

Caribbean Plio-Quaternary (5-0 Ma) Plate Interaction and Basin Development, Colombia-Venezuela-Trinidad Oil Province*

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Pre-5 Ma Setting, Western Venezuela

Before the uplift of the Merida Andes in western Venezuela, sedimentation throughout this region was occurring in the "Catatumbo-Apure Foreland Basin" since Early Oligocene time (Higgs, in review, a). Uplift of the Santander Massif by eastward thrusting on the Mercedes-Caño Tomas Fault (Figure 1; Paris et al., 2000; Corredor, 2003) drove the basin subsidence, as shown by marked WSW thickening of the Catatumbo fill (F.E. Audemard, 1991, isopach maps figs. 14, 15).

5 Ma Uplift of Merida Andes, Sierra de Perija, Etc.

Merida Andes uplift by bivergent thrusting (NW, SE) breached the Catatumbo-Apure Basin and drove new Maracaibo and Barinas foreland basins (Figure 3), as shown by an influx of coarser deposits that thicken toward Merida (Betijoque, Rio Yuca formations). Merida uplift started near 5 Ma, based on three criteria: (1) pre-uplift strata of probable middle Miocene age, preserved as steeply dipping intramontane erosional remnants (La Cope Formation, Figure 2; Macellari, 1984; Higgs et al., 1995); (2) Merida Andes apatite fission-track ages, 17 of 22 samples giving 4.9 Ma and younger (Kohn et al., 1984); and (3) a likely Pliocene age for the Betijoque (e.g., Gonzalez de Juana et al., 1980; F.E. Audemard, 1991), and thus the Rio Yuca also (presumed coeval; LEV, 1997), although these alluvial formations are commonly considered upper Miocene-Pliocene (LEV, 1997). In most previous interpretations, the age of initial orogenic uplift of the Merida Andes is older, generally Miocene, following Giegengack (1984).

Simultaneously, uplift of the Perija, Santa Marta, Lara-Falcon, and Guajira ranges also occurred. All but Guajira verge mainly NW (Kellogg, 1984; Boesi and Goddard, 1991; ANH, 2005; Mora and Garcia, 2006). Kellogg (1984) inferred a Pliocene age for the major uplift in Perija, based on stratigraphic relationships and fission-track ages. Perija backthrusting (Duerto et al., 2006) was insufficient to assist Maracaibo basin subsidence, as shown by NW thinning of Mio-Pliocene isopachs in the basin (F.E. Audemard, 1991, fig. 15). Falcon-Lara uplift was likewise interpreted as Pliocene by Macellari (1995); here the thrust front advanced rapidly, reaching as far as Guajira(?) before the plate-boundary jump at 2.5 Ma (see below), suggesting detachment on the easy-slip Carib Halite, within the Cretaceous rift fill (Higgs, 2008b, Triassic-Recent development). During this

Pliocene thrust advance, the Burro Negro Fault ([Figure 1](#)) was probably a sinistral lateral ramp; it may previously have been a Cretaceous rift intragraben fault, controlling thicker and/or more laterally continuous halite deposition on its NE side (Higgs, 2006; Higgs, in review, b).

The Pliocene orogenic uplift promoted deep circulation of meteoric water, such that halite-dissolution subsidence locally outweighed uplift, forming the La Gonzalez, Gulf of Venezuela, Lower Guajira, Carora, and Cesar-Rancheria supraorogenic basins ([Figure 3](#); Higgs, 2006; Higgs, in review, b).

This regional shortening starting near 5 Ma is attributed to jamming of the South Caribbean Fault (Higgs, 2006; Higgs, in review, a) ([Figure 1](#)), where low-angle subduction of the Caribbean Plate beneath South America was occurring (Pindell et al., 1998). Subduction choking is attributed to the first arrival of incoming overthickened Caribbean Plateau lithosphere in the Santa Marta-Guajira sector (compare the present distribution of Caribbean Plateau, Meschede and Frisch, 1998, fig. 2). Choking caused some of the interplate convergence, oriented NW-SE (companion abstracts), to be accommodated subsequently by shortening in the overriding plate, producing the uplifts described above.

Caribbean-South America Plate Boundary Jump

Some time after the 5 Ma start of subduction choking, resistance to the distributed shortening described above, and also to shortening in the Eastern Cordillera (Dengo and Covey, 1993), driven by the collision against South America of the Panama Arc at the rear of the Caribbean Plate ([Figure 3](#)), forced a plate reorganization. The Caribbean assumed its current eastward relative motion (c. 085 degrees), as measured by GPS studies (Perez et al., 2001; Weber et al., 2001; Trenkamp et al., 2002). The plate boundary jumped inboard, from the S Caribbean-Roques-S Grenada Basin-Testigos-Bajos-Trinidad S coast fault linkage ([Figure 1](#)), to its present position, namely the E Cordillera Frontal-Chitaga-Bocono-San Sebastian-El Pilar-C Range fault system (Molnar and Sykes, 1969; Dewey, 1972; F.A. Audemard et al., 2000; Weber et al., 2001). Studies of modern and historical earthquakes confirm that the entire linkage is active (Paige, 1930; Dewey, 1972; Pennington, 1981; Perez and Aggarwal, 1981; Russo et al., 1993; F.A. Audemard et al., 2000; Paris et al., 2000). Other major faults shown in [Figure 1](#) are currently inactive (e.g., Santa Marta, Bucaramanga, S Caribbean, Oca, Roques, Urica), but they remain conspicuous as they are not long abandoned (since 2.5 Ma; see below).

By virtue of the plate-boundary jump, a region named the Northern Andes Block (NAB; Higgs, in review, a) was annexed by the Caribbean Plate and now moves essentially east with that plate (Perez et al., 2001; Trenkamp et al., 2002). The NAB is bordered in the far south by an uncertain plate-boundary sector (Molnar and Sykes, 1969; Paris et al., 2000), probably the ENE-trending oblique-dextral Ibague Fault ([Figure 1](#)), interpretable as a transform. To the WSW the Buenaventura Fault (Ingeominas, 1988) may be the continuation of the Ibague. A minimum dextral offset of 30 km on the Ibague Fault (Montes et al., 2005) is consistent with 2 cm/yr of Caribbean eastward relative motion since 2.5 Ma (see below). The NAB is the northern part of the "North Andean Block" (Kellogg, 1984) and the synonymous "Cordilleran terrane" (Dewey and Pindell, 1985). The NAB embraces the "Maracaibo block" (sensu Mann et al., 2006), which is bisected by the Oca-Ancon fault system trending roughly E-W (e.g., F.A. Audemard et al., 2000). The only obvious sector of the Oca at outcrop is in the west, sharply separating the Perija-Santa Marta Mountains from the Lower Guajira Basin (F.A. Audemard et al., 2000; Paris et al., 2000). This is probably another Cretaceous intragraben fault, reactivated in a N-down sense to form the Lower Guajira Basin by halite dissolution, during Perija-Santa Marta uplift (5- 0 Ma; Higgs, in review, b). To the east, no continuous linear fault crossing Falcon and assignable to the Oca is evident on topographic or geologic maps (e.g., Bellizzia, 1976; but see dashed

line of Pimentel, 1984). Four active, nonaligned faults in this region (F.A. Audemard et al., 2000) may or may not link and are probably halite-dissolution faults, consistent with saline springs in Falcon (Urbani, 1991). A strike-slip component (F.A. Audemard et al., 2000), too small for GPS detection (Perez et al., 2001), may reflect regional E-W compressive stress.

Two of the plate-boundary sectors, namely the Eastern Cordillera Frontal and Bocono faults, are currently dextral thrusts, reflecting their NE trend, relative to eastward Caribbean Plate motion. A kink, not shown in [Figure 1](#), in the Bocono Fault near Merida city trends ENE and is thus not suitably oriented to be a releasing bend, contrary to the La Gonzalez Basin pull-apart model of Schubert (1980). This basin is more likely an active halite-dissolution basin (Higgs, 2006; Higgs, in review, b). Farther east, the trend of the San Sebastian-El Pilar faults (c. 080 degrees) causes near-transcurrent dextral transpression (F.A. Audemard et al., 2000), as shown by raised Quaternary beach- and shallow-marine deposits in central Venezuela, Araya, Margarita, Coche Island, and the Northern Range of Trinidad (Mendez, 1997; Sisson et al., 2005; Weber, 2005). However, the transpression is widely masked by Neogene (11-0 Ma) pseudo-extensional basins formed by halite dissolution; e.g., Gulf of Barcelona, Gulf of Paria-Trinidad Basin, Carupano-North Coast Basin (Higgs, 2006; Higgs, in review, b). The two gulfs rupture the central and eastern Venezuela mountains, whose ongoing collapse is indicated by other supramontane halite-dissolution basins (Valencia, Caracas, Santa Lucia, Tuy, San Juan Graben). Superimposed on the Gulf of Paria-Trinidad Basin since 2.5 Ma is a pull-apart, comprising the northern Gulf and western Caroni region. Pull-apart here is due to rightward stepover between the El Pilar and Central Range faults ([Figure 1](#)). A much older onset of pull-apart, at 11 or 12 Ma (Algar and Pindell, 1993; Pindell et al., 1998; Pindell and Kennan, 2001; Pindell et al., 2005), requires plate transcurrence from that time, contrary to the evidence enumerated below, that transcurrence began near 2.5 Ma. In a later interpretation, Pindell and Kennan (2007) refer to the Gulf of Paria as a "low-angle extensional detachment basin."

Dating of Caribbean Plate-Motion Change

At least eight geological indicators across northern South America indicate that the change from southeastward to eastward Caribbean motion, relative to South America, occurred in Late Pliocene time (c. 2.5 Ma):

(1) Accelerated uplift of the Eastern Cordillera and Merida Andes in late Pliocene or early Quaternary time, due to focusing of the plate boundary (previously a 500 km-wide belt of distributed shortening) upon this bivergent thrust belt, where thrusting changed from orthogonal to dextral. Intense uplift of the Eastern Cordillera starting in late Pliocene time is indicated by tilting of the Middle Magdalena Basin and by palynological studies in the Bogota Basin (Van der Hammen et al., 1973; Gomez et al., 2003; Torres et al., 2005). In the Merida Andes, the start of faster uplift is approximately dated by an influx of (?Plio-) Quaternary conglomerates on both flanks (Carvajal, Guanapa formations; LEV, 1997). A relatively recent start of rapid uplift is also consistent with (A) survival of erosional remnants, at high altitude near Merida, of a paleosol formed at much lower elevations (Giegengack, 1984), and (B) insufficient altitude for glaciation until late Pleistocene time (Schubert and Vivas, 1993).

(2) The Plio-Quaternary age of the Cariaco pull-apart basin, at the San Sebastian-El Pilar stepover ([Figure 1](#); Schubert, 1982; Goddard, 1988; Jaimes and Mann, 2003). Plio-Quaternary deposits here are much thicker than underlying upper Miocene deposits (Goddard, 1988), consistent with post-2.5

Ma pull apart superimposed on post-11 Ma halite-dissolution subsidence in this and the encompassing Barcelona Bay-Tortuga Platform area (Higgs, 2006; Higgs, in review, b).

(3) Calculated E-W pull-apart extension of 50 km in the Gulf of Paria (Weber, 2005), equating to the current relative plate velocity of 2 cm/yr (Weber et al., 2001) for 2.5 m.y.

(4) Restoration of the shelf edge east of Trinidad (e.g., Case and Holcombe, 1980) into near alignment (NW-SE) by removing an assumed 50 km of dextral offset along trend with the Central Range Fault (c. 070 degrees).

(5) Quaternary (and late Pliocene?) subsidence of the Nariva Swamp in Trinidad (e.g., Kugler, 1961), attributable to transpression on the adjacent NNW-dipping Central Range Fault since 2.5 Ma, loading the footwall.

(6) Alignment of the Roques and Testigos Faults with, respectively, the Urica and Los Bajos Faults, by restoring 50 km of dextral slip on the El Pilar Fault; i.e., 2 cm/yr for 2.5 m.y. (Figure 1). This agrees well with the view that El Pilar displacement "has been estimated at as much as 1,000 km, although a new reconstruction of the South Caribbean boundary amounts to only 55 km of strike-slip" (F.A. Audemard et al., 2000, p. 62).

(7) Restoration of the Maracaibo block "out of the way" of Villa de Cura nappe southeastward emplacement (Figure 3; cf. Pimentel, 1984), by moving it west by the same 50 km. Calculated apparent dextral offset along the Bocono Fault Zone is only 35 km ($50 \times \sin 45^\circ$ fault trend), compared to previous estimates of 290 and 100 km of dextral slip (Dewey and Pindell, 1985, 1986), supporting the objection of Salvador (1986) that the Merida Arch pre-Cretaceous basement high crosses the Andes nearly orthogonally "with no major horizontal displacement." The 35 km value is close to the 0-40 km estimates of most earlier authors (summary in Salvador, 1986). Glacial moraines about 10,000 years old are offset 66 m dextrally by the main strand of the Bocono Fault Zone (Schubert and Sifontes, 1970). Extrapolating this value gives 17 km since 2.5 Ma, consistent with the calculated 35 km for the entire fault zone. Thus, the popular concept of northward "escape" of the Maracaibo block (Mann and Burke, 1984), incorporated in Pangea reconstructions (Pindell and Dewey, 1982; Pindell, 1985), is questionable.

(8) Three other lines of evidence that the preceding southeastward Caribbean relative motion lasted until at least Pliocene time:

(i) The pronounced expression of the South Caribbean accretionary prism on bathymetric and seismic profiles (Silver et al., 1975), with thrusts reaching up into the interpreted Pliocene section (Ruiz et al., 2000; Flinch et al., 2003). However, even the frontal thrusts terminate below the Quaternary (Flinch et al., 2003, fig. 2), consistent with accretion ending at 2.5 Ma.

(ii) The southeasterly overall trend of the Barbados accretionary prism southern lateral edge, east of Trinidad (e.g., Mascle and Moore, 1990, fig. 1).

(iii) The kilometeric Pliocene subsidence of Columbus Channel foredeep (Di Croce et al., 1999).

The change to eastward Caribbean relative motion ended thrust-belt shortening in southern Trinidad, thereby terminating the driving mechanism of the Caribbean foreland basin (Higgs, 2008a, 2008b). However, east of Maturin city ([Figure 1](#)), the Caribbean foreland basin has been buried by further subsidence (Deltana-Columbus Channel Basin and southern Columbus Basin; also area of "Reciente" outcrop of Pimentel, 1984). This is interpretable as compactional subsidence, combined in the southern Columbus Basin with eastward gravitational extension toward the Atlantic Ocean floor (Bevan, 2007). West of Maturin, eastern and central Venezuela have been rebounding for progressively longer westward (hence "Pleistoceno" and steadily older outcrop westward; Pimentel 1984), reflecting the eastward migration of the Caribbean nappe suture point, whereby the Caribbean load was diachronously severed by eastward lengthening of the South Caribbean Fault subduction zone (Higgs, 2008a). This rebound has removed (eroded) the Caribbean foreland basin fill in central Venezuela, exposing Proto-Caribbean foreland basin deposits.

Caribbean Plate Velocity Relative to the Mantle

The Caribbean Plate is moving east relative to South America at about the same rate (c. 2 cm/yr) that South America drifts west relative to the mantle; hence the Caribbean Plate is essentially stationary in the mantle reference frame (Pindell et al., 2006). These conditions are presumed (Higgs, in review, a) to have applied since the 2.5 Ma plate-motion change. Between the 2.5 reorganization and the one at 72 Ma (late Campanian; Higgs, 2008a, 2008b), the velocity of the Caribbean leading edge relative to South America can be calculated, over two consecutive sectors:

(1) Ecuador to Guajira corner, amounting to about 1100 km of eastward travel between 72 and 35 Ma (i.e., 2.5 cm/yr); followed by

(2) Guajira corner to the Paria Peninsula tip, totaling about 1100 km of SE travel between 35 and 2.5 Ma (3.5 cm/yr; i.e., eastward component 2.5 cm/yr). Simultaneously, the Americas drifted west relative to the mantle at 2-3 cm/year throughout Cenozoic time (Pindell et al., 2006). Thus, Caribbean average eastward absolute velocity has never exceeded 0.5 cm/yr since 72 Ma. This is slower than typical trench rollback rates (1-2 cm/yr; Conrad and Lithgow-Bertelloni, 2006); therefore, the arc may have varied between "extensional" and "neutral" in the Dewey (1980) classification.

Exploration Implications

The proposed younger age of Merida uplift (5 Ma), and the younger switch (2.5 Ma) to Caribbean-South America transcurrence, among other concepts presented here, have important implications for petroleum exploration in NW Colombia, Venezuela and Trinidad, affecting predictions and models of paleogeography (sand depositional fairways), burial/heat-flow history (organic maturation), timing of structuration, etc..

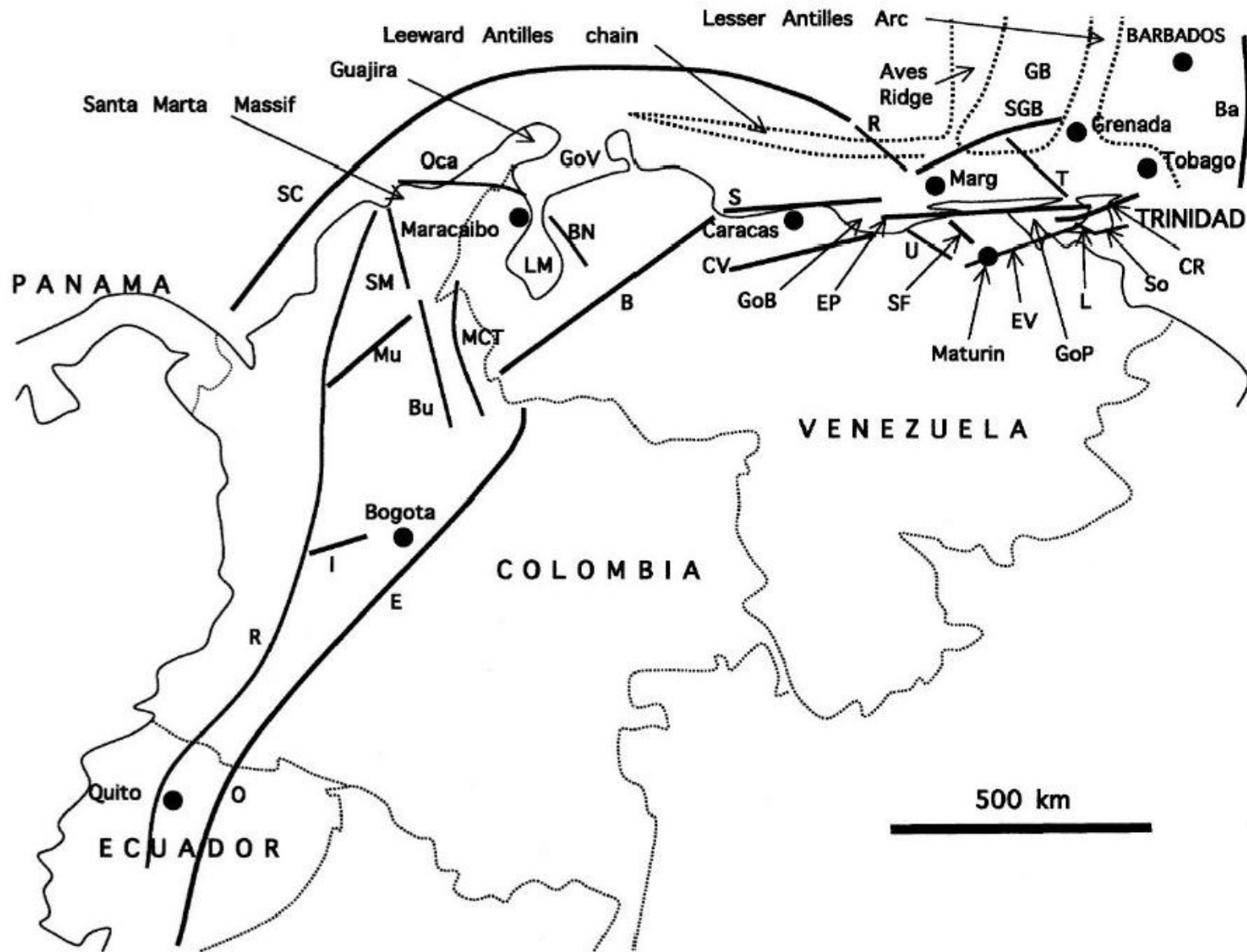


Figure 1. Location map and major faults of northwestern South America. Basins: GB=Grenada, GoB=Gulf of Barcelona, GoP=Gulf of Paria, GoV=Gulf of Venezuela, LM=Lake Maracaibo, SGB=South Grenada Basin. Faults: B=Bocono, Ba=Barbados accretionary prism frontal thrust, BN=Burro Negro, Bu=Bucaramanga, CR=Central Range, CV=central Venezuela frontal thrust, E=East Andean frontal thrust, EP=El Pilar, EV=eastern Venezuela frontal thrust, I=Ibague, L=Los Bajos, MCT=Mercedes-Caño Tomas, Mu=Murrucucu, O=Oriente, R=Romeral, R=Roques Canyon, S=San Sebastian, SC=South Caribbean, SF=San Francisco, So=Southern sole thrust, SM=Santa Marta, T=Testigos, U=Urica. Marg=Margarita island. Dotted outline of Aves Ridge, Leeward Antilles extinct arc, and Lesser Antilles Arc is the approximate 1500 m isobath. Tobago and Barbados mark the leading (eastern) edge of Caribbean crystalline crust. Main sources: Kugler, 1961; Parnaud et al., 1995; Villamil, 1999; F.A. Audemard et al., 2000; Paris et al., 2000; Escalona and Mann, 2006.

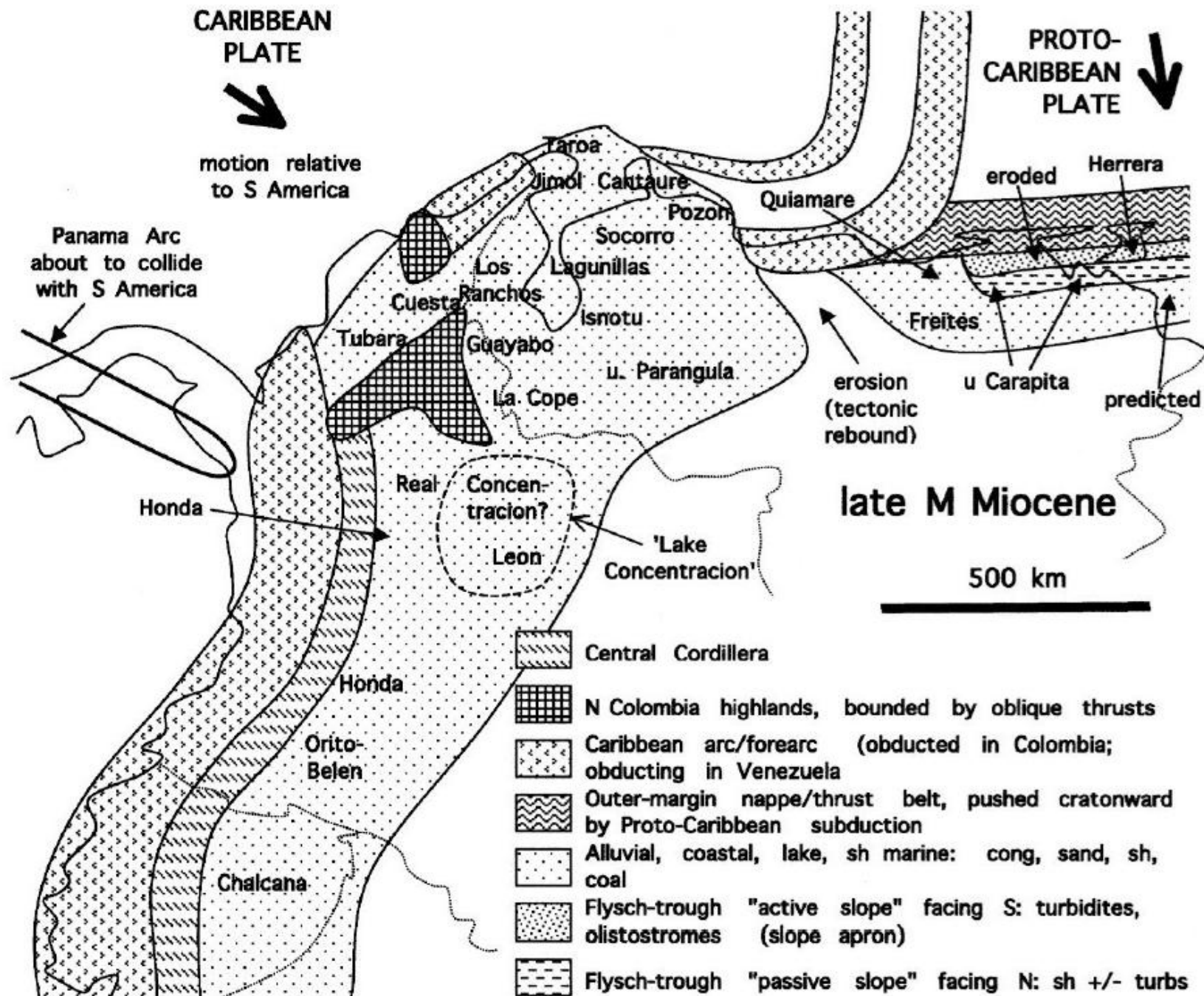


Figure 2. Late middle Miocene (12 Ma; *Gt. fohsi robusta* zone) paleogeographic map of northwestern South America. This map follows on from Figure 3 in Higgs, 2008b (northern South America Triassic-Recent history).

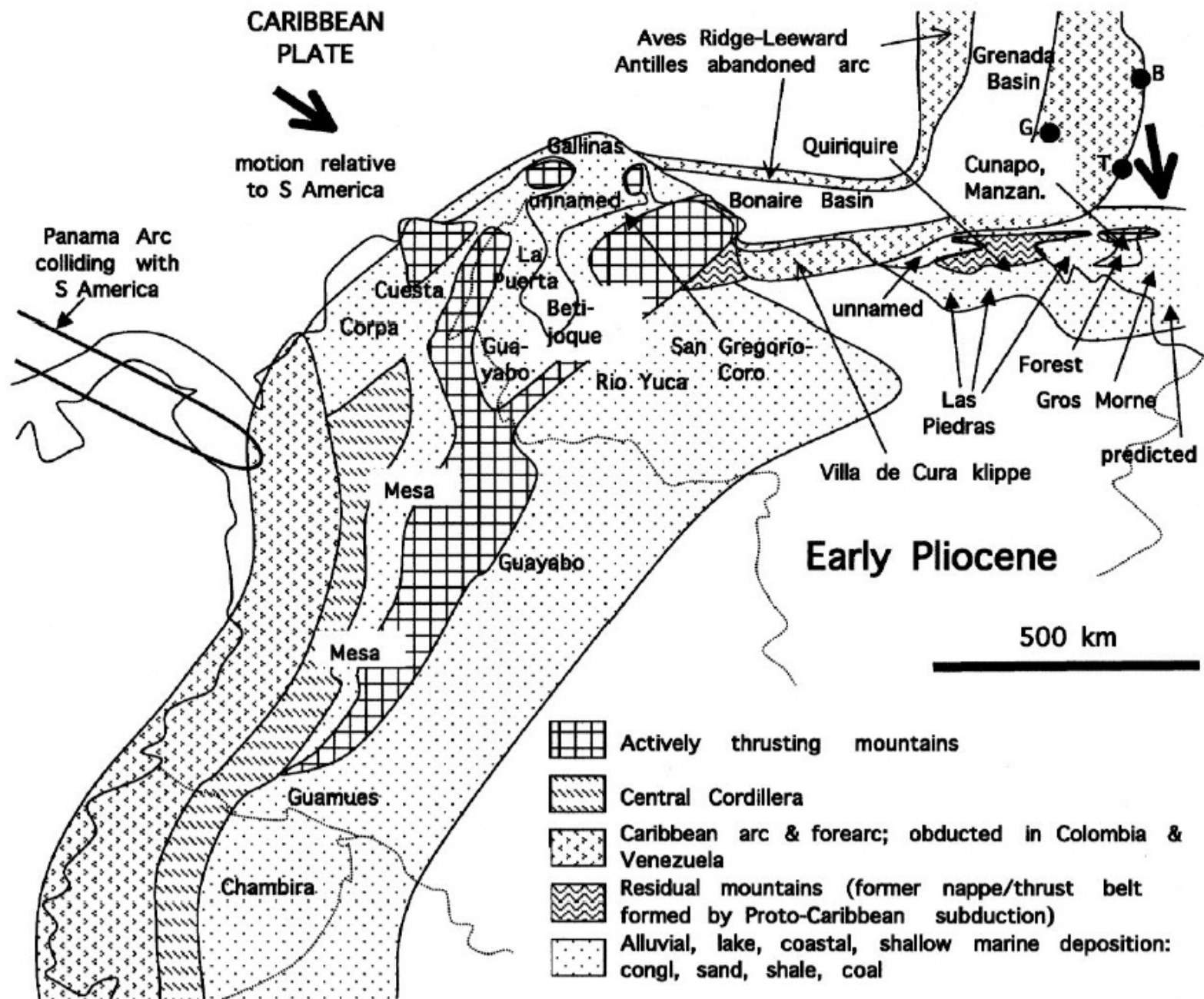


Figure 3. Early Pliocene paleogeographic map of northwestern South America. Not shown on the Caribbean nappe: (1) post-obduction basins in Colombia (Cauca-Patia; Atrato-Choco-Pacifico), and (2) syn-obduction halite-dissolution basins/formations in Venezuela (Tuy/Aramina; Carupano/Cubagua). B=Barbados, G=Grenada, T=Tobago.

References Cited

- Algar, S.T., and J.L. Pindell, 1993, Structure and deformation history of the Northern Range of Trinidad and adjacent areas: *Tectonics*, v. 12, p. 814-829.
- ANH, 2005, Cesar Rancheria Basin: Bogota, Colombia, Asociacion Nacional de Hidrocarburos promotional brochure (http://www.anh.gov.co/html/i_portals/index.php), Accessed February 14, 2008.
- Audemard, F.A., M.N. Machette, J.W. Cox, R.L. Dart, and K.M. Haller, 2000, Map and database of Quaternary faults in Venezuela and its offshore regions: U.S. Geological Survey, Open-File Report 00-018.
- Audemard, F.E., 1991, Tectonics of western Venezuela: PhD thesis, Rice University, Houston, Texas, 245 p.
- Bellizzia, A., 1976, Mapa geologico y estructural de Venezuela: Caracas, Venezuela, Ministerio de Energia y Minas, 1:500,000.
- Bevan, T., 2007, Structural cross sections of the Columbus Basin, Trinidad and Tobago: an integrated geological model based on a comprehensive 3D seismic database (abstract): Fourth Geological Conference of the Geological Society of Trinidad and Tobago, CD.
- Boesi, T., and D. Goddard, 1991, A new geologic model related to the distribution of hydrocarbon source rocks in the Falcon Basin, northwestern Venezuela, *in* K.T. Biddle, ed., Active Margin Basins: AAPG Memoir 52, p. 303- 319.
- Case, J.E., and T.L. Holcombe, 1980, Geologic-tectonic map of the Caribbean region: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1100, 1:2,500,000.
- Conrad, C.P., and C. Lithgow-Bertelloni, 2006, How mantle slabs drive plate tectonics: *Science*, v. 298, p. 207-209.
- Cooper, M.A., F.T. Addison, R. Alvarez, M. Coral, R.H. Graham, A.B. Hayward, S. Howe, J. Martinez, J. Naar, R. Peñas, A.J. Pulham, and A. Taborda, 1995, Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia: AAPG Bulletin, v. 79, p. 1421-1443.
- Corredor, F., 2003, Eastward extent of the Late Eocene-Early Oligocene onset of deformation across the northern Andes: constraints from the northern portion of the Eastern Cordillera fold belt, Colombia, and implications for regional oil exploration: Asociacion Colombiana de Geologos y Geofisicos del Petroleo, VIII Simposio Bolivariano de la Exploracion Petrolera en las Cuencas Subandinas, Memoria 1, p. 34-45.
- Dashwood, M.F., and I.L. Abbotts, 1990, Aspects of the petroleum geology of the Oriente Basin, Ecuador, *in* J. Brooks, ed., Classic Petroleum Provinces: Geological Society (London), Special Publication 50, p. 89-117.
- Dengo, C.A., and M.C. Covey, 1993, Structure of the Eastern Cordillera of Colombia: Implications for trap styles and regional tectonics: AAPG Bulletin, v. 77, p. 1315-1337.
- Dewey, J.F., 1972, Seismicity and tectonics of western Venezuela: Bulletin of the Seismological Society of America, v. 62, p. 1711-1751.
- Dewey, J.F., 1980, Episodicity, sequence, and style at convergent plate boundaries, *in* D.W. Strangway, ed., The Continental Crust and Its Mineral Deposits: Geological Association of Canada, Special Paper 20, p. 553-573.
- Dewey, J.F., and J.L. Pindell, 1985, Neogene block tectonics of eastern Turkey and northern South America: Continental applications of the finite difference method: *Tectonics*, v. 4, p. 71-83.
- Dewey, J.F., and J.L. Pindell, 1986, Neogene block tectonics of Turkey and northern South America: Continental applications of the finite difference method: Reply: *Tectonics*, v. 5, p. 703-705.
- Di Croce, J., A.W. Bally, and P. Vail, 1999, Sequence stratigraphy in the Eastern Venezuelan Basin, *in* P. Mann, ed., Caribbean basins: Amsterdam, Elsevier, p. 419-476.
- Duerto, L., A. Escalona, and P. Mann, 2006, Deep structure of the Merida Andes and Sierra de Perija mountain fronts, Maracaibo Basin, Venezuela: AAPG Bulletin, v. 90, p. 505-528.
- Escalona, A., and P. Mann, 2006, Tectonic controls of the right-lateral Burro Negro tear fault on Paleogene structure and stratigraphy, northeastern Maracaibo Basin: AAPG Bulletin, v. 90, p. 479-504.

- Flinch, J.F., J. Amaral, A. Doucet, B. Mouly, C. Osorio, and J.M. Pince, 2003, Onshore-offshore structure of the northern Colombia accretionary complex (abstract): AAPG International Conference, Barcelona (<http://www.searchanddiscovery.net/documents/abstracts/2003barcelona/index.htm#F>), Accessed February 14, 2008.
- Ghosh, S.K., and O. Odreman, 1987, Estudio sedimentológico-paleoambiental del Terciario en la zona del Valle de San Javier, Estado Mérida: Sociedad Venezolana de Geólogos, Boletín 31, p. 36-46.
- Giegegack, R., 1984, Late Cenozoic tectonic environments of the central Venezuelan Andes, *in* W.E. Bonini, R.B. Hargraves, and R. Shagam, eds., The Caribbean-South American Plate Boundary and Regional Tectonics: GSA Memoir 162, p. 343-364.
- Goddard, D., 1988, Seismic stratigraphy and sedimentation of the Cariaco Basin and surrounding continental shelf, northeastern Venezuela: 11th Caribbean Geological Conference, Barbados, Transactions, p. 34:1-34:21.
- Gomez, E., T.E. Jordan, R.W. Allmendinger, K. Hegarty, S. Kelley, and M. Heizler, 2003, Controls on architecture of the Late Cretaceous to Cenozoic southern Middle Magdalena Valley Basin, Colombia: GSA Bulletin, v. 115, p. 131-147.
- Gonzalez de Juana, C., J.M. Iturralde, and X. Picard, 1980, Geología de Venezuela y de sus cuencas petrolíferas: Caracas, Ediciones Foninves, 1031 p.
- Higgs, R., 2006, Colombia-Venezuela-Trinidad "Caribbean Oblique Collision Model" revised: Sociedad Venezolana de Geofísicos, XIII Congreso Venezolano de Geofísica, Caracas, Memorias CD (<http://www.congresogeofisicsovg.org/dyncat.cfm?catid=4378>), Accessed February 14, 2008.
- Higgs, R., 2008a, Caribbean Arc revised geological history affecting Circum-Caribbean petroleum exploration: Search and Discovery Article #30056 (2008).
- Higgs, R., 2008b, Colombia-Venezuela-Trinidad prolific oil province: Revised Triassic-Recent depotectonic history: Search and Discovery Article #30057.
- Higgs, R., in review, a, Caribbean-South America oblique collision model revised, *in* K.H. James, M.A. Lorente, and J. Pindell, eds., Geology of Middle America and Origin of the Caribbean Plate: Geological Society (London) Special Publication.
- Higgs, R., in review, b, The vanishing Carib Halite Formation (Neocomian), Venezuela-Trinidad prolific petroleum province, *in* K.H. James, M.A. Lorente, and J. Pindell, eds., Geology of Middle America and Origin of the Caribbean Plate: Geological Society (London) Special Publication.
- Higgs, R., J. Pindell, and O. Odreman, 1995, Mesozoic-Cenozoic tectonics and sedimentation in the Venezuelan Andes region, and implications for petroleum exploration: Venezuela, Ministerio de Energía y Minas, IX Congreso Latinoamericano de Geología, Field Trip Guidebook 6, 80 p.
- Ingeominas, 1988, Mapa Geológico de Colombia: Bogotá, Instituto Nacional de Investigaciones Geológico-Mineras, 1:1,500,000.
- Jaimes, M.A., and P. Mann, 2003, Tectonic origin of the Cariaco Basin, Venezuela: pull-apart, extinct pull-apart or fault-normal extension? (abstract): AAPG Annual Meeting Program.
- Kellogg, J.N., 1984, Cenozoic tectonic history of the Sierra de Perijá, Venezuela-Colombia, and adjacent basins, *in* W.E. Bonini, R.B. Hargraves, and R. Shagam, eds., The Caribbean-South American Plate Boundary and Regional Tectonics: GSA Memoir 162, p. 239-261.
- Kiser, G.D., 1989, Relaciones estratigráficas de la cuenca Apure/Llanos con áreas adyacentes, Venezuela suroeste y Colombia oriental: Sociedad Venezolana de Geólogos, Monografía 1, 77 p.
- Kiser, G.D., 1994, Santa Marta Massif: a major element in the tectonic-sedimentary evolution of northern South America: Sociedad Venezolana de Geólogos, V Simposio Bolivariano de la Exploración Petrolera en las Cuencas Subandinas, Memoria, p. 317-335.
- Kohn, B.P., R. Shagam, P.O. Banks, and L.A. Buckley, 1984, Mesozoic- Pleistocene fission-track ages on rocks of the Venezuelan Andes and their tectonic implications, *in* W.E. Bonini, R.B. Hargraves, and R. Shagam, eds., The Caribbean-South American Plate Boundary and Regional Tectonics: GSA Memoir 162, p. 365-384.
- Kugler, H.G., 1961, Geological map and cross-sections of Trinidad: Petroleum Association of Trinidad, 1:100,000.
- Kugler, H.G., 2001, Treatise on the geology of Trinidad, part 4. The Paleocene to Holocene formations of Trinidad: Basel, Switzerland, Natural History Museum, 309 p.

- LEV, 1997, Lexico estratigrafico de Venezuela, 3ra edicion: Venezuela, Ministerio de Energia y Minas, Boletin de Geologia, Publicacion Especial 12 (<http://www.pdvsa.com/lexico/lexicoh.htm>), Accessed February 14, 2008.
- Macellari, C., 1984, Late Tertiary tectonic history of the Tachira Depression, southwestern Venezuelan Andes, *in* W.E. Bonini, R.B. Hargraves, and R. Shagam, eds., The Caribbean-South American Plate Boundary and Regional Tectonics: GSA Memoir 162, p. 333-341.
- Macellari, C.E. 1995, Cenozoic sedimentation and tectonics of the southwestern Caribbean pull-apart basin, Venezuela and Colombia, *in* A.J. Tankard, R. Suarez, and H.J. Welsink, eds., Petroleum Basins of South America: AAPG Memoir 62, p. 757-780.
- Macsotay, O., V. Vivas, and P. Moticska, 1995, Biostratigraphy of the Piemontine Nappe of north-central Venezuela: Senonian to Eocene gravitational sedimentation: Venezuela, Ministerio de Energia y Minas, Boletin de Geologia, Publicacion Especial 10, p. 114-123.
- Mann, P., and K. Burke, 1984, Neotectonics of the Caribbean: Reviews of Geophysics and Space Physics, v. 22, p. 309-362.
- Mann, P., A. Escalona, and M.V. Castillo, 2006, Regional geologic and tectonic setting of the Maracaibo supergiant basin, western Venezuela: AAPG Bulletin, v. 90, p. 445-477.
- Masche, A., and J.C. Moore, 1990, ODP Leg 110: tectonic and hydrologic synthesis: Proceedings of the Ocean Drilling Program, Scientific Results, v. 110, p. 409-422.
- Mendez, J., 1997, El Cuaternario en Venezuela (<http://www.pdvsa.com/lexico/q00w.htm>), Accessed February 14, 2008.
- Meschede, M., and W. Frisch, 1998, A plate-tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean Plate: Tectonophysics, v. 296, p. 269-291.
- Molnar, P., and L.R. Sykes, 1969, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity: GSA Bulletin, v. 80, p. 1639-1684.
- Montes, C., R.D. Hatcher, Jr., and P.A. Restrepo-Pace, 2005, Tectonic reconstruction of the northern Andean blocks: oblique convergence and rotations derived from the kinematics of the Piedras-Girardot area, Colombia: Tectonophysics, v. 399, p. 221-250.
- Mora, A., and A. Garcia, 2006, Cenozoic tectono-stratigraphic relationships between the Cesar Sub-basin and the southeastern Lower Magdalena Valley Basin of northern Colombia: AAPG, Search and Discovery Article #30046 (<http://www.searchanddiscovery.com/documents/2006/06134mora/index.htm>), Accessed February 14, 2008.
- Paige, S., 1930, The earthquake at Cumana, Venezuela, January 17, 1929: Bulletin of the Seismological Society of America, v. 20, p. 1-10.
- Paris, G., M.N. Machette, R.L. Dart, and K.M. Haller, 2000, Map and database of Quaternary faults and folds in Colombia and its offshore regions: U.S. Geological Survey, Open-File Report 00-0284.
- Parnaud, F., Y. Gou, J.-C. Pascual, I. Truskowski, O. Gallango, and H. Passalacqua, 1995, Petroleum geology of the central part of the Eastern Venezuela basin, *in* A.J. Tankard, R. Suarez, and H.J. Welsink, eds., Petroleum basins of South America: AAPG, Memoir 62, p. 741-756.
- Pennington, W.D., 1981, Subduction of the Eastern Panama Basin and seismotectonics of northwestern South America: Journal of Geophysical Research, v. 86(B11), p. 10753-10770.
- Perez, O.J., and Y.P. Aggarwal, 1981, Present-day tectonics of the southeastern Caribbean and northeastern Venezuela: Journal of Geophysical Research, v. 86(B11), p. 10791-10804.
- Perez, O.J., R. Bilham, R. Bendick, J.R. Velandia, N. Hernandez, C. Moncayo, M. Hoyer, and M. Kozuch, 2001, Velocity field across the southern Caribbean plate boundary and estimates of Caribbean/South-American plate motion using GPS geodesy 1994-2000: Geophysical Research Letters, v. 28, p. 2987-2990.
- Pimentel, N., 1984, Mapa geologico estructural de Venezuela: Ministerio de Energia y Minas, 1:2,500,000.
- Pindell, J.L., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean: Tectonics, v. 4, p. 1-39.
- Pindell, J. and J.F. Dewey, 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179-211.

- Pindell, J.L., R. Higgs, and J.F. Dewey, 1998, Cenozoic palinspastic reconstruction, paleogeographic evolution and hydrocarbon setting of the northern margin of South America, *in* J.L. Pindell and C. Drake, eds., *Paleogeographic Evolution and Non-glacial Eustasy, Northern South America: SEPM Special Publication 58*, p. 45-85.
- Pindell, J., and L. Kennan, 2001, Processes and events in the terrane assembly of Trinidad and Eastern Venezuela, *in* R.H. Fillon, N.C. Rosen, and P. Weimer, eds., *Petroleum Systems of Deep-Water Basins: Global and Gulf of Mexico Experience: CSSEPM Foundation, 21st Annual Research Conference, Transactions*, p. 159-192.
- Pindell, J., and L. Kennan, 2007, Cenozoic kinematics and dynamics of oblique collision between two convergent plate margins: The Caribbean-South America collision in eastern Venezuela, Trinidad and Barbados, *in* L. Kennan, J. Pindell, and N. Rosen, eds., *The Paleogene of the Gulf of Mexico and Caribbean Basins: Processes, Events, and Petroleum Systems: GCSSEPM Foundation, 27th Annual Research Conference, Transactions*.
- Pindell, J., L. Kennan, W.V. Maresch, K.-P. Stanek, G. Draper, and R. Higgs, 2005, Plate-kinematics and crustal dynamics of Circum-Caribbean arc-continent interactions: tectonic controls on basin development in Proto-Caribbean margins, *in* H.G. Ave Lallement and V.B. Sisson, eds., *Caribbean-South American Plate Interactions, Venezuela: GSA Special Paper 394*, p. 7-52.
- Pindell, J., L. Kennan, K.-P. Stanek, W.V. Maresch, and G. Draper, 2006, Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved: *Geologica Acta*, v. 4, p. 303-341.
- Ruiz, C., N. Davis, P. Bentham, A. Price, and D. Carvajal, 2000, Structure and tectonic evolution of the south Caribbean basin, southern offshore Colombia: A progressive accretionary system: *Sociedad Venezolana de Geologos, VII Simposio Bolivariano de la Exploracion Petrolera en las Cuencas Subandinas, Memoria*, p. 334-355.
- Russo, R.M., R.C. Speed, E.A. Okal, J.B. Shepherd, and K.C. Rowley, 1993, Seismicity and tectonics of the southeastern Caribbean: *Journal of Geophysical Research*, v. 98(B8), p. 14299-14319.
- Salvador, A., 1986, Comments on "Neogene block tectonics of eastern Turkey and northern South America: Continental applications of the finite difference method" by J.F. Dewey and J.L. Pindell: *Tectonics*, v. 5, p. 697-701.
- Saunders, J.B., 1997a, Trinidad stratigraphic chart and geological map: Trinidad and Tobago Ministry of Energy, 1:100,000.
- Saunders, J.B., 1997b, General explanatory notes and changes from H.G. Kugler's 1959 map: Trinidad and Tobago Ministry of Energy, Explanatory Notes for 1997 Geological Map of Trinidad, p. 2-12.
- Schubert, C., 1980, Late-Cenozoic pull-apart basins, Bocono fault zone, Venezuelan Andes: *Journal of Structural Geology*, v. 2, p. 463-468.
- Schubert, C., 1982, Origin of Cariaco Basin, southern Caribbean Sea: *Marine Geology*, v. 47, p. 345-360.
- Schubert, C., and R.S. Sifontes, 1970, Bocono Fault, Venezuelan Andes: Evidence of post-glacial movement: *Science*, v. 170, p. 66-69.
- Schubert, C., and L. Vivas, 1993, *El Cuaternario de la Cordillera de Merida, Andes Venezolanos*: Merida, Universidad de Los Andes/Fundacion Polar, 345 p.
- Silver, E.I., J.E. Case, and H.J. MacGillavry, 1975, Geophysical study of the Venezuelan borderland: *GSA Bulletin*, v. 86, p. 213-226.
- Sisson, V.B., H.G. Ave Lallement, M. Ostos, A.E. Blythe, L.W. Snee, P. Copeland, J.E. Wright, R., A. Donelick, and L.R. Guth, 2005, Overview of radiometric ages in three allochthonous belts of northern Venezuela: old ones, new ones, and their impact on regional geology, *in* H.G. Ave Lallement and V.B. Sisson, eds., *Caribbean-South American Plate Interactions, Venezuela: GSA Special Paper 394*, p. 91-117.
- Torres, V., J. Vandenberghe, and H. Hooghiemstra, 2005, An environmental reconstruction of the sediment infill of the Bogota basin (Colombia) during the last 3 million years from abiotic and biotic proxies: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 226, p. 127-148.
- Trenkamp, R., J.N. Kellogg, J.T. Freymueller, and H.P. Mora, 2002, Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations: *Journal of South American Earth Sciences*, v. 15, p. 157-171.
- Van der Hammen, T., J.H. Werner, and H. Van Dommelen, 1973, Palynological record of the upheaval of the northern Andes: A study of the Pliocene and Lower Quaternary of the Colombian Eastern Cordillera and the early evolution of its high-Andean biota: *Review of Palaeobotany and Palynology*, v. 16, p. 1-122.

Villamil, T., 1999, Campanian-Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 153, p. 239-275.

Weber, J.C., 2005, Neotectonics in the Trinidad and Tobago, West Indies segment of the Caribbean-South American plate boundary: *Geological Institute of Hungary, Occasional Papers*, v. 204, p. 21-29.

Weber, J.C., T.H. Dixon, C. Demets, W.B. Ambeh, P. Jansma, G. Mattioli, J. Saleh, G. Sella, R. Bilham, and O. Perez, 2001, GPS estimate of relative motion between the Caribbean and South American plates, and geologic implications for Trinidad and Venezuela: *Geology*, v. 29, p. 75-78.