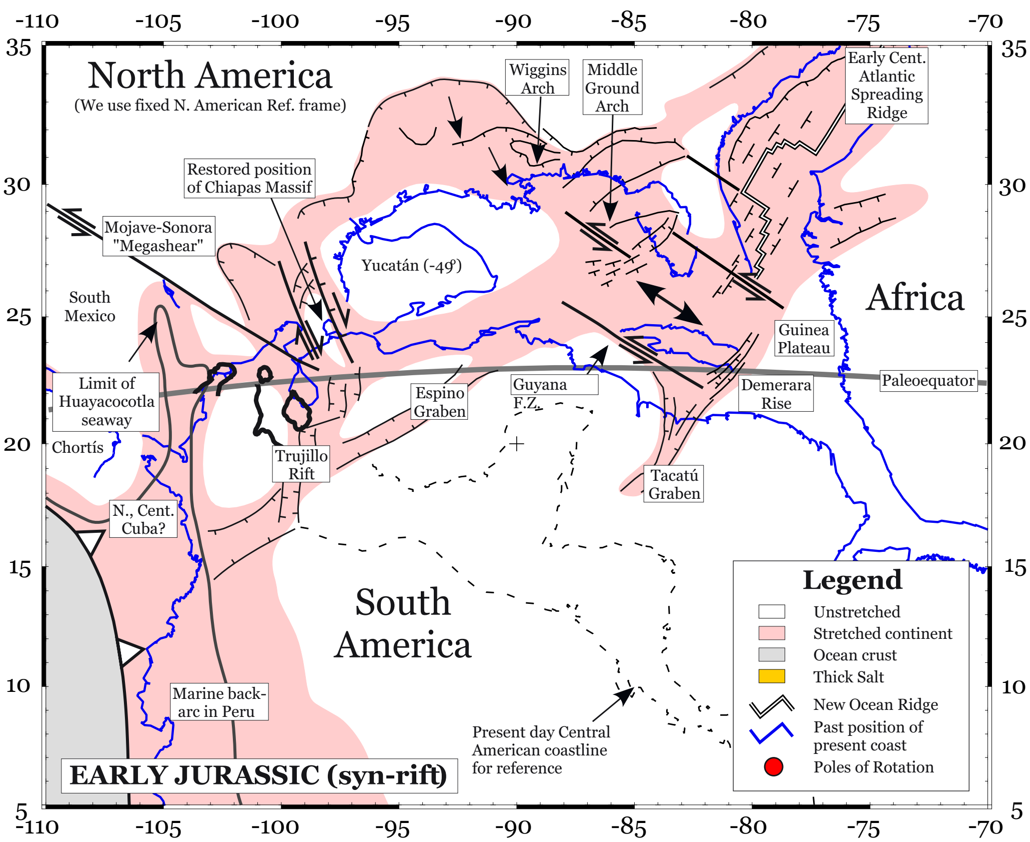

Figure 1. Early Jurassic plate reconstruction (Atlantic continent-ocean boundary fit, post-early stretching), Mercator projection. This and all subsequent paleogeographic maps shown relative to a fixed North America. Modified from Pindell *et al.*, 2000d.

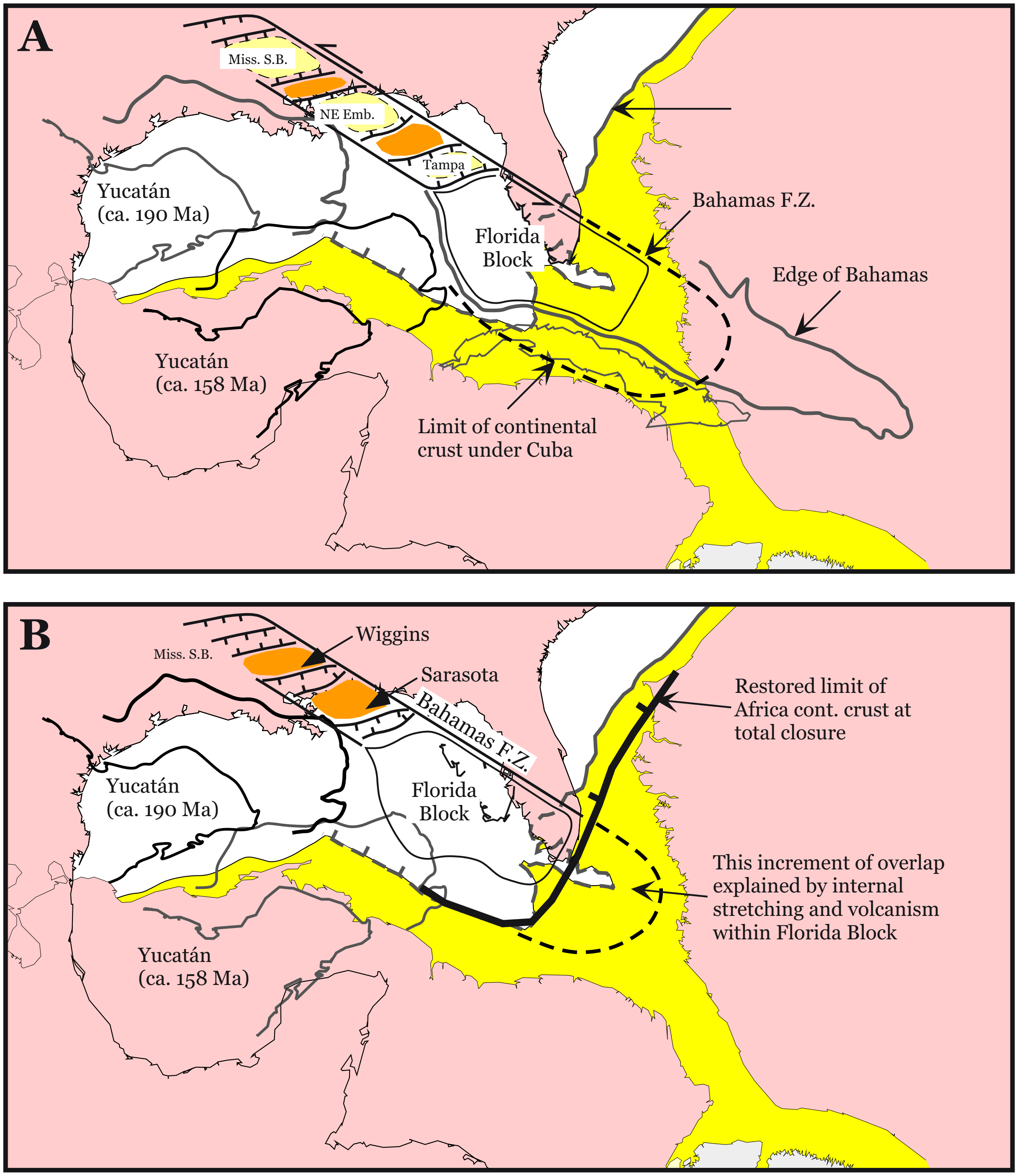

Figure 2. Maps showing: a) continental overlap problem between the South Florida-Bahamas and Guinea Plateau of Africa, when the Atlantic Ocean is closed, and b) our solution to it, which requires (1) closing the pull-apart basins of Florida, Mississippi and Louisiana, and (2) restoring crustal extension within the Florida-Bahamas block.

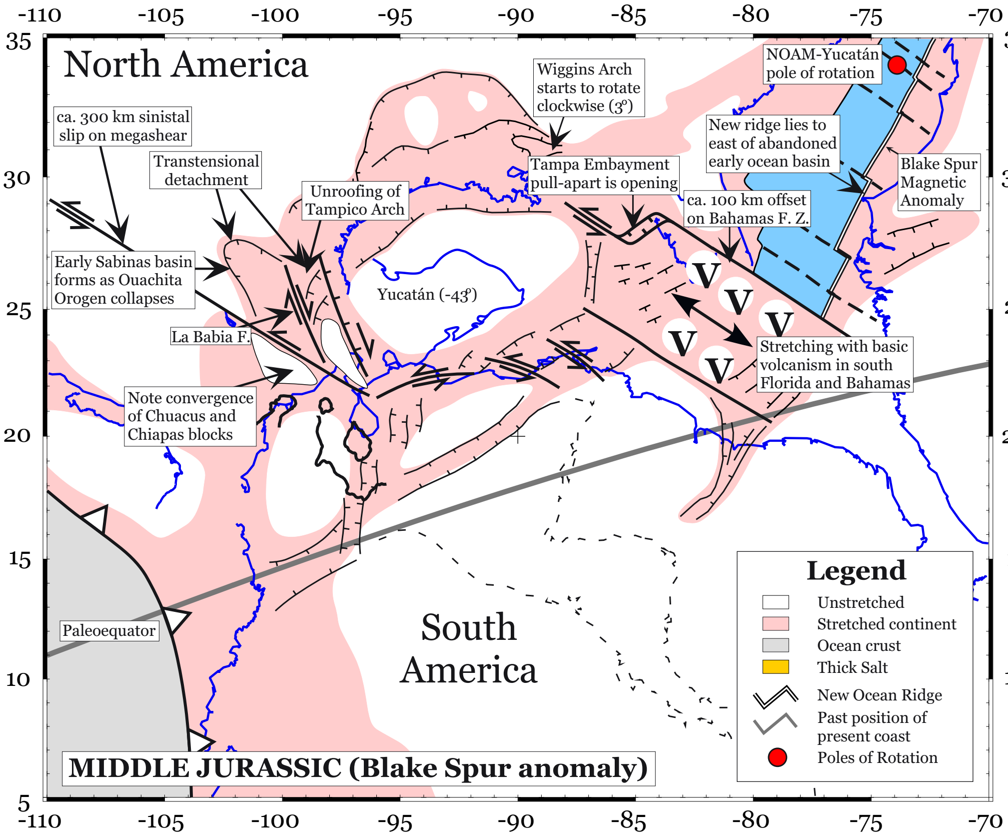

Figure 3. Middle Jurassic (Bathonian, Blake Spur magnetic anomaly time) plate reconstruction.

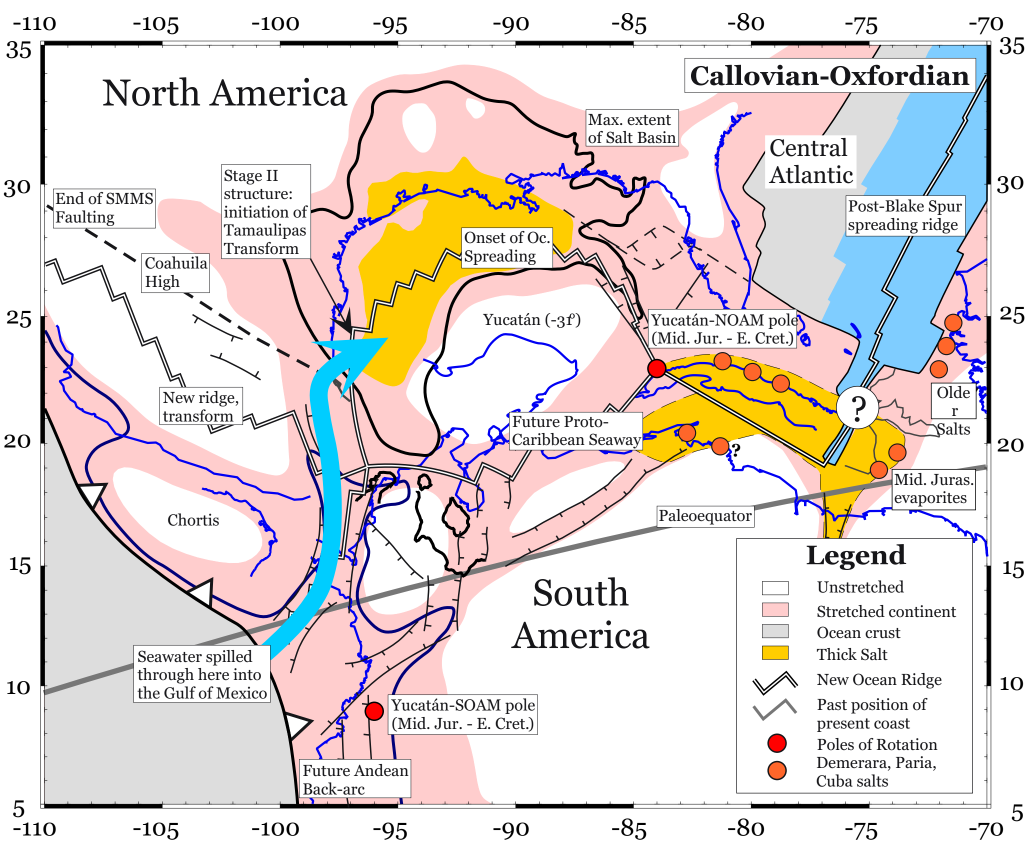

Figure 4. Early Oxfordian (interpolated plate positions) plate reconstruction. Modified from Pindell *et al.*, 2000d.

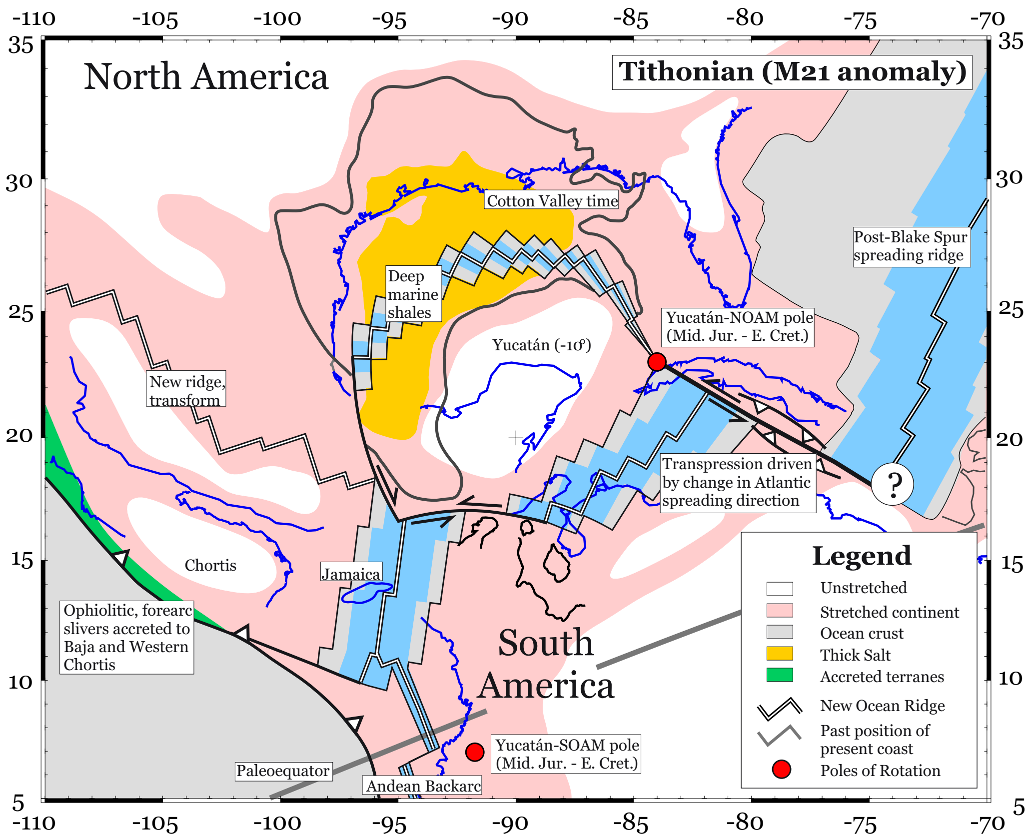

Figure 5. Late Jurassic (Tithonian, anomaly M-21) plate reconstruction.

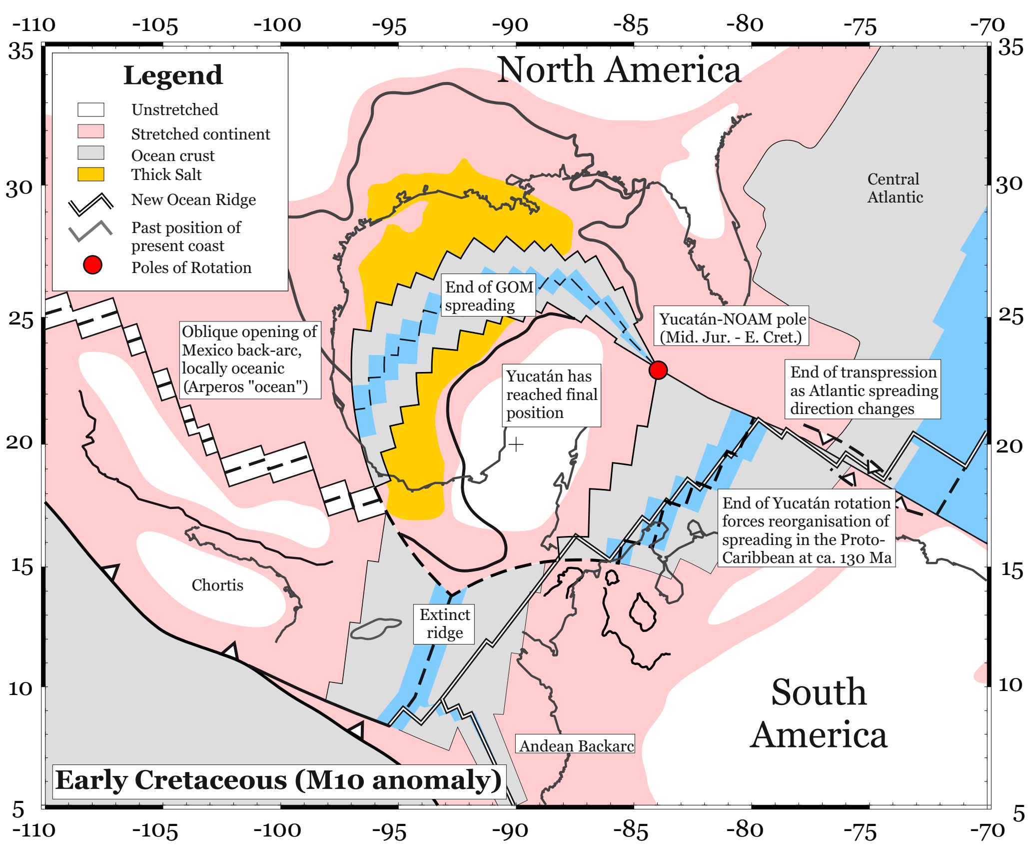

Figure 6. Early Cretaceous (Valanginian, anomaly M-10) plate reconstruction. Modified from Pindell *et al*., 2000d.

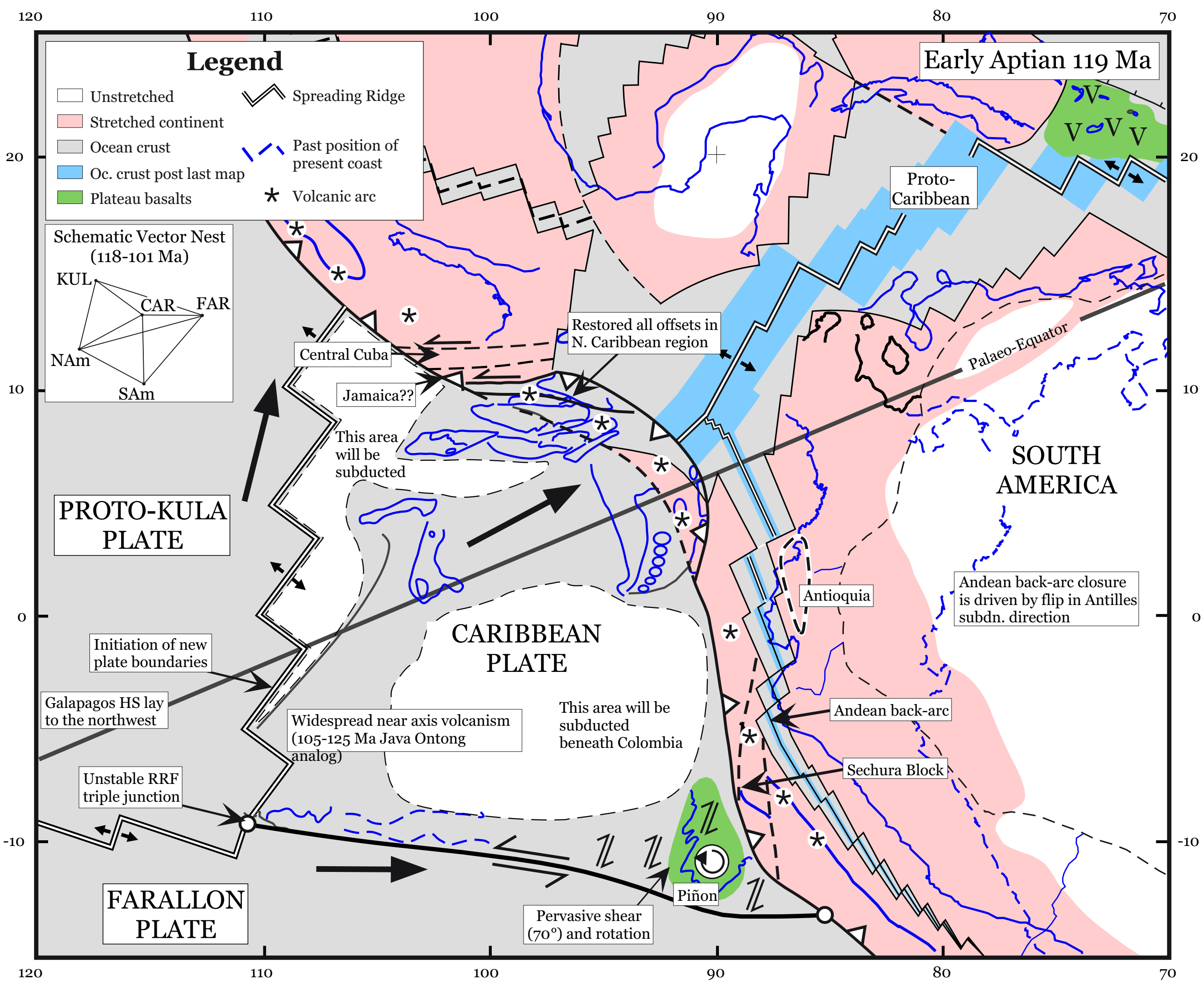

Figure 7. Early Cretaceous (Aptian, anomaly M-0) plate reconstruction.

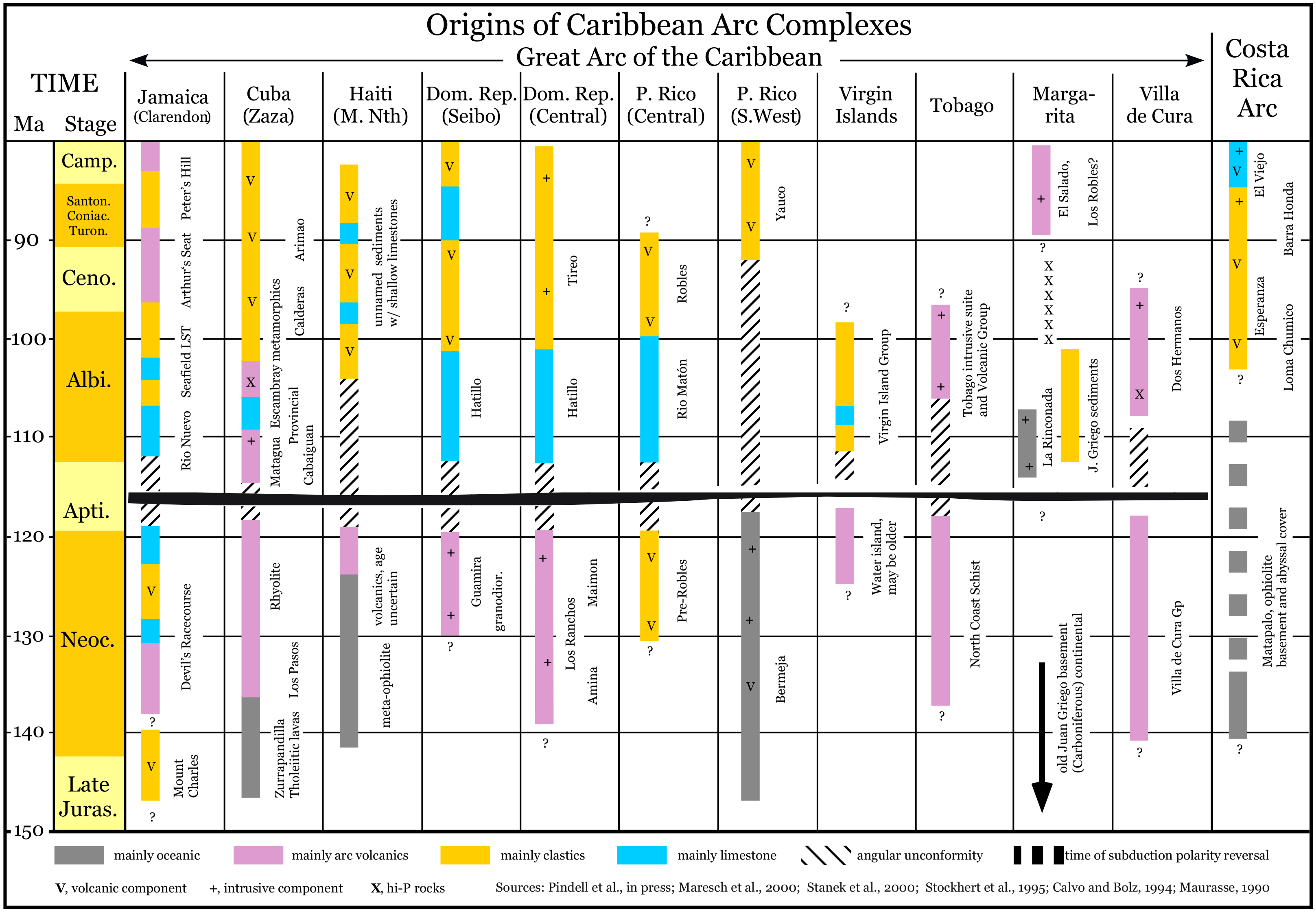

Figure 8. Rock columns for circum-Caribbean terranes, showing Aptian level of inferred subduction polarity reversal, based on evidence for orogeny, severe unconformity, change in arc geochemistry, and/or shift in location of volcanis axis. Note that Costa Rica shows no such event, and that the Costa Rican arc was built on oceanic crust from Albian times only. The collective fragments of the Great Caribbean Arc are all older than the Costa Rican arc.

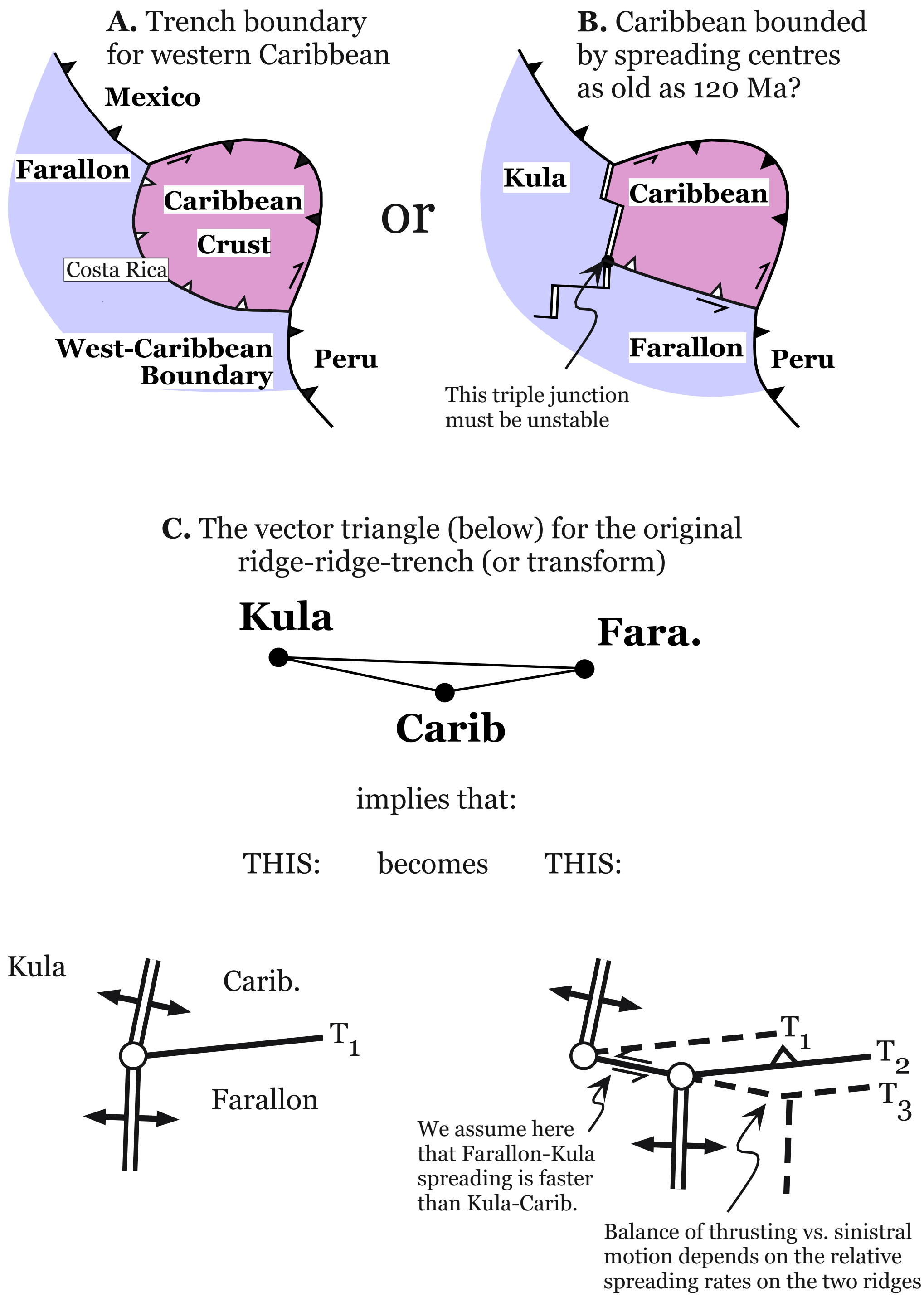

Figure 9. Comparison of traditional (*e.g.*, Pindell, 1993) and new (this paper) models for the inception of the western Caribbean plate boundary. A. The trailing edge of the Caribbean is created by the initiation of a trench linking Mexico and northern South America. Although, this is a satisfactory configuration for the Cenozoic, it results in an unrealistic curvature for the trench out towards the Pacific when the Caribbean lay west of the Americas at *ca.* 120 Ma. Interaction of the Caribbean Plate with Peru, Ecuador and Chortis, combined with relatively little subsequent internal change allows us to be confident about the position of Costa Rica as shown on Figures 8 and 10. B. Alternatively, the Caribbean can be bounded on the west by both a ridge and a trench. A Kula-Farallon spreading ridge is likely to have been in the vicinity at the time and approaching the trench may have broken up into a more complex array of ridges, transforms and trenches. C. The Kula-Caribbean-Farallon triple junction must be unstable. Regional geology and plate motion models suggest that the Farallon Plate was moving faster to the east with respect to South America than the Caribbean. In this case, spreading on the Kula-Farallon spreading center must have been faster than on Kula-Caribbean, with sinistral motion occurring on the early Panama trench.

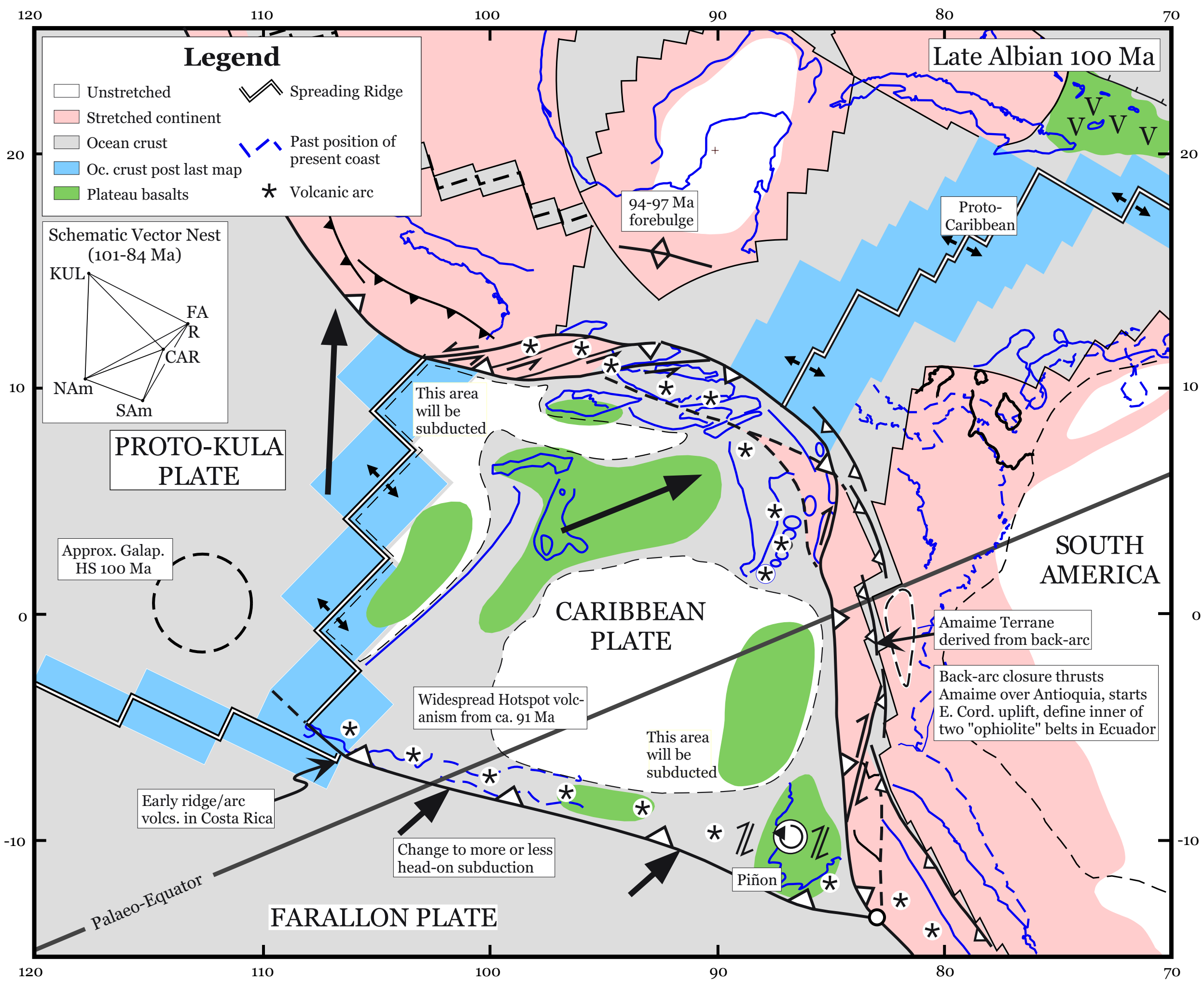

Figure 10. Middle Cretaceous (late Albian, interpolated positions) plate reconstruction.

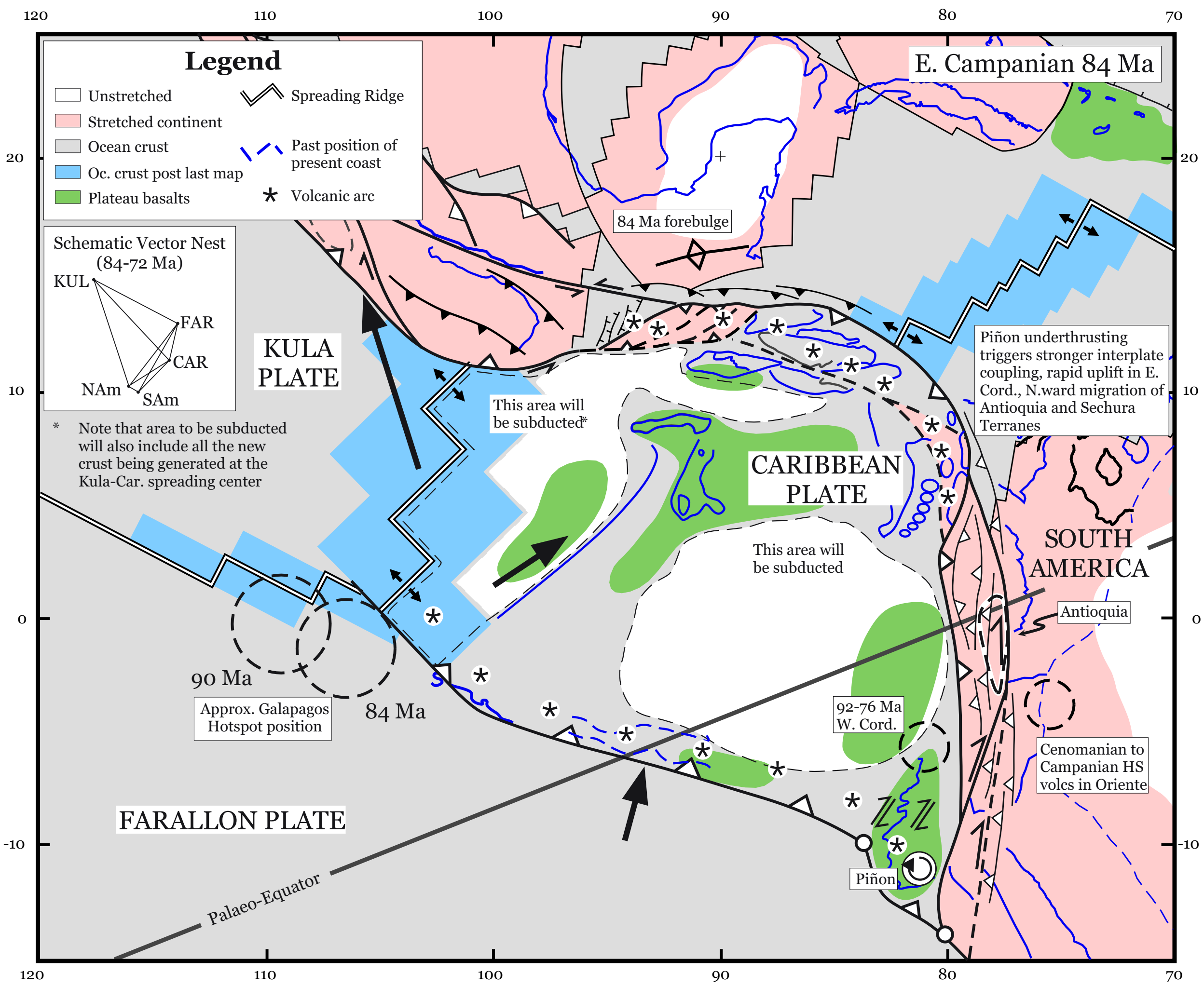

Figure 11. Late Cretaceous (Early Campanian, anomaly 34) plate reconstruction.

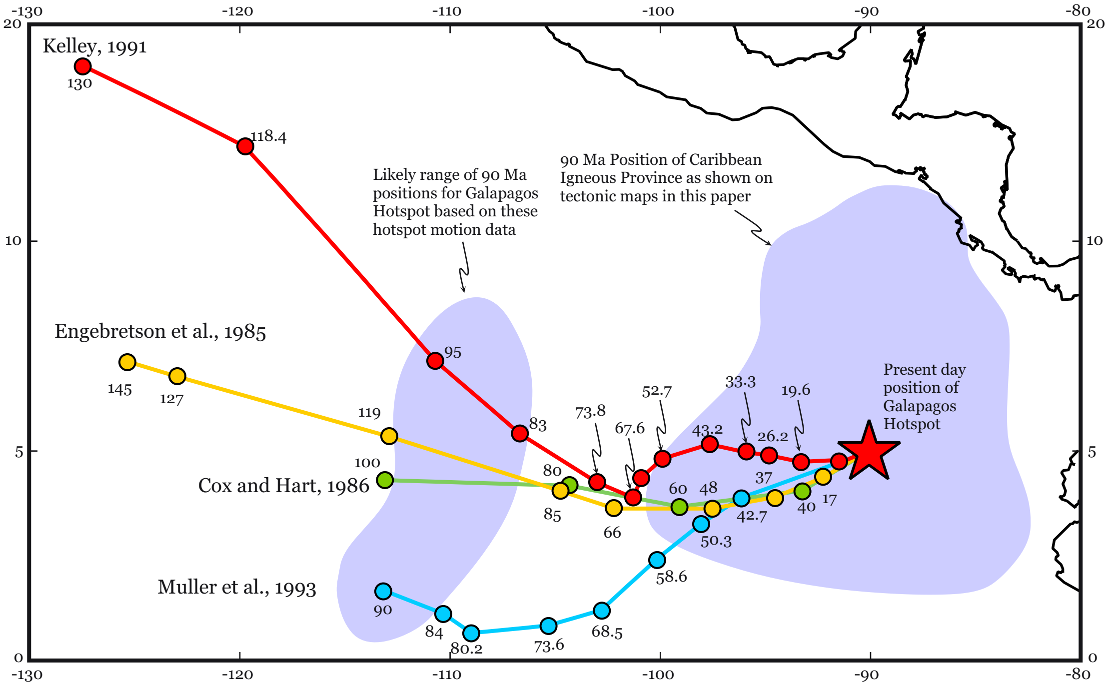

Figure 12. Estimated positions of the Galapagos hotspot through time, relative to North America. If hotspot-North American motion determinations are accurate at all, and if the reversal occurred at 120Ma as we believe, with Caribbean-American contact beginning in Campanian time, then the Galapagos hotspot has had nothing to do with the Caribbean Plate.

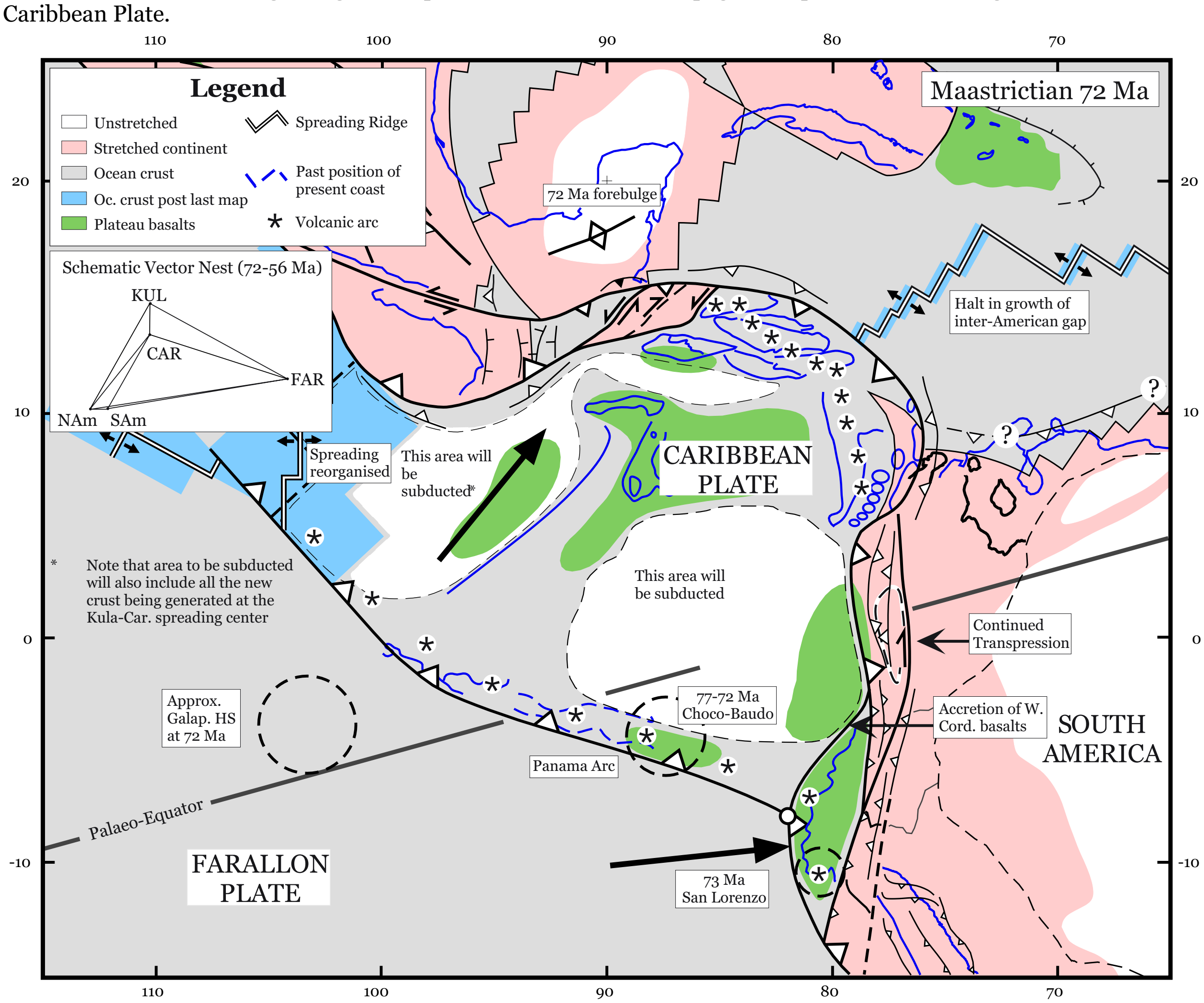

Figure 13. Latest Cretaceous (Maastrichtian, anomaly 32) plate reconstruction.

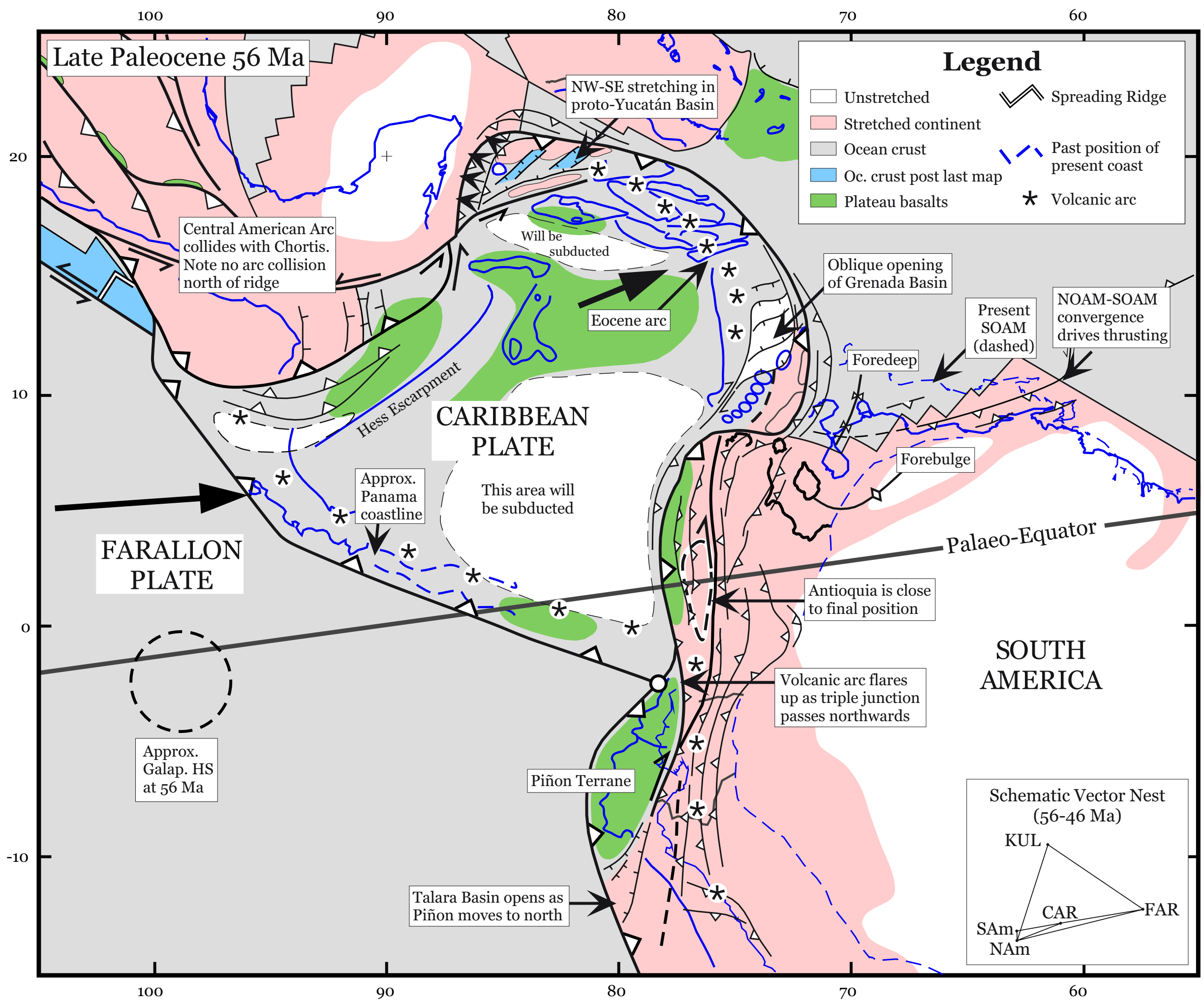

Figure 14. Paleocene (anomaly 25) plate reconstruction.

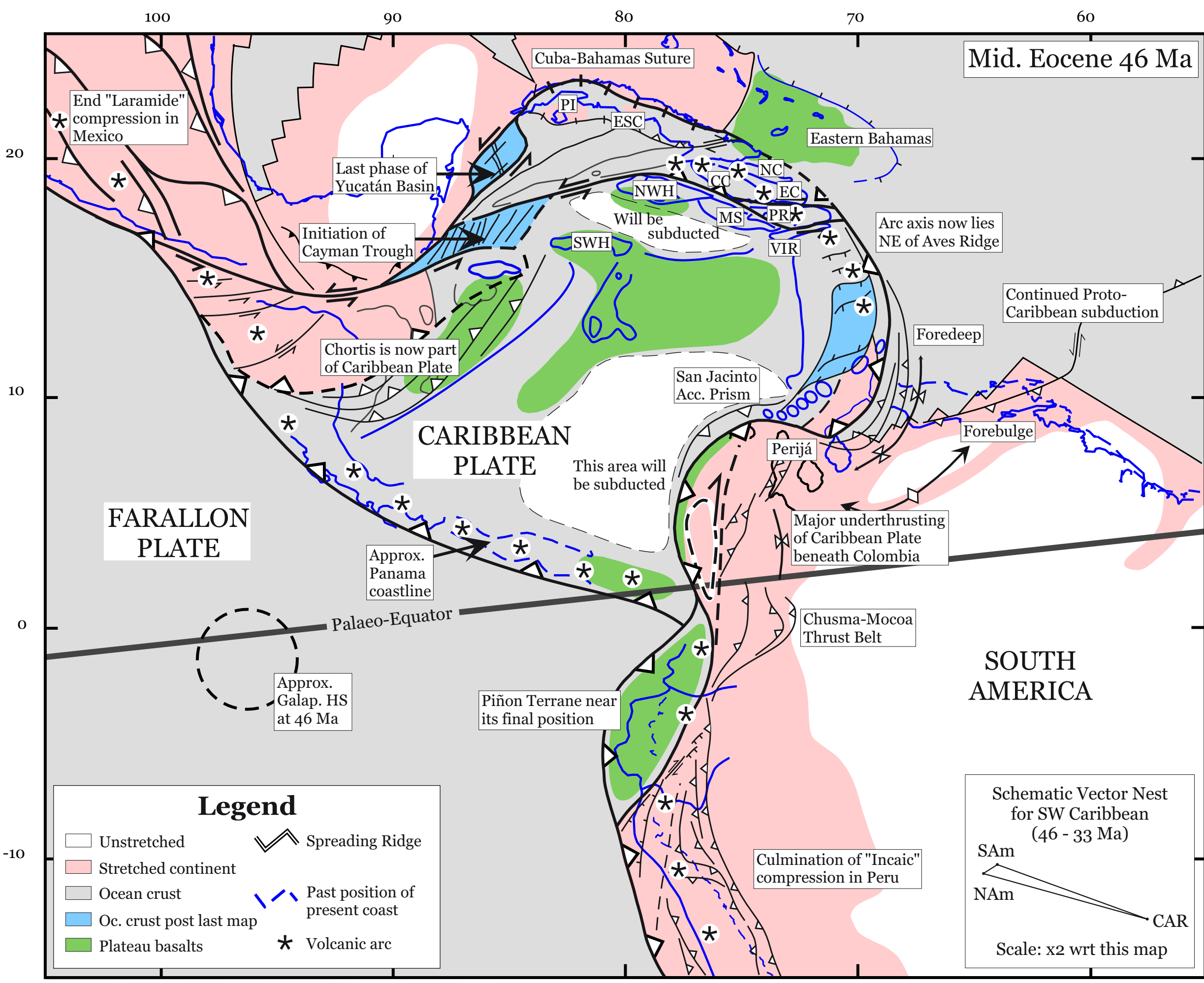

Figure 15. Middle Eocene (anomaly 21) plate reconstruction. Key to abbreviations: PI, Isle of Pines; ESC, Escambray; SWH, Southwest Haiti; NWH, Northwest Haiti; CC, Central Cordillera; NC, Northern Cordillera; SC, Southern Cordillera; MS, Muertos Shelf; PR, Puerto Rico; VIR, Virgin Islands.

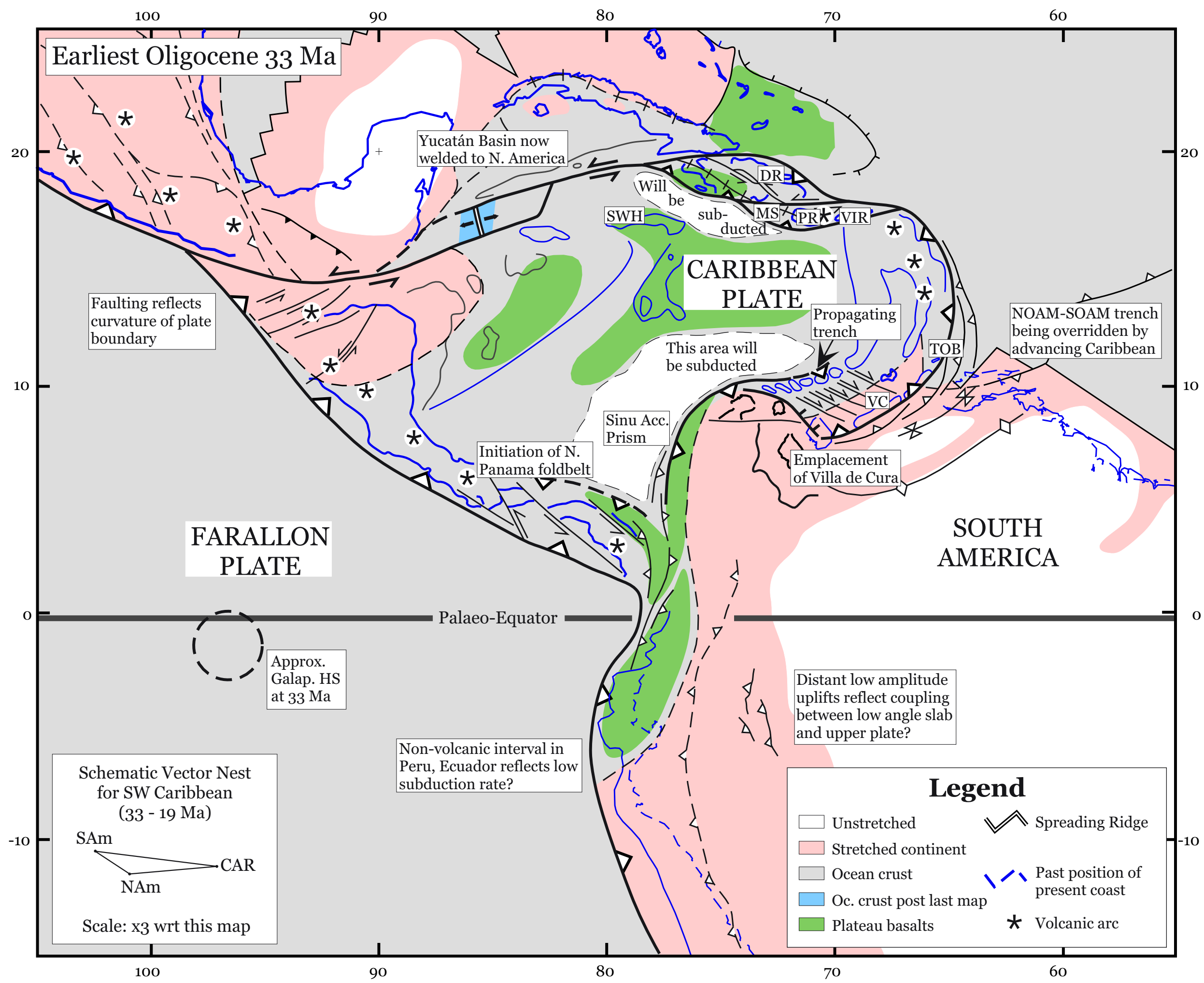

Figure 16. Early Oligocene (anomaly 13) plate reconstruction. Key to abbreviations: DR, Dominican Republic; TOB, Tobago; VC, Vila de Cura Klippe.

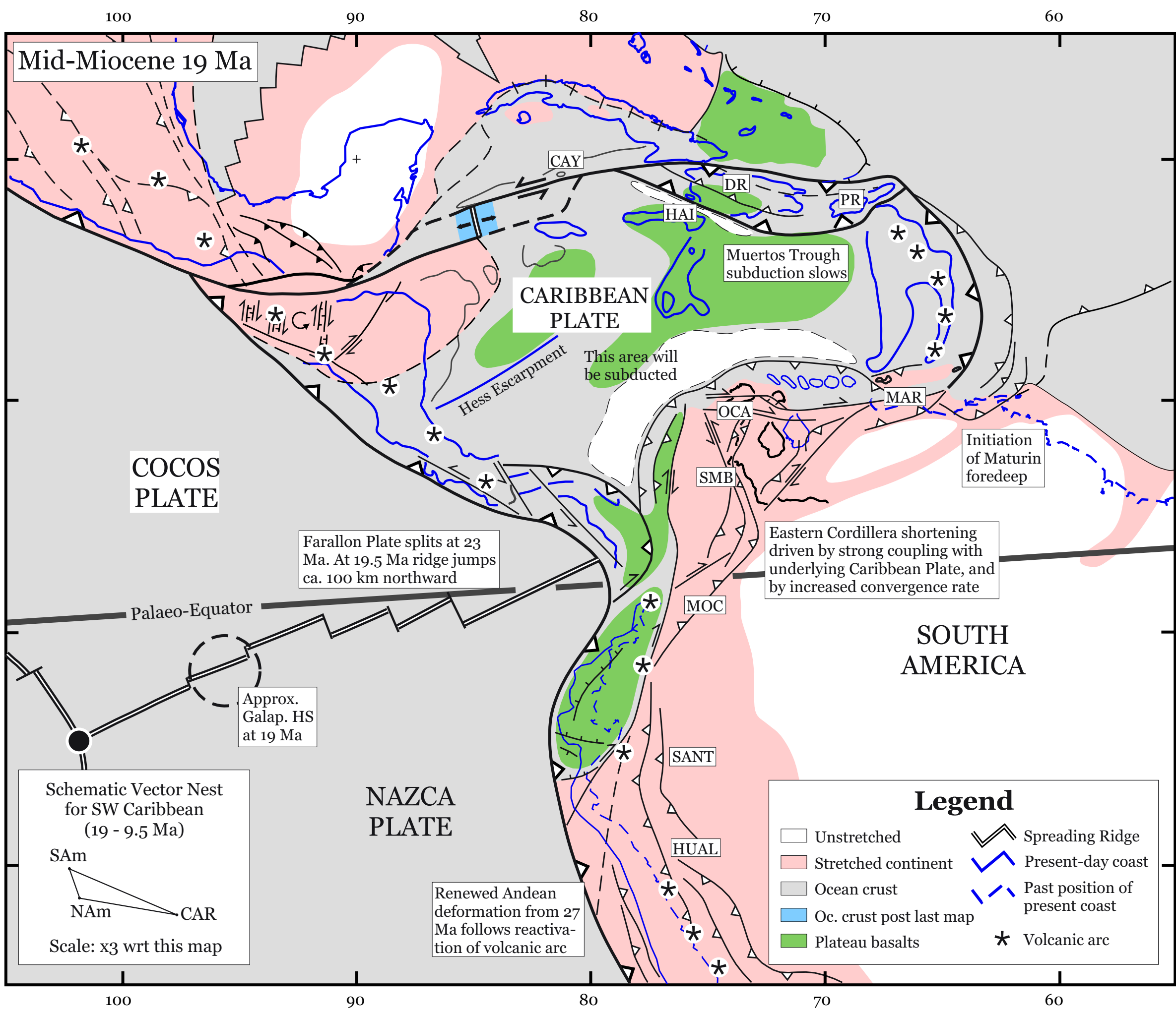

Figure 17. Early Miocene (anomaly 6) plate reconstruction. Key to abbreviations: CAY-MAN, Cayman Trough; MAR, Margarita; OCA, Oca Fault; SMB, Santa Marta-Bucaramanga Fault; MOC, Mocoa Fault; SANT, Santiago Basin; HUAL, Huallaga Basin.

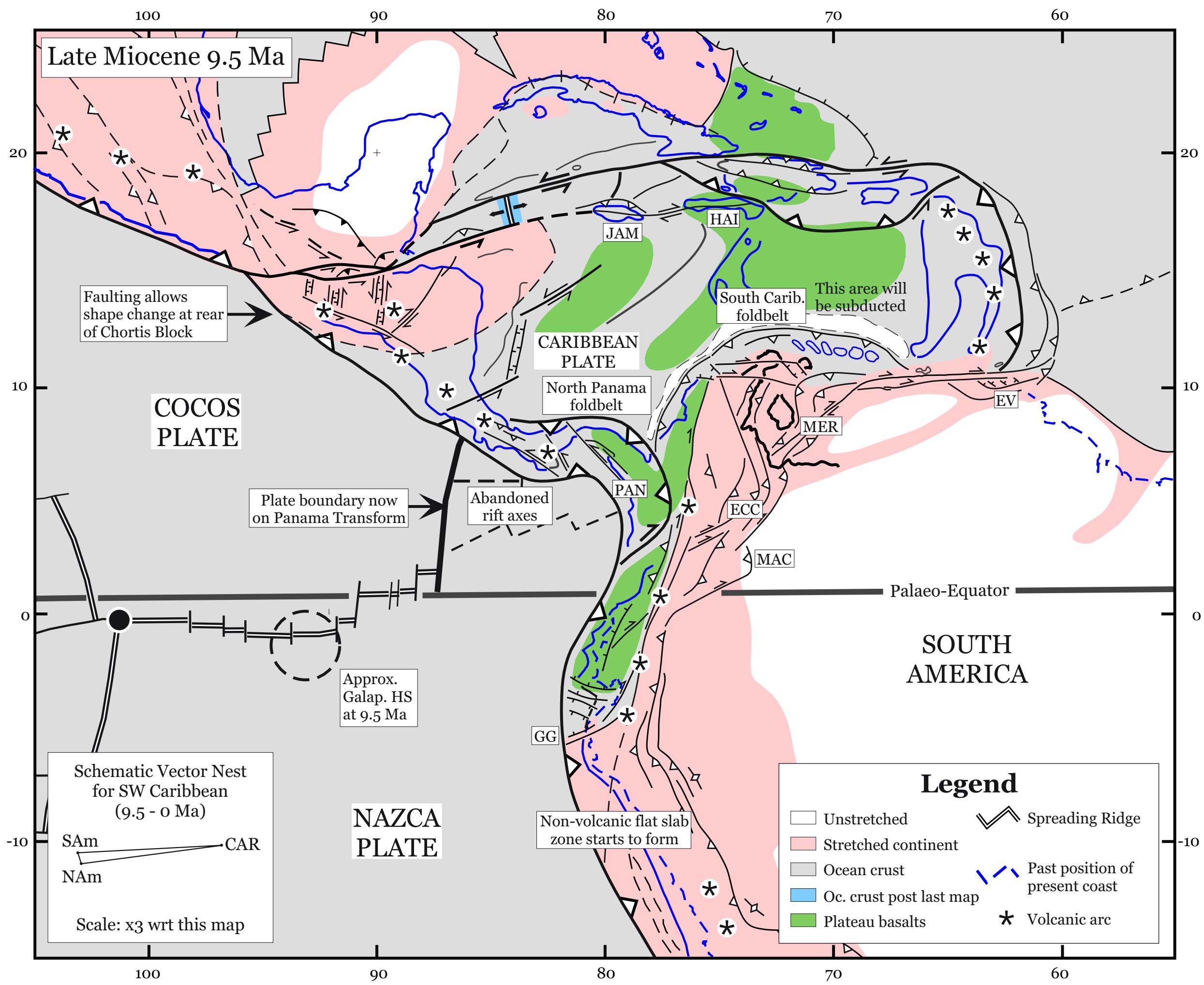

Figure 18. Late Miocene (anomaly 5) plate reconstruction. Key to abbreviations: JAM, Jamaica; HAI, Haiti; EV, East Venezuela-Trinidad transcurrent shear zone; MER, Mérida Andes; ECC, Eastern Cordillera of Colombia; MAC, Sierra de la Macarena; GG, Gulf of Guayaquil.