MESOZOIC-CENOZOIC TECTONIC AND STRATIGRAPHIC DEVELOPMENT OF THE EASTERN CARIBBEAN AND NORTHERN SOUTH AMERICA: IMPLICATIONS FOR EASTERN VENEZUELA AND TRINIDAD

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INTRODUCTION

This discussion outlines some of the primary plate-tectonic controls on stratigraphic and structural development of the northern margin of South America. It covers such items as relative plate motions, regional stratigraphy, allochthonous nappe emplacement history, gross palinspastic reconstruction of the margin through time, basin subsidence histories, Jurassic rift geometry, and an outline of Tertiary orogenesis. The latter, Tertiary orogenesis, controlled the region's hydrocarbon maturation and migration history. The assessment also outlines the potential tectonic control on relative sea level during stratigraphic development, by identifying when and how tectonics may have affected the margin.

NEOTECTONIC CONSIDERATIONS: CARIBBEAN AND AMERICAN RELATIVE PLATE MOTION

The neotectonic development of northern South America is naturally an extension of earlier Tertiary developments, and it is therefore helpful to consider briefly the gross Tertiary relative motions of the Caribbean and American plates which have helped to create to the neotectonic configurations of Miocene and younger age.

Tertiary timescale poles of rotation for the Caribbean

The Tertiary motions of the Caribbean relative to the American Plates can be approximated as follows. North America-South America motion can be measured directly from the seafloor magnetics in the North and South Atlantic Oceans, via Africa (Ladd, 1976; Pindell et al., 1988). Gross Caribbean-North America motion can be measured by magnetics and fault trends at the Cayman Trough Spreading Center and Swan and Oriente Fault Systems, although this analysis has been contested over the years (see below), and additional factors such as northern plate boundary zone deformation must be considered. Caribbean-South American motion cannot be directly measured because mainly convergent or strike-slip boundaries have separated those plates for most of the Tertiary, and plate boundary deformation is complex. However, Caribbean-South American motion can be inferred by computing that motion via North America (difference of NoAm-SoAm, and NoAm-Carib).

The Cayman Trough has long been interpreted to have formed as a direct result of Caribbean-North American relative motion (Hess and Maxwell, 1953; Molnar and Sykes, 1969; Jordan, 1975). A pole of rotation located at 50°S, 64°W near the Falklands (Jordan, 1975) essentially describes opening flow lines for the Cayman Trough on an Eocene to Recent timescale, as well as much of the earthquake data for recent times, particularly in the western Caribbean. Rates of opening have been estimated by various means to be between the disparate values of 12 and 40 mm/yr, and generally are inferred to have occurred over a period back to the Eocene (Holcombe et al., 1973; Macdonald and Holcombe, 1978; Minster and Jordan, 1978; Rosencrantz et al., 1988; Sykes et al., 1982; DeMets et al., 1990). However, without going into a full review, most workers now consider that 20 mm/yr between the Caribbean and North America seems to best satisfy the various admittedly controversial constraints, especially for Neogene time (Dewey and Pindell, 1986; Burke, 1988; Rosencrantz and Mann, 1991; Pindell and Barrett, 1990; Pindell, et al., 1988).

Along with the debate on the rate of relative motion, there also has been debate on the pole position for Quaternary times, and how far back in time such a pole can be used to approximate the relative plate motion (Minster and Jordan, 1978; Sykes et al., 1982; Stein et al., 1988; Demets et al., 1990). Minster and Jordan (1978) modified slightly the original Jordan (1975) pole to account for interactions with other plates in addition to the Caribbean and North America; this pole lies near Valparaiso, Chile at 33.8°S,70.5°W, and also satisfactorily describes long-term Cayman Trough flowlines. An important element of either of these poles, however, is that they predict sinistral transtension at the Puerto Rico Trench. Such motion at the trench is not supported by the regional seismicity there (Sykes et al., 1982), nor does it account for the presence of rocks belonging to the Caribbean plate lying to the north of small-circle flowlines extended from the southeastern tip of the Bahamas Platform (Figure 1). These observations, as well as the record of seismicity from the Lesser Antilles Benioff Zone, led Sykes et al. (1982) to suggest a quite different pole position for Caribbean-North America, one lying far to the east of the others at 66°S, 48°E (or 66°N, 132°W), allowing the Puerto Rico Trench to be transpressional (azimuth of 065°-070°), while synchronously maintaining general transform motion along the Cayman Trough. Thus, we have two distinct sets of calculated poles for North America-Caribbean (Figure 2), one based on western Caribbean seismic and fault trace data (Minster and Jordan, 1978), and another which incorporates eastern Caribbean seismic data (Sykes et al., 1982); both assume an internally rigid Caribbean plate that follows the basic tenets of plate tectonic theory. More recently, Stein et al. (1988) has attempted to satisfy the two original azimuthal data sets by suggesting an intermediate pole position. This pole also assumes a rigid Caribbean plate, but drives the azimuthal error estimates from the original two studies to their limits (Figure 3). This so-called NUVEL-1 pole, although strictly allowable by the error limits from the eastern and western Caribbean, only truly satisfies the azimuthal data between 80°W and 85°W along the Cayman Trough, and like the Minster and Jordan pole it also predicts a slight component of extension in the Puerto Rico Trench.

This dilemma between eastern and western data sets motivated Dewey and Pindell (1985) to suggest distinct eastern and western portions of the Caribbean plate, separated at the Beata

Ridge. They attributed a value of about 40 km sinistral NNE trending shear to the Beata Ridge for Neogene time that could account for the more northerly azimuth of motion recorded by the eastern Caribbean's seismicity. Western Caribbean azimuths were viewed by them as it was by Minster and Jordan (1978). This possible explanation for the dilemma between the two data sets is assessed more fully below.

Most recently, Speed and Larue (1991) have offered another explanation to help substantiate poles like NUVEL-1 (Stein et al., 1988). This explanation assumes that the Puerto Rico Trench is, in fact, an extensional feature forming under active transtension. These authors suggest that seismicity between the Caribbean and North American Plates in the northern Lesser Antilles and Puerto Rico area can be largely ignored. This view would emphasize the western azimuthal data set over the eastern one, and assumes a single, rigid Caribbean plate rotating about a pole relative to North America that is similar to the NUVEL-1 pole (Demets et al., 1990).

The case for Neogene offset at the Beata Ridge

Figure 4 shows a generalized map fo the Beata Ridge. The elongate, relatively uplifted feature is defined by ridges adjacent to high-angle faults. Very young sediments are ponded between some of the ridges. Elevations relative to the surrounding seafloor are on the order of 1 to 3 km. Seismic sections show that the faults cut recent sediments, suggesting active tectonic deformation. In terms of history, samples derived by dredging and drilling of the ridge and analyzed for paleodepth fluctuations on the order of 1000m by estimates of proximity to the CCD by corrosion of forams suggest Eocene shallowing, Oligocene deepening, Miocene shallowing, and post-Miocene deepening (Benson et al., 1970; Holcombe et al., 1990). It is unknown if the ridge is currently being uplifted or subsiding, or if it is stationary. Active seismicity may or may not be occurring, because events measuring less than about 4 to 4.5 would not be detected with the existing seismographic network (W. McCann, pers. comm., 1986). One shallow event of magnitude ~5.0 was, however, noted by Molnar and Sykes (1969) on the southern part of the ridge (~14.5°N, ~72.5°W), who interpreted the solution to indicate E-W sinistral shear, or N-S dextral shear. Kafka and Weidner (1981) reinterpreted the solution as a thrust with an azimuth of shortening oriented NE-SW (Figure 5).

To the east of the point where the Beata Ridge merges with the Greater Antilles island arc in Hispaniola, the deep crust and sediments of the Venezuelan basin can be traced by seismic reflection lines and compressional seismicity under the Muertos accretionary prism and southern margin of the Antillean arc at least 30 to 40 km north of the trench (W. McCann, pers. comm., 1991; Byne et al., 1985; Ladd et al., 1990). Onshore Hispaniola at the intersection of the island with the Beata Ridge, NNE trending normal faults (J. Pindell, unpublished field data, 1981) occur along the abruptly terminated eastern margin of the Sierra Bahoruco (southern peninsula), and a number of small igneous intrusions lie on and along the extension of this margin northward into the Azua Basin, where they have been determined to be very young (Pleistocene) suggesting recently active deep crustal faults along the zone. West of this trend, the ridge itself becomes subaerial (Sierra Baharuco) and is undergoing collision with the Central Cordilleran arc of Hispaniola (Biju-Duval et al., 1983; Heubeck and Mann, 1991). If the magnitude of convergence in south-central Hispaniola is less than that at the Muertos Trough, then a component of sinistral shear may be inferred for the deformation of the Beata Ridge. This question is currently under study (Pindell et al., unpublished work).

Single channel seismic profiles across the ridge show high angle (essentially vertical) faults adjacent to the ridges (e.g., Moore and Falquist, 1976), which have long been interpreted as normal faults (Fox et al., 1970; Fox and Heezen, 1975; Case and Holcombe, 1980). However, classical views of extension do not provide a clear explanation for the periodic uplift/subsidence history along the ridge to relative elevations of 1 to 3 km, although rift flank uplift may play a role. To my knowledge, only one multi-channel seismic line (Figure 6, located in Figure 4) has been published across the Beata Ridge (lines S and T, in Dengo and Case, 1990). These lines show more clearly the style of faulting along that portion of the ridge than do single channel lines. I interpret this section to indicate compression at that part of the ridge rather than extension, and note that single channel lines in this area simply show high angle faults. The youth of the deformation is clear from the dipping reflectors at the sediment surface. I suggest that it is reasonable that many of the other faults previously mapped as extensional along the ridge may be compressional as well.

Fro the above, I suggest that the Beata Ridge is an active zone of significant deformation. Figure 7 shows a cross-section of the ridge (position identified in Figure 4), showing ridges, folds and high-angle faults as mapped by single channel seismic (from Case and Holcombe, 1980). In Figures 7a, b and c, respectively, possible interpretations of extensional, mixed, and convergent faulting are shown that appear to satisfy the meager known information. All interpretations are probably sinistral as well as that shown, as the magnitude of underthrusting at the Muertos Trough appears to be higher than convergence in south-central Hispaniola. Figure 7a does not easily explain the uplifted topography unless the ridge was once much higher, which may have been the case in the Miocene, although rift flank uplift is a possibility. Figure 7b with mixed normal and thrust faults does not seem kinematically sound, although it may be plausible in shear zones. Figure 7c might explain the topography best, and satisfies conceptions of convergent wrench zones. We are currently assessing additional seismic and gravity data to help resolve these possibilities. Despite this uncertaintly as to the precise nature of deformation, it is clear that the ridge is an active zone of deformation, possibly of significant scale. The following discussion of the Puerto Rico Trench argues further for the probability for a sinistral component of motion along the ridge, but for now the east-west component of motion (i.e., convergent vs. extensional, Fig 7) is not resolved. I conclude by suggesting two possibilities for Beata Ridge tectonism shown in Figure 8, which may explain the primary deformation features along the Ridge for Neogene time. Figures 8a and 8b favor convergent and extensional interpretations of Beata Ridge Faults, respectively. A potentially logical aspect of the model in Figure 8b is for the presumably extensional faults which trend SE along the eastern flank of the southernmost Ridge (see Figure 4) to serve as accomodation faults for sinistral shear to the north. This aspect would reduce or eliminate the crustal scale offsets to continue to the SW of the Ridge in the Colombian Basin, and may explain why the Beata Ridge dies out to the south in the vicinity of these SE-trending faults.

Transtension vs transpression at the Puerto Rico Trench

Speed and Larue (1991) have outlined a kinematic model for the Puerto Rico Trench area which portrays the trench as a sinistrally transtensional fault zone, involving upper crustal normal faulting and deeper plastic strain in the portion of the Atlantic (North American) plate within the trench. The Atlantic crust is seen as effectively being pulled "out" of the pre-existing Benioff zone (Figure 9). Further, they consider that the oblong-shaped Puerto Rico-Virgin Islands Terrane (PRVIT) is rotating CCW, such that extension can be variable along the trench and that compression is produced locally along the Muertos Trough. The model is based on the well-known observation that Neogene-aged extensional faults are a common feature of much of the northeastern Caribbean (e.g., Larue and Ryan, 1991; Larue et al., 1991). Speed and Larue (1991) acknowledge that most seismicity at the plate interface suggests an azimuth of relative motion of ENE, which would be transpressional at the east-trending trench, but claim that their structural assessment should take precedent over seismicity and state that "our structural data implies that the slip vectors of earthquakes in the dipping seismic zones are poor criteria for [assessing] relative plate motions" (p. 575).

Speed (1985) and Speed et al. (1991) advocate active ESE convergence in the southeastern Caribbean area between the Caribbean and South American plates. This is contested by Robertson and Burke (1991), who argue for SE compression arising from E-W strike-slip offset in the area. I note that the transtensional interpretation of the Puerto Rico Trench (Figure 9) is required in order to have ongoing ESE convergence in the southeastern Caribbean, because Neogene north-south convergence between North and South America has been occurring so slowly (Pindell et al., 1988). If Speed and Larue (1991) are correct about transtension in the Puerto Rico Trench, then the rotation of a single, rigid Caribbean Plate without motion at the Beata Ridge can satisfy Speed's model for active ESE convergence in the southeastern Caribbean, as shown to be statistically allowable by Stein et al. (1988) and Demets et al. (1990). If not, then ongoing convergence in the southeastern Caribbean must be questioned (e.g., Robertson and Burke, 1989; 1991). Such is the importance of the kinematics of the Puerto Rico Trench to the understanding of southeastern Caribbean tectonics, and vice-versa.

For many reasons, I believe a transtensional interpretation of the Puerto Rico Trench is entirely unsatisfactory. Further, as outlined in a later section, I suggest here that southeastward convergence in the southeastern Caribbean as envisioned by Speed (1985) and Dewey and Pindell (1985; 1986) terminated about 8 or 9 million years ago in the Late Miocene, and that the relative plate motion there since that time has been either east-west shear (Robertson and Burke, 1989) or, more likely, transtensional at about 080°-085° relative to E-W trending faults such as the El Pilar and Coche-North Coast Faults. This change in tectonic style in the southeastern Caribbean requires a break from the Caribbean flow lines derived from the Cayman Trough. Further, the change is probably directly related to the onset of deformation at Beata Ridge, and, since so little is known about the behavior of the Beata Ridge, is probably the best way to date that deformation. Four of the chief arguments against transtension at the Puerto Rico Trench are outlined briefly below:

1. In any model for Caribbean-American relative motion, the northeastern portion of the Plate must have migrated eastward from the southeastern tip of the Bahamas Bank. In Figure 1, a flow line about the DeMets (1990) pole for NoAm-Carib is drawn eastward from the SE Bahamas, and trends slightly south of east near the Puerto Rico Trench. Note that the northeasternmost limit of the Virgin Islands platform lies north of this flow line, as does part of the Anguilla Platform. These terranes clearly were once part of the Caribbean Plate. The seafloor bathymetry to the north of these terranes is also shown in Figure 1. It is clear from dredging, seismic reflection, and the bathymetry that Caribbean rocks extend well to the north of the flowline (entire stippled area). Despite local down-to-the-north extensional faulting in the northern edge of the Caribbean terranes (inner trench wall collapse), which could have allowed some northward movement of Caribbean rocks relative to Caribbean crust, I find it extremely unlikely that the entire area of Caribbean rocks to the north of the flowline arrived there by such extension. Furthermore, rotation of the PRVIT could not have produced the encroachment either, because the encroachment continues to the NW flank of the block, where such rotation would impart extension rather than compression. A more easterly (or ENE) trend of PRVIT motion relative to North America is required to get the Caribbean rocks to their present positions as shown in Figure 1.

2. CCW roation of the PRVIT was suggested by Speed and Larue (1991) to explain convergence at the Muertos Trough. However, the Venezuelan Basin underthrusts the Muertos Trough at Hispaniola (Byrne et al., 1985; Ladd et al., DNAG seismic lines, 1990) just as it does at Puerto Rico. In actuality, convergence may be greater to the south of Hispaniola than it is at Puerto Rico, as suggested by the wider larger accretionary prism south of the Dominican Republic,

although this may be due to greater sedimentation there, too. Convergence south of the Dominican Republic cannot be explained by PRVIT rotation because the Mona Passage is probably the "end" of the PRVIT block. Further, because the Muertos Trough is convergent south of the Dominican Republic, the only way that Caribbean/NoAm motion can follow the Demets et al. (1990) flow line of Figure 1 is for Dominican Republic to be actively pulling away from the Bahamas. This is clearly not the case, as shown by (1) the post-early Pliocene uplift history of northern Dominican Republic and geometry of the Septentrional Fault as determined by gravity (Erikson et al., in review); (2) the seismicity of the inclined seismic zone northeast of Samaná (Bracey and Vogt, 1973); and the compressional folds mapped with Gloria II sonar between the Bahamas and Dominican Republic (Dolan et al., manuscript in prep). To the contrary, deformation with a strong component of N-S compression is the primary active tectonic mode across the Dominican Republic and Muertos Trough from the Bahamas to the Venezuela Basin. In this area, North America-Venezuelan Basin motion clearly has a N-S convergent component.

3. The deep seismicity data for the Puerto Rico Trench region indicates an azimuth of motion toward the ENE as shown in Figure 1c of Speed and Larue (1991) (see Figure 9 of this paper). This is disregarded by Speed and Larue (1991) in favor of their interpretation of near surface extensional features. I note that the determination of poles of rotation for nearly all pairs of plates (e.g., Demets et al., 1991) normally relies heavily on plate boundary seismicity, with support from azimuths of individual faults. Why should we be expected to disregard seismicity at the Puerto Rico Trench? As Sykes et al. (1982) have shown, and as concurred by Stein et al. (1988), the ENE azimuth of plate interface shocks continues well down the Lesser Antilles: this trend is not restricted to some "non-behaving" portion of the America-Caribbean plate boundary in the area of Puerto Rico.

4. The rapid Pliocene subsidence of the Puerto Rico forearc, or north slope terrane, (Sieglie and Moussa, 1984) is attributed by Speed and Larue (1991) to extensional collapse of the inner wall of the trench during transtensional motion. I suggest that this subsidence is interpreted equally well by considering that the Puerto Rican forearc crossed over the southeasterly extension of the buoyant Bahamian ridge (Bahamas Fracture Zone) at about Pliocene time, as required by any model of Caribbean Plate migration with a mainly eastward azimuth of motion. The north slope terrane may simply be in the process of subsiding to the depths of the much deeper Atlantic basin. Further, such a crossing of the Bahamas Fracture Zone probably contributed to the extensive normal faulting that Larue and Ryan (1991) and Larue et al. (1991) have noted.

From the above, transtension probably is not occurring at the Puerto Rico Trench at a scale necessary for the Venezuelan Basin to have a southward component of motion relative to North American crust. The Caribbean rocks north of Puerto Rico and the Virgin Islands must have arrived there by easterly or even east-northeasterly migration from the southeastern tip of the Bahamas Bank (North America). In either case, the motion of the Venezuelan Basin relative to North America must have had an even greater northerly component of relative motion, as indicated by the convergence at the Muertos Trough Foldbelt (Dewey and Pindell, 1985; Byrne et al., 1985).

I do not contest the evidence for Neogene-Recent extension near the trench, or even onshore Puerto Rico; such evidence is well known (e.g., Maley et al., 1974; Jany et al., in press; Larue and Ryan, 1991; Larue et al., 1991; Erikson et al., 1990). Furthermore, in light of (1) paleomagnetic evidence for late Miocene CCW rotation of Puerto Rican limestones (Reid et al., 1991), (2) the predictable collapse of the northern Puerto Rican forearc terrane as it crossed the Bahamas Ridge, and (3) reasonable predictions for the rate of subduction rollback of Jurassic-aged Atlantic crust from the Caribbean crust at the Puerto Rico Trench, evidence for extension at the surface should be, and is, widespread. But such surface indications cannot be wholly attributable to a transtensional azimuth of motion between North America and the Venezuelan Basin. In a N-S cross-section, convergence clearly dominates extension.

The vector triangle inset of Figure 1 shows a plausible set of finite motions among blocks in the northeastern Caribbean for the last 9 million years which is consistent with the geology and seismicity of the fault zones bounding the blocks. The 9 Ma age is derived from a later discussion. Although such a vector triangle suffers from not being able to show block rotation, such as that of the PRVIT, the construction has the power to estimate internally-consistent offsets and trends of motion on fault zones that otherwise cannot be measured. In the vector traingle, I have assumed eastward migration of Caribbean rocks of the PRVIT from a point at the SE tip of the Bahamas in order for those rocks (shaded area of Figure 1) to have migrated to their present position. This allows construction of the E-W North America-Puerto Rico tie line, although the length is not well constrained due to uncertain rates of motion. I have assumed the 20mm/yr value usually cited for North America-Caribbean motion, but some motion could pass through Muertos Trough-Anegada Passage that is not taken up along the Puerto Rico Trench system. The next step is to consider the convergence at the Muertos Trench for this 9 Ma period, whose north-south component I minimally estimate as 35 km, as noted above. This allows construction of a point representing the Venezuelan Basin to the north of the point for Puerto Rico; the tie line between North America and the Venezuelan Basin denotes relative motion of the eastern Caribbean relative to North America in the NE Caribbean vicinity, in full agreement with northeastern Caribbean seismicity (Sykes et al., 1982). From here, a tie line with the trend of the small circle flow lines of the Demets et al. (1990) pole in the area of the Puerto Rico Trench is drawn ESE from the North American point. In the absence of accurate rate assessments, we again can at best estimate N-S components of motion. The distance along a north-south line from the Eastern Caribbean point to the western Caribbean point approximates the N-S component of motion which would have occurred over the last 9 Ma if a boundary between them existed in this area. From the construction, a value for such an offset of 65 km is inferred. I suggest that this discrepancy is due to fault offsets and deformations at the Beta Ridge. However, depending on the position of a pole defining the relative motion of the eastern and western Caribbean plates, offset need not be as high as 65 km along th Beata Ridge. The N-S vector in the trinagle construction cannot be used as a small circle flow line because it only represents the N-S component of motion. Thus, the precise nature and magnitude of deformation at the Beata Ridge is not determinable at present because a pole for motion between the Colombian and Venezuelan Basins is not available from existing data. If the pole lies close to the Beata Ridge, then total offset there may be small while allowing a N-S component of motion of 65 km near Puerto Rico. I now take the construction one step further to incorporate the probable rollback velocity of Atlantic crust and the forearc extension of PRVIT in the area of the Puerto Rico Trench. If the true strike of the Puerto Rico Trench north of Puerto Rico is drawn as a vector (vector a) from North America, this vector intersects the Eastern Caribbean-Puerto Rico vector about mid-way between those points. The distance between this new point and the Puerto Rico point defines the magnitude of the N-S component of extension (about 20 km) between North American crust and Puerto Rico (vector segment b). This value for extension in the trench zone is feasible in view of the mapped surface structures of the trench region (e.g., Larue and Ryan, 1991; Larue et al., 1991). However, I would attribute the cause of such extension mainly to subduction rollback of the Atlantic crust, and secondarily to whole-body block rotations of PRVIT. If wholly due to rollback, 20 km over 9 Ma is approximately 2.2 mm/yr. This is a very slow prediction for rollback velocities of Jurassic crust, implying that, if anything, the vectors of Figure 1 show lesser northerly components of relative motion than is probably the true case. A faster rollback velocity would require a greater northward component of motion to keep pace with the trench axis and to maintain compressional seismicity at the plate interface.

Concerning Caribbean plate kinematics, I emphasize that the azimuth of motion for North America-Eastern Caribbean in the vector triangle of Figure 1 is very close to the azimuth of motion computed from the seismicity of the northeastern Caribbean by Sykes et al. (1982). If strict rules of plate tectonics (i.e., rigid blocks separated by fault zones) are followed, this azimuth appears to be achievable only by acknowledging a probable sinistral deformation along the Beata Ridge. It would appear, then, that the individual studies of relative motion by Sykes et al. (1982) and by Jordan (1975) may both be correct, in that they independently derived the motion of the eastern and western parts of the Caribbean "plate", respectively. Both studies assumed a single rigid Caribbean Plate and thus extrapolated their results to areas where their data do not necessarily apply. Stein et al. (1988) also assumed a rigid plate but interpolated a pole mid-way between the other poles by pushing the limits of error for both data sets. This solution provides kinematic predictions for local deformation around the Caribbean that are not warranted anywhere because their pole is not a best-fitting solution to any data set for a specific plate pair. Finally, I note the study by Heubeck and Mann (1991) who concur from E-W changes in plate boundary style in Hispaniola that the Beata Ridge must be a zone of relative motion between eastern and western Caribbean plates.

Late Miocene Transition from transpression to transtension in East Venezuela-Trinidad?

As discussed above, a transpressional interpretation of the Puerto Rico Trench in accord with its seismicity (Sykes et al., 1982) and regional geology is best explained if deformation has occurred along the Beata Ridge over latter Cenozoic time which has allowed the Venezuelan Basin to have a northward component of motion relative to the Colombian Basin. This has fundamental implications for the southeastern Caribbean region, in that it nullifies the Caribbean-South American convergence predicted there by the Jordan (1975) or Stein et al. (1988) poles of rotation. Specifically, if the Sykes et al. (1982) pole for the eastern Caribbean is accurate for recent times, then the southeastern Caribbean must be undergoing dextral transtension rather than transpression as postulated by Speed (1985) and Speed et al. (1991).

However, evidence for Tertiary Caribbean-South American convergence in the southeastern Caribbean region is overwhelming. For example, the Eastern Venezuelan and South Trinidad Basins are bounded on the north by well-developed fold-thrust belts including Neogene rocks, and the Maturin and South Trinidadian foredeep basins are clearly load related (Dewey and Pindell, 1985; 1986; Speed, 1985; Pindell and Barrett, 1990). Furthermore, if the Sykes et al. (1982) pole is invoked on a timespan extending more than about ten million years, overlap problems develop between the crusts of the Caribbean (Margarita) and South American (Coast Ranges) plates. Such overlap problems are avoided by considering a transpressive arrival of the Caribbean Plate in northeastern South America, e.g., motion about the Jordan (1975) pole.

Upon closer examination of the geology and neotectonic development of the southeastern Caribbean, the primary signal of the latest phase of development is one which is dominated by a component of regional N-S extension. As outlined below, this phase began in the Late Miocene, perhaps at about 9 Ma, and it would appear that the Sykes et al. (1982) pole can be invoked for the eastern Caribbean back to that time. Furthermore, it also appears that the development of the well-known convergent features in Eastern Venezuela and Trinidad mainly predated this last neotectonic phase. It may thus be implied that the onset of deformation along the Beata Ridge also began at about 9 Ma, thereby allowing the subsequent disparate azimuths of motion for the Colombian and Venezuelan Basins. Prior to Beata Ridge deformation, the entire Caribbean Plate probably followed Cayman Trough flowlines (Jordan, 1975; Minster and Jordan, 1978). During Beata

Ridge deformation, the eastern half possessed a more northerly component of relative motion (Sykes et al., 1982). Such a change in plate motions at that time is consistent with the geology of the Puerto Rico Trench in that 9 million years of motion about the Sykes et al. (1982) pole is sufficient, assuming a rate 20 mm/yr, to have allowed the migration of Caribbean rocks to their present position north of the flowlines predicted by Cayman Tough-derived poles of rotation.

The Late Miocene age for the development of two halves of the Caribbean plate is derived from geological aspects of different ages interpreted to be caused by transpression and transtension in the southeastern Caribbean, outlined as follows. Care must be taken, of course, not to confuse true transtension with upper level orogenic extensional collapse during continued convergence and overthickening. Figure 10 shows a number of examples of geology that I suggest relate to this change to transtensive plate relative motion.

1. Numerous large-offset extensional faults in the Carupano Shelf/Tobago/Margarita area trend about 080° to 085° (Case and Holcombe, 1980; Gonzales de Juana et al., 1980; Robertson and Burke, 1989). This trend falls into a compressional rather than an extensional orientation in models of continued transpression. Such faulting suggests that the relative motion is more northeasterly than the fault strikes of 080° to 085°, perhaps 070°-080°. Only then would the faults lie in an extensional orientation, and they are likely to have dextrally oblique slip as well. Perhaps even more important in this area is the well-developed subaerial unconformity that lies beneath the Upper Miocene (note paleontological date has been revised from middle Miocene) to Recent sections offshore. Locally, the post-unconformity section is up to 13,000 feet thick (Robertson and Burke, 1989) in addition to the water depth (Figure 10). Once the Carupano Shelf was exposed and eroded in Middle Miocene time, presumably due to the convergence of the Caribbean crust over the South American crust that is well documented for that time to the south in the Serrania, I find it very difficult to envision how over 3 km of subsequent subsidence could have occurred if compression has continued to the present. A component of relative motion involving N-S extension in conjunction with the observed faults appears justified.

2. Bedplanes of the Late Miocene-Recent La Pica, Quiriquire, La Piedra and Mesa Formations of the Maturin Basin of eastern Venezuela are little deformed and dip south up to 5° (Borger, 1952, Figure 10). These formations are frequently cut locally by high-angle normal faults (Figure 10), but reverse faults are rare (Gonzales de Juana, et al., 1980). These formations form a non-thrusted overlap assemblage above a deeply eroded terrestrial unconformity above the Frontal, Pirital, and other thrusts and folds of the subsurface portion of the northern Maturin Foldbelt (Figure 10). Basal ages of the overlap assemblage are within the Upper Miocene, demarking the termination of thrusting and erosion, and renewed deposition. The age of this sequence generally matches that of the section above the unconformity offshore in the Carupano

Basin. I suggest that the termination of convergence and the onset of a N-S extensional component of motion allowed for the renewed deposition, possibly by relaxing some of the pre-existing thrusts (note the geometry of Upper Miocene bedding over eroded Oligocene and Lower Miocene on El Furrial seismic line, Figure 10). I further suggest that with continued N-S relaxation into the Late Miocene-Pliocene, faults such as the Coche-North Coast and El Pilar may have become the primary dextral-oblique faults, such that the normal component upon them allowed for isostatic rebound of area to the south of them. The normal component of motion appears to have exceeded 3 km, as shown by the wells in the Carupano Basin and by Robertson and Burke (1989) on their seismic lines. The magnitude of isostatic rebound to the south (footwall) will vary with fault dip, but typically would be in the ballpark of 50 to 70% of the subsidence on the hanging wall (Carupano). Such an mechanism for uplift on the footwall could account for average elevations near the faults of about 1 to 2 km. We note that the Serrania del Interior and Northern Range of Trinidad have elevations within this range. Further, because the isostatic response would operate over a flexural wavelength of 100 to 200 km to the south with only minor faulting, as is observed, this mechanism can account for the presently-southward regional dip of the fluvial-deltaic Late Neogene beds above the Late Miocene unconformity in the Maturin Basin. It also may explain why the Orinoco River flows so far from the thrust front in the basin, and why oil fields such as Quiriquire have accumulated in this section adjacent to the thrust front.

The same scenario is seen in Trinidad. Submarine thrusting of "deep" water sediments in the Central Range reached shallow water depths in the Middle Miocene as recorded by the Tamana limestone (deposition in photic zone). In contrast, Late Miocene to Recent sedimentation is cut more by large offset normal faults than by thrust faults, especially for faults whose orientation is 080° or higher. Only In the Caroni Basin, a southward dipping wedge of sediment thickens from the Northern Range toward the south and terminates against a high angle fault system along the northern margin of the Central Range. Basal bedplanes in the mainly Upper Miocene section of the basin fill of the Caroni onlap northward an erosional peneplain of probable Middle Miocene age, before wedging out at the margin of the Northern Range. The southward thickening of bedding suggests normal faulting along the Central Range boundary, with associated rotational subsidence of the Caroni Basin. The Central Range boundary fault zone, however, appears "flowerish" in seismic sections; this aspect, combined with strike-slip shear indicators in Central Range Miocene outcrops, suggests a right-lateral mainly transtensional origin for the late Neogene of the Caroni Basin, although locally the Central Range bounding faults appear convergent. If the fault-bounded block (Caroni) includes the Northern Range as well as the Caroni basement, then block rotation during faulting, in association with flexural uplift due to unloading north of Trinidad along the North Coast Fault, could have caused uplift in the northern part of the rotating block, thereby elevating the Northern Range above sea level. This uplift can be achieved without motion on the elusive El Pilar fault trace in Trinidad.

3. Unroofing of Northern Range, Trinidad. At least 5 to 7 km of overburden rested upon the rocks of the Northern Range during their metamorphism. By Miocene time, Ar-Ar ages became locked in, representing cooling through about 300°C (Speed and Foland, 1989; Pers. Comm.). This cooling may represent the time of thrusting above cooler rocks, and/or erosion of the pyle during uplift. 300°C, however, still represents significant overburden, and typical erosion rates would likely "have difficulty" removing such volumes since the Middle Miocene. Therefore, we suggest an extensional mode of removal of the Northern Range overburden, namely northward dipping normal or transtensional faulting of the Carupano-Tobago shelf along the Coche-North Coast Fault zone offshore. We note that the final phase of deformation in the Northern Range is a brittle extension along fault trends of roughly E-W. Progressive exposure of deeper layers of rock and normal weathering processes then created the existing landscape of the Northern Range. We know of no remaining allochthons within the Northern Range, except possibly for the Sans Souci-Toco Formations, probably a klippen originating from the accretionary prism of the Caribbean Plate when it overthrust the Northern Range (see Algar work). We find it hard to acknowledge continuing compressional deformation (transpression) in light of these observations.

4. The fault-bounded bodies of high-grade metamorphic and ultramafic rock and serpentinite along the north coast of Araya-Paria (Gonzales de Juana et al., 1980), and possibly the volcanic rocks of Sans Souci in Trinidad, are presumably remnants of a once-larger body of oceanic material or an accretionary prism which had overthrust the Araya-Paria and Northern Range terranes in the Oligocene to Medial Miocene, thereby driving the metamorphism whose minerals give Miocene cooling ages (Speed and Foland, 1989). Presently, the northern margins of the peninsulas are defined by high angle faults and the oceanic/accretionary basement to the north of these peninsulas in the Carupano Basin lies at depths greater than 10,000 feet below sea level (e.g., HH1-6 well). Across much of the Carupano and Tobago platforms, a pronounced Middle? Miocene unconformity below the Late Miocene to Recent sequences suggests subaerial exposure at that time Bellizzia et al., 1985). I suggest that the Carupano and Tobago shelf areas were involved in the Oligocene to Middle Miocene overthrusting that drove the deformation in the Araya-Paria and Northern Range of Trinidad. The oceanic/arc/prism rocks of the Carupano and Tobago platforms must have been structurally as high at that time as the now-isolated klippen along the coasts of the peninsulas. This period of deformation probably drove the SE-ward emplacement of the Serrania del Interior and central and southern Trinidad thrust belts as well. Thrusting in these belts largely ceased in the Late Miocene, perhaps around 8 to 10 Ma. Since then, I envision that a N-S extensional component of the Caribbean-SoAm motion has allowed the Carupano shelf to subside by normal faulting at the north-dipping Coche and North Coast faults. The area to the south of that

fault (plus or minus the El Pilar) rebounded isostatically over a wavelength typical of flexure (100 to 200 km) to its present elevation (major part of Serrania del Interior topography), causing the latter Neogene sediments of the Maturin to acquire southward dips after their deposition.

These arguments have important implications concerning the timing and style of deformation in the northern Maturin Basin. Ongoing convergence is generally assumed because of the apparent tectonic setting of the area. However, an unconformity developed across the main fold-thrust belt in the early part of the Late Miocene, and most workers consider that the main period of thrusting terminated at the Frontal, Pirital, and other thrusts at that time (e.g., Talukdar et al., 1988). However, some interesting subsurface geometries occur there now, which are usually considered to have resulted from ongoing convergence of a lesser intensity. In particular, the unconformity above deformed Carapita and beneath the Upper Miocene La Pica, which was probably subaerial as indicated by the high degree of angular unconformity, is itself offset by faults, and the overlying section fills basin-like pockets bounded by these faults. These pockets of sediment do not appear as though they were deposited under continuing compression (Figure 10, Aymard et al., 19901, El Furrial section). Rather, they may suggest extension superimposed upon the pre-existing convergent fold-thrust belt, allowed by normal motion on some of the original thrust planes. A component of extension within the peneplained fold-thrust belt may have initiated the subsidence that led to deposition of musch of the La Pica, Quiriquire, La Piedras, and La Mesa formations.

To close, I cannot at this point prove a young extension in the Maturin Basin on the little data I have worked with. However, from what I have seen, I would suggest that the youngest offsets on faults within these basins be interpreted with an open mind, bearing in mind that extension may post-date the main compressional phase of fold-thrust development.

From all of the above, Figure 11 shows Tertiary Caribbean-South American relative motion history and includes the postulated Late Miocene change in motion of the eastern Caribbean Plate (onset of Beata deformation). The vectors in Figure 11 have been computed by finite difference via North America and Africa, and I have used the Minster and Jordan (1978) pole for [western] Caribbean-North American motion throughout the Tertiary. The rate of displacement can be estimated from the Cayman Trough spreading and subsidence history and fault motions along the southesatern Trough (Rosencrantz et al., 1988; Rosencrantz and Mann, 1991), and also the rate of eastward foredeep basin propagation along northern South America (Pindell et al., 1988). Both methods favor rates of 30mm/yr and 20 mm/yr before and after 26 Ma. These rates at the Cayman Trough are equivalent to 16 mm/yr and 24 mm/yr at the southern Caribbean plate boundary zone, which were used to construct Figure 11, because the southern pbz is closer to the pole of rotation. Finally, note that the Blanquilla path shows actual Caribbean relative motion (assumed fixed to

Caribbean crust), and that the Tobago and "Margarita" paths prior to 28 Ma diverge from Caribbean motion because of the Paleogene opening of the Grenada Basin, discussed next.

Opening of the Grenada Basin and Paleogene convergence in western Venezuela

Pindell (1985a) and Pindell and Barrett (1990) argued that the Grenada Basin opened in a N-S direction (Figure 12a) for the following reasons: 1) magnetic anomalies in the Basin trend east-west in a radial fashion (Figure 12b), and may be related to seafloor spreading (Westbrook, in Speed and Westbrook, 1984); 2) the bounding southeastern margin of the Aves Ridge is so abrupt that a transform rather than rift origin seems more likely; 3) most extensional faults to the north of the Basin have an E-W strike similar to the magnetic anomalies (Figure 12b); 4) Caribbean motion relative to South America could not have been convergent at that time, because the Caribbean crust was undergoing active convergence with North America (Bahamas) at that time, and convergence between North and South America was essentially nill; a third plate or platelet must have been involved; 5) a natural driving mechanism for north-south opening is evident from plate reconstructions involving the entrance of the Caribbean Plate from the Pacific. Subduction rollback of Proto-Caribbean crust and transform drag between the Caribbean and South American crusts would have provided oblique extensional stresses in the leading edge of the southeastern Caribbean, similar to the oblique opening of the Andaman Sea of southeast Asia. Thus, the "Lara Terrane" or "Grenada Terrane" (that portion of the Caribbean plate to the east of the Grenada Basin in the Paleogene) was proposed as the corner of the Caribbean plate that was dragged off and subsequently emplaced during Tertiary time as allochthonous bodies (Lara Nappes) onto the South American margin. The Grenada Basin was the oceanic basin formed in the wake of that terrane during its extension from the main body of the Caribbean Plate (Figure 12a). As pointed out in Pindell and Barrett (1990), the model also provides an explanation for the apparent delay in the onset of Tertiary volcanism in the southern Lesser Antilles relative to the northern Lesser Antilles (Speed, 1985), in that the Lara or Grenada terrane would have had a much slower eastward component of motion during the Paleogene than would the remainder of the Caribbean Plate to the north of the Grenada Basin. Consideration of clockwise rotation of the Lara Terrane about the crudely-estimated opening pole for the Grenada Basin in Figure 12b shows how the Lara Terrane would have a lesser eastward component of motion than the Caribbean. Finally, the predicted N-trending basement fault along the eastern flank of the northern Lesser Antilles, which would have operated during basin opening, provides a mechanism for elevating Jurassic oceanic rocks to the surface at La Desirade and Guadaloupe, which lie along that trend (Pindell and Barrett, 1990).

This mechanism and its kinematics are currently being worked up by Pindell and Cande, and therefore are not treated here in any more detail. However, an important implication of the model is shown in Figure 11. As far as South America was concerned, it was the Lara/Grenada Terrane with which Tertiary arc collision took place, and NOT the Caribbean Plate. Therefore, the opening of the Grenada Basin must be incorporated into assessments of the arc collision. During Basin opening, the Lara/Grenada terrane had a much more southerly trend of motion than did the Caribbean. This motion should be associated with Paleogene orogenesis in the Maracaibo and central Venezuelan regions, and was probably driven by subduction rollback of the Jurassic lithosphere of the Proto-Caribbean margin until sufficiently thick continental crust entered the trench, thereby terminating the convergence. Concurrently, the Caribbean Plate was following the arcuate path of motion as defined by the Cayman Trough relative to North America, as shown by the Blanquilla path in Figure 11. From the plate modeling outlined later, I suggest that the Grenada Basin began to form in the Late Paleocene (59 Ma) but was not fully opened until the Early Oligocene (about 28 to 30 Ma). Since that time the southeastern part of the Caribbean Plate (Tobago, Grenadines, etc.) has essentially followed Caribbean flowlines, as shown in Figure 11.

North and South American relative motions

Figures 13 and 14 show North and South American relative motion history. Erikson (thesis in preparation) has interpreted the Mesozoic stratigraphic development of eastern Venezuela in terms of the motions. He has pointed out the potential significance of Jurassic rifting from Yucatan, Late Jurassic deceleration and shift in trend of motion (related to the Nevadan Orogeny of western USA?) which probably led to earliest Cretaceous transpression followed by transtension between northeastern South America and the Bahamas. In addition, I suggest that the termination of seafloor spreading in the Proto-Caribbean occurred in the Albian, and was associated with the opening of the Equatorial Atlantic. Cande and Pindell (work in progress using the most recent data) confirm the findings of Figures 13 and 14. In particular, there is definite post-Middle Eocene convergence between North and South America as shown, and little or no relative motion for Late Cretaceous to Middle Eocene time.

Additional points to make here are, firstly, that the predicted Jurassic section of northern South America is likely to be directly correlative and lithologically similar to the coeval section of Sierra Guaniguanico of western Cuba, which represents the northeastern margin of the Yucatan Block (Pindell, 1985b). There, the Jurassic rocks (San Cayetano Formation and overlying sequences) are hydrocarbon source rocks. This correlation may have important implications for northern South America if the Jurassic section exists at depth in the Eastern Venezuelan and Trinidad Basins. Secondly, it is predicted, due to the scissors-like rotational opening of the Proto-Caribbean (Pindell, 1985) that the timing of marine incursion after rifting probably youngs westward in Venezuela, just as it youngs southward along eastern Yucatan. This may provide an explanation for Jurassic stratigraphic differences in the Eastern Venezuelan and Maracaibo Basins.

PALINSPASTIC RECONSTRUCTION OF ANDEAN OROGENESIS AND ARC ACCRETION

Other critical analyses that must be considered for northern South American paleogeography are (1) the removal of accreted arc terranes and (2) the palinspastic reconstruction of Andean Orogenesis.

Accreted terranes: The terranes which have been accreted to the original, pre-Jurassic continental basement include the Panamanian arc and basement, the Western Cordillera of Colombia, the Ruma metamorphics of the Guajira Peninsula, the Santa Ana ultramafics of Paraguana, the Lara Nappes including the Siquisiqui ophiolites of the southern Falcon region and the Villa de Cura and other klippen of central Venezuela, the northwestern tip of the Araya Peninsula (NW of the Manzanillos Fault?) and other klippen along the northern Arraya-Paria coast, Margarita, Tobago, and possibly the Toco terrane of the Northern Range of Trinidad. Panama probably arrived adjacent to the Western Cordillera in the mid-Miocene, although the exact location of the suture is debatable, either the Atrato Basin or actually within the northwestern Western Cordillera, and the Western Cordillera was accreted to the Central Cordillera of Colombia during the Late Cretaceous. As for the rest of the allochthons, the tectonic model outlined later shows that they were progressively emplaced as the Caribbean Plate and Lara/Grenada Terrane migrated eastwards or southeastwards throughout the Tertiary. The eastward migration of the point of most rapid subsidence in the clastic foredeep basins, as well as the migration of the erosional peripheral bulge ahead of the migrating foredeep basin, record very clearly this easterly progression. The foredeep sediments over which these allochthons sit record the arrival of the allochthons from point to point along the margin.

Andean orogenesis: The net palinspastic restoration of Andean orogenesis requires, once again, the construction of vector triangles denoting relative offsets among various blocks. The methodology as it applies to northwest South America is outlined in Dewey and Pindell (1985; 1986), and is not repeated here. However, Figure 15 shows updated estimates of Andean displacements and shortenings using the vector triangle method, which I am using in current analyses of the plate tectonic evolution of northern South America. Changes and improvements in detail are due mainly to (1) incorporation of shortening in the Sierra Perija; (2) construction of site-specific vector triangles at three different points in order to diminish the distorting effects of curvilinear small-circle displacements; (3) the use of two Caribbean "plates for the post 9 Ma interval, allowing transtension for Eastern Caribbean-South America for that time (described above); (4) use of a 50 km offset along the El Pilar fault in Venezuela as possibly recorded by the offset of the Villa de Cura allochthonous rocks and those similar metamorphic rocks of the northwesternmost tip of the Araya Peninsula, and (5) rates of Caribbean-North American motion as measured in the Cayman Trough by Rosencrantz et al. (1988) and modified by Rosencrantz and Mann (1991), about the Minster and Jordan (1978) pole of rotation (defined above). Because the southern Caribbean lies closer to the pole of rotation than does the Cayman Trough, the actual rate near latitude 10°N is 16 and 24 mm/yr before and after 26 Ma, respectively. These rates are then merged with NoAm-SoAm displacement rates to derive Caribbean-SoAm motion history (see Figure 11).

Of interest to the Eastern Venezuelan Basin area is part B of Figure 15. I show offsets for the last 9 Ma only because the Caribbean Plate had not arrived until that time in this area, and it would be improper to assess total motions beginning at 15 Ma as in the west. The NoAm-SoAm tieline at this location is computed from the Atlantic opening history (Figures 13, 14). NoAm-western Caribbean is computed from Cayman Trough flowlines and rates about the Minster and Jordan (1978) pole. Note that the position of the western Caribbean point relative to SoAm lies at about 108° from SoAm, the approximate trend of motion assumed by Speed (1985). However, as discussed earlier, such a trend of motion violates Lesser Antilles seismicity and requires transtension rather than transpression at the Puerto Rico Trench for this interval. Recall that the value for the northward component of motion of the Eastern Caribbean relative to the western Caribbean in the discussion on the Puerto Rico trench area was 65 km. In Figure 15B, this value for the N-S component is also plotted for the Eastern Caribbean relative to the Western Caribbean. Note that this places the Eastern Caribbean point slightly to the north of the South American point, which is required in order for east-west trending faults of the southeastern Caribbean to be transtensional. Note also that the trend of motion between NoAm and the Eastern Caribbean now matches the azimuth derived from seismicity at the plate interface. For these reasons, I believe that vector nest of Figure 15B approximates fairly well the actual motions of the southeastern Caribbean. Transtension between the Eastern Caribbean and northeastern SoAm is fully compatible with, in fact essential to, the regional geological development and neotectonics of the eastern half of the Caribbean Plate and its boundaries.

Collectively, the analyses of Figure 15 lead to the pre-Campanian configuration of Figure 16. The dotted areas of Figure 16 are areas which have been overthrust (thin-skinned) by their adjacent thrust systems. Acknowledgement of such overthrusting helps to understand why there are abrupt facies changes at the thrusts between the foredeep basin and Cordilleran sections, such as along the Llanos of northeastern Colombia. I consider that northern South America was a rifted margin with several marginal offsets in the basement crust, which helps to explain the geometry of the thrust systems in Venezuela and Trinidad. Zones where the thrust belts are offset to the southeast may relate to underlying basement marginal offsets, with thicker Mesozoic sections to the east of each marginal offset. We propose the Guajira, Caracas, and Sucre Salients, and the Trujillo, Barcelona, and Paria Reentrants, as sites of protruding, less-rifted continental crust and sites of greater lithospheric attenuation, respectively. The NW-SE trending segments would be the sites of transform slip relative to Yucatan during early rifting, whereas the NE-SW trending segments are the true rifted margins. See Figure 17 for an approximate reconstruction with the Yucatan Block during Permian-Early Jurassic time.

The foregoing constraints on plate motions and palinspastic restoration are incorporated into the following assessment of the regional evolution of northern South America. The evolution occurred mainly in two phases, first a Jurassic-Cretaceous rift-drift phase during which the Proto-Caribbean seaway and South American passive margins were formed, and, second, a Cenozoic phase of transpression (followed by late Neogene transtension) between the originally passive margin and the allochthonous Caribbean-derived terranes. Pindell (1991) outlines the relationship between the plate motions, primary structural and stratigraphic history, and history of hydrocarbon development.

PALEOTECTONICS: THE DEVELOPMENT OF NORTHERN SOUTH AMERICA

This section will develop an outline of the tectonic history of northern South America. The main elements to that history are shown as a series of paleogeographic maps in which stratigraphic units are portrayed on paleotectonic maps. After Jurassic rifting from Yucatan and throughout the bulk of the Cretaceous, northern South America was a passive margin developing along the widening Proto-Caribbean Seaway. Therefore, aside from the geometry of rifting from the Yucatan Block, we do not show consecutive paleotectonic maps for the Cretaceous interval. The pre-Campanian reconstruction of Figure 16 satisfies the tectonic framework for the entire Cretaceous (prior the latest Cretaceous accretion of the Western Cordillera of Colombia), and the disposition of Cretaceous stratigraphic units for any given stage may be plotted on that basemap with a fair degree of accuracy. Note that latitude and longiture coordinates of the various Andean blocks are offset by the magnitudes of the fault zones betwen them according to Figure 15.

Regional stratigraphy

The general stratigraphy of northern South America is summarized for the present purposes in a number stratigraphic columns included herein. These numerous columns (collectively presented as Figure 18) were originally compiled by Edward Robinson, and are locally updated.

Paleodepth estimates for marine strata and various notes are included on the columns to elucidate the significance of certain rock units. Key references for each section are usually given as well.

The Geometry of Jurassic breakup, and the Cretaceous passive margin

Figure 17 shows the approximate initial relationship between northern South America and Yucatan. Marginal offsets between these two blocks, as inferred by the style of Cenozoic thrusting and stratigraphic development along the margin, are realigned providing additional control on the general reconstruction outlined by Pindell (1985) and Rowley and Pindell (1989). The depiction of Jurassic paleogeography (Figure 23) shows the development of features pertaining to rifting. The opening of the Proto-Caribbean must have occurred with a component of counterclockwise rotation of the Yucatan Block relative to South America, just as also occurred between Yucatan and North America in the Gulf of Mexico. This rotational behavior was similar to that of Iberia between Europe and Africa during the Jurassic separation of those continents..

The Jurassic section of northern South America is poorly known because of limited exposure. However, there was probably a Late Jurassic marine shelf which complemented the passive margin slope and rise sediments of Paria and the Northern Range of Trinidad. In structural sections interpreted from seismic sections of the Serrania del Interior (Talukdar et al., 1988), a thick, unsampled unit below the Neocomian Barranquin Formation may be Jurassic shelf sediments. Those authors infer that the unknown section is Paleozoic in age, but Paleozoic rocks of the region, although poorly known, are generally metamorphosed such as the Dragon Gneiss of Paria, and the section in question appears folded and thrusted concordantly with the Serrania and, therefore, is probably not composed of previously metamorphosed rock. This factor in conjunction with the known Middle to Late Jurassic marine section from the conjugate western Cuban margin leads me to suggest that a very thick Middle? and Late Jurassic marine section underlies the Serrania, and probably Trinidad as well. To the west, the Las Brisas Formation in the Caracas Group of the Coast Ranges possesses shallow-water faunal forms, suggesting Jurassic marine shelf development at least in that area. In short, the well known Cretaceous sedimentary cycle that begins with the Barranquin Formation (Hauterivian-Valanginian) may actually be the second Mesozoic sedimentary cycle after Jurassic rifting. Furthermore, as the Jurassic in Cuba is source rock prone, Jurassic rocks of Eastern Venezuela also may be source prone.

The kink and deceleration in the NoAm-SoAm relative motion vector of Figures 13 and 14 may have played a role in early sedimenation along the NE South American margin. Pindell (1985b) suggested that motion at the long left-lateral Bahamaian transform during development of this kink may have tectonically uplifted the Bahamian basement to the photic zone after which reef building occurred to form the eastern Bahamas. Tied to the same mechanism may have been an early uplift or an interruption in thermal subsidence in NE South America. Such an interruption may have been followed by renewed depositon that is recognized as the Neocomian Barranquin Formation transgression. Erikson (in progress) is assessing accumulation rates for the Barranquin to see how that depositon related to basement subsidence, and whether the subsidence history may be related to minor tectonism at the end of the Jurassic. Figure 19 shows a possible scenario for Late Jurassic tectonism in eastern Venezuela and the Bahamas that is in accord with the Atlantic kinematics, discussed more fully by Erikson (in progress).

Coming west along the margin, this event was probably not felt because of distance to the long transform at the Bahamas. Instead, active rifting may have occurred throughout the Late Jurassic because of the rotational opening of the Proto-Caribbean. In effect, the geologic manifestations of the Jurassic rifting must have propogated westwards over time: southeastern Yucatan and northwestern South America probably remained in close proximity until the onset of Cretaceous time (Pindell, 1985b) because these areas lay at the apex of the fan-like opening. Such a migrating rift history is also apparent in the geology of Yucatan, where the age of rift-related red beds and subsequent marine transgression becomes younger from north to south (Middle Jurassic San Cayetano in the north, latest Jurassic Todos Santos in the south (Pardo, 1975; Lopez-Ramos, 1975).

During continued plate separation, South America and the Bahamas became fully separated, and the SoAm margin continued to subside passively. Seafloor spreading in the Proto-Caribbean probably ceased in the Albian, at about the same time that rifting had progressed to drifting in the Equatorial Atlantic between Guinea and Brazil. The Albian also marked the onset of compressional tectonism in the central Andes (Bolivia to southern Ecuador), as well as an intense period of deformation throughout the island arc complexes of the Greater Antilles and the obducted allochthonous complexes of northern South America. I suggest that all such arc complexes lay at that time in the Pacific, connecting the subduction zone from Ecuador to western Mexico. A single continuous string of arcs could have run southward from offshore Mexico into Chortis, through Cuba, Hispaniola, Puerto Rico, the Virgin Islands, the Aves Ridge, the Western Cordillera of Colombia, and finally back into the continental arc terrane of southern Ecuador and Peru. All of these areas experienced Albian orogenesis, as defined by the age of metamorphism, deformation, and the shifting of magmatic axes. Pindell and Barrett (1990) suggested that the island arc between North and South America underwent a flipping of subduction polarity at about that time due to the arrival of buoyant Caribbean seafloor crust (Burke et al., 1978), such that from the Late Albian on the arc was able to migrate relatively eastwards into the Proto-Caribbean realm, subducting Proto-Caribbean crust and triggering eastwardly-progressive arc-continent collision around the rim of the Proto-Caribbean Seaway.

It is still unclear how the Albian period of plate boundary reconfiguration may have affected the northern margin of South America. It is a widely held belief that marine deepening took place at that time, and several workers have suggested that such subsidence is related to the approach of island arcs from the north (e.g., Maresch, 1974). However, I know of no sedimentological evidence whatsoever of an orogenic terrane necessarily near the autochthonous portions of the margin in the Late Cretaceous. Furthermore, subsidence histories of autochthonous sections show no rapid acceleration in Late Cretaceous sedimentation that would imply the arrival of a large tectonically driven load (Pindell et al., 1991). Furthermore, the relative motion history of plates in the region is not consistent with compression along the margin until the Cenozoic arrival of the Caribbean Plate and related terranes (see discussion on Grenada Basin above, and Figures 13, 14).

The apparent deepening of marine conditions which took place at the end of the Albian without accelerated sedimentation may be related to the following. First order sea level was on the rise at the time, such that by the Turonian it may have been over 200 hundred meters higher than in the Albian. It si well known that reefs died and carbonate production slowed at that time as well, such that sedimenation may not have been able to keep pace with thermal subsidence. Thermal subsidence over the next 30 million years (into the Campanian) would have amounted to several hundreds of meters. The thermal subsidence, sea level rise, and further subsidence caused by sedimentation, minus the accumulated thickness of sediment, could have produced water depths of many hundreds of meters above what had been a typical passive margin shelf (El Cantil Formation) in the Albian. I infer that paleontologically determined water depths in this outer shelf setting would be considered "deep water". Another more theoretical cause may have been the onset of in-plane stress as a result of the death of the seafloor spreading ridge in the Proto-Caribbean, or to the Andean orogenesis to the west, or both, both of which would have been directly related to the opening of the Equatorial Atlantic.

In the Late Cretaceous, the northeastern Colombian, Venezuelan, Trinidadian and Guyana margins received mainly pelagic and/or fine clastic deposits due to high eustatic sea level (strandline far south). Source rocks were deposited across much of the shelf; the Simiti, La Luna, Querecual/San Antonio, and Naparima Hill Formations comprise Cenomanian to Campanian? oil-prone biogenic cherts, phosphates, pelagic carbonates and shales. Upwelling of relatively cold, nutrient rich waters due to the easterly trade winds, and high sea level, may have contributed to source rock development and to the absence of a carbonate bank platform.

Toward the end of the Cretaceous, Campanian to Maastrichtian uplift of the Central Cordillera of Colombia, as shown by the dominance of K-Ar cooling ages on metamorphic minerals at that time, tectonically loaded the area occupied by the Colon Formation in western Venezuela and NE Colombia. The Cordilleran uplift was probably caused by the accretion of the Western Cordillera. Although disputed by some, water depths and sedimentation rates both appear to have accelerated in the Colon Basin. At a time when first-order sea level is inferred to have been dropping, this is best achieved by a tectonic driving factor, i.e. flexural loading of the area by the uplift of the adjacent Cordillera. I suggest that any attempts to correlate sequence boundaries within the Colon Shale with global curves must be held in suspicion, due to the tectonic control of the basin at the time. In Eastern Venezuela and Trinidad, this effect is not seen. In contrast, the coeval prograding San Juan Formation and equivalents probably signal regional shallowing, or lowering of first order sea level.

Cenozoic phase of South American-Caribbean interaction

At the start of the Cenozoic, deposition along the shelf was still entirely derived from the Guyana shield or Central Andes of Colombia to the south or southwest, except possibly for the northwestern Maracaibo and Cesar basins. In those areas, interaction with the migrating Caribbean Plate had begun before the end of the Paleocene, with clastic input reaching NW Maracaibo from Guajira Peninsula. The Guajira basement and its Cretaceous section was probably deeply imbricated itself by thrusts well beneath the allochthonous Ruma matamorphics, which explains why the Guajira was uplifted and eroded in the Paleocene rather than depressed and buried like the basement of the Maracaibo Basin.

Metamorphic complexes with oceanic/arc affinity that are allochthonous with respect to South America such as the Ruma, Santa Ana, Siquisique, Villa de Cura, western Araya, Margarita, and Tobago occur along northern South America (Case and MacDonald, 1973; Martin-Bellizia and de Arozena, 1972; Bartok et al., 1985; Maresch, 1974; Avé Lallemant, 1990; Snoke et al., 1990). The metamorphism is mainly mid-Cretaceous in age and thus probably occurred in the Pacific, as mentioned above. The Ruma, Santa Ana, Siquisique, Villa de Cura and various para-allochthonous assemblages of the South American outer margin were obducted southward into Cenozoic flysch basins which formed above the Mesozoic shelf sediments and basement (Maresch, 1974; Beck, 1978; Gonzales de Juana et al., 1980). In Venezuela's Coast Range, basement and Mesozoic Caracas Group shelf sediments have since been uplifted between La Victoria and San Sebastian Faults (Fig. 1; Schubert, 1988; Kohn et al., 1984), thereby isolating the Villa de Cura klippe from other areas originally derived from the Caribbean Plate. In the west, Neogene Oca and Boconó motions have offset the southern limit of the allochthons and their foredeep basins, complicating the original thrust geometry which was once a curvilinear continuous feature.

The southward obduction of allochthonous rocks at various points along northern South America can be dated between (1) the age of accelerated (load-induced) subsidence of the autochthonous platform, and (2) the age of the youngest overthrust foredeep deposits and/or the oldest overlap assemblage across the thrusts responsible for the emplacement of the allochthon. In the Siquisique area, obduction is dated as Early to Medial Eocene by the age of overthrust flysch (Paleocene-Lower Eocene Trujillo Formation) and by the onset of rapid subsidence in the northern Maracaibo Basin (Figure 20, subsidence curve A). At Guarumen (Figure 20, curve B) Medial-Late Eocene obuction is indicated both by the age of overthrust flysch and subsidence. At Barcelona (Figure 20, curve C) Late Oligocene-Early Miocene obduction is indicated by the overthrust Roblecito Formation and by subsidence history. In south-central Trinidad (Figure 20, curve E) Late? Miocene-Quaternary obduction is indicated by the overthrust Lengua/Cruse and younger Formations and by subsidence. At Anzoategui in the Eastern Venezuelan Basin (Figure 20, curve D), farther from the region of loading, accelerated subsidence is slightly delayed relative to that at Barcelona due to southward foredeep migration. In Trinidad, peak subsidence rates occurred since Late Miocene, but moderately fast rates earlier in the Miocene, if real and not due to unrecognized repeated section, may have been driven by Orinoco deltaic deposition near the shelf edge. There is clearly an eastward migration in the position of tectonically driven peak sediment accumulation and basement subsidence. This migration is directly associated with Caribbean Plate and Lara Terrane migration. Rates of migration appear to be about 20% slower than those measured at the Cayman Trough, consistent with motion around the Minster and Jordan (1978) pole. Furthermore, like the migration of the point of peak subsidence, there is a corresponding migration of a peripheral bulge in the autochthon about 250 km ahead of the Caribbean Plate, defined by the eastwardly migrating area over which subaerial erosion took place (Figure 21) throughout the Tertiary. The position of this bulge over time is critical to the history of hydrocarbon behavior. At any given time during the Tertiary, oils could have migrated updip from thrust front and foredeep basin kitchens to, but not over, the peripheral bulge. Thus, Figure 21 helps to show the aerial distribution of potentially charged sandstone reservoirs for different times in the Tertiary. For example, no oil could have been migrating into Maturin basin reservoirs until the Oligocene, probably the latter Oligocene. Finally, it was the subaerial erosion at this bulge that appears to have fed the voluminous southerly-derived clastic systems of the Scotland Formation of Barbados and the allochthonous Guarico Formation of central Venezuela.

In addition to identifying the onset of tectonic load-related sediment accumulation (allochthon emplacement) above formerly passive margin sections, the subsidence histories of Figure 20 show that the migrating Cenozoic foredeep basin was the <u>first</u> loading event along northern South America. The absence of rapid Cretaceous subsidence "events" other than slow thermal subsidence in the autochthon further substantiates the argument for passive margin sedimentation without arc collision or other primary tectonic events in that period.

Seismic tomopgraphic evidence for Eocene to Recent underthrusting of Proto-Caribbean crust beneath South America??

Seismic tomography allows the recognition of high velocity areas of the upper mantle that may indicate the position of subducted oceanic slabs far more deeply than do seismic Benioff zones. Tomographic studies in the Caribbean (Hilst, 1990; summarized here in Fig. 22) can be integrated with assessments of the relative motions of plate pairs to help document the fate of now vanished oceanic crust. They show (Hilst, 1990) that : (1) >1300 km of crust (Atlantic slab, i.e. Proto-Caribbean) has been subducted beneath the eastern Caribbean, giving a minimum Caribbean/Atlantic convergence. (2) Slab dip increases southwards across 15°N beneath the Lesser Antilles Arc, that I suggest may be due to the Cretaceous (north) vs. Jurassic (south) age (and thus average density) difference in the subducting slab there (Westbrook, in Speed and Westbrook, 1984). (3) Caribbean crust underthrusts the Maracaibo, Guajira, Paraguana, and Leeward Antilles area southward to ~8°N and 300km depth, that I suggest pertains to (a) the Middle Miocene to Recent NE migration of these terrains relative to South America, (b) the southerly component of western Caribbean/South American transpression, and (c) the N-S convergence between NoAm and SoAm for the Middle-Miocene to Recent interval. (4) A strip-like "slab" may occur beneath northern South America which from west to east (Maracaibo to Gulf of Paria) shallows from ~550 to the depth of unsubducted crust and whose southern "edge" becomes more northerly from 7°N in the west to 11°N in the east. East of the Gulf of Paria this slab (item 4) appears continuous with the northwest-dipping Atlantic (South American Plate) crust, but west of the Gulf of Paria it appears vertically detached from, and overthrust by, South America. Although this slab is only suggested and not definitively shown by the tomographic results, its existence is a distinct possibility because of the well-documented convergence between North and South America on the order of several hundred km since the Eocene (Figure 13). (5) Finally, an apparent "tomographic gap" separates this strip-like slab beneath SOAm from the downgoing Atlantic slab to the north beneath the central Caribbean. Although the "gap" exists in a current north-south cross-section of deeply subducted crust, I note that if the documented cross-sections of subducted slabs were returned to the surface to follow the natural curvature of the earth, the gap would become closed. In other words, the north-south line length of subducted crust nearly matches the distance along the earth's surface from the Puerto Rico Trench to the line above the southern limit of the subducted strip-like Proto-Caribbean lithosphere beneath SoAm. Thus, the gap could have formed by extension in the subducted slab during subduction to depths that now have a longer cross-sectional line length than the earth's surface. Because the slabs are deeper to the west, the north-south width of the gap becomes greater to the west and pinches out to the east.

Of particular note here is the coincidence of the eastward point of the apparent dislocation between the Proto-Caribbean crust and the crust of South America (i.e., item 4 at the Gulf of Paria) with the world's most negative onshore Bouguer gravity anomaly. I consider the possibility that the negative anomaly may be partially caused by "scissoring" of the crust at this point which may lie within attenuated continental crust of the original passive margin. The underthrust portion of the crust beneath South America at and just west of the scissor point would provide a potential zone of abnormal continental crustal thickness, which may contribute to the anomaly, in conjunction with the thick sedimentary section of the Maturin Basin and Orinoco Delta and also the overthrust edge of the Caribbean Plate (Margarita/Araya Peninsula/Tobago).

At this point, the reliability and full implications of the seismic tomographic results beneath SoAm are unclear. Hilst and I are currently further assessing these items in the light of Caribbean geology, to refine and solidify their implications. Pindell et al. (1991) show Tertiary reconstructions of northern South America which incorporate a north-vergent boundary where northern South American continental crust overthrusts the Proto-Caribbean lithosphere ahead of the eastwardly-advancing Caribbean Plate. This convergent boundary would satisfy post-Middle Eocene convergence between North and South America. In this work, I reserve judgement and avoid the use of this proposed boundary (see next section).

Tertiary paleogeographic maps.

Figures 23-32 outline the Tertiary evolution and sedimentation of northern South America as I currently see it at roughly 7 to 10 million year intervals. These maps represent only a progress report on our assessment of the full paleogeographic evolution, and thus I will not attempt to discuss the evolution in great detail. Some of the main points to make, however, are as follows.

1. The southward component of Paleogene compression in the Maracaibo-Lara area is best explained by an oblique opening model for the Grenada Basin (discussed above; Figure 12a). Opening of the Grenada Basin appears to have occurred from the Paleocene to the Early Oligocene, and was driven by transform drag and subduction rollback of the Proto-Caribban margin and adjacent Jurassic oceanic crust.

2. Rates of plate migration of 16 and 24 mm/yr before and after 26 Ma (scaled to the Cayman Trough) appear to explain the timing of foredeep and peripheral bulge migration along northern South America.

3. Strike-slip offset between the Caribbean Plate and South America is distributed along the basal emplacement thrusts of the allochthons (e.g., Villa de Cura), offshore faults, extension within the Falcon-Bonaire Basin, and the Oca and Merida fault systems. Because the emplacement of the allochthons was a function of transpressive motion, there is absolutely no need to "find" many hundreds of km of offset superimposed upon a pre-existing orogenic terrane, as is so commonly attempted. The allochthons were emplaced coevally with and as a direct function of the strike-slip history, and not before.

4. The migrating peripheral bulge is defined by erosion and/or shallowing approximately 250 km to the east of the point of peak subsidence in the foredeep basins. The subsequent migration of the foredeep basin is marked by the southeastward marine transgression above the section previously eroded by the peripheral bulge uplift. In the Barinas Basin, Paleocene and Early Eocene erosion is followed by Late Eocene southeastward transgression of the Gobernador and Paguey Formations (leading fringe of foredeep). In the Guarico Basin, Middle and Late Eocene erosion is followed by latest Eocene-Oligocene southeastward transgression of the La Pasqua and Roblecito Formations (leading fringe of foredeep). In the Maturin Basin, late Eocene and Oligocene shallowing and erosion is followed by Late Oligocene and Miocene southeastward transgression of the Late Oligocene to Middle Miocene Merecure and Oficina Formations.

5. At about 9 Ma, the transpressive phase in the Eastern Venezuelan Basin was completed, and the Eastern Venezuelan and Trinidadian area entered transtension (see above, and Figures 10, 11). Normal faulting on N-dipping faults allowed isostatic rebound of the Maturin and parts of Trinidad, producing southward dips on bedplanes in Upper Miocene to recent sediments.

Neogene-Recent Northward Thrusting at South Caribbean Foldbelt

The northeastward escape of the Maracaibo Block during the Panama-Colombia collision since the Medial? Miocene (Mann and Burke, 1984; Dewey and Pindell, 1985; 1986) has augmented the convergent component of Caribbean/South America relative motion west of the Boconó Fault by at least 100 km, and has caused folding to propagate northward into the Caribbean Plate's stratigraphy above a basal décollement within the South Caribbean Foldbelt (Guajira to Orchila Canyon, Case and Holcombe, 1980). The motions of these blocks relative to South America combined with convergence between North and South America since the Middle Miocene to produce nearly 300 km of underthrusting by the Caribbean crust beneath northwestern South America (Figure 22).

TIMING OF HYDROCARBON MATURATION

Although Jurassic rift-related petroleum source rocks may have been deposited locally, primary known source rocks in northern South America are Upper Cretaceous and were deposited well after Jurassic rifting such that they were not affected by rift-related heat flow. In the absence of Cretaceous volcanism in the autochthon, geothermal gradients may be assumed to have been fairly normal by the medial Cretaceous. Maturation was thus a function of depth of burial, which was insufficient in each of the northern South American basins (localities A-E, Fig. 20) until the time of local foredeep development. Thus, maturation may be predicted to have occurred in the

Maracaibo Basin in the Eocene, younging eastward into the Miocene in the Eastern Venezuelan Basin, and the Late Miocene-Recent in Trinidad. A second phase of rapid deposition (Bockmeulen, et al., 1983) and hence maturation of Neogene age has occurred in the inter-Andean basins of the west (e.g., southern Maracaibo, Barinas, Llanos) due to Miocene uplift and erosion of Andean ranges and flexural loading of the basins. These predicted maturation times are corroborated by more direct studies (Talukdar et al., 1985; 1988). Pindell (1991) discusses the relation of plate tectonics to hydrocarbon history around the Caribbean and northern South America more fully.

LIST OF REFERENCES

Algar, S.T., and Pindell, J. L., 1991a, Structural development of the Northern Range of Trinidad, and implications for the tectonic development of the southeastern Caribbean, in K. A. Gillezeau, ed., Transactions, Second Geol. Conf., Geol. Soc. Trinidad and Tobago, Port-of-Spain, p. 6-22.

Algar, S. T., and Pindell, J. L., 1991b, Stratigraphy and sedimentology of the Toco region of the Northern Range, N.E. Trinidad, in K. A. Gillezeau, ed., Transactions, Second Geol. Conf., Geol. Soc. Trinidad and Tobago, Port-of-Spain, p. 56-69.

Avé Lallemant, H.G., 1990, The Caribbean-South American Plate boundary, Araya Peninsula, Eastern Venezuela: Caribbean Geological Conference, 12th, Transactions, St. Croix., p. 461-471.

Aymard, R., Pimentel, L., Eitz, P., Lopez, P., Chaouch, A., Navarro, J., Mijares, J., and Periera, J. G., 1990, Geological integration and evaluation of Northern Monagas, Eastern Venezuelan Basin, in: Brooks, J., ed., Classic Petroleum Provinces, Geological Society, Special Publication, 50, p. 37-53.

Bartok, P.E., Renz, O., and Westermann, G.E.G, 1985, The Siquisique ophiolites northern Lara State, Venezuela: A discussion on their Middle Jurassic ammonites and tectonic implications: Geological Society of America Bulletin, v. 96, p. 1050-55.

Beck, C. M., 1978, Polyphasic Tertiary tectonics of the interior range in the central part of the western Caribbean chain, northern Venezuela: Geologie en Mijnbouw, v. 57, p. 99-104.

Beets, D. J., Maresch, W. V., Klaver, G. Th., Mottana, A., Bocchio, R., Beunk, F. F., and Monen, H. P., 1984, Magmatic rock series and high-pressure metamorphism as constraints on the tectonic history of the southern Caribbean, in Bonini, W.E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 95-130.

Bellizzia, A., 1985, Sistema Montanoso del Caribe - una Cordillera aloctona en la parte norte de America del Sur, VI Congress Geológico Venezolano, Caracas, p. 6657-6836.

Benson, W. E., Gerard, R. D., and Hay, W. W., 1970, Summary and conclusions, in: Bader, R. G., and others, eds., Initial Reports of the Deep Sea Drilling Project: Washington, D. C., U. S., Gov. Printing Office, 4, 659-673.

Biju-Duval, B., Bizon, G., Mascle, A., and Muller, C., 1982, Active margin processes: field observations in southern Hispaniola: American Association Petroleum Geologists Memoir 34, p. 325-344.

Bockmeulen, H., Barker, C., and Dickey, P.A., 1983, Geology and Geochemistry of Crude Oils, Bollivar Coastal Fields, Venezuela: American Association of Petroleum Geologists Bulletin, v. 67, No. 2, p.242-270.

Borger, H. D., 1952, Casse history of Quiriquire field, Venezuela, AAPG Bull., 36, 2291-2330.

Bracey, D. R., and Vogt, P. R., 1970, Plate tectonics in the Hispaniola area: Geological Society of America Bulletin, v. 81, p. 2855-2860.

Burke, K., Fox, P. J., and Sengor, A. M. C., 1978, Buoyant ocean floor and the evolution of the Caribbean: Journal of Geophysical Research, v. 83, p. 3949-3954.

Burke, K., 1988. Tectonic evolution of the Caribbean: Annual Reviews Earth and Planetary Science, v. 16, p. 201-230.

Byrne, D. B., G. Suarez, and W. R. McCann, 1985, Muertos Trough subduction-microplate tectonics in the northern Caribbean?, Nature, 317, 420-421.

Case, J. E., and T. Holcombe, 1980, Geologic-tectonic map of the Caribbean Region, U.S.G.S. Miscellaneous Investigations Series, Map I-1100, Scale 1:2,500,000.

Case, J.E., and MacDonald, W.E., 1973, Regional gravity anomalies and crustal structure in northern Colombia: Geological Society of America Bulletin, v. 84, p. 2905-2916.

Chevalier, Y., Stephan, J-F., Darboux, J-R., Gravelle, M., Bellon, H., Bellizia, A., and Blanchet, R., 1988, Obduction et collision pre-Tertiaire dans les zones internes de la Chaine Caribe venezuienne, sur le transect Ile de Margarita-Peninsule d'Araya, C. R. Acad. Sci., Paris, t. 307, Serie II, p. 1925-1932.

Demets, C., R. Gordon, D. Argus, and S. Stein, 1990, Current plate motions, Geophys. J. Int., 101, 425-478.

Dengo, G., 1953, Geology of the Caracas region: Geological Society of America Bulletin, v. 64, p. 7-40.

Dengo, G., and Case, J. E., 1990, eds., Decade of North American Geology, volume H, The Caribbean Region, Geological Society of America, Boulder, Co.

Dewey, J. F., and Pindell, J. L., 1985, Neogene block tectonics of Turkey and northern South America: Continental applications of the finite difference method: Tectonics, v. 4, p. 71-83.

Dewey, J. F., and Pindell, J. L., 1986, Neogene block tectonics of Turkey and northern South America: Continental applications of the finite difference method: Reply: Tectonics, v. 5, 703-705.

Erikson, J. P., Pindell, J. L., Karner, G. D., Fuller, E., Dent, L., and Sonder, L., (submitted to GSA Bulletin, 1991), Causes and effects of subsidence and deposition in a transpressional plate boundary zone: sedimentology and gravity in the Neogene Cibao Basin of Hispaniola.

Erikson, J., Pindell, J. L., and Larue, D. K., 1990, Mid-Eocene-Early Oligocene sinistral transcurrent faulting in Puerto Rico associated with formation of the northern Caribbean plate boundary zone, J. Geology, v.98, p. 365-384.

Fabre, A., 1983, La subsidencia de la Cuenca del Cocuy (Cordillera Oriental de Colombia) durante el Cretaceo y el Terciario inferior. Primera Parte: Estudio cuantiativo de la subsidencia: Geologia Norandina, No. 8, Diciembre 1983.

Fox, P. J., and Heezen, B. C., 1975, Geology of the Caribbean crust, in Nairn, A. E. M., and Stehli, F. G., eds., The Ocean Basins and Margins, The Gulf of Mexico and the Caribbean, Plenum, New York, p. 421-465.

Fox, P. J., Ruddiman, W. F., Ryan, W. B. F., and Heezen, B. C., 1970, The geology of the Caribbean crust, I: Beata Ridge, Tectonophysics, 10, 495-513.

Gealey, W., 1980, Ophiolite obduction mechanism, In: Ophiolites, I. Gass, ed., Procedings of the Symposium on ophiolites, Cyprus.

Gonzalez de Juana, C., Munoz, N.G.J., and Vignali, M.C., 1965, On the geology of eastern Paria (Venezuela): Caribbean Geological Conference, 4th, Transactions, Trinidad.

Gonzalez de Juana, C., Iturralde de Arozena, J. M., and Cadillat, X., 1980, Geologia de Venezuela y de sus Cuencas Petroleras., Caracas, Ediciones, Foninves.

Hess, H. H., and Maxwell, J. C., 1953, Caribbean research project, Geol. Soc. Amer. Bull., 64, 1-6.

Heubeck, C., and Mann, P., 1991, Geologic evaluation of plate kinematic models for the North American-Caribbean plate boundary zone, Tectonophysics, 191, 1-26.

Holcombe, T. L., Ladd, J., Westbrook, G., Edgar, N. T., Bowland, C., 1990, Caribbean marine geology; ridges and basins of the plate interior, in: Dengo, G., and Case, J. E., eds., Decade of North American Geology, the Caribbean region, Geol. Soc. Amer., Boulder Co., 231-260.

Holcombe, T. L., P. R. Vogt, J. E. Matthews, and R. R. Murchison, 1973, Evidence for sea floor spreading in the Cayman Trough, Earth Planet. Sci. Letts., 20, 357-371.

Jany, I., K. M. Scanlon, and A. Mauffret, Marine Geophys. Res., submitted paper, 1990.

Jordan, T. H., 1975, The present-day motions of the Caribbean Plate, J. Geophys. Res., 80, 4433-4439.

Kafka, A., and D. J. Weidner, 1981, Earthquake focal mechanisms and tectonic processes along the southern boundary of the Caribbean Plate, J. Geophys. Res., 86, 2877-2888.

Kohn, B.P., Shagam, R., and Subieta, T., 1984, Results and preliminary implications of sixteen fission-track ages from rocks of the western Caribbean Mountains, Venezuela, in Bonini, W.E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 415-421.

Ladd, J. W., 1976, Relative motion of South America with respect to North America and Caribbean tectonics: Geological Society of America Bulletin, v. 87, p. 969-976.

Ladd, J. W., Holcombe, T. L., Westbrook, G. K., and Edgar, N. T., 1990, Caribbean marine geology; active margins of the plate boundary, in: Dengo, G., and Case, J. E., eds., The Caribbean Region: Boulder, Co., Geological Society of America, The Geology of North America, vol. H., 261-290.

Ladd, J. W., and Watkins, J. S., 1978, Tectonic development of trench-arc complexes on the northern and southern margins of the Venezuelan Basin, in: Watkins, J. S., Montadert, L., and Dickerson, P. W., eds., Geological and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 363-371.

Larue, D. K., and H. Ryan, 1991, Extensional tectonism in the Mona Passage, Puerto Rico and Hispaniola, a preliminary study, Trans. 12th Carib. Geol. Conf., p. 223-230.

Larue, D. K., J. Joyce, and H. Ryan, 1991, Neotectonics of the Puerto Rico Trench: extensional tectonism and forearc subsidence, Trans. 12th Carib. Geol. Conf., p. 232-247.

Lopez Ramoz, E., 1975, Geological summary of the Yucatan Peninsula, in: Nairn, A. E. M., and Stehli, F. G., eds., The Ocean Basins and Margins, v. 3, The Gulf of Mexico and The Caribbean: Plenum, New York, p. 257-282.

MacDonald, K., C., and Holcombe, T. L., 1978, Inversion of magnetic anomalies and sea floor spreading in the Cayman Trough, Earth Planet Sci. Letters, 40, 407-414.

Maley,T. S., Sieber, F. D., and Johnson, G. L., 1974, Topography and structure of the western Puerto Rico trench, Geol. Soc. Amer., Bull., 85, 513-518.

Mann, P., and K. Burke, 1984. Neotectonics of the Caribbean: Reviews of Geophysics and Space Physics, v. 22, p. 309-362.

Maresch, W. V., 1974, Plate tectonics origin of the Caribbean mountain system of northern South America: Discussion and proposal: Geological Society of America Bulletin, v. 85, p. 669-682.

Martin-Bellizia, C., and de Arozena, J.M.I., 1972, Complejo ultramafico zonado de Tausabana-El Rodeo, gabro zonado de Siraba-Capuana, y complejo subvolcanico estratificado de Santa Ana, Paraguana, Estado Falcon, in Caribbean Geological Conference, 6th, Transactions.

Minster, J. B., and Jordan, T. H., 1978, Present-day plate motions, J. Geophys. Res., 83, 5331-5354.

Molnar, P., and Sykes, L. R., 1969, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity: Geological Society of America Bulletin, v. 80, p. 1639-1684.

Moore, G. T., and Falquist,D. A., 1976, Seismic profile tying Caribbean DSDP sites 153, 151, and 152, Geol. Soc. Amer. Bull., 87, 1609-1614.

Muessig, K. W., 1984, Structure and Cenozoic tectonics of the Falcon Basin, Venezuela and adjacent areas, in: Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 217-230.

Pardo, G., 1975, Geology of Cuba, in: Nairn, A. E. M., and Stehli, F. G., eds., The Ocean Basins and Margins, v. 3, The Gulf of Mexico and The Caribbean: Plenum, New York, p. 553-615.

Pennington, W. D., 1981, Subduction of the eastern Panama basin and seismotectonics of northwestern South America: Journal of Geophysical Research, v. 86, p. 10753-10770.

Perez de Mejía, D., Kiser, G. D., Maximowitsch, B., and Young, G. A., 1980, Geologia de Venezuela, in Felder, B., ed., Evaluacion de Formaciones en Venezuela, Schlumberger Surenco, p. I-1 - I-23.

Pindell, J. L., Erikson, J. P., and Algar, S. T., 1991, The relationship between plate motions and sedimentary basin development in northern South America: from a Mesozoic passive margin to a Cenozoic eastwardly-progressive transpressional orogen, in K. A. Gillezeau, ed., Transactions, Second Geol. Conf., Geol. Soc. Trinidad and Tobago, Port-of-Spain, p. 191-202.

Pindell, J. L., 1985a, Plate tectonic evolution of the Gulf of Mexico and Caribbean Region, PhD thesis, University of Durham, England, 265 pp.

Pindell, J. L., 1985b, Alleghenian reconstruction and the subsequent evolution of the Gulf of Mexico, Bahamas and Proto-Caribbean Sea: Tectonics, v. 4, p. 1-39.

Pindell, J. L., Erikson, J. P., and Algar, S., 1991 (in press), The relationship between plate motions and sedimentary basin development in northern South America: from a Mesozoic passive margin to a Cenozoic eastwardly-progressive transpressional orogen, Transactions, Geological Conference, 2nd, Trinidad and Tobago Geological Society, Port-of-Spain, 1990, p. 191-202.

Pindell, J. L., 1990, Arguments for a Pacific origin for the Caribbean Plate, in: Larue, D. K. and Draper, eds., Transactions, Caribbean Geological Conference, 12th, Christianstadt, St. Croix., 1-4.

Pindell, J. L., and Barrett, S. F., 1990. Geologic evolution of the Caribbean: a plate-tectonic perspective, in Case, J. E., and G. Dengo, eds., Decade of North American Geology, volume H, Geological Society of America, Boulder, Co., p. 405-432.

Pindell, J. L., Cande, S. C., Pitman, W. C., Rowley, D. B., Dewey, J. F., LaBrecque, J., and Haxby, W., 1988, Plate-kinematic framework for models of Caribbean evolution: Tectonophysics, v. 155, p. 121-138.

Pindell, J. L., and Dewey, J. F., 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179-212.

Pindell, J. L., 1991, Geologic rationale for hydrocarbon exploration in the Caribbean and adjacent regions, Journal of Petroleum Geology, v. 14, 237 257.

Potter, H.C., 1973, The overturned anticline of the Northern Ranges of Trinidad near Port of Spain. Journal of the Geological Society of London, v. 129, p.133 - 138.

Reid, J. A., P. Plumley, and J. H. Schellekens, 1991, Paleomagnetic evidence for Late Miocene CCW rotation of north coast carbonate sequences, Puerto Rico, Geophys. Res. Letters, v. 18, p. 565-568.

Robertson, P., and Burke, K., 1989, Evolution of southern Caribbean plate boundary, vicinity of Trinidad and Tobago, AAPG Bull., 73, 490-509.

Robertson, P., and Burke, K., 1989, Evolution of southern Caribbean plate boundary, vicinity of Trinidad and Tobago:reply, AAPG Bull., v. 75, 1795-1796.

Rohr, G.M., 1990, Paleogeographic maps, Maturin Basin of eastern Venezuela and Trinidad, in K. A. Gillezeau, ed., Transactions, Second Geol. Conf., Geol. Soc. Trinidad and Tobago, Port-of-Spain, p. 88-105.

Rosencrantz, E., and Mann, P., 1991, SeaMARC II mapping of transform faults in the Cayman Trough, Caribbean Sea, Geology, 19, 690-693.

Rosencrantz, E., Ross, M., and Sclater, J. G., 1988, Age and spreading history of the Cayman Trough as determined from depth, heat flow, and magnetic anomalies: Journal of Geophysical Research, v. 93, p. 2141-2157.

Rowley, D. B., and Pindell, J. L., 1989, End Paleozoic-Early Mesozoic western Pangean reconstruction and its implications for the distribution of Precambrian and Paleozoic rocks around Meso-America, Precambrain Research, 42, 411-444.

Royden, L., and B. C. Burchfiel, 1989, Are systematic variations in thrust belt style related to plate boundary processes? (The Western Alps vs. the Carpathians), Tectonics, v. 8, p. 51-61.

Russo, R.M., Speed, R.C., and Okal, E.A., 1990, Seismicity and tectonics of the southeastern Caribbean: Transactions of the American Geophysical Union, v. 71, No. 17, p. 641.

Salvador, A., and Stainforth, R.M., 1965, Clues in Venezuela to the geology of Trinidad, and vice versa: Caribbean Geological Conference, 4th, Transactions, Trinidad, p. 31-40.

Schubert, C., 1982, Origin of Cariaco Basin, southern Caribbean Sea: Marine Geology, v. 47, p. 345-360.

Schubert, C., 1988, Neotectonics of La Victoria Fault Zone, north-central Venezuela: Journal of South American Earth Sciences, Annales Tectonicae, v. II, p. 58-66.

Shaw, P. R., and Cande, S. C., 1990, High-resolution inversion for South Atlantic plate kinematics using joint altimeter and magnetic anomaly data, J. Geophys. Res., 95, no. B3, 2625-2644.

Sieglie, G. A., and Moussa, M. T., 1984, Late Oligocene-Pliocene transgressive-regressive cycles of sedimentation in northwestern Puerto Rico, in: Schlee, J. S., ed., Interregional unconformities and hydrocarbon accumulation, AAPG Memoir, 36, 89-95.

Silver, E. A., Case, J. E. and Macgillavry, H. J., 1975, Geophysical study of the Venezuelan borderland: Geological Society of America Bulletin, v. 86, p. 213-226.

Snoke, A. W., Yule, J. D., Rowe, D. W., Wadge, G., and Sharp, W. D., 1990, Stratigraphic and structural relationships on Tobago, West Indies, and some tectonic implications, in: Larue, D. K. and Draper, G., eds., Transactions, Caribbean Geological Conference, 12th, Christianstadt, St. Croix., 389-402.

Speed, R. C., 1985, Cenozoic collision of the Lesser Antilles Arc and continental South America and origin of the El Pilar Fault: Tectonics, v. 4, p. 40-70.

Speed, R.C., and Foland, K.F., 1989, Structural evolution of the Northern Range of Trinidad: New data: Geological Society of America, 1989 Annual Meeting, Abstracts and Programs, v. 21, No. 6, p. 318.

Speed, R. C., and Larue, D. K., 1991, Extension and transtension in the plate boundary zone of the northeastern Caribbean, Geophys. Res. Letters, v. 18, p. 573-576.

Speed, R. C., and Westbrook, G. K., 1984, Lesser Antilles Arc and adjacent terranes, Ocean Margin Drilling Program, Regional Atlas Series, Atlas 10: Marine Science International, Woods Hole, Mass., 27 plates.

Speed, R. C., Russo, R., Weber, J., and Rowley, K. C., 1991, Evolution of southern Caribbean plate boundary, vicinity of Trinidad and Tobago: Discussion, AAPG Bull., 75, 1789-1794.

Stein, S., DeMets, C., Gordon, R.G., Brodholt, J., Argus, D., Engeln, J.F., Lundgren, P., Stein, C., Wiens, D.A., and Woods, D.F., 1988, A test of alternative Caribbean Plate relative motion models: Journal of Geophysical Research, v. 93, No. B4, p. 3041-3050.

Sykes, L., McCann, W. R., and Kafka, A., 1982, Motion of the Caribbean Plate during the last 7 million years, J. Geophys. Res., 87, 656-676.

Talukdar, S., Gallango, O., and Chin-A-Lien, M., 1986, Generation and migration of hydrocarbons in the Maracaibo Basin, Venezuela: An integrated basin study: Advances in Organic Geochemistry, 1985, in Organic Geochemistry, v. 10, p. 261-279, 1986.

Talukdar, S., Gallango, O., and Ruggiero, A., 1988, Generation and migration of hydrocarbons in the Maturin Sub-basin, eastern Venezuelan Basin, Organic Geochemistry, v. 13, p. 537-547.

Talukdar, S., and de Toni, B., 1988, Geochemical modeling in the unexplored Guarumen sub-basin, Venezuela: Bolivarian Symposium III, Caracas, 1988, p. 755-782.

Hilst, R.D., van der, 1990, Tomography with P, PP and pP delay-time data and the three-dimensional mantle structure below the Caribbean region: Geologica Ultraiectina, Mededelingenvan de Faculteit Aardwetenschappen der Rijksuniversiteit te Utrecht, No.67.

Vasquez, C.A., 1988, Structural map of top of Cretaceous Llanos Basin, Colombia: Bolivarian Symposium III, Caracas, 1988, p. 579-611.

Vierbuchen, R. C., 1984, The geology of the El Pilar fault zone and adjacent areas in northeastern Venezuela: in: Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 189-212.

Zambrano, E., Vasquez, E., Duval, B., Latreille, M., and Coffinieres, B., 1972, Paleogeographic and petroleum synthesis of western Venezuela: Editions Technip, Paris, 59 p.

FIGURE CAPTIONS:

Fig. 1. Map of Puerto Rico Trench region, showing flowline about the Demets et al. (1990) pole of rotation for Caribbean-North America. Shaded area denotes the portion of the Caribbean Plate that sits north of the hypothetical flow line. This factor in conjunction with well-known convergence at the Muertos Trough as far west as Beata Ridge makes the Demets et al. (1990) flow line highly improbable. A more easterly trend of motion must be responsible for deriving the shaded area from the southeaastern tip of the Bahamas Bank. The vector triangle inset is discussed in detail in the text.

Fig. 2. Various proposed Euler poles of rotation for Caribbean-North America.

Fig. 3. Azimuth data for constraining NoAm-Caribbean motion. Note that the longitudinal position of the Beata Ridge (72°W) divides the eastern and western data sets. Motion at the Beata Ridge would allow the two data sets to be satisfied with the highest degree of confidence.

Fig. 4. Map of Beat Ridge area, drawn with fault interpretations after Case and Holcombe (1980). SL-ST is line of seismic section in Figure 6. Heavy dot at southern end of Beata Ridge is location of seismic event of Figure 5. Section a-b is sketched in Figure 7. Bathymetry in km.

Fig. 5. First-motion solution for shallow magnitude 5 quake in the southern Beata Ridge (see Figure 4 for location), reinterpreted from Molnar and Sykes 91969) by Kafka and Weidner (1981).

Fig. 6. Multifold seismic line S and T (in Dengo and Case, 1990) and my compressional interpretation, position shown in Figure 4.

Fig. 7. Schematic cross-section a-b, position shown on Figure 4. Faults appear nearly vertical on single channel seismic lines. Simplistic interpretations above the section (A, B, C) may be viable candidates for actual style of faulting, with motion indicators (arrows) relative to ridge axis.

Fig. 8. Simplistic models for structural style of Beata Ridge, following interpretations in Figure 7. No preference is given here at the present time (Pindell and others, work in progress). However, as discussed in text, net deformation must account for a ~65 km N-S component of relative motion at the Puerto Rico Trench.

Fig. 9. Speed and Larue (1991) model for extension at the Puerto Rico Trench. Note that their cross section is drawn in the only possible position that allows for net extension, i.e., at the two trailing flanks of the CCW rotating PRVIT. This section is not representative of the regional motions of the area.

Fig. 10. Collection of figures to illustrate probable N-S extensional component of relative motion in southeastern Caribbean. A, interpretations of N-S seismic sections showing large displacement normal faulting (after Robertson and Burke, 1989; Gonzales de Juana et al., 1980). B. Cross section of Quiriquire field in northern Maturin basin showing erosional angular unconformity beneath undeformed Late Miocene-Recent beds which have a regional southward dip (after Borger, 1952). C. Seismic section across El Furrial structure showing Late Miocene-Recent depositional pockets above deformed erosional unconformity above Lower Miocene and older formations (after Aymard et al., 1990). D. Extensional faulting affecting Pliocene and Younger Las Piedras Formation (after Gonzales de Juana et al., 1980). Schematic cross section of maturin thrust front, showing angular unconformity and overlying non-compressed section (after Aymard et al., 1990). E. Maps showing erosional area of Carupano-Tobago Platform beneath Late Miocene and younger marine sequences (after Bellizzia, 1985). Note that erosion cuts deeper into pre-Miocene section toward the south, in accord with maximum middle Miocene uplift toward the south during overthrusting which drove the emplacement of the Serrania del Interior.

Fig. 11. Flow lines of the Caribbean relative to South America, as derived in text. Note that Blanquilla path describes true Caribbean motion back to Paleocene. Prior to 28 Ma, Margarita and Tobago paths denote relative motion of the Lara or Grenada terrane, which had a more southerly component of motion than the Caribbean Plate during the opening of the Grenada Basin. Transtensional motion after 9 Ma describes motion of the Eastern Caribbean Plate, independent of the Western Caribbean after the onset of deformation at the Beata Ridge. Vector triangle (plotted at half scale of map) defines relative motions of the Caribbean, South American, and Lara/Grenada terrane during the opening of the Grendada Basin. The vector between SoAm and Grenada terrane approximates the convergent component and trend of allochthon emplacement in western and central Venezuela.

Fig. 12. (a) Simple model for the opening of the Grenada Basin after Pindell and Barrett (1990). (b) Geological map of the Grenada Basin region (after Case and Holcombe, 1980; Speed and Westbrook, 1984) with features mentioned in text. Axes of relative positive and negative magnetism in the Grenada Basin shown by plus and minus signs, respectively. Pole of rotation shown in central Venezuelan Basin defines approximate opening history of the Grenada basin. The positions of the Aves Ridge relative to the Lara or Grenada terrane at various times during basin opening are shown in the lower left of the figure. The fault system responsible for this opening may have been a dextral transform-ridge-transform linkage similar but of different sense to Cayman Trough. Southern transform would define southeastern edge of Aves Ridge, central spreading axis (E-W orientation) would create Grenada Basin, and northern transform segment (dashed in Figure 12b) would cross La Desirade and then follow the bathymetric notch of the northern Lesser Antilles platform. Note that the opening of the basin would allow southeastward migration of the Aruba-Orchila Islands, the Villa de Cura Klippe, Tobago and the Tobago forearc basin, the Barbados accretionary prism, Margarita, the southern Lesser Antilles platform, the basement of the Falcon Basin, and other complexes toward South America in the Paleogene. This phase could represent the southerly convergence direction of Barbados argued for by Speed (1985; and many other papers).

Fig. 13. Flow lines of South America relative to North America since the Triassic (after Pindell et al., 1988; recently confirmed by Cande and Pindell, 1991). LT = Late Triassic; COB = continent-ocean boundary reconstruction; BSMA = Blake Spur magnetic anomaly.

Fig. 14. Separation history of NoAm-SoAm, derived from Figure 13. Termination of seafloor spreading in Proto-Caribbean (time of maximum NoAm-SoAm separation by spreading) believed to be Late Albian. However, there is no actual control on motions for magnetic Quiet Period (dashed line). The rates inferred for segment 3 are therefore rough estimates. Note difference in rate of convergence for the Tertiary of western and eastern SoAm due to rotational motion of SoAm relative to NoAm (see Figure 13).

Fig. 15. Detailed vector diagrams defining relative motions of blocks and plates at three positions along northern South America (A, B, C). Scale at right applies to all vectors. Solid line tielines have trend and offset control; dashed lines have trend only; dotted lines are derived from the construction and predict offsets and trends at zones which otherwise have no direct assessment. These are especially useful for approximating convergent and divergent components of transpression and transtension, respectively. Modified after Dewey and Pindell (1985; 1986). Important aspects of input are described in text.

Fig. 16. Pre-Campanian reconstruction of northern South America, as derived from vector offsets for blocks in Figure 16, and by the removal of obducted allochthonous terranes. This configuration more accurately represents Late Jurassic, Cretaceous and early Tertiary geography than the present geography. Dotted areas are those which have been overthrust during Andean orogenesis. Arrows defining approximate trend of overthrusting are shown. Limit of Paleogene

thrusts is shown for reference, and to show the portion of the original shelf where facies control is limited.

Fig. 17. Approximate Permo-Triassic reconstrucution with the Yucatan Block, showing marginal offset geometries between the two. ENE trends are rift zones, NW trends are transfer zones. Rifting and ocean opening involved CCW rotation of Yucatan away from South America.

Fig. 18. Numerous stratigraphic columns from northern South America, keyed to map for position. Compiled originally by E., G. Robinson.

Fig. 19. Schematic sketch of one possible scenario (!!) for transpression between the Bahamas and NE South America at the end of the Jurassic. This minor tectonism may have interrupted the normal, thermally-driven stratigraphic development of this margin, such that the Neocomian Barranquin Formation has been assumed to represent the transgression after rifting.

Fig. 20. Tectonic and Basin map of northern South America showing the location of sediment accumulation (subsidence) curves plotted in graph. Note systematic eastward progression of the time of maximum (foredeep) subsidence and infilling (sections A-E). After Pindell et al. (1991).

Fig. 21. Locations at various times of the migrating peripheral bulge ahead of the Caribbean allochthonous thrust systems. Bulge defines the southeasterly limit of hydrocarbon migration from overthrusted and foredeep kitchens of the migrating Caribbean-South American arc-continent collision. Bulge positions are plotted on reconstructed basemap (pre-Andean orogenesis).

Fig. 22. Summary of implications from seismic tomographic imaging (Hilst, 1990). Heavy lines are contours to center of inferred subducted slabs beneath Caribbean area (after Pindell et al., 1991).

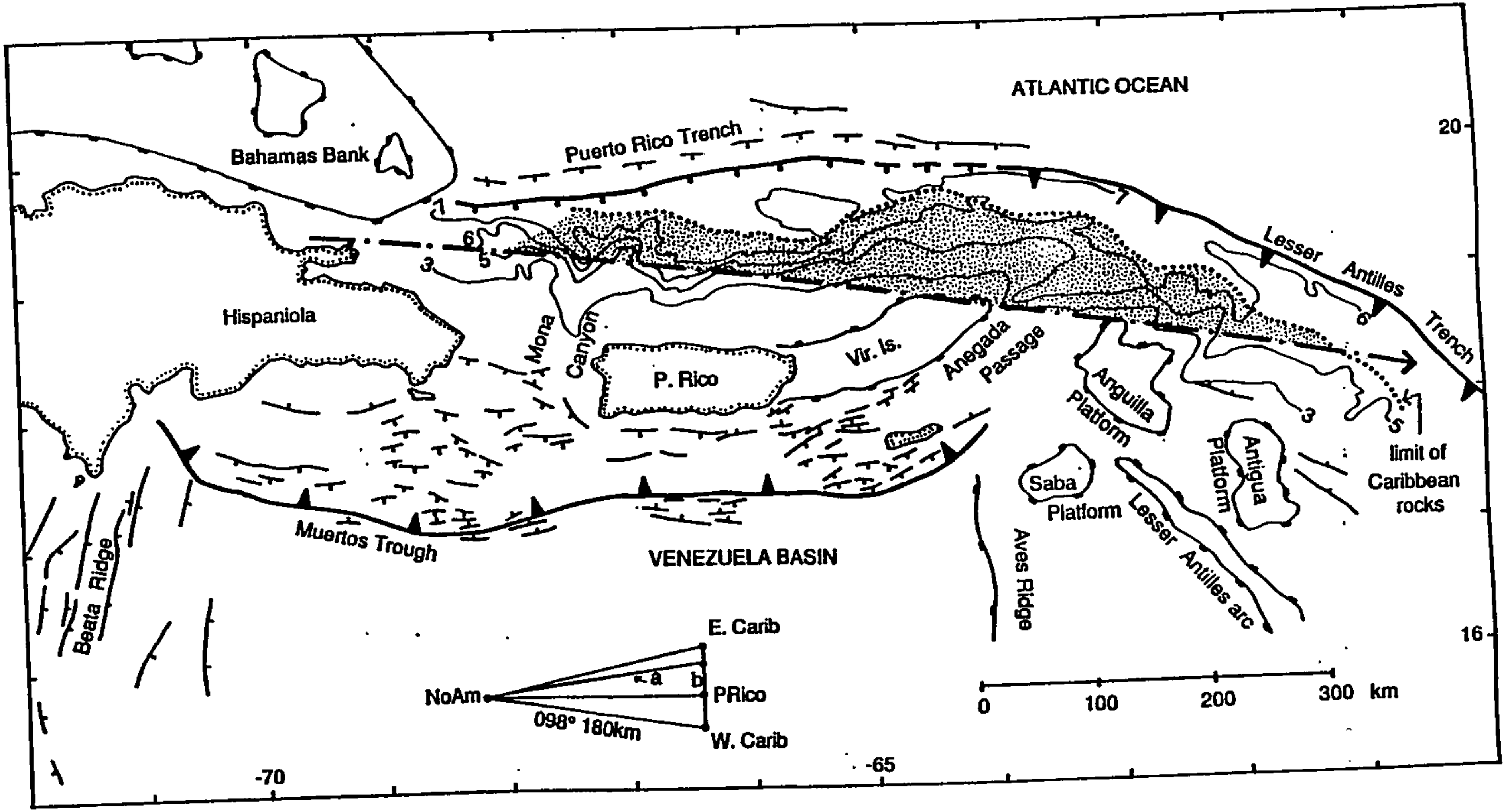
Fig. 23. Jurassic marginal geometry and rift information. (from Pindell in progress).

Fig. 24. Medial Cretaceous paleogeography (source rock interval). (from Pindell in progress).

Fig. 25. Late Paleocene paleogeography showing Caribbean Plate rounding the Andean corner. Foredeep basin is beginning to impinge upon the northern margin. Peripheral bulge is eroding Cretaceous stratigraphy in central Venezuela. Grenada basin begins to open. (from Pindell in progress).

Fig. 26. Middle Middle Eocene paleogeography. Grenada Basin is opening, allowing SE-ward migration of the allochthonous terranes toward the northern margin. Peripheral bulge is eroding Cretaceous to Paleocene? stratigraphy of central Venezuela. Caratas Formation of Eastern Venezuela Basin is shallowing due to its presence on the back side of the arriving peripheral bulge. This is time of peak subsidence and maturation in northern Maracaibo Basin, beneath Misoa delta and Trujillo flysch. Garrapata Formation (redated as this age) is orogenic flysch derived from north. Guarico flysch is derived from southerly peripheral bulge. These two units are still not in tectonic juxtaposition (Lara nappes not emplaced yet). (from Pindell in progress).

Fig. 27. Late Middle Eocene paleogeography. Migration continues, with bulge approaching Serrania del Interior depocenter (Pena Blanca Formation shallowing) and Trinidad (San Fernando chaotic deposition). Eroded material feeds Scotland Formation clastic wedges to the north. In NW South America, isostatic rebound occurs due to the propagation of a new transform north of the borderlands terrain. Rivers across subaerial Maracaibo Basin begin to flow to the south, and presumably channel into Roblecito foredeep of eastern central Venezuela. (from Pindell in progress).


ATLANTIC OCEAN
Bahamas Bank
Puerto Rico Trench
Hispaniola
Mona
Canyon
P. Rico
Vir. Is.
Anegada
Passage
Anguilla
Platform
Lesser
Antilles
Trench
Antigua
Platform
Saba
Platform
Lesser Antilles arc
Aves Ridge
limit of
Caribbean
rocks
Beata Ridge
Muertos Trough
VENEZUELA BASIN
E. Carib
PRico
W. Carib
NoAm
a
b
098° 180km
0
100
200
300
km
20
16
-70
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1
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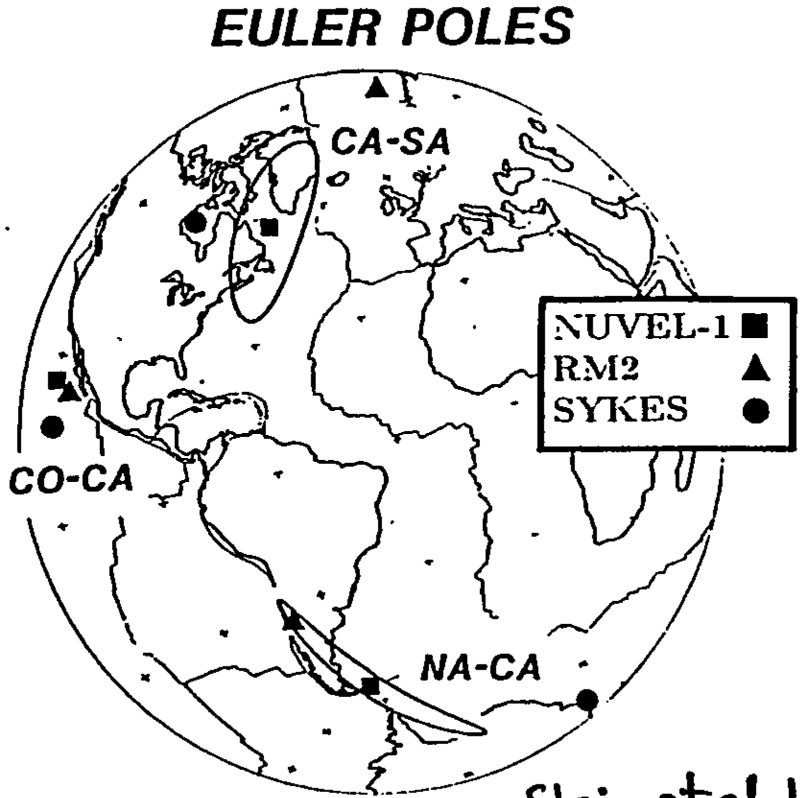
7

fig 1



Stein et al 1988

Fig. 4. Euler poles for NA-CA, Caribbean-South America, and CO-CA relative motions. Rotation convention is right-hand rule, first plate rotates counterclockwise with respect to second plate. All NUVEL-1 poles are derived from the global dataset.

fig 2

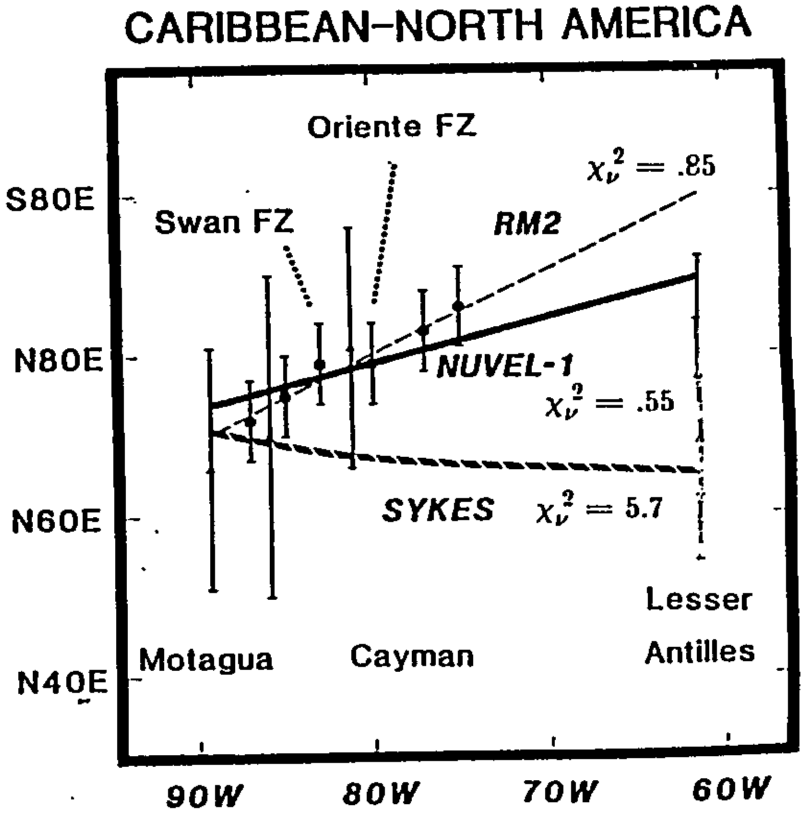


Fig. 3. Azimuth data for NA-CA relative motion from transform faults (dots) and slip vectors (triangles), compared with predictions of different models. Global models RM2 or NUVEL-1, which incorporate the *Jordan* [1975] geometry, provide a better fit to the aggregate of the data, as shown by the values of χ^2_ν, than the *Sykes et al.* [1982] model. Note the consistent trend of the data across the Cayman Spreading Center.

Stein et al 1988

fig 3

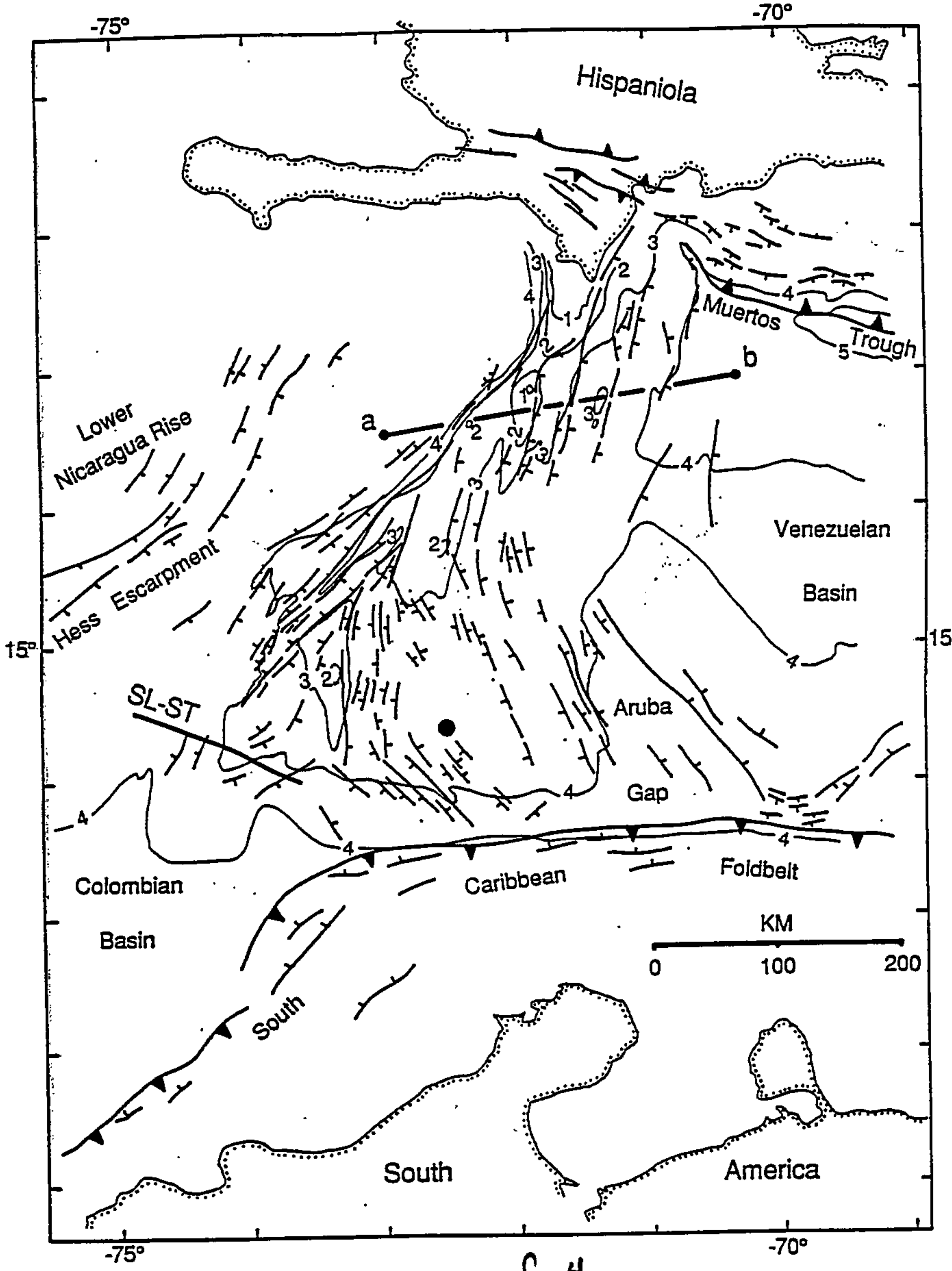
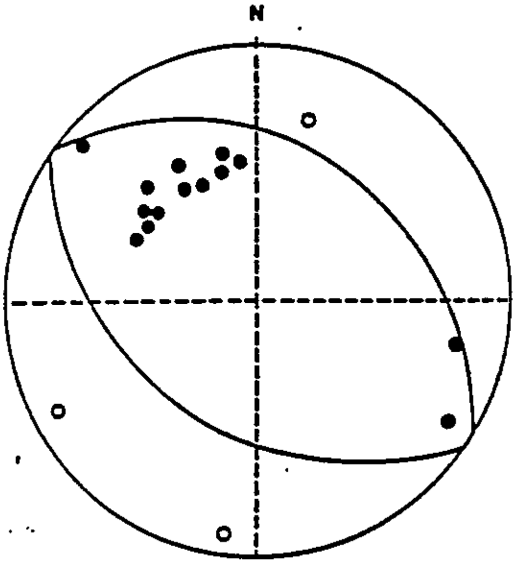

-75°
-70°
Hispaniola
Muertos
Trough
Lower
Nicaragua Rise
Hess Escarpment
a
b
Venezuelan
Basin
15°
15°
SL-ST
Aruba
Gap
Colombian
Basin
Caribbean
Foldbelt
South
KM
0
100
200
South
America
-75°
-70°

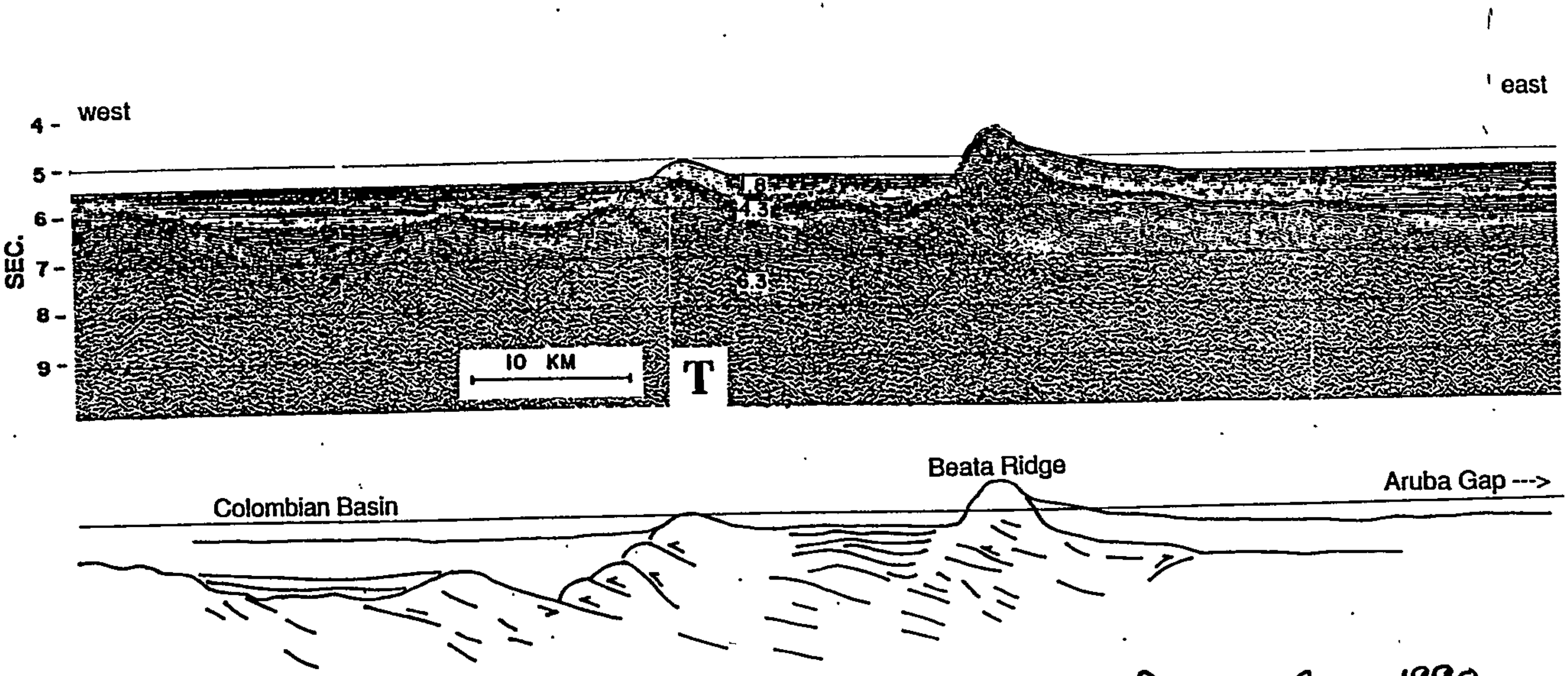
fig 4



21 AUG 1963
(MOLNAR & SYKES, 1969)

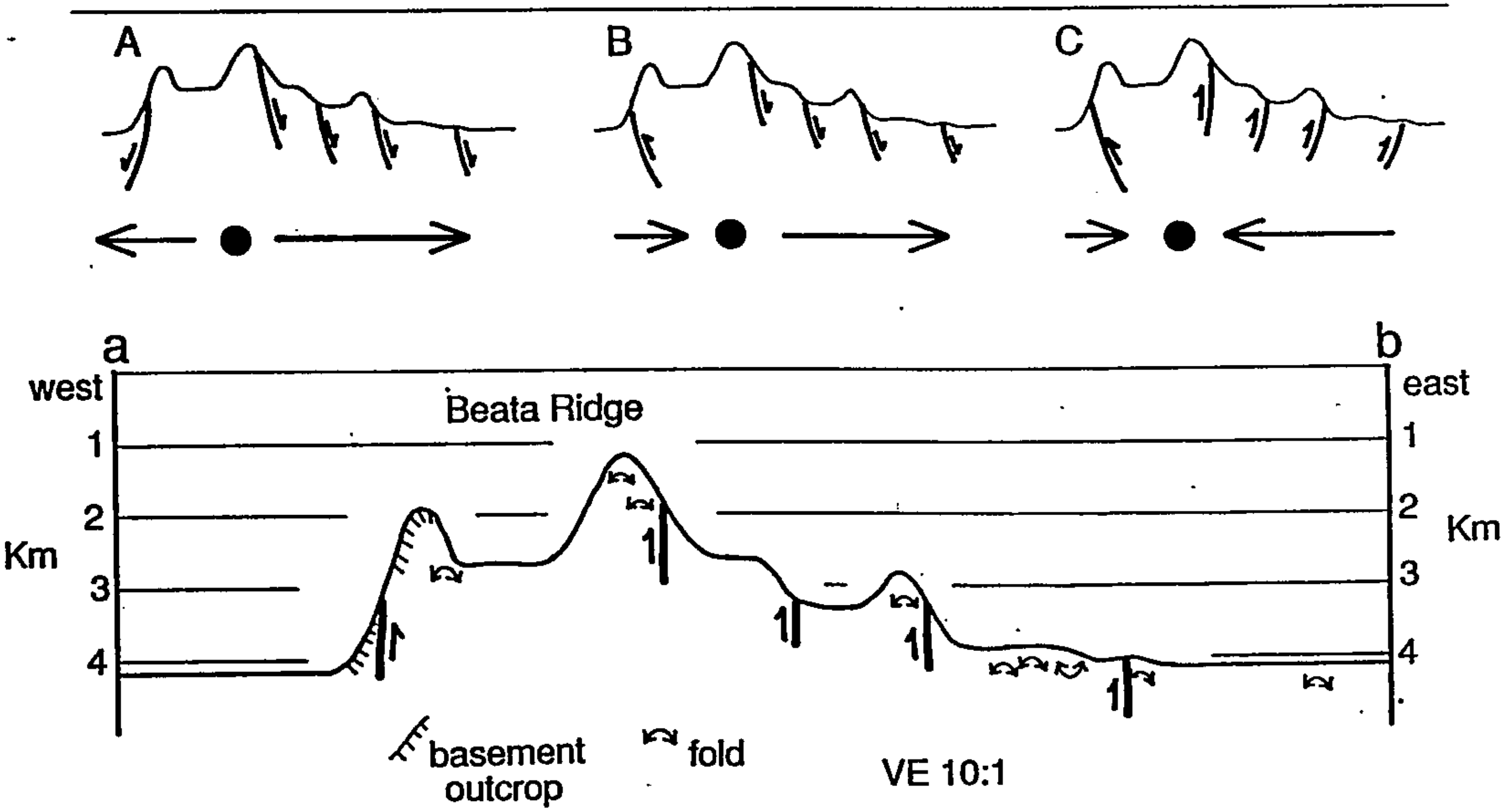
Fig. 13. The P wave data for event 10 (August 21, 1963) as determined by Molnar and Sykes [1969]. Dotted lines are the focal planes determined by Molnar and Sykes [1969]. Solid lines are possible focal planes drawn by the authors. Kafka + Wiedner 1981

fig 5



in Dengo + Case, 1990

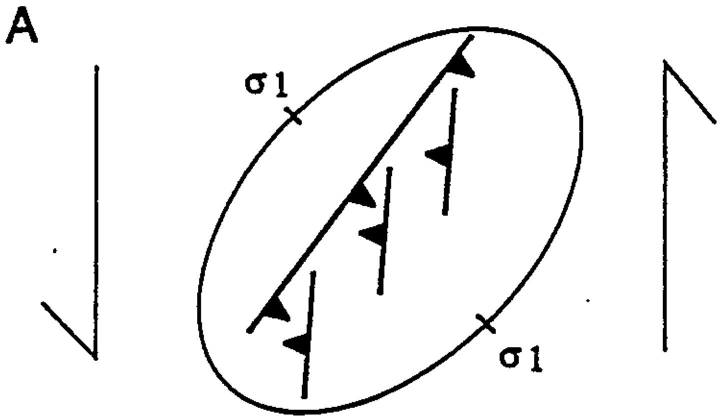
fig 6



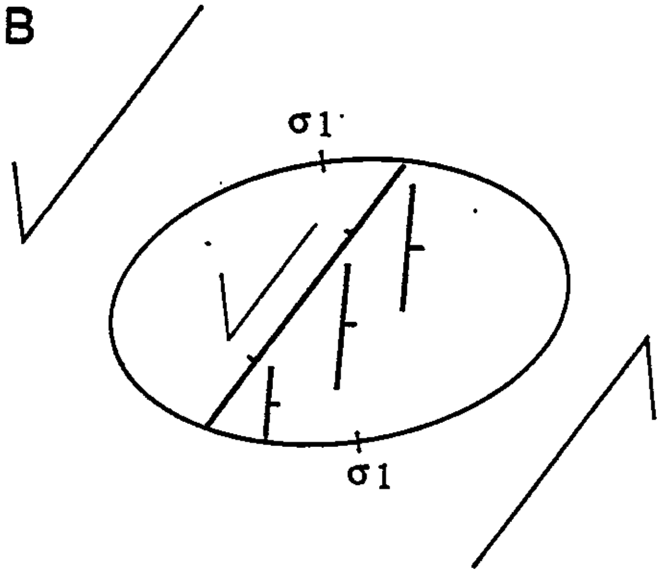
A
B
C
a
b
west
east
Beata Ridge
1
2
3
4
Km
1
2
3
4
Km
basement outcrop
fold
VE 10:1

fig 7

BEATA RIDGE MODELS



sinistral transpression at 000°



sinistral shear at 037°

fig 8

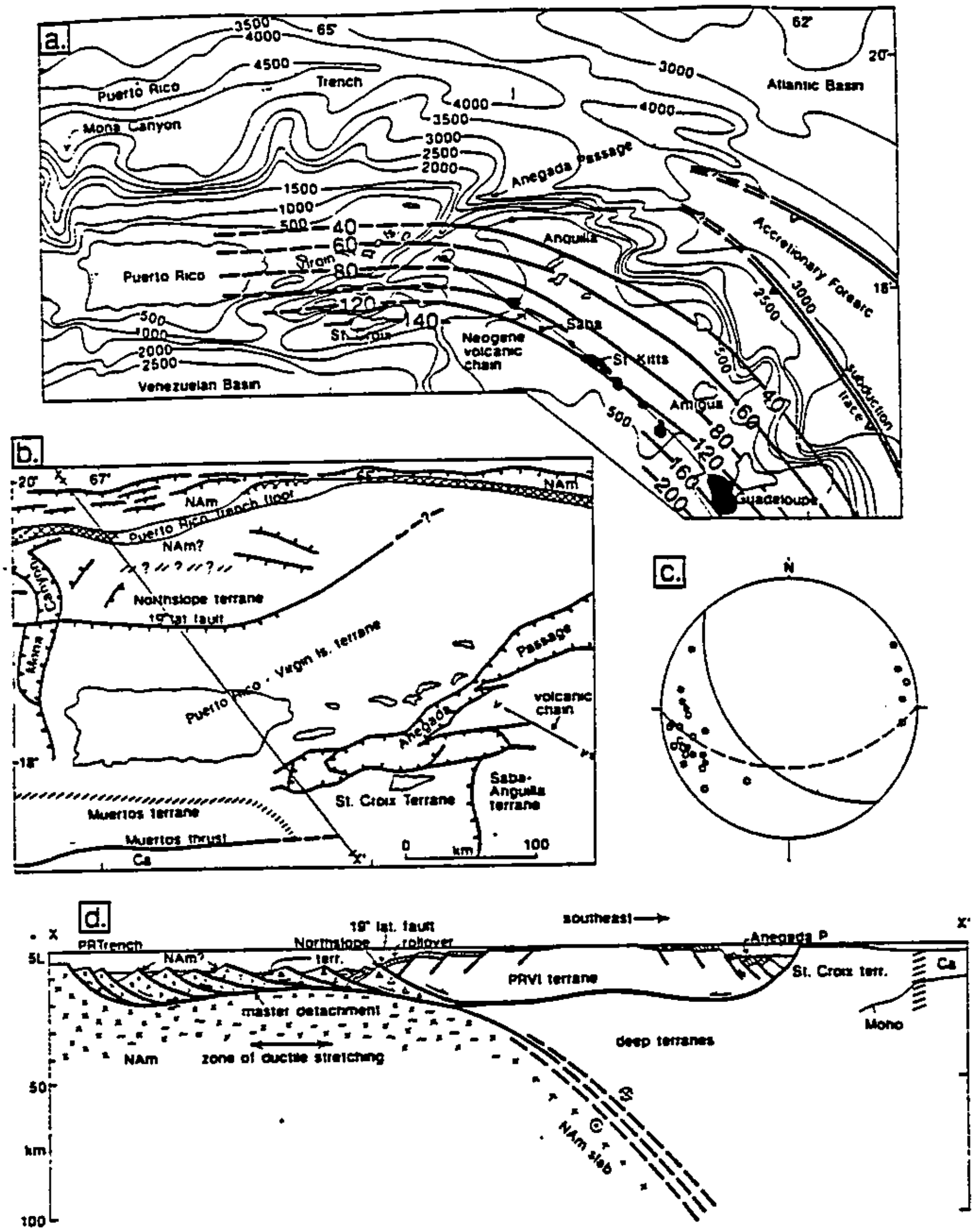
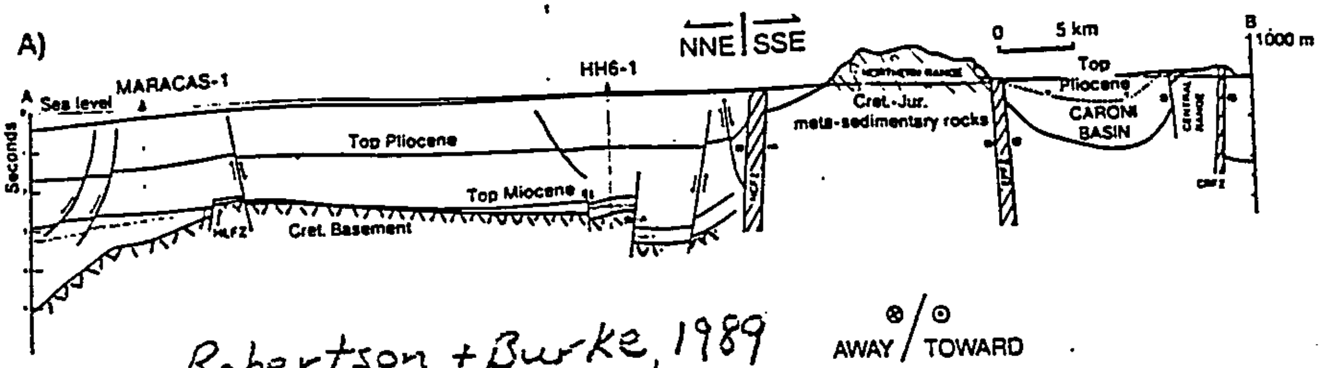


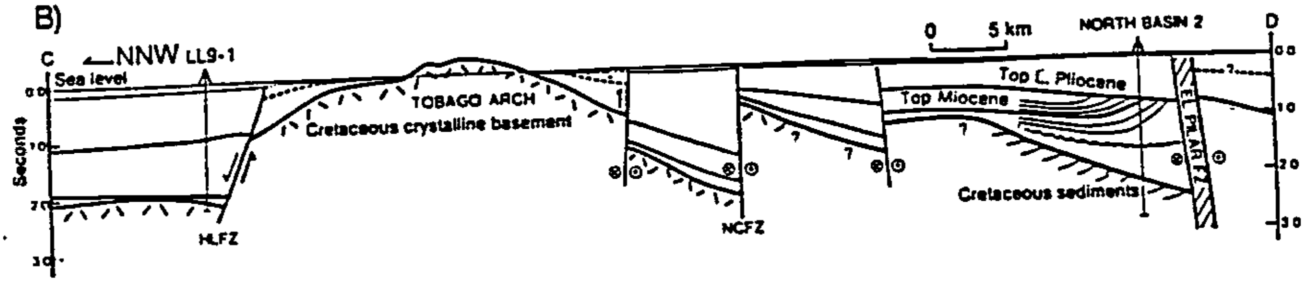
Fig. 1: a) bathymetric map of NE Caribbean region; bathymetric contours in fathoms; intermediate weight contours are depth to dipping seismic zone (km) - solid line teleseismic, dashed line from local network [McCann and Sykes, 1984]; subduction trace is between plates below sedimentary forearc. b) map of plate boundary zone showing terranes and major faults; hachured lines are approximate terrane boundaries; ticks on faults indicate downthrown side; Ca is Caribbean plate; NAm is North American plate. c) slipvectors on shallowly dipping planes from focal mechanisms in dipping seismic zone (hypocenters below 40 km and great circles showing attitude of seismic zone); filled circles and solid great circle east of about 63°5W, open circles and dashed great circle west; equal area net, lower hemisphere; from published sources including Fischer and McCann, 1984; Harvard CMT. d) cross section along xx' shown on c), illustrating model discussed in text; brick pattern for platformal cover; sand pattern for graben sediments, motion across the top of the NA slab is left-lateral strike slip.

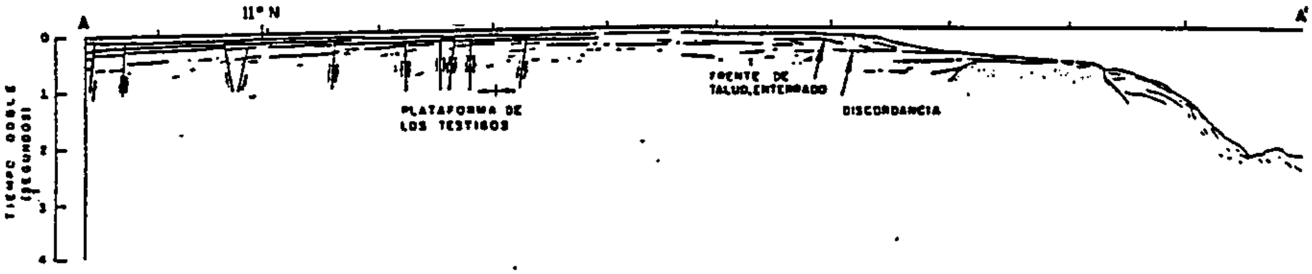
Speed + Larue 1991

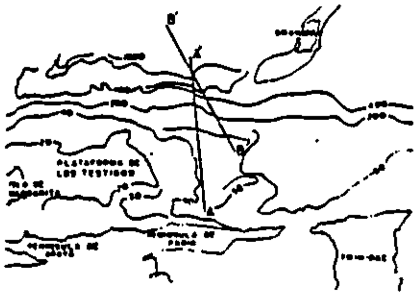
fig 9

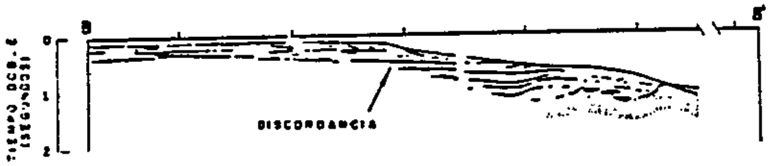


Robertson + Burke, 1989









Gonzalez de Juana, 1980

Gonzalez de Juana et al 1980

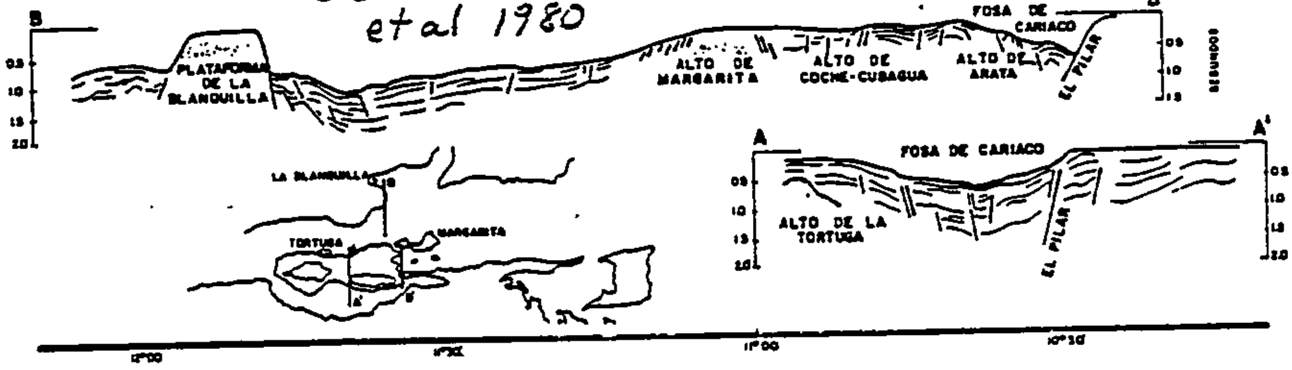
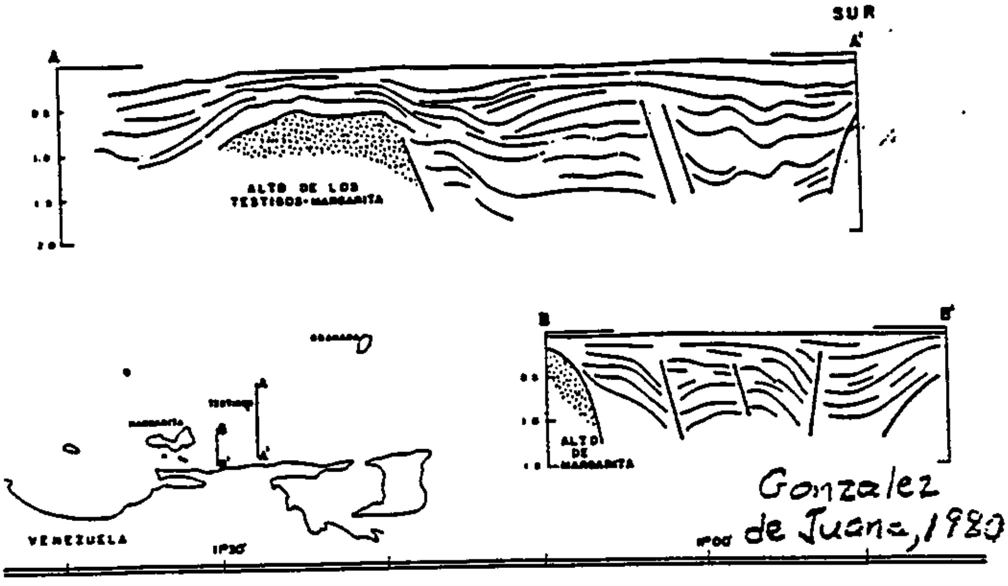


fig 10a



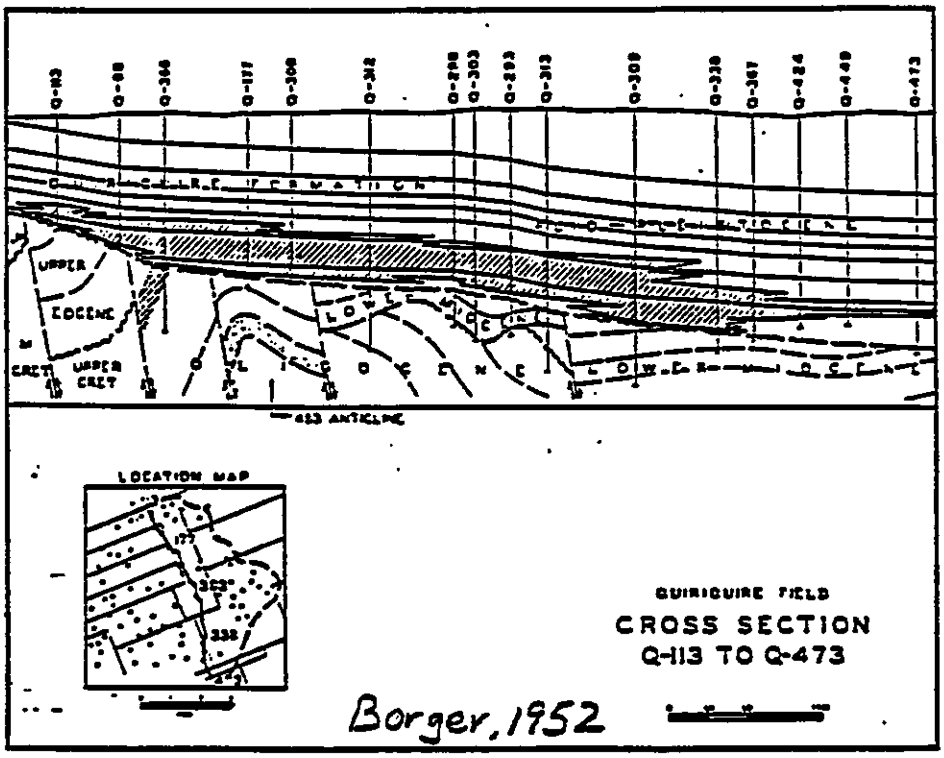
Gonzalez de Juana, 1980

-10a

sediments offer little prospects for the genesis of petroleum. There is evidence that oil in the Quiriquire reservoir had its origin in the basinward, brackish to marine facies of these beds. Exploratory wells downdip from the field found some gas and numerous shows of heavier-than-water oils.

MIGRATION AND ACCUMULATION

Migration of oils into the reservoir has been continuous since the beds were deposited and continues to-day as evidenced by the oil seeps north of the field. Thick beds of gilsonite are not only found at the base of the Pliocene section but

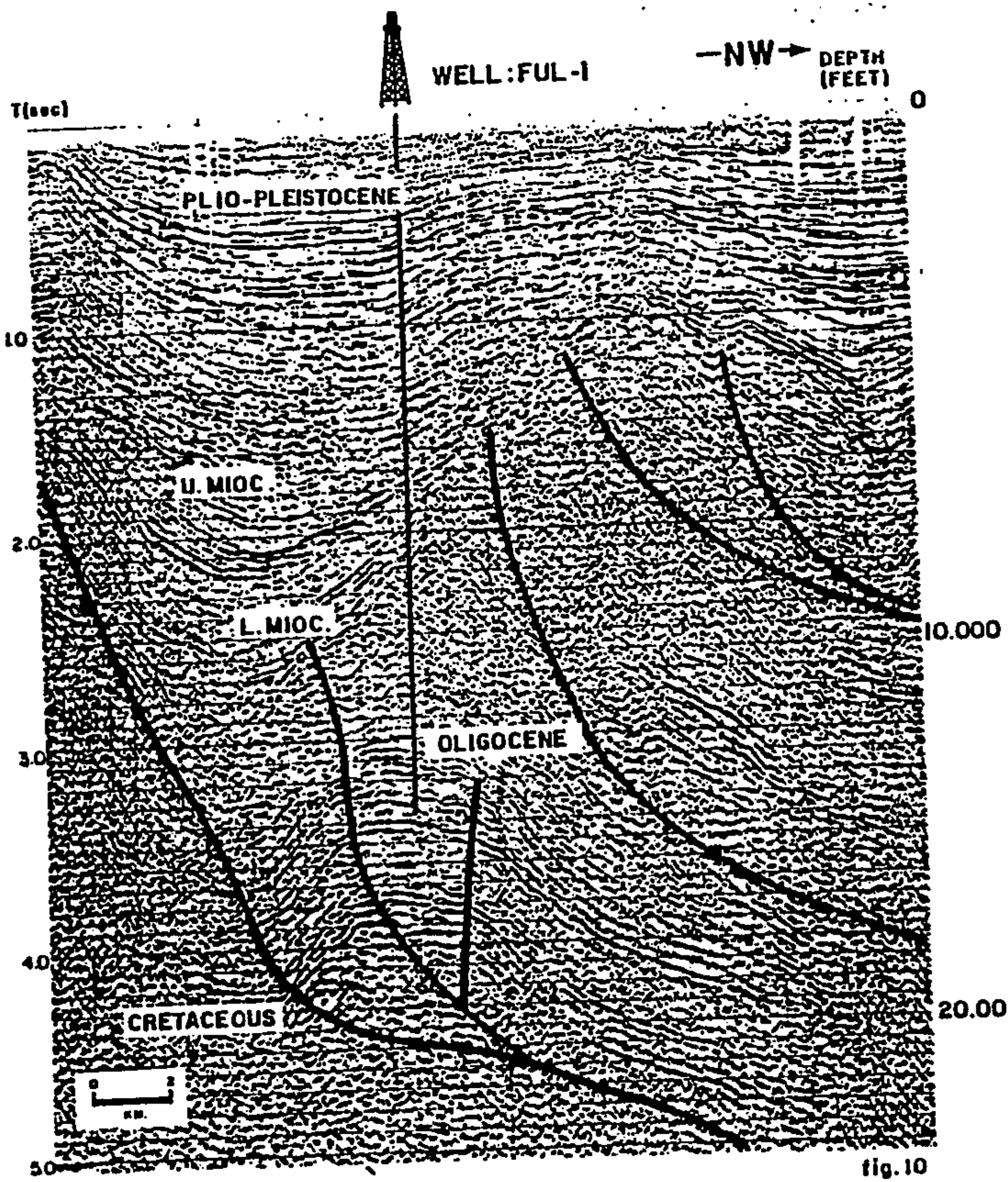


Borger, 1952

FIG. 18.—Cross section Q-113 to Q-473. North-south line of section across field, showing reservoir outline above truncated Miocene to Cretaceous formations.

fig 10b cont.

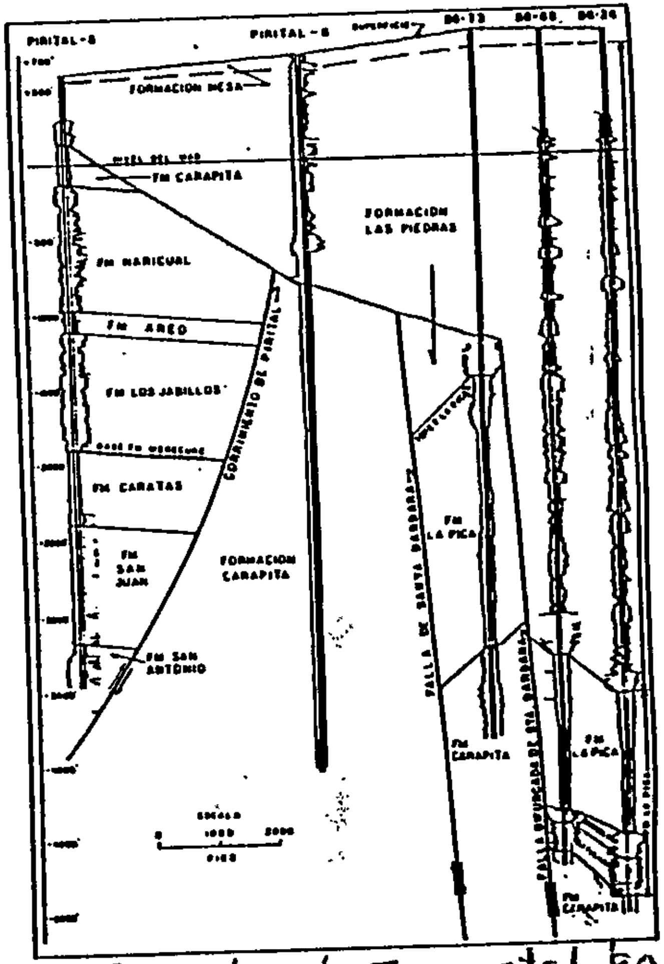
fig 10, cont.



Aymard et al., 1991

Fig. 10. El Furrial Field.

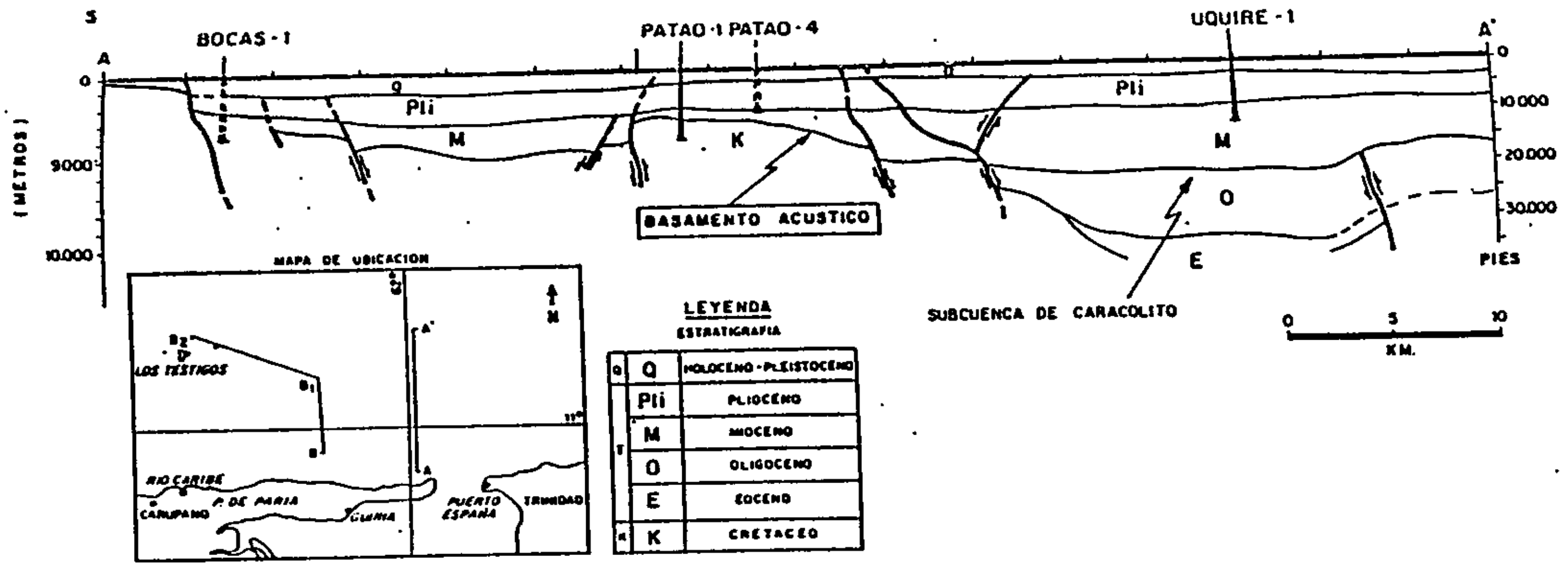
10c



Gonzalez de Juana et al 80

10d1

SECCION 1



SECCION 2

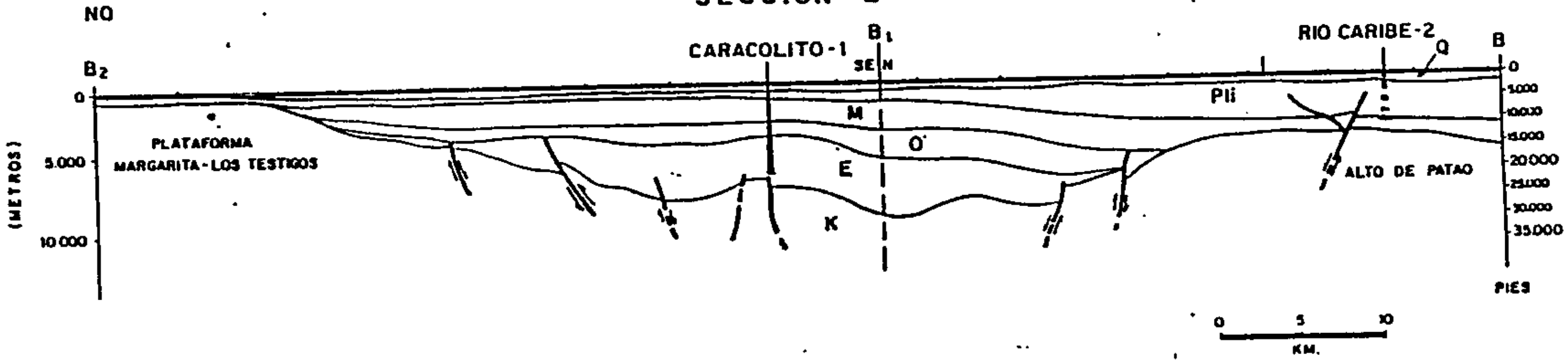


FIG. 41 SECCIONES GEOLOGICAS 1 Y 2 DE LA CUENCA DE CARUPANO
(PEREIRA, 1985, Figs. 7 y 7A)

fig 10' cont.

10E

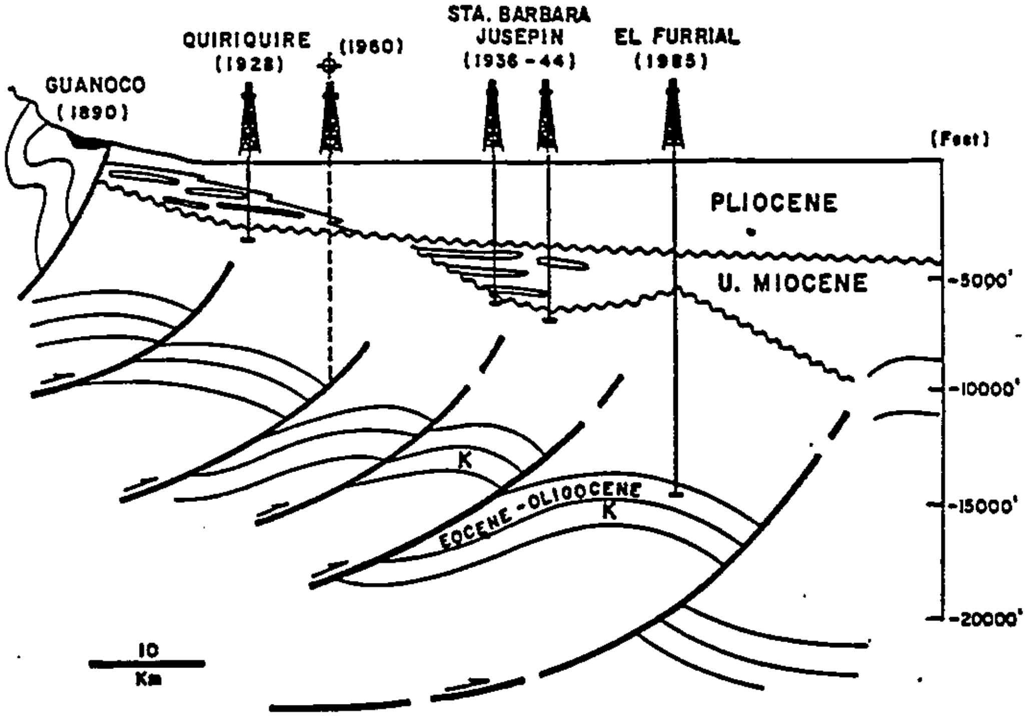
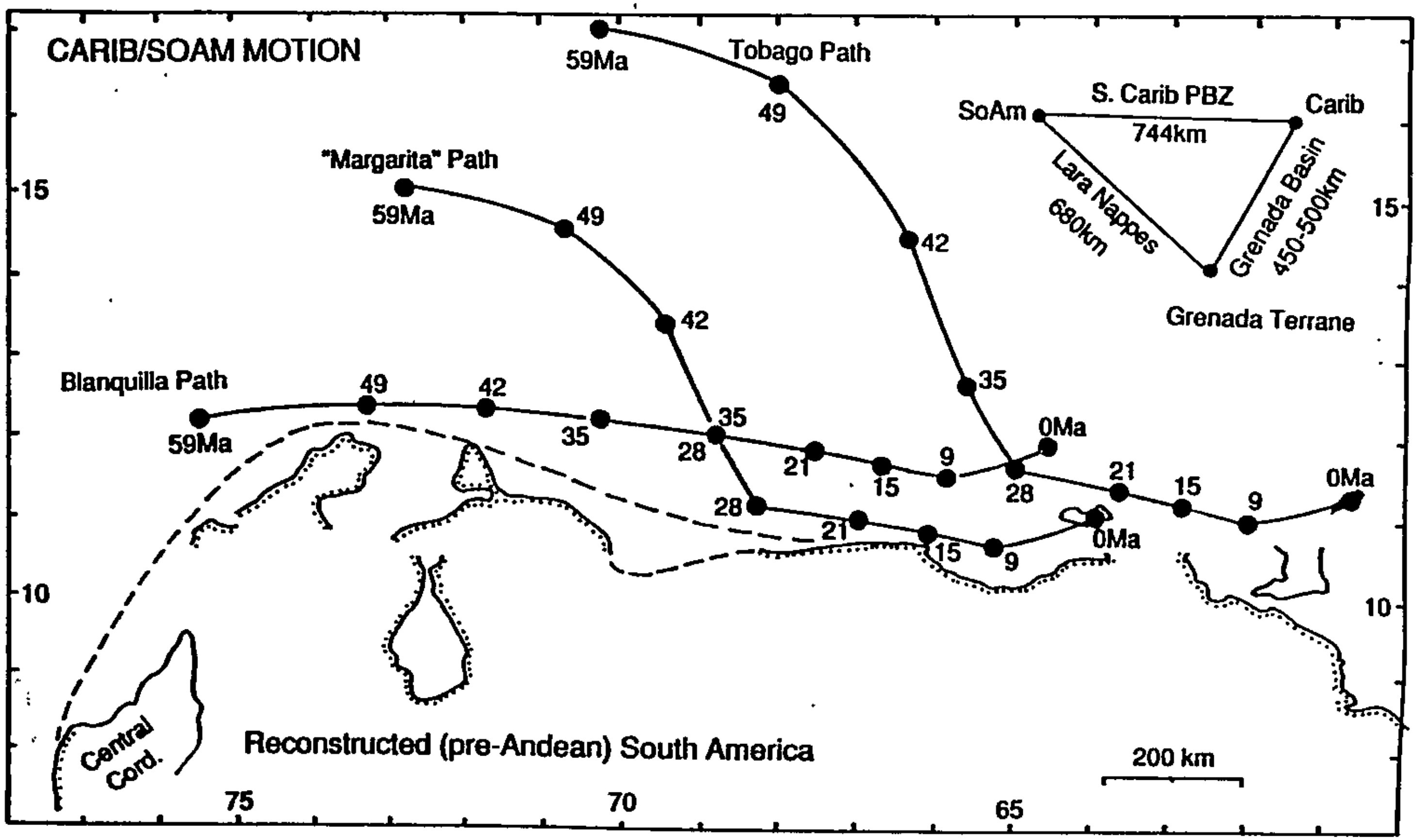


Fig. 2. History of exploration.

Aymardetal, 1990

D1.

Fig 11


CARIB/SOAM MOTION
Tobago Path
59Ma
49
42
35
0Ma
"Margarita" Path
59Ma
49
42
35
28
21
15
9
0Ma
Blanquilla Path
59Ma
49
42
35
28
21
15
9
28
21
15
9
0Ma
S. Carib PBZ
SoAm
Carib
744km
Lara Nappes
680km
Grenada Basin
450-500km
Grenada Terrane
Central Cord.
Reconstructed (pre-Andean) South America
200 km
15
10
75
70
65

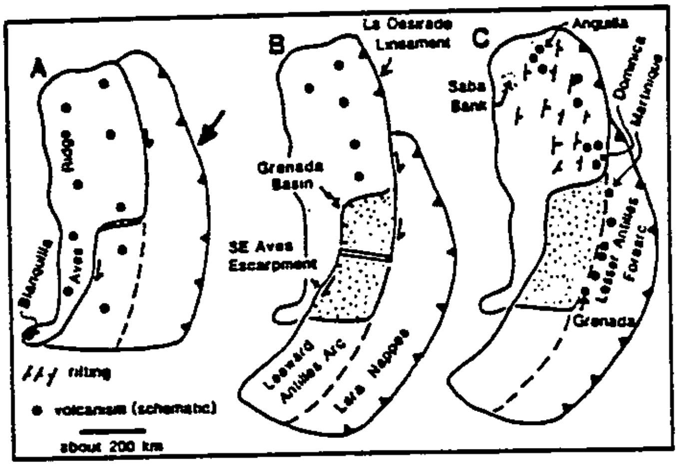
A
Ridge
Aves
Blanquilla
rifting
volcanism (schematic)
about 200 km
B
La Desirade
Lineament
Grenada
Basin
SE Aves
Escarpment
Leeward
Antilles Arc
Lara Nappes
C
Anguilla
Saba
Bank
Dominica
Martinique
Lesser Antilles
Forearc
Grenada

figure 12a.

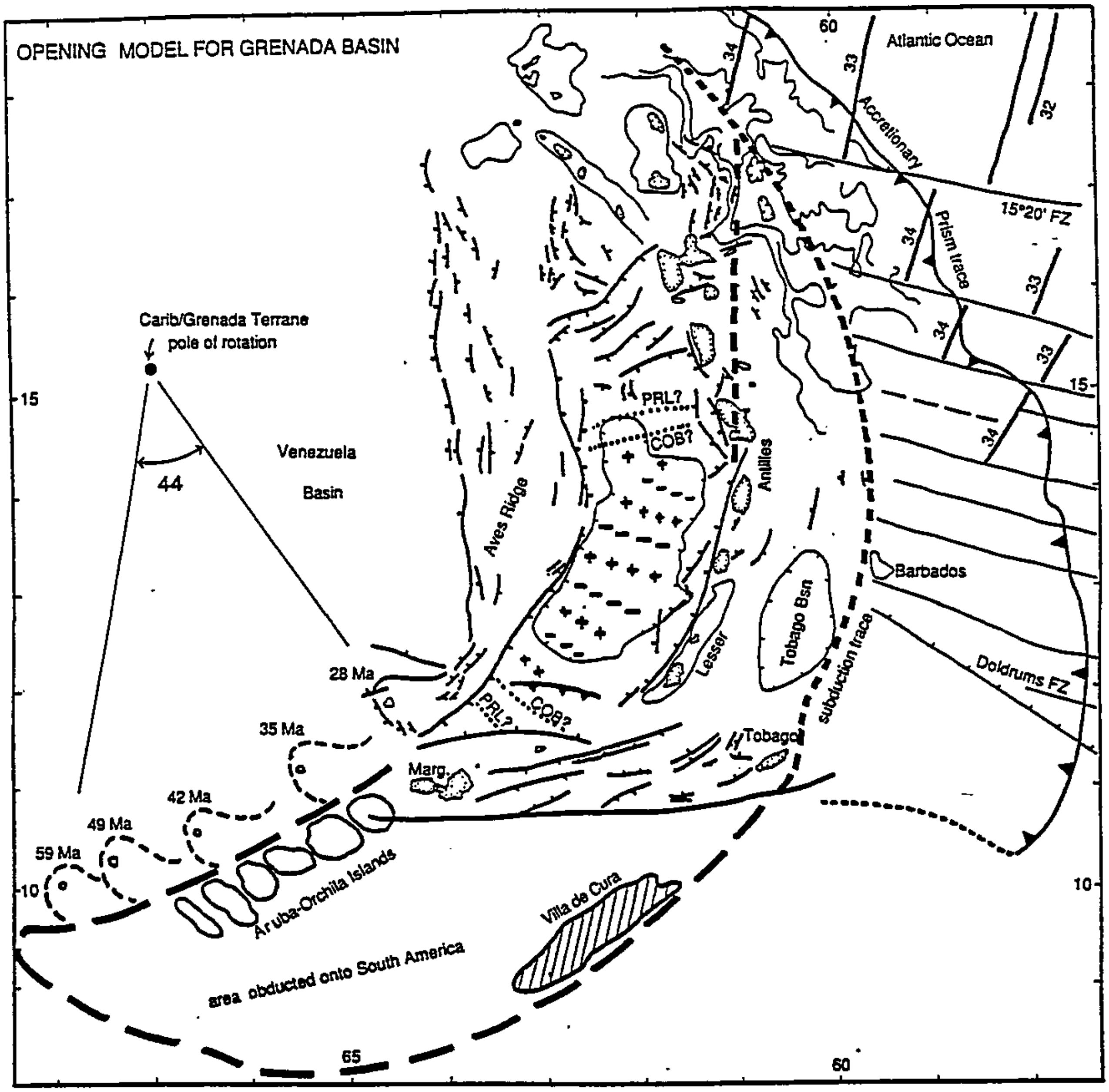

OPENING MODEL FOR GRENADA BASIN
Carib/Grenada Terrane pole of rotation
44
Venezuela Basin
Aves Ridge
Atlantic Ocean
Accretionary Prism trace
15°20' FZ
Doldrums FZ
Barbados
Tobago Bsn
Tobago
Lesser Antilles
subduction trace
PRL?
COB?
28 Ma
35 Ma
42 Ma
49 Ma
59 Ma
Marg.
Aruba-Orchila Islands
Villa de Cura
area obducted onto South America
60
65
15
10
32
33
34

fig 12b

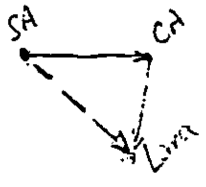
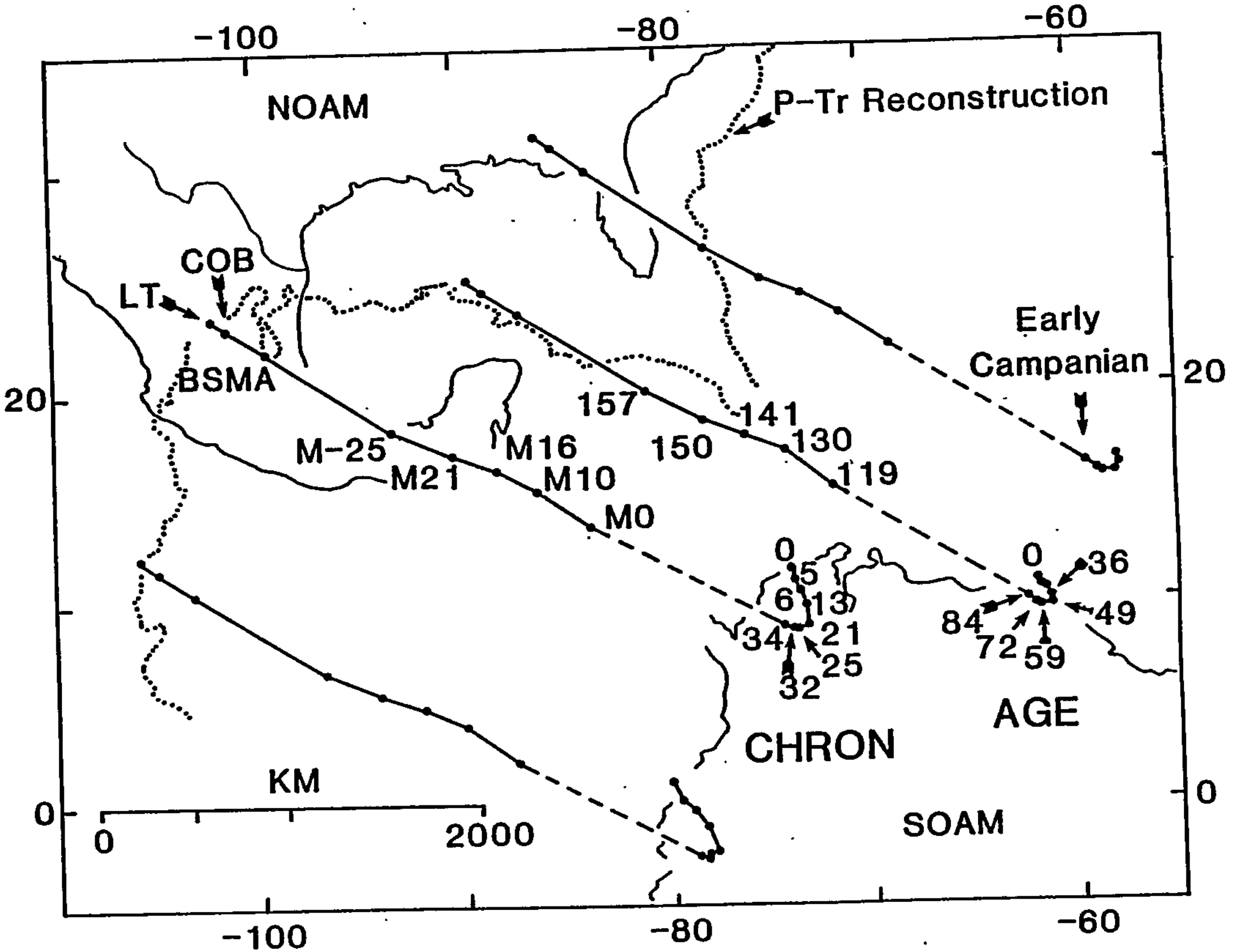
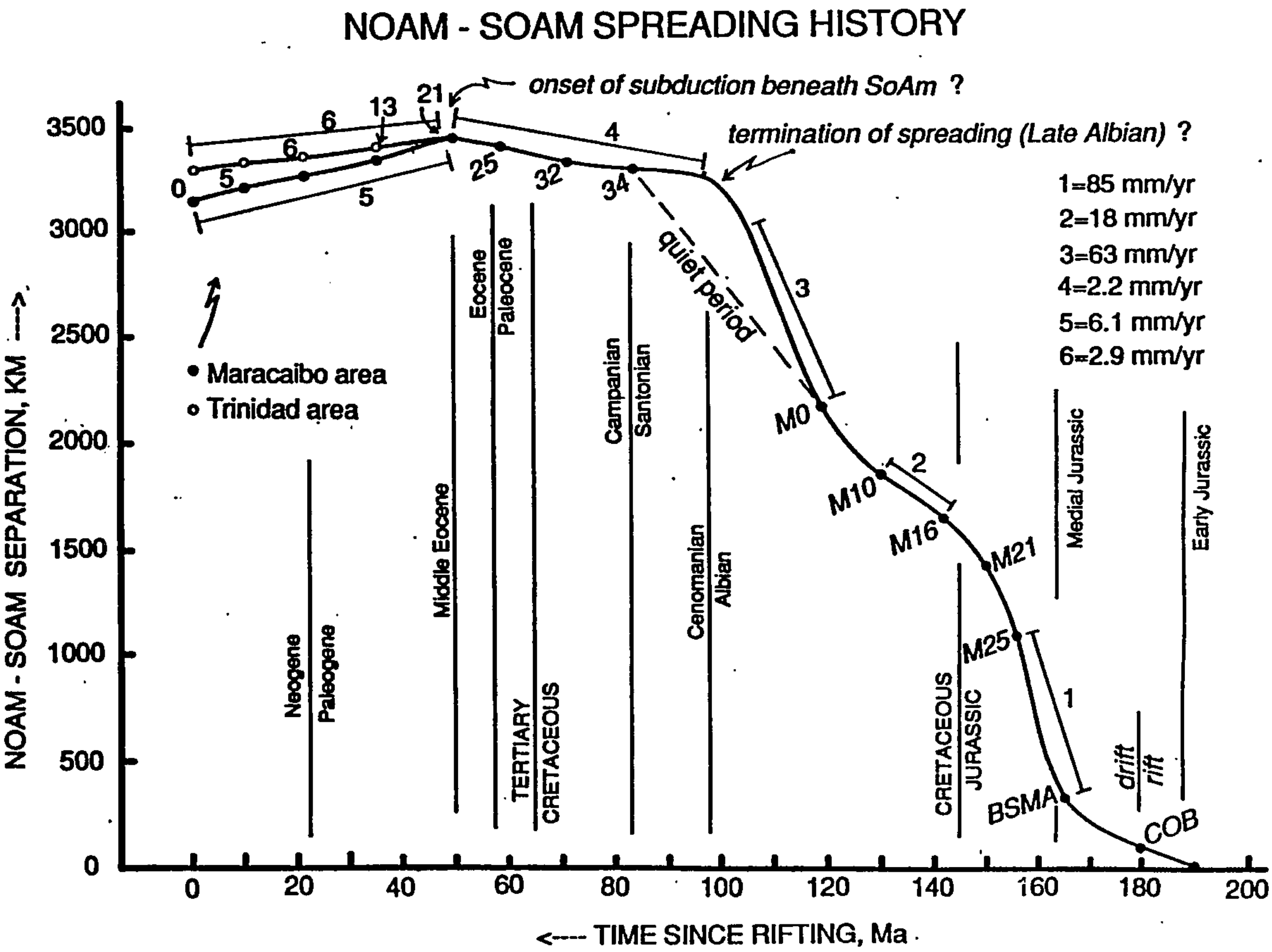

SA
CA

Fig 13

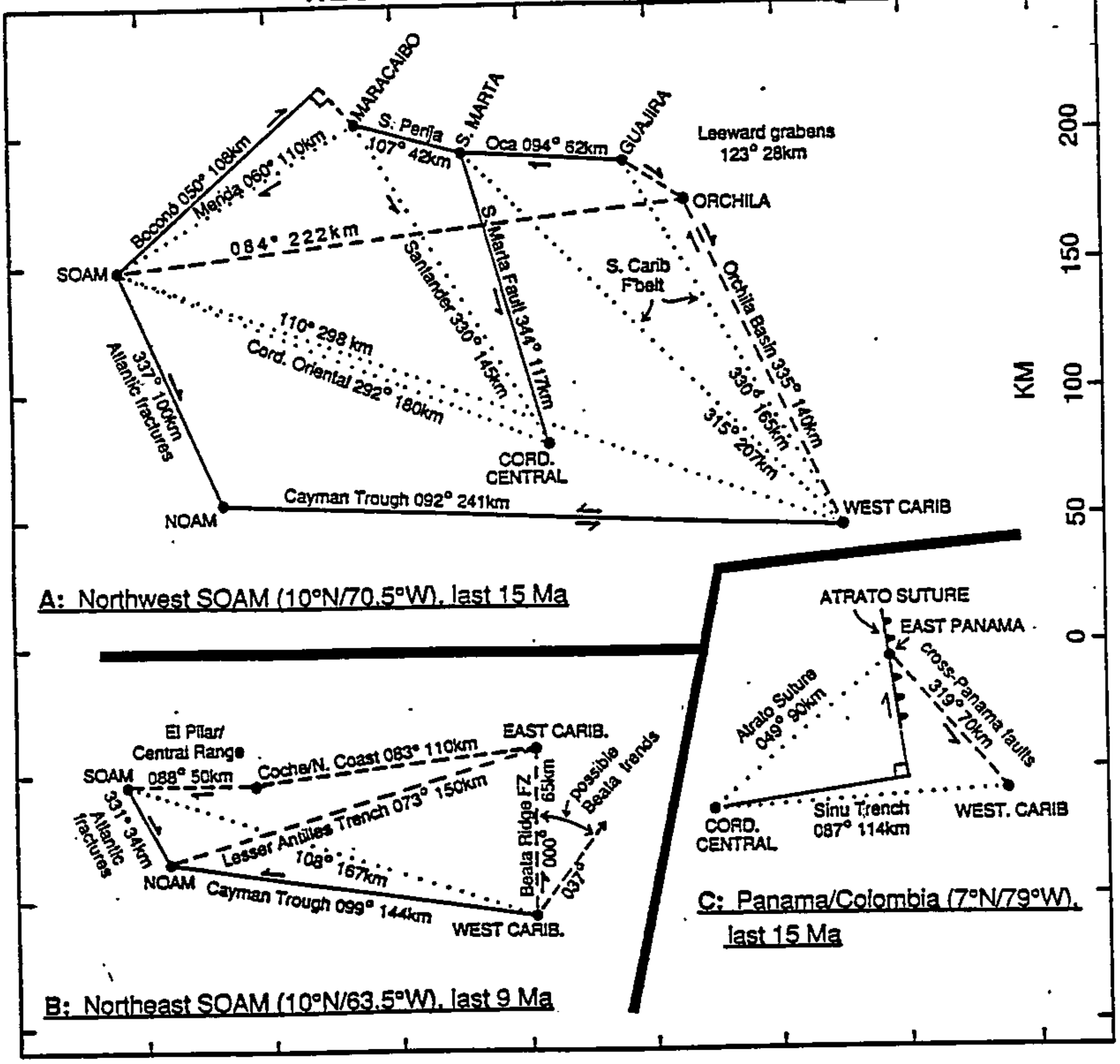


After Pindell et al., 1988, Tectonophys.


NOAM - SOAM SPREADING HISTORY
onset of subduction beneath SoAm ?
termination of spreading (Late Albian) ?
1=85 mm/yr
2=18 mm/yr
3=63 mm/yr
4=2.2 mm/yr
5=6.1 mm/yr
6=2.9 mm/yr
● Maracaibo area
○ Trinidad area
NOAM - SOAM SEPARATION, KM --->
3500
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
100
120
140
160
180
200
<---- TIME SINCE RIFTING, Ma
0
5
6
13
21
25
32
34
quiet period
M0
M10
M16
M21
M25
BSMA
COB
Neogene
Paleogene
Middle Eocene
Eocene
Paleocene
TERTIARY
CRETACEOUS
Campanian
Santonian
Cenomanian
Albian
CRETACEOUS
JURASSIC
Medial Jurassic
drift
rift
Early Jurassic

8.4

NEOGENE MOTION VECTORS

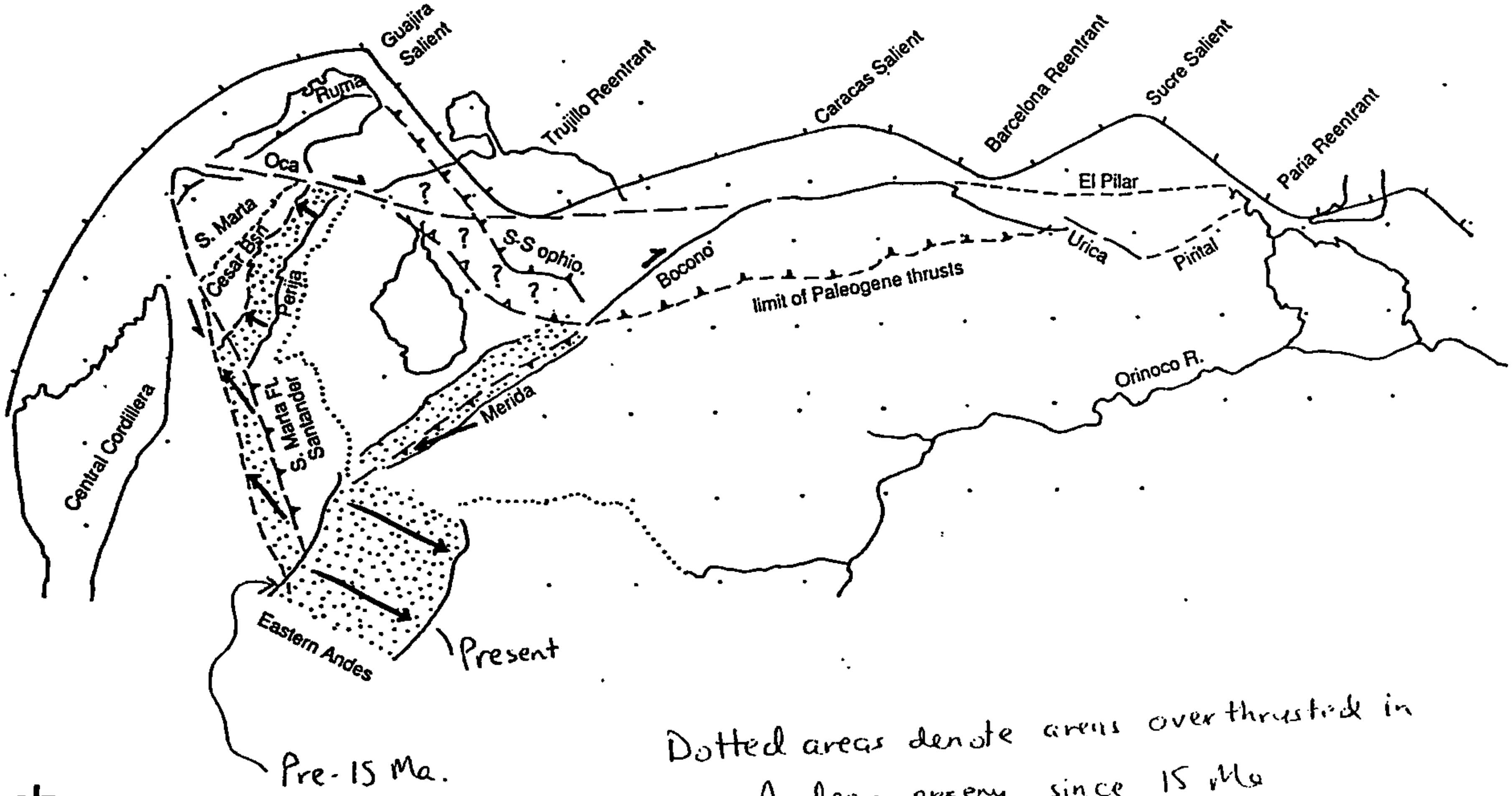


A: Northwest SOAM (10°N/70.5°W), last 15 Ma

B: Northeast SOAM (10°N/63.5°W), last 9 Ma

C: Panama/Colombia (7°N/79°W), last 15 Ma

fig 15



PRE-CAMPANIAN CONFIGURATION

Dotted areas denote areas overthrusted in Andean orogeny since 15 Ma

Fig 16

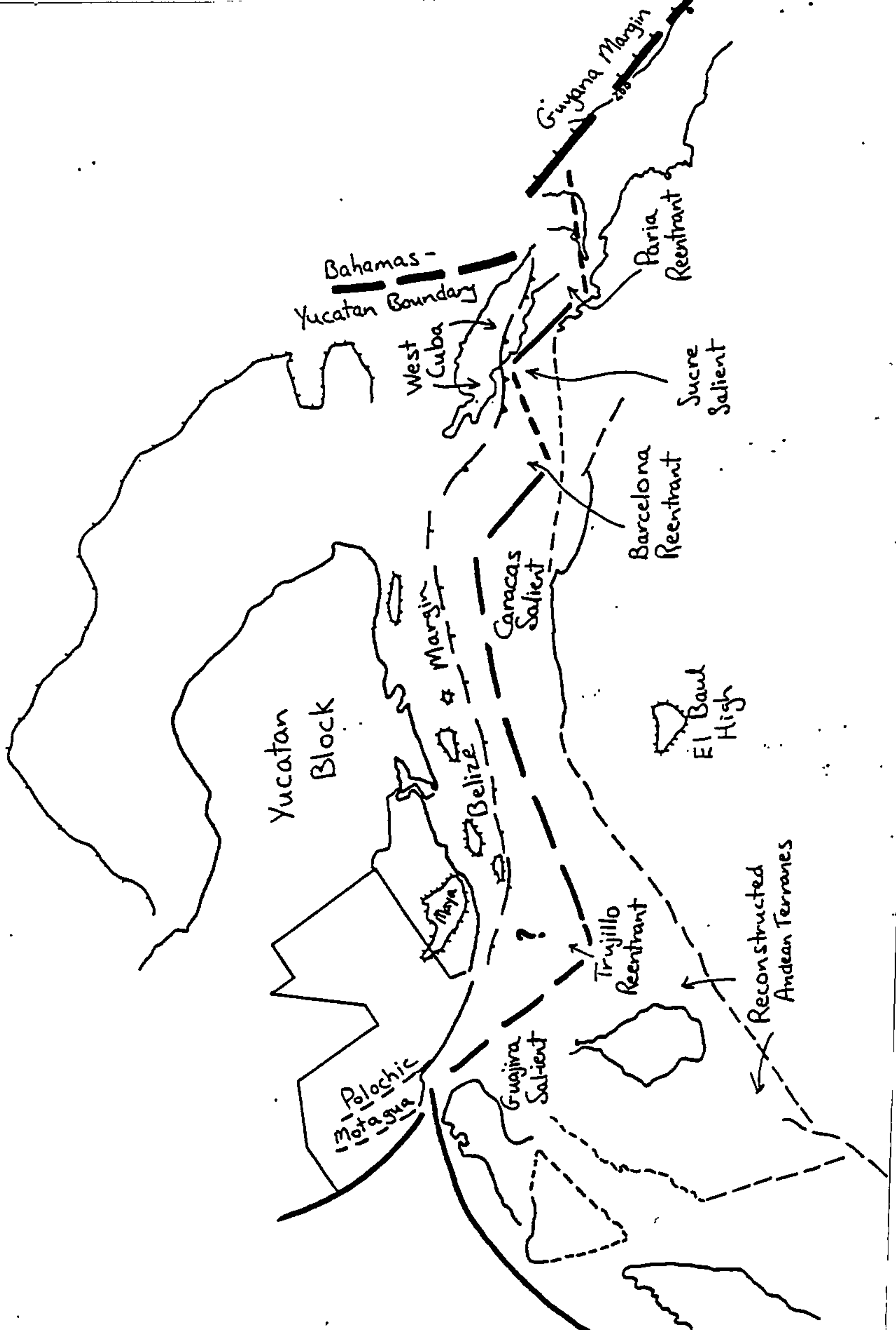

Guyana Margin
Bahamas-Yucatan Boundary
Paria Reentrant
West Cuba
Sucre Salient
Barcelona Reentrant
Caracas Salient
Belize Margin
Yucatan Block
El Baul High
Belize
Maya
?
Trujillo Reentrant
Reconstructed Andean Terranes
Guajira Salient
Polochic
Motagua

fig 17

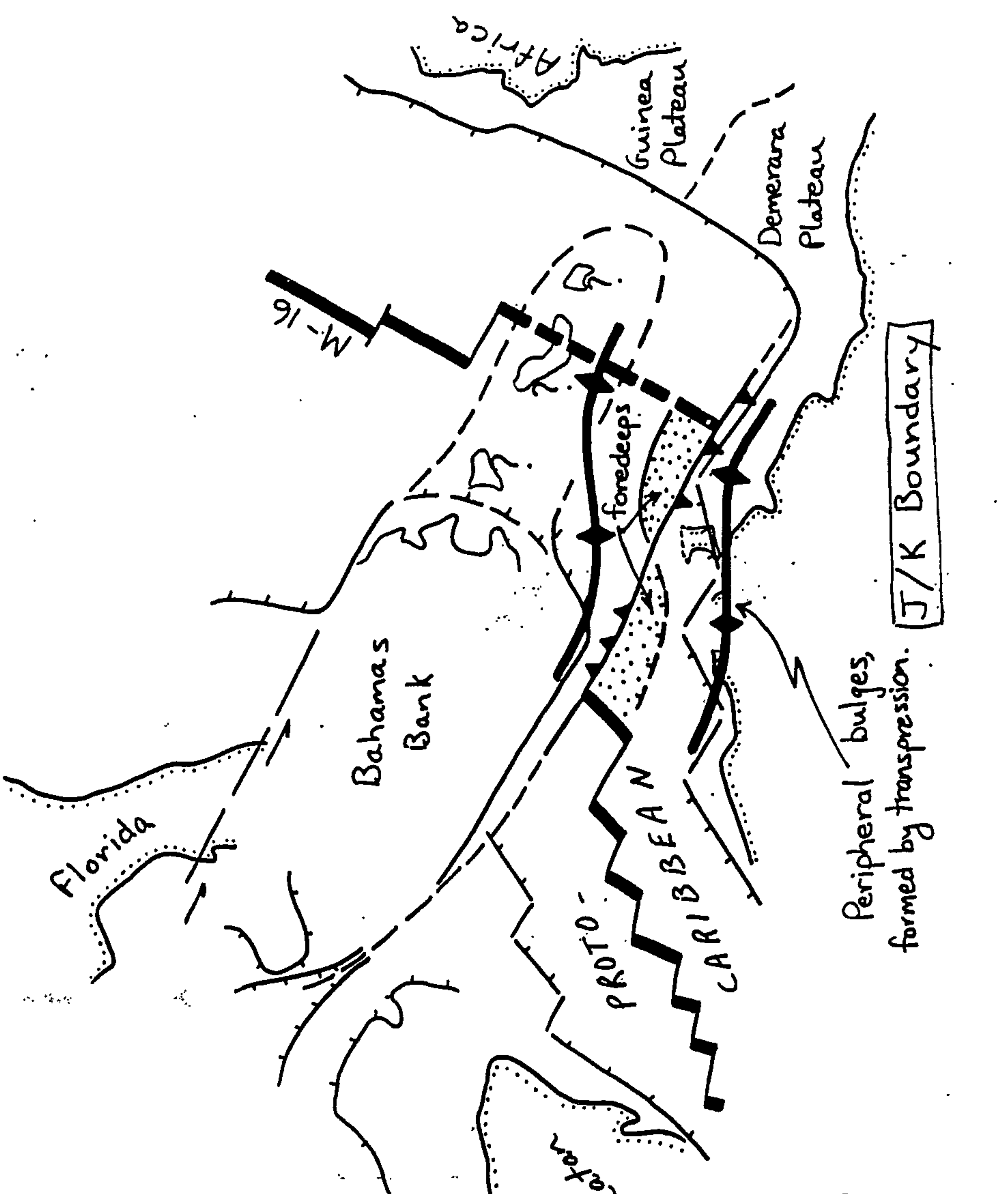
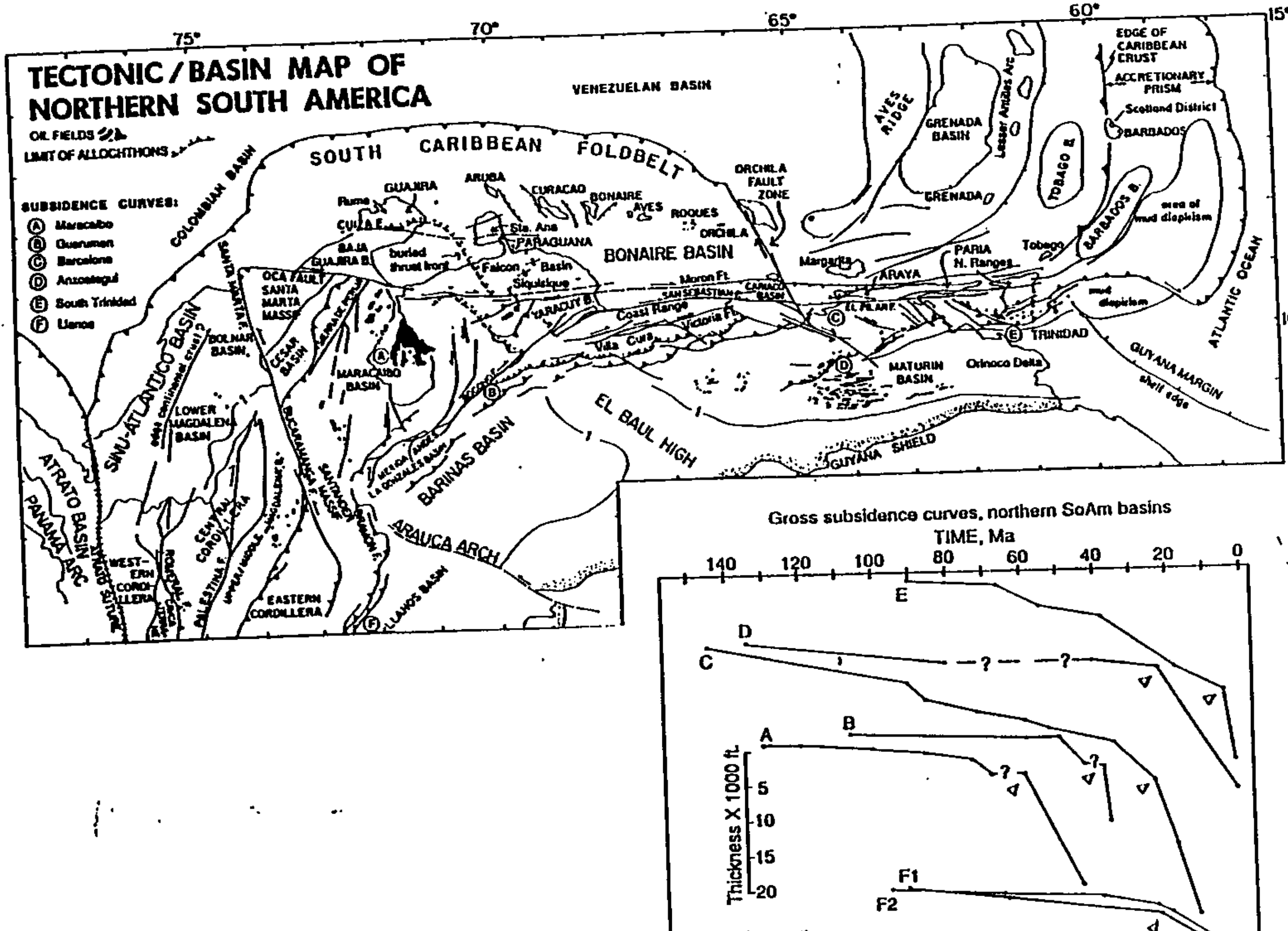

Africa
Guinea Plateau
Demerara Plateau
M-16
foredeeps
J/K Boundary
Bahamas Bank
Florida
PROTO-CARIBBEAN
Peripheral bulges, formed by transpression.
Yucatan

fig 19

fig 20



Gross subsidence curves, northern SoAm basins

Sources for sections:
A; Zambrano et al., 1972; Bockmeulen et al., 1983.
B; Talukdar and de Toni, 1988.
C, D; Perez de Mejia et al., 1980.
E; Rohr, 1990, Pers. comm.
F1, F2; Fabre, 1983; Vasquez, 1988.

Migration of Caribbean Thrust Front and Peripheral Bulge

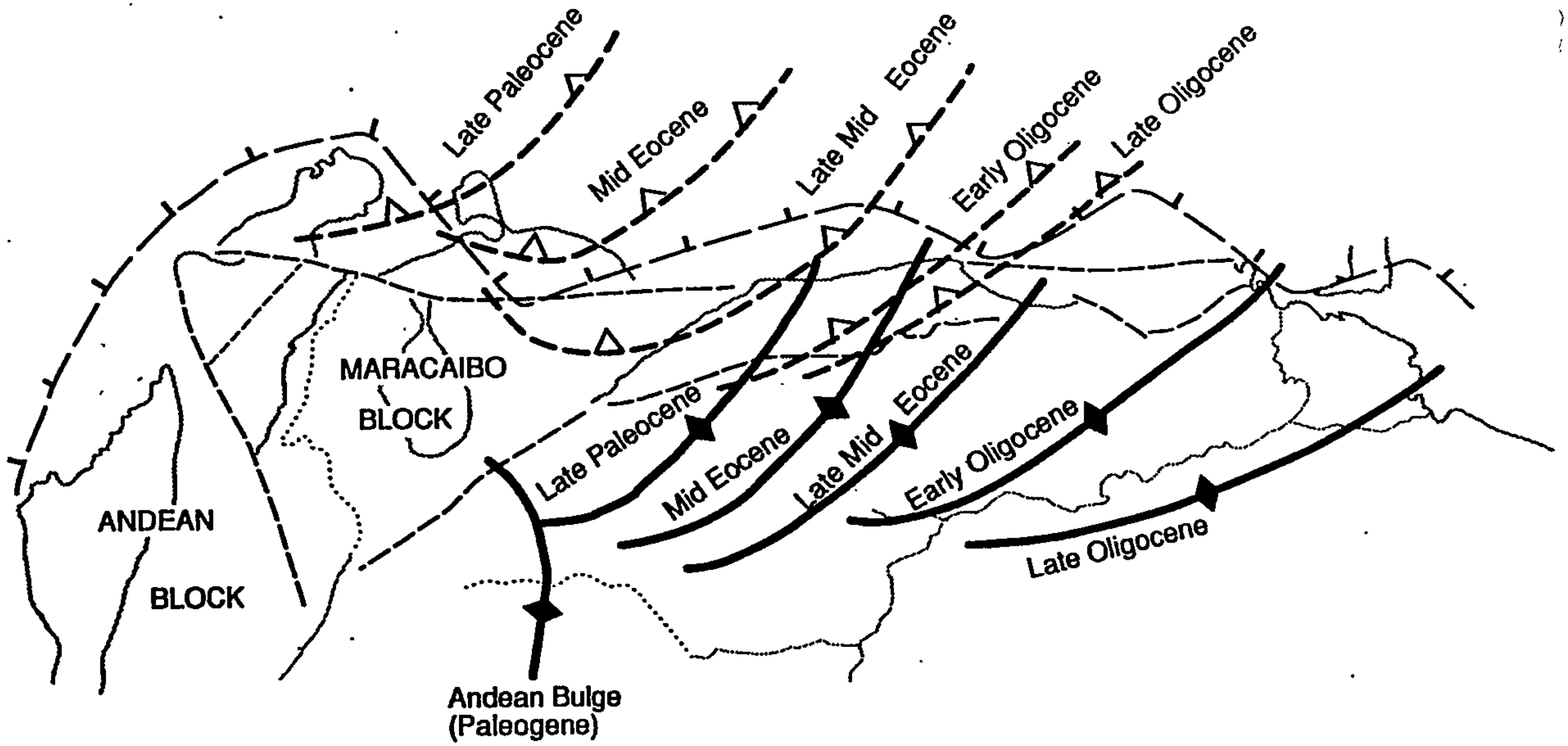


fig 21

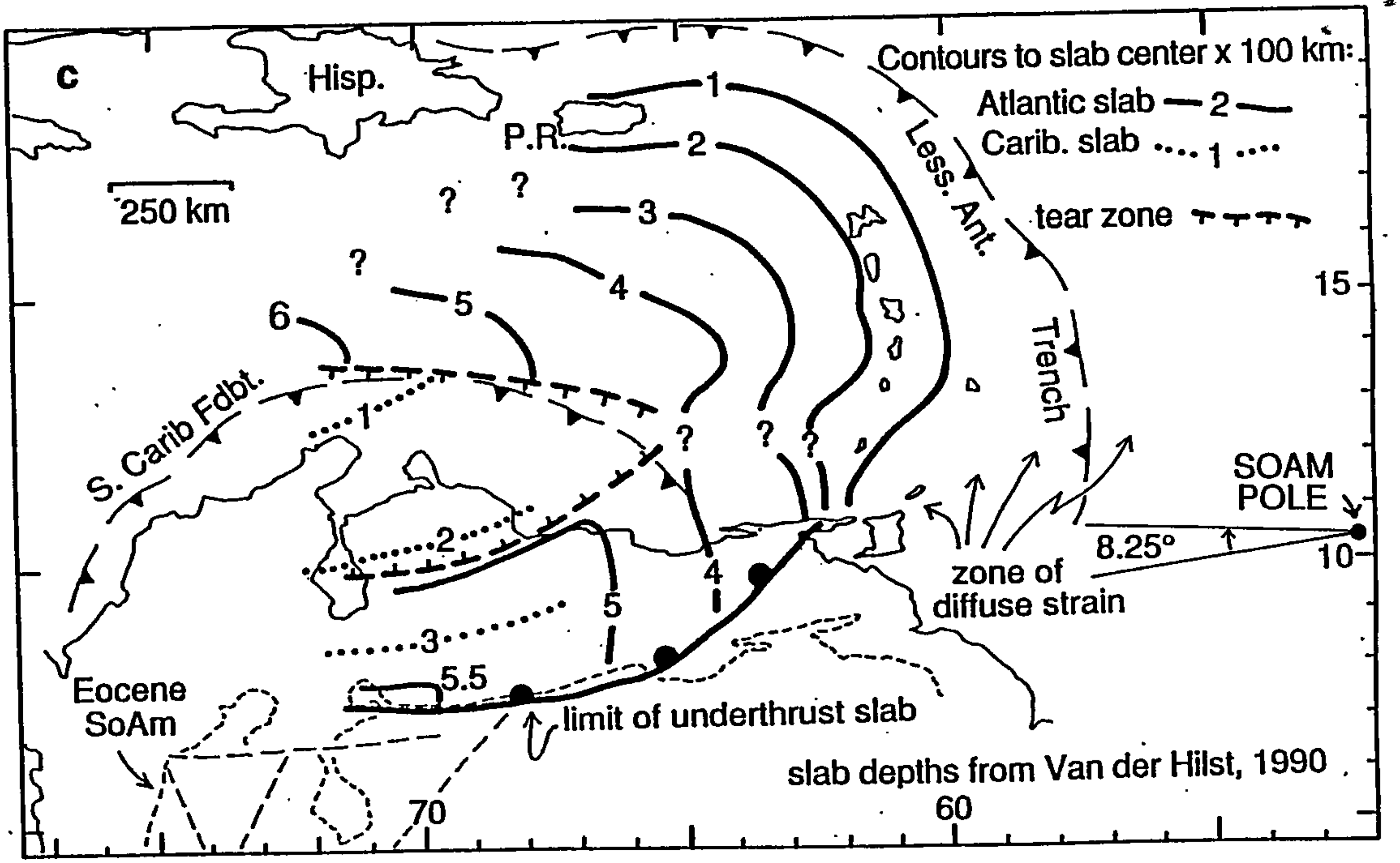

c
Hisp.
P.R.
250 km
Contours to slab center x 100 km:
Atlantic slab — 2 —
Carib. slab ···· 1 ····
tear zone
Less. Ant.
Trench
1
2
3
4
5
6
?
S. Carib Fdbt.
1
2
3
4
5
5.5
SOAM POLE
8.25°
15
10
zone of diffuse strain
limit of underthrust slab
Eocene SoAm
slab depths from Van der Hilst, 1990
70
60

fig 22