Colombia-Venezuela-Trinidad "Caribbean Oblique Collision Model" revised

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Summary

The Caribbean Oblique Collision Model, that northern South America was a late Jurassic-Miocene passive margin, destroyed by diachronous (Paleocene-Miocene) collision with the east-migrating Caribbean Arc, requires three major revisions: (1) rifting persisted about 25 m.y. later than the model dictates, based on diverse evidence for a thick (c. 4 km) but partly vanished (dissolved) lowest Cretaceous halite unit, here named the Carib Halite Formation, deposited in a graben complex reaching from Colombia (Bogotá halite) through Venezuela to Trinidad; (2) orogenic onset was neither diachronous nor caused by Caribbean collision. Instead, orogeny began along the entire NW Colombia-Venezuela-Trinidad former passive margin in latest Cretaceous time, due to southward Proto-Caribbean subduction (too slowly to produce an arc), caused by North-South America convergence. Subduction pushed the outermost former passive-margin rift block southward as a "Slope Nappe", thus metamorphosing the overridden rift and passive-margin outer-shelf succession (*e.g.* Caracas Group, Caribbean Group), which in turn moved south in a "Shelf Nappe". The nappe load produced a south-migrating forebulge, datable as Campanian (*e.g.* Tres Esquinas Member super-condensed section), followed by a Proto-Caribbean Foreland Basin, containing Campanian and younger southward-fining olistostromes and turbidites; and (3) the Caribbean Arc arrived in Venezuela about 30 m.y. later than the Caribbean Model claims, reaching Guajira corner in mid-Oligocene time, after obliquely colliding eastward along the NE-trending western sector of the (already active) Colombia-Venezuela-Trinidad margin. Late arrival explains the block faulting and volcanism in the Gulf of Venezuela-Falcón Basin (Late Oligocene) in terms of "transform pullapart", as the Arc migrated SE along this SE-trending middle sector of the margin. The Arc then reached the ENE-trending eastern sector (Caracas-Trinidad), where the same SE relative motion caused oblique obduction of a Caribbean forearc nappe, comprising the Villa de Cura-Margarita-Tobago belt, driving a Caribbean Foreland Basin that diachronously superceded the Proto-Caribbean Foreland Basin (Miocene changeover in central Venezuela; Quaternary in Trinidad).

As the Caribbean Nappe sutured progressively eastward along Colombia and Venezuela, continuing Caribbean-South America plate convergence behind the suture point was accommodated by southeastward flat-slab subduction at the South Caribbean Fault, which propagated eastward, keeping pace with the suture point. In mid-Oligocene time, the subduction zone choked in Colombia (Panamá-Barranquilla segment), due to the arrival of Caribbean Plateau thickened crust, causing initial uplift of the Eastern Cordillera bivergent orogen, forming foreland basins on each side. The Santander Massif was also uplifted, as an oblique (sinistral) bivergent orogen, with flanking foreland basins: the Lower Magdalena; and the "Catatumbo Foreland Basin", whose Oligo-Miocene deposits thin ENE, onlapping the former Proto-Caribbean "Maracaibo Thrust Belt", hence the "Eocene unconformity".

The same choking mechanism affected the Santa Marta segment of the subduction zone near the start of Pliocene time (c. 5 Ma), forming the bivergent Mérida Andes, with flanking foreland basins, and the mainly NW-vergent Perijá-Santa Marta ranges. Mountains also formed throughout the Gulf of Venezuela-Falcón region, aided by rapid NW thrust advance (halite decollement).

At about 1.5 Ma, Caribbean relative motion changed to its current direction of 085 degrees (GPS). The plate boundary moved to the Eastern Cordillera-Mérida Andes bivergent oblique thrust system, passing NE into the coastal San Sebastián-El Pilar Fault Zone, whose 080 trend causes highly oblique dextral transpression.

The Carib Halite coincides with a Venezuela-Trinidad "Berriasian faunal gap" and with a Berriasian-Valanginian eustatic low that isolated the "Carib Graben" from the ocean. Neogene underground halite dissolution provoked by the 11-0 Ma long-term glacioeustatic low (rainier climate) produced "pseudo-extensional" basins on the Caribbean/Proto-Caribbean orogen (*e.g.* Gulf of Paria, Carúpano, North Coast basins), despite the background tectonic shortening (pre- and post-1.5 Ma), which causes the basins to invert upon halite exhaustion (C and S Trinidad, Margarita, Tobago). Dissolution basins also formed in the younger, western mountains (*e.g.* Bogotá, Cesar-Ranchería, Gulf of Venezuela, Carora basins). Buried halite remnants can account for widespread saline springs, and heat-flow and gravity anomalies. At outcrop the dissolved-halite weld is indicated by discontinuities in hardness or metamorphic grade of juxtaposed formations (e.g La Quinta-Río Negro; Chancellor-Laventille).

These new concepts will affect petroleum exploration in Colombia, Venezuela and Trinidad, changing interpretations and predictions of subsidence history, paleogeography, structure and traps (decollement; dissolution collapse), seismicity (acute transpression; collapse), paleo-heatflow effect on maturation (high halite conductivity), evaporite-related source rocks, seals, *etc.*

Colombia-Venezuela-Trinidad basin history

Introduction

In the popular "Caribbean-South America dextral oblique collision model" (Pindell *et al.* 2006, p. 329), hereafter abbreviated to "Caribbean Model", Venezuela and Trinidad are interpreted as a north-facing Cretaceous-Miocene passive margin (Proto-Caribbean spreading after Jurassic rifting), destroyed by oblique (diachronous) Paleocene-Miocene collision with the relatively SE-migrating Caribbean Plate frontal arc (Dewey & Pindell 1986; Pindell *et al.* 1988; Pindell & Barrett 1990; Stephan *et al.* 1990; Pindell 1991, 1993, 1995; Pindell *et al.* 1998). The Caribbean Model has strongly influenced exploration in this prolific oil and gas province. However, the model needs three fundamental corrections, listed below, as shown by subsurface and outcrop sedimentological studies by the author in Colombia, Venezuela and Trinidad, and an exhaustive synthesis of the English and Spanish literature.

The present zigzag configuration of the continental margin, comprising Sector 1 trending NE (Panamá-Guajira), Sector 2 trending SE (Gulf of Venezuela-Falcón), and Sector 3 trending ENE (Caracas-Trinidad), is essentially inherited from the Mesozoic rifting apart of the western Pangea supercontinent (Pindell & Dewey 1982; Pindell 1985; Stephan 1985). Later modification of this configuration by northward migration of the block lying west of the Boconó Fault (Pindell 1985; Stephan 1985) is contested below. Rifting was followed by sea-floor spreading, forming a Cretaceous shelf that faced the Proto-Caribbean Ocean (*e.g.* Ross & Scotese 1988).

Caribbean Model revision 1: rifting continued later

Rifting, generally considered to have ended in Late Jurassic time in Venezuela (*e.g.* Oxfordian; Pindell & Kennan 2001b, p. 198 and figs 4-6), in fact continued about 25 m.y. longer, until Berriasian-Valanginian time (Neocomian, earliest Cretaceous), based on abundant evidence for a (largely dissolved) halite unit of this age, deposited in a graben system that reached from Bogotá, northeastward to Venezuela then eastward to Trinidad (see below).

Caribbean Model revision 2: orogeny started earlier

An orogenic northern highland was uplifted along the entire NW Colombia-Venezuela-Trinidad margin from Campanian time, recorded initially by three hitherto enigmatic stratigraphic phenomena of Campanian-Maastrichtian age, attributed by the author (Higgs, in review) to migration of the Proto-Caribbean forebulge southward across the former passive margin: (1) the Tres Esquinas Member of western Venezuela, a glauconitic-phosphatic super-condensed section (Ghosh 1984) capping the La Luna Formation, interpretable as submerged forebulge arch deposits; (2) in eastern Venezuela, an unconformity separating the shaly San Antonio Formation (Campanian) and sandy San Juan Formation (Campanian-Maastrichtian), tentatively attributed by Villamil and

Pindell (1998, p. 306) to shallowing caused by the initial application of compressive stress on the margin prior to the onset of Proto-Caribbean subduction (see below). This uplift is attributed here to continentward passage of the Proto-Caribbean forebulge, leaving a subaerial unconformity (ravinement surface) that separates passive margin outer-shelf deposits below from foreland basin inner-shelf (N-facing) strata above; and (3) in Trinidad, a biostratigraphically defined hiatus inferred between Campanian hemipelagic strata (Naparima Hill Fm) and overlying Maastrichtian marine shales (Guayaguayare Fm; Saunders & Bolli 1985; Saunders 1997a stratigraphic chart). Instead of a hiatus, a forebulge condensed section is proposed here, analogous to the Tres Esquinas, thin and undetected (neither exposed nor cored), separating passive margin mid-shelf deposits (Naparima Hill, cf. La Luna) from foreland basin outer shelf (Guayaguayare).

As well as these proposed forebulge effects, two other lines of sedimentological evidence discussed below indicate that an early northern source area existed from Campanian time in Trinidad, and from at least Paleocene time throughout Venezuela: (1) facies distribution, specifically, a northern belt of Campanian and younger turbidites and olistostromes, fining southward into shales; and (2) turbidite mineralogy, especially the presence of staurolite and glaucophane.

Thus, orogeny in Venezuela began at about 80 Ma (Campanian), predating the Caribbean arrival time invoked by Pindell and co-workers by about 20 m.y. in the west (Guajira, Paleocene) and 65 m.y. in the east (Trinidad, Miocene). (In fact, the Caribbean did not arrive in the west until mid-Oligocene time, c. 30 Ma; see below.) The orogeny reflects Proto-Caribbean subduction (Sykes *et al.* 1982; Wielchowsky *et al.* 1991; Pindell *et al.* 1991, 2006) under all three sectors of the margin, accommodating slow latest Cretaceous-Recent convergence (<400 km) between North and South America, demonstrated by Atlantic magnetic anomaly analysis (Pindell *et al.* 1988; Müller *et al.* 1999). Convergence was too slow for the subducting slab ever to reach sufficient depth for arc magmatism (Pindell *et al.* 1991, 2005, 2006). Subduction drove continentward the outermost-margin rifted-basement block and its Jurassic-Cretaceous rift and passive-margin cover (slope and outermost shelf deposits), as a "Slope Nappe". In Sector 3, the Slope Nappe metamorphic basement is of mixed meta-ophiolite and meta-sedimentary composition (Tacagua, Manicuare, El Copey Fms; La Rinconada, Juan Griego, Los Robles Gps), and locally contains glaucophane and staurolite (González de Juana *et al.* 1980; Avé Lallement *et al.* 1993; Stöckhert *et al.* 1995; Avé Lallement 1997; Sisson *et al.* 1997). These metamorphics are interpreted here as resulting from Late Paleozoic (Hercynian) continental collision (cf. Bartok 1993). Stretching lineations trending WSW (Stöckhert *et al.* 1995; Avé Lallement 1997) are interpreted here as retrograde, reflecting sinistral obliquity of Proto-Caribbean subduction (relative motion SSW approx.).

The Slope Nappe load metamorphosed the overridden rift and outer-shelf cover dominating the present Lara-Costa-Araya-Paria-Northern Range and Caucagua-El Tinaco belts, including formations interpreted (Higgs, in review) as Jurassic rift clastics (Tucutunemo; lower Caracas Gp; lower Caribbean Gp), rift volcanics (Los Naranjos, Tiara, Las Hermanas, Sans Souci) as at Siquisique (Bartok *et al.* 1985), and Cretaceous outer-shelf deposits (*e.g.* upper Caracas Gp; Carúpano Fm; upper Caribbean Gp), again locally with WSW stretching lineations (Algar & Pindell 1993; Avé Lallement 1997; Weber *et al.* 2001b; Cruz *et al.* 2003; Avé Lallement & Sisson 2005). The metamorphic grade is lower greenschist (Frey *et al.* 1988; LEV 1997), as in other cases of thrust-related metamorphism (Warr *et al.* 1991, 1996). The metamorphics were subsequently uplifted in a "Shelf Nappe", in Paleocene or Eocene time in central Venezuela (Miocene in Trinidad; Higgs, in review), as shown by clast compositions in north-derived olistostromes (see below). Radiometric (Ar-Ar) ages from these metamorphosed cover rocks, and from their Hercynian basement (*e.g.* Dragon Gneiss), are mostly Oligo-Miocene, interpreted previously as metamorphic (crystallization) ages (Foland *et al.* 1992; Speed *et al.* 1992, 1997; Weber *et al.* 2001b), but instead attributed here to cooling caused by Shelf Nappe uplift. A Shelf Nappe basement complex (El Tinaco) is intruded by Jurassic rift mantle peridotite (Tinaquillo Complex; Ostos *et al.* 2005), a probable feeder of rift volcanics.

Thus the metamorphics of the Cordillera de la Costa, Araya and Paria Peninsulae, Northern Range and Margarita island, all assigned here to the Shelf and Slope Nappes, are not tectonically far derived: thrusting was probably less than 100 km, from the northern quadrant. In contrast, previous authors, guided by the Caribbean Model, interpreted most of these rocks as continental material carried far (100s km) from the west in the Caribbean accretionary complex (Algar & Pindell 1993; Stöckhert *et al.* 1995; Avé Lallement 1997; Speed & Smith-Horowitz 1998; Pindell & Kennan 2001a).

The in-sequence Slope and Shelf Nappes drove a thrust belt and Proto-Caribbean Foreland Basin, continuous alongstrike from NW Colombia, through Venezuela to Trinidad, migrating continentward (Colombian portion largely unknown due to later burial under Lower Magdalena Basin and uplift/erosion in Santander-Santa Marta-Perijá mountains). This "arc-precursor" basin owes its preservation (Venezuela-Trinidad) to the lack of arc magmatism and uplift (limited subduction). Nappe/thrust-belt highlands fed turbidites and olistostromes southward into a deep-sea trough confined to Sectors 2 and 3. The trough closed to the west (Maracaibo) and was connected in the east to the Atlantic Ocean. Trough deposition began in Campanian-Maastrichtian time, represented by the Paracotos Formation (LEV 1997) in central Venezuela and the Galera-Morvant-Arima coeval formations in Trinidad (Saunders 1997a stratigraphic chart). These earliest trough deposits were derived from, then overrun and slightly

metamorphosed by, the Slope Nappe. The trough persisted until Eocene time in central Venezuela, and Miocene in Trinidad (replaced diachronously by Caribbean Foreland Basin; see below). The Paleocene suite of north-derived trough formations is (W to E): Matatere - Garrapata/Los Cajones - "northern Vidoño" - Chaudiere. The Eocene suite is: Matatere - Cautaro - Caratas - Pointe a Pierre.

Glaucophane and staurolite occur in the eastern Venezuela and Trinidad trough sandstones (Hedberg 1937; Suter 1960; Kugler 2001), reflecting the northern, Slope Nappe source (neither mineral is known in the Venezuelan Shield to the south). The Slope Nappe also fed deep-sea sands northward, as shown by glaucophane and staurolite in the Eocene Scotland Group of Barbados (Senn 1940, citing unpublished work by Hedberg). Olistoliths in the trough deposits include "remnant" (donor unknown) Lower Cretaceous shelly limestone in Trinidad (Salvador & Stainforth 1968), whose source is interpreted here as the outermost-shelf cover of the Slope Nappe, which was later completely eroded off the Shelf Nappe (Northern Range). The missing limestone was probably depositionally contiguous with the Laventille Formation limestone, now exposed in the unroofed Shelf Nappe. However, the Laventille limestone is largely massive (Kugler 1974; Potter 1974) due to recrystallization by burial under the Slope Nappe, masking the fossils. In central Venezuela, the Los Cajones Formation (Macsotay *et al.* 1995) contains olistoliths of phyllite and recrystallized limestone (*e.g.* Mucaría Fm and Morro del Faro Mbr; González de Juana *et al.* 1980), whose interpreted source is the Shelf Nappe passive-margin cover (Cretaceous), metamorphosed under the Slope Nappe, then uplifted and unroofed. Unroofing occurred no later than Early Eocene time, as constrained by the Paleocene-Early Eocene age of the Los Cajones (Macsotay *et al.* 1995).

On the other side of the deep-sea trough was a north-facing shelf and slope, whose Paleocene formations include (W to E): Guasare/Trujillo - Guárico - informal "Vidoño" or "Naricual" (Sams 1995; Rodríguez *et al.* 2004) - Lizard Springs. The Eocene formations include: Misoa/Trujillo - Guárico - informal "Caratas" or "Naricual" - Lizard Springs. In Paleocene-Eocene time, this inland seaway (including the deep-sea trough) reached about 1,000 km westward from Trinidad to western Venezuela, behind the Proto-Caribbean coastal mountains; its closed, marine-gulf configuration caused strong tides (*e.g.* Misoa Formation tidal shelf; Higgs 1996, 1997).

In the far west (Sector 1), the Proto-Caribbean Foreland Basin was "overfilled" (Covey 1986; *i.e.* no deep-sea trough). The initial Campanian-Paleocene formations were shallow marine and continental: Umir/Colón/Molino suite, followed by Los Cuervos/Marcelina/Cerrejón. This foreland basin merged southwest, alongstrike, into another basin that occupied much of Colombia and reached beyond, into Ecuador and Peru (*e.g.* Pindell & Tabbutt 1995, figs 5-6). This, the "Early Pre-Andean Foreland Basin" of Cooper

et al. (1995), was driven by oblique collision of the Caribbean Arc, specifically by the load of an obducted forearc nappe (Amaime Terrane); the name "Caribbean Foreland Basin" is appropriate. The Caribbean Arc was oriented north-south and was migrating approximately eastward relative to South America (*e.g.* Pindell *et al.* 1988, fig. 4A), therefore the Caribbean Nappe suture point migrated northeastward along Sector 1. The Caribbean Foreland Basin thus also migrated northeast; it contains shallow marine and continental formations (*e.g.* Monserrate-Guadalupe and younger), merging north into the Proto-Caribbean Foreland Basin and diachronously superceding it, and overlying the Cretaceous passive margin (Villeta). Behind the migrating suture point, further Caribbean-South America plate convergence was accommodated at a backthrust (South Caribbean Fault), at which eastward flat-slab subduction of Caribbean oceanic lithosphere occurred. The South Caribbean Fault thus propagated northeastward scissor style, keeping pace with the moving suture point, its northeastern tip separating regions (alongstrike) of opposite subduction polarity (cf. Pindell & Tabbutt 1995, fig. 6).

Caribbean Model revision 3: Caribbean arrived later

According to the established model, the Caribbean Arc reached westernmost Venezuela (Guajira "corner", at the junction of Sectors 1 and 2) in Paleocene time (*e.g.* Pindell & Tabbutt 1995, fig. 7; Villamil 1999, fig. 7). This inference was based on the assumption that subsidence in the Eocene "Maracaibo foredeep" (*e.g.* Pindell *et al.* 1988, figs 4A, B) was driven by the obducting Caribbean Nappe load (see also Stephan *et al.* 1990, plate 10), depite two serious problems with this idea: (1) for the nappes to be close enough to cause this subsidence required an unlikely eastward protruberance of the southern portion of the Caribbean Arc, compared to the northern portion (*e.g.* Pindell *et al.* 1988, fig. 4), implying much faster advance in the south than in the north, to bring the nappes sufficiently far east (Lugo & Mann 1995, fig. 23A); and (2) the Maracaibo Eocene foredeep deposits thicken dramatically, and paleobathymetrically deepen, to the northeast (Zambrano *et al.* 1970, 1971, figs 8-10, 17; Lugo & Mann 1995, fig. 13), where they abut partially coeval Matatere Formation olistostromal deposits that occupy SW-vergent thrust sheets (Stephan 1977, 1985). These relationships clearly indicate that the Maracaibo foredeep was driven by thrusting toward the SW, but this is precisely perpendicular to the *southeastward* Caribbean obduction predicted by the Caribbean Model. This prompted the highly unlikely interpretation that the massive loading responsible for Maracaibo Basin subsidence took place at a long lateral ramp joining two sectors of the Caribbean nappe front (Dewey & Pindell 1986, fig. 2B). This implausible model has been perpetuated by many subsequent authors (*e.g.* Stephan *et al.* 1990, pl. 10; Lugo & Mann 1995, fig. 21; Parnaud *et al.* 1995, fig. 2d; Escalona & Mann 2006a, fig. 4a), despite being recognised as "problematic" by Lugo and Mann (1995, p. 717). The difficulty vanishes if Maracaibo

foredeep loading is attributed instead to an outer-margin nappe emplaced southwestward, driven by Proto-Caribbean subduction, as argued above.

It is proposed here that the Caribbean Arc in fact reached Venezuela about 30 m.y. later than invoked by the Caribbean Model, passing Guajira in mid-Oligocene time. This would explain Late Oligocene block faulting and volcanism in the Gulf of Venezuela-Falcón Basin (Boesi & Goddard 1991; Macellari 1995) as transform-related pullapart caused by the Caribbean Arc ripping SE along this SE-trending portion of the margin (Sector 2). A Caribbean relative motion change from eastward (while the Arc traversed Sector 1) to southeastward is implied. The metamorphic basement of Falcón Basin therefore consists of *Proto-Caribbean* nappe (unroofed Shelf Nappe, including the Siquisique complex), not Caribbean nappe as interpreted by previous authors (Boesi & Goddard 1991; Macellari 1995; Pindell *et al.* 1998), all of whom envisaged the Falcón Basin forming *after* the Caribbean Arc had passed, by an unclear pullapart mechanism.

In Early Miocene time the Caribbean Arc reached the ENE-trending (080 degrees approx.) eastern part of the margin (Sector 3), where the same southeastward relative motion caused oblique obduction of a Caribbean forearc nappe along the entire sector, onto the back of the (active) Slope/Shelf Nappe belt. This Caribbean Nappe is locally exposed as an erosional remnant (Villa de Cura Klippe; Smith *et al.* 1999) and as inliers on Margarita (El Salado Granite) and Tobago, surrounded by post-obduction deposits underlying the modern shelf (see below). These Villa de Cura, Margarita and Tobago rocks are all arc-related (Stöckhert *et al.* 1995; Snoke *et al.* 2001; Unger *et al.* 2005), yet they lie in a *forearc* position, relative to the present Caribbean (Lesser Antilles) Arc and its southwestward prologation (Testigos-Tortuga gravity high; *e.g.* Pimentel 1984). This relationship suggests that the conventional forearc ophiolite tract (*e.g.* Dickinson 1995, p. 234 and fig. 6.6) has been removed by subduction erosion of the forearc leading edge, as described below.

Behind the east-migrating Caribbean Nappe suture point in Sector 3, further Caribbean-South America convergence was accommodated at the eastern continuation of the South Caribbean Fault subduction zone, propagating (eastward) scissor style, as described for Sector 1. This eastern portion of the South Caribbean Fault lies immediately outboard of the accreted arc complex, which comprises four elements (N to S): Aruba-Orchila remnant arc; interarc Bonaire Basin; outer arc Testigos-Tortuga ridge; and forearc Villa de Cura-Margarita (El Salado Granite and Punta Carnero forearc-basin deposits)-Tobago belt. The lengthening South Caribbean Fault was connected to the suture point by a series of eastwardly jumping transform fault, represented by the NW-SE faults cutting the accreted arc complex (*e.g.* Pindell *et al.* 1998, figs 1, 21), including the Charallave Fault (*e.g.* Pimentel 1984). The final transform was the Roques Canyon Fault (Pimentel 1984; Pindell *et al.* 1998,

figs 1, 21). The transforms projected southeastward into successive thrust-belt lateral ramps (*e.g.* Urica, San Francisco Faults), which connected to the frontal thrust, whose final position was the Maturín-Trinidad South Coast Thrust. Each transform jump signified the transference to the South America Plate of another strip of the Caribbean Plate arc complex.

The new nappe load established a second (eastern) Caribbean Foreland Basin, superceding the Proto-Caribbean Foreland Basin diachronously (Miocene changeover in central Venezuela; Quaternary in Trinidad). The western part (Guárico-Anzoátegui) of the new basin has been erosionally removed by tectonic rebound west of the suture point, explaining: (1) unroofing of the plains to progressively older levels (of the Proto-Caribbean fill) westward, exposing crystalline basement at El Baúl (*e.g.* Pimentel 1984). The enigmatic El Baúl Arch, traditionally considered to trend SE but reinterpreted as ESE by Kiser and Bass (1985), based on regional basement magnetic contour trends (their fig. 3), is interpreted here to trend ENE instead (equally permitted by the magnetic contour trends), and to represent the erosionally exhumed (rebounded) western end of the Proto-Caribbean forebulge; and (2) the absence of Villa de Cura clasts, with their distinctive metavolcanic foliation, in even the youngest surviving strata on the eroding foreland (early Middle Miocene, Quiamare Fm).

In the east, the Caribbean Foreland Basin is represented by the Maturín-Deltana-Columbus Basin, specifically the Upper Miocene-Quaternary interval in the west (La Pica, Las Piedras, Mesa Fms), and Plio-Quaternary in the east, reflecting progressively later arrival of the Caribbean Nappe load eastward. Only the Deltana-Columbus sub-basin is still subsiding (see below), while the Maturín sub-basin rebounds.

Maracaibo Thrust Belt and "Eocene unconformity"

In the Lake Maracaibo region, the final Proto-Caribbean tectonic effect prior to the Late Oligocene transit of the Caribbean Arc along Sector 2 was the Early Oligocene southwestward propagation of the Proto-Caribbean thrust front to its ultimate position in the present-day Lake Maracaibo region. Thus, the Eocene shelf formations deposited there, on the former passive side of the Proto-Caribbean Foreland Basin (Misoa, Paují Fms), underwent Early Oligocene uplift and erosion in a thrust belt. Subsequently, in Late Oligocene time, renewed subsidence and deposition took place (see below), forming the "post-Eocene unconformity" ("discordancia post-eocena"; Zambrano *et al.* 1971, p. 533; commonly abbreviated to "Eocene Unconformity", *e.g.* Pindell *et al.* 1998, p. 73). A previous interpretation of this unconformity, whereby "erosion was driven by isostatic rebound of the south flank of the Falcón Basin ... at the inception of transcurrent faulting there" (Pindell *et al.* 1998, p. 73), does not explain the intensity and style of faulting (see below), or the great

thickness of eroded sediment, locally exceeding 2 km (Escalona & Mann 2006b, fig. 20). Similarly, Escalona and Mann (2006b) invoked isostatic rebound upon cessation of the tectonic load imposed by a lateral ramp (Burro Negro Fault) delimiting Caribbean nappes verging SE (*sic*). Pindell *et al.* (1998, p. 73) also considered "erosion of topography produced by compression during Late Eocene ... emplacement" of Caribbean nappes, but discounted this model because "compressional features are not common and normal faults cut the section".

Some of the faults under Lake Maracaibo have been interpreted as SW-vergent thrusts (Munro 1985, figs 2, 8; Lugo & Mann 1995, figs 19, 20; see also González de Juana *et al.* 1980, lámina I, fig. 1), consistent with the new Maracaibo Thrust Belt model. Other faults are aligned approximately north-south (*e.g.* Icotea Fault) and are interpreted here as lateral ramps to the Early Oligocene thrusting. The Icotea was interpreted as a sinistral strike-slip fault by Krause (1971), and dextral by Munro (1985).

Lower Magdalena and "Catatumbo Foreland Basin"

In mid-Oligocene time, overthickened Caribbean Plateau oceanic crust (Muehlberger 1992; Meschede & Frisch 1998) arrived at and choked the South Caribbean Fault subduction zone, in the Panamá-Barranquilla segment of Sector 1. Supporting this proposal, Caribbean Plateau thickened crust abuts the Colombian portion of the South Caribbean Fault today (Meschede & Frisch 1998, fig. 2). Further Caribbean-South America convergence was therefore accommodated by shortening in the overriding plate, causing: (1) onset of uplift of the Eastern Cordillera (Villamil 1999) by orthogonal compression (NW-SE relative plate motion), initiating foreland basins on both flanks (Llanos; Middle- and Upper Magdalena Basins); and (2) uplift of the Santander Massif (Villamil 1999) by oblique (sinistral) bivergent thrusting, both: (a) the westward on the Santa Marta-Bucaramanga Fault, driving the Lower Magdalena Basin (Oligocene-Pleistocene), interpreted previously as a complex, polygenetic basin (A. Reyes *et al.* 2000; J.P. Reyes *et al.* 2000), but reinterpreted here as extensional-forebulge deposits (cf. Decelles & Giles 1996) overlain by foreland-basin strata (less faulted); and (b) eastward on the Cocuy-Bramón-Mercedes Thrust (cf. Pindell *et al.* 1998, fig. 2), driving a basin named here the Catatumbo Foreland Basin (Upper Oligocene-Miocene). The Catatumbo succession, comprising many formations (Ceibote, Fausto, Ranchos, Guayabo, Palmar, Isnotú, Parángula, La Copé, León, Icotea, La Rosa, *etc.*), thichens and coarsens toward the WSW, as shown by isopach maps (F.E. Audemard 1991, figs 14, 15). In contrast, Mann *et al.* (2006) considered this interval to thicken *westward*, toward the Perijá range (their "Perijá Clastic Wedge", p. 473), thus dating Perijá uplift, despite the fact that seismic profiles orthogonal to Perijá show little or no westward thickening of the interval (*e.g.* their fig. 14; also Duerto *et al.* 2006, figs 12, 13).

Catatumbo Foreland Basin deposition onlapped eastward over the newly subsiding Maracaibo Thrust Belt, forming the Eocene Unconformity. The unconformity is onlapped by the Icotea and La Rosa Formations under present-day Lake Maracaibo (Zambrano *et al.* 1970, 1971), and by the Palmar and Isnotú Formations in the present northwestern flank of the Mérida Andes (Palmar is thickest in the far SW, in Táchira, and pinches out northeastward (Sutton 1946; González de Juana *et al.* 1980, fig. VI-41 and p. 534)). The thrust belt became progressively deactivated during this interval, diachronously southeastward, as the SE-migrating Caribbean Arc cut off the "Proto-Caribbean push" and opened the Falcón-Gulf of Venezuela pullapart. After the thrust belt had been completely onlapped, Miocene foreland sedimentation in the Catatumbo Foreland Basin merged northeast into Falcón-Gulf of Venezuela post-pullapart sedimentation (thermal subsidence).

Pliocene uplift of the Mérida, Perijá, Santa Marta and Falcón mountains

In the so-called Maracaibo Block (Dewey & Pindell 1985), comprising the sub-triangular area of western Venezuela and northernmost Colombia delimited by the Santa Marta-Bucaramanga, Boconó and South Caribbean Faults, uplift of mountain ranges began at about 5 Ma. One of these ranges was the bivergent Mérida Andes. Although most authors consider Mérida Andes uplift to have started in Eocene, Oligocene or Miocene time (*e.g.* Zambrano *et al.* 1970, 1971, fig. 12; González de Juana *et al.* 1980, fig. VI-9; Pindell *et al.* 1998, fig. 19), the onset is considered here to have been near 5 Ma (start of Pliocene), based on two lines of evidence: (1) an abrupt change to coarser clastic deposition on the Mérida Andes flanks (Betijoque, Río Yuca Fms), coupled with a change in the direction of thickening, toward the Mérida Andes rather than toward the Santander Massif (*e.g.* F.E. Audemard, fig. 16; Mann *et al.* 2006, fig. 14). In other words, this change marked the initiation of the Mérida and Barinas-Apure Foreland Basins, superceding the Catatumbo Foreland Basin (which was now bifurcated by the Mérida Andes). Although these two formations are continental and thus difficult to date, an age of principally Pliocene is likely (*e.g.* González de Juana *et al.* 1980, fig. VI-41 and p. 541; F.E. Audemard 1991, fig. A11); and (2) seventeen out of twenty two apatite fission-track ages obtained in the Mérida Andes by Kohn *et al.* (1984) are 4.9 Ma and younger.

The Perijá mountains are also interpreted here to have commenced uplift at about 5 Ma. Kellogg (1984, p. 247) inferred a "Pliocene age for the major uplift of the Sierra de Perijá" based on stratigraphic relationships and apatite fission-track ages. The Perijá range is mainly NW vergent (Kellogg 1984), with relatively minor backthrusting on its southeast flank (Duerto *et al.* 2006), insufficient to cause Pliocene sediments in the Mérida Foreland Basin to thicken toward the Perijá front (*e.g.* Duerto *et al.* 2006, figs 12, 13 seismic profiles). The Santa Marta mountains are Pliocene according to Polson and Henao (1968).

Pliocene mountains also formed throughout the Guajira-NE Zulia-Falcón-Lara region (Macellari 1995, fig. 20), including the present Gulf of Venezuela (contrast Macellari 1995, fig. 20), by rapid NW thrust advance enabled by a halite decollement (see below). The Burro Negro Fault is interpreted here as a lateral ramp (sinistral) for this Pliocene thrust advance. The Burro Negro is also inferred to have functioned earlier, as the southwestern strike-slip master fault during basin pullapart (Late Oligocene), and in Jurassic-earliest Cretaceous time as an intragraben fault controlling thicker and/or more laterally continuous halite deposition on its NE side, hence the efficient later decollement. Thus, the Burro Negro was active on at least three separate occasions, as a Jurassic-Cretaceous rift fault, then an Oligocene master fault, then a Pliocene sinistral lateral ramp, in contrast to the Eocene dextral lateral ramp interpretation of Escalona and Mann (2006a). Since being uplifted in Pliocene time, these northern mountains have widely collapsed by buried-halite dissolution, forming (late Pliocene and?) Quaternary supraorogen basins, including the Lower Guajira-Gulf of Venezuela Basin and the Carora Basin. The Cesar-Ranchería Basin, never previously explained satisfactorily, is a halite-dissolution basin formed by local collapse of the Santander-Santa Marta-Perijá mountains.

All of these Pliocene orogenic deformations in the Maracaibo Block are attributed to the same subduction-choking mechanism that earlier affected Colombia. Again supporting this model, Caribbean Plateau thickened crust locally abuts the Venezuelan portion of the South Caribbean Fault (Meschede & Frisch 1998, fig. 2). Like Colombia, compression in the Maracaibo Block was NW-SE (relative plate motion), resulting in orthogonal shortening in the Mérida Andes and the Falcón-Gulf of Venezuela region, and sinistrally oblique shortening in the NNE-trending Perijá range (Tigre Fault strike slip?).

Plate boundary shift, c. 1.5 Ma

Caribbean relative motion switched from SE to its current direction of nearly due east (085 +/- a few degrees), as determined from GPS studies (Pérez *et al.* 2001; Weber *et al.* 2001b; Trenkamp *et al.* 2002), at approximately 1.5 Ma. The relative velocity simultaneously decreased to its current value of about 2 cm/yr (Pérez *et al.* 2001; Weber *et al.* 2001b), roughly half its previous rate (see below). The cause inferred here was the collision of the Panamá Arc, at the tail end of the Caribbean Plate (*e.g.* Pindell *et al.* 1988, fig. 4), against South America (NW Colombia; Sector 1). The collision caused the Caribbean Plate to annex the Northern Andean Block, comprising western Venezuela and NW Colombia, north of the Ibagué Fault (at latitude of Panamá). This block is the northern part of the North Andean Block of Kellogg (1984), which is synonymous with the Cordilleran terrane of Dewey and Pindell (1985). Thus, the Caribbean-South America plate boundary switched, in the west, from a diffuse belt of shortening spanning the Maracaibo Block, as described above, to the

bivergent thrust system of the Mérida Andes (Boconó Fault Zone) and the Eastern Cordillera. Uplift in the Mérida Andes accelerated, as indicated by a coarsening of deposition in the flanking foreland basins (Carvajal, Guanapa Fms; LEV 1997) and by attainment of altitudes sufficient for glacial effects (see below). Plate convergence across the Eastern Cordillera and Mérida Andes was now dextrally oblique (eastward relative plate motion), a conclusion reached for the Mérida Andes long ago based on seismology (Dewey 1972, especially fig. 10). Dextral slip along the Mérida Andes is therefore young (since about 1.5 Ma) and small; it calculates as 23 km, assuming Caribbean relative motion toward 085 degrees, across the 045-trending Mérida Andes, at 2 cm/yr since 1.5 Ma, *i.e.* 30 km multiplied by cosine 40 degrees. This estimate is far less than those of Dewey and Pindell (1985, 1986; 290km, 100 km), Pindell *et al.* (1998; min. 150 km) and James (2000; 300 km), and reconciles the objection of Salvador (1986, p. 699) that the Mérida Arch pre-Cretaceous basement high, defined by drilling in the Maracaibo and Barinas Basins, crosses the Andes nearly orthogonally "with no major horizontal displacement". The 23 km value is close to the 0-40 km estimates of most earlier authors (summary in Salvador 1986). Furthermore, glacial moraines about 10,000 years old are offset 66 m dextrally by the Boconó Fault (Schubert & Sifontes 1970), giving a calculated displacement rate of 6.6 mm/yr. This value extrapolates to 10 km since 1.5 Ma, consistent with the 23 km estimate for the entire Boconó Fault Zone. Moreover, palinspastically restoring 23 km of dextral displacement on the Boconó Fault Zone, combined with only 10 km on the Oca Fault, an E-W trending, dextral strike-slip fault (F.A. Audemard & Singer 1996; F.A. Audemard *et al.* 2000) activated by the 1.5 Ma plate-motion change, would restore the Maracaibo Block "out of the way" of Miocene southeastward (relative) obduction of the Villa de Cura Nappe (*e.g.* Pimentel 1984, outcrop labeled 15).

Thus, the concept of northward tectonic escape of a Maracaibo Block or (larger) Cordilleran terrane, involving more than 100 km of dextral slip on the Boconó Fault Zone (Dewey & Pindell 1985, 1986; Pindell *et al.* 1998), an idea reiterated by many later authors and important for Pangea reconstructions (*e.g.* Pindell 1985; Bartok 1993), is a misconception, for three reasons: (1) the dextral slip is less than 30 km; (2) the block is moving nearly due east (085), rather than north; and (3) the block is not an independent entity, but part of the Caribbean Plate.

Farther east, the plate boundary in central and eastern Venezuela and Trinidad (Sector 3) shifted from the complex linkage outlined above (South Caribbean Fault - Roques Canyon transform - San Francisco lateral ramp - Maturín/Trinidad South Coast frontal thrust) to the current plate boundary, a dextral strike-slip fault zone comprising the coastal San Sebastián, La Victoria, El Pilar, Coche, North Coast and allied faults; the name is abbreviated here to Sebastián-Pilar Fault Zone. F.A. Audemard *et al.* (2000, p. 62) likewise interpreted the Boconó-Sebastián-Pilar

system as the active plate boundary. The Sebastián-Pilar Fault Zone is seismically active, as shown by outcrop studies, historical records, and modern hypocenters (Russo *et al.* 1993; F.A. Audemard *et al.* 2000). The faults trend approximately 085, sub-parallel to the current relative plate-motion direction (085 plus or minus a few degrees), such that highly oblique transpression or transtension would be predicted. In fact transpression is occurring (F.A. Audemard *et al.* 2000, p. 62), as indicated by Pleistocene-Recent raised beaches and shallow-marine deposits at various coastal localities in central Venezuela, Araya Peninsula, and Margarita and Coche islands (discussion and references in Méndez 1997; Sisson *et al.* 2005a). Over much of the coastal region, however, this transpression is masked by subsidence of pseudo-extensional salt-dissolution basins atop the orogen, in which dissolution subsidence outweighs transpressive uplift (see below).

The maximum dextral offset on the Sebastián-Pilar Fault Zone, assuming 2 cm/yr eastward Caribbean relative velocity since 1.5 Ma, is 30 km. This value agrees well with the conclusion of F.A. Audemard *et al.* (2000, p. 62) that 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 along this major fault system". Limited displacement is consistent with the interpretation mentioned earlier that the Costa-Araya-Paria-Northern Range belt is *not* tectonically derived far (100s km) from the west.

Based on GPS readings at two stations in Trinidad, Weber *et al.* (2001a) concluded that most of the Caribbean-South America relative motion is occurring on the Warm Springs Fault, oriented SW-NE in the Central Range, notwithstanding that: (1) geological maps indicate that this fault must have a sinuous trace, if indeed it cuts across the entire country (Kugler 1961; Saunders 1997a), and is thus more likely a thrust (Kugler 1961 cross sections) than a strike-slip fault. Furthermore, most range-parallel faults are offset by NW-SE faults, as shown by the maps of Kugler (1961) and Saunders (1997a); and (2) one of the two GPS sites is north of the El Pilar Fault, while the other is south of the Los Bajos Fault (site locations in Weber *et al.* 2001a, table 1). Either of these two other faults could also (or instead) have accommodated the displacement measured by GPS, particularly the El Pilar, because the Los Bajos, known to have accommodated about 10 km of dextral slip in Late Miocene or later time, and possibly since the Pliocene (Wilson 1940, 1968), is probably an extinct (since 1.5 Ma) lateral ramp slightly offsetting the now-inactive Maturín-Trinidad South Coast Thrust. Indeed, dextral slip on the El Pilar may be responsible for small-scale folds and faults in Pleistocene shales in northern Caroni Basin (Robertson & Burke 1989). Aside from its petroleum-exploration implications, this question of whether or not the Central Range is accommodating substantial strike slip is of social importance. According to Weber *et al.* (1999), the Warm Springs Fault "has no record of either historic earthquakes since Columbus first landed

on the island in 1498, nor instrumentally recorded earthquakes since the local seismic network was first established in 1953", therefore it is possible that the fault "has stored ~ 5 meters of motion which could potentially be released in a major forthcoming earthquake".

The Caribbean Foreland Basin in eastern Venezuela and Trinidad (Maturín-Deltana-Columbus Basin) was deprived of its thrust-load driving mechanism when the plate boundary jumped north at 1.5 Ma, abandoning the Maturín-Trinidad South Coast Thrust, and plate interaction changed from weakly to strongly oblique. In the Maturín sector, tectonic rebound is now occuring, exhuming Pleistocene deposits (denoted 2 in Pimentel 1984). Nevertheless, subsidence continues (at the surface) in the Deltana-Columbus sector, as shown by ongoing deltaic and shelf deposition (denoted 1, Recent, in Pimentel 1984). This subsidence is probably due to shale withdrawal, eastward toward the continental slope (Wood 2000, 2001), and shale compaction.

The estimated date of 1.5 Ma for the plate-motion change is based largely on biogeographic studies by Keller *et al.* (1989), suggesting that the Pacific-Caribbean linking seaway cutting across the Panamá-Colombia collision zone was a shallow sill between 2.4 and 1.8 Ma (*i.e.* collision incomplete), and closed completely by 1.8 Ma (latest Pliocene). Complete suturing, with uplift of the present-day Panamá mountains, would have been achieved some time later. The 1.5 Ma age is also consistent with: (1) the assumed Pleistocene age of the Carvajal and Guanapa Formations flanking the Mérida Andes (LEV 1997); (2) the lack of evidence of glacial effects earlier than Late Pleistocene in the Mérida Andes (Schubert & Vivas 1993; Méndez 1997), suggesting that elevation was insufficient for glacier development until then; (3) the presence of erosional remnants, at high altitude in the Mérida Andes, of a paleosoil characteristic of much lower elevations (Giegengack 1984), whose survival means that strong uplift is relatively recent; and (4) the Pleistocene-Recent age of the uplifted beach and marine sediments along the central and eastern Venezuela coast.

Tectonic erosion of Caribbean Plate leading edge

Pindell *et al.* (2006, p. 312) stated that the Caribbean (Lesser Antilles) Arc "has been essentially neutral since the Eocene opening of the Grenada intra-arc basin"; the latter reflects "extensional arc" behaviour according to these authors (extensional, compressional or neutral arc classification of Dewey 1980). The neutral interpretation was based on the belief that compressional arcs, which by definition migrate toward the downgoing plate faster than the roll-back velocity of this plate, invariably show shortening and uplift, producing Andean-type high topography. However, this is not the only possible response in compressional arcs, which may instead accommodate the shortening by subduction erosion, whereby blocks of the overriding plate are torn off and

carried down into the subduction zone (also known as "tectonic erosion", a variety of "ablative subduction"; Tao & O'Connell 1992). Tectonic erosion has clearly affected the Caribbean Arc, based on two lines of evidence: (1) the forearc contains rocks of arc composition (Villa de Cura, Margarita, Tobago), rather than the usual strip of forearc ophiolite, as described above, suggesting removal of the latter by subduction erosion (Tao & O'Connell 1992, fig. 17); and (2) the blueschist-grade metamorphism of Villa de Cura *arc* rocks indicates deep burial in a subduction zone (Unger *et al.* 2005), requiring removal of arc blocks from the overriding plate by ablative subduction (cf. Unger *et al.* 2005, fig. 13), prior to their obduction as the Villa de Cura Nappe. Furthermore, tectonic erosion can cause extension in the arc (Dickinson 1995, p. 223 & fig. 6.3), and might thus be responsible for the Grenada inter-arc basin, possibly reflecting an Eocene episode of particularly vigorous tectonic erosion.

Present Caribbean Plate velocity relative to South America is about 2 cm/yr, essentially eastward (Pérez *et al.* 2001; Weber *et al.* 2001a). Meanwhile North and South America are drifting westward at about 2 cm/yr relative to the mantle (Minster & Jordan 1978), therefore currently the Caribbean Plate is essentially stationary in the mantle reference frame (Pindell *et al.* 1998). However, Caribbean relative velocity was much higher between 30 and 1.5 Ma. During that time interval, the eastward component of (southeastward) Caribbean Arc migration was about 1,000 km, from the Guajira corner to its current position (forearc edge under Barbados; Dickinson 1995, fig. 6.13), disregarding the 30 km it has travelled since 1.5 Ma (2 cm/yr). In other words, the average eastward relative velocity was about 3.4 cm/yr, roughly twice the velocity implied by the Caribbean Model (same distance in twice the time, 60-0 Ma). Simultaneously, the Americas drifted westward relative to the mantle at 2-3 cm/year throughout Cenozoic time (Pindell *et al.* 2006). Thus, the Caribbean Arc moved eastward at 0.4-1.4 cm/yr relative to the mantle, probably exceeding the roll-back velocity of the Lesser Antilles trench, at least occasionally (trenches normally roll back at < 1 cm/yr; Pindell *et al.* 2006), implying that the Caribbean Arc was of the compressional variety, consistent with the evidence for tectonic erosion.

Neogene salt-dissolution basins

Associated with the mountain ranges of NW Colombia, Venezuela and Trinidad are numerous Neogene basins. Such basins can be relatively small and surrounded by mountains (*e.g.* Bogotá, Cesar-Ranchería, La González, Monay, Carora, Hueque, Aroa-Yaracuy, Lake Valencia, Santa Lucía, Tuy, Gulf of Cariaco, San Juan Graben, Caroni, South Trinidad). Other basins are relatively large and can completely rupture a mountain range (*e.g.* combined Gulf of Barcelona-Cariaco Trough; Dragon's Mouth), or terminate a range laterally (Gulf of Paria). In still other cases, the basins are even larger than the associated mountains: for example, the mountains of

Guajira and Paraguaná Peninsulae partially surrounded by the Gulf of Venezuela Basin; and the mountains of Margarita and Tobago islands encircled by the eastern Venezuela and Trinidad shelf basins (Tortuga-Margarita, Cubagua-Coche, Carúpano and North Coast Basins).

All of these basins can be interpreted to have formed by mountain collapse due to underground dissolution of a thick (km) halite layer, here named the Carib Halite Formation (see also Higgs, in review). Other origins have been proposed for these basins, but are shown below to be unsatisfactory. There is little *direct* evidence of the inferred halite, due to the susceptibility of halite to surface- and large-scale subsurface dissolution (Warren 1999). However, indirect evidence for the halite (besides the basins themselves), and for paleo- and present-day *dissolution* of halite, is plentiful and widespread, as discussed below.

The fill of these basins is characterized on seismic profiles by listric growth faults, giving the appearance of extensional basins, but laboratory models have shown that such faults also characterize halite-dissolution basins (Ge & Jackson 1998), which can therefore be called "pseudo-extensional basins". The models also produced features resembling flowers structures, above the sides of the modeled halite body (Ge & Jackson 1998, figs 12, 16), simulating graben-floor steps or diapir walls. Such pseudo-flowers possibly explain Gulf of Paria structures previously interpreted as flowers (Payne 1991, fig. 9 and p. 75; Babb & Mann 1999, figs 31, 32 and p. 533), although this basin now partly overlies a near-strike-slip plate boundary (since 1.5 Ma), hence the flowers could be genuine. The maximum age span of the syntectonic (growth-faulted) interval is Late Miocene to Recent (González de Juana *et al.* 1980; Beck 1985; Castro & Mederos 1985; Pérez de Mejía & Tarache 1985; Goddard 1988; Payne 1991; Babb & Mann 1999; Flinch *et al.* 1999), for example the Manzanilla through Cedros formations in the Gulf of Paria. In the younger, Plio-Quaternary mountain ranges (*e.g.* western Venezuela), the basin fill is correspondingly younger (see below).

Interpreted halite-dissolution basins of diverse ages occur on other continents in various tectonic settings (summaries in Warren 1999 and Higgs, in review). However, the inferred thickness (see below) and lateral extent of dissolved or dissolving Carib Halite, and the depth of dissolution, all far exceed those of any other example known to the author. Apparently, the scale and depth of dissolution of the Carib Halite are unique in the world, and possibly in the stratigraphic record, and must therefore have been facilitated by one or more particularly favorable circumstances. The following three fortuitous factors are proposed, all of which have applied throughout the Late Miocene to Quaternary period of dissolution of the Carib Halite: (1) thrust-nappe-belt location, producing a large hydraulic head and extensive fracturing, both of which promoted meteoric-water infiltration and deep

hydrothermal circulation; (2) near-equatorial climate with high rainfall, and even higher during each post-glacial climatic recovery (cf. "pluvial" episode following the last glaciation in Venezuela; González de Juana *et al.* 1980, p. 698); and (C) highly permeable aquifers immediately below and/or above the Carib Halite, *e.g.* sandy La Quinta Formation below and Río Negro above in western Venezuela (see below), and fractured-metamorphic lateral equivalents of these in the Shelf and Slope Nappes, fractured by nappe tectonics. In particular, a climatic (rainfall) connection with the long-term 11-0 Ma glacioeustatic sea-level low (Haq *et al.* 1988 chart) is suggested, given that biostratigraphic data from the inferred halite-dissolution basins (references above) indicate that all of the Late Miocene foram zones are generally represented, meaning that subsidence began at or soon after 11 Ma. Thus the 11-0 Ma glacioeustatic low is inferred here to reflect a global climate change (polar glaciation) that resulted in long-term wetter conditions in northern South America, facilitating massive underground halite dissolution by increased meteoric-water ingress at nappe/thrust-belt highland catchments. Supporting this suggestion, tectonosedimentary evidence in the European Alps suggests a "more erosive climate" since the Late Miocene, possibly "associated with the onset of glaciation or the formation of the modern Gulf Stream" (Willett *et al.* 2005).

Many of the post-11 Ma pseudo-extensional basins are attributed to halite-dissolution subsidence within nappe- and thrust belts that were (are) simultaneously shortening (*e.g.* Gulf of Paria, Carúpano-North Coast Basin); in other words, dissolution subsidence outweighed orogenic uplift. In Trinidad, eastern and central Venezuela (Sector 3), the uplift component is now (since 1.5 Ma) provided by transpressive uplift along the Sebastián-Pilar Fault Zone, and by rebound either side of this zone, but is nevertheless outweighed in most of the basins by dissolution subsidence. Onshore Trinidad, however, the Late Miocene to early Quaternary basin fill (Manzanilla-Cruse through Cedros interval) has been folded, thrusted and uplifted (except in western Caroni Basin; *e.g.* Kugler 1961 map and cross sections), suggesting basin inversion in Early Quaternary time due to halite exhaustion, prior to deactivation of the Trinidad thrust belt at the 1.5 Ma plate-motion change.

Alternative subsidence mechanisms have been suggested for the proposed salt-dissolution basins. First, subsidence by divergence of strike-slip faults (*e.g.* Santa Lucía and Tuy Basins; Schubert 1988) or by pullapart (*e.g.* La González Basin, Cariaco Trough, Lake Valencia Basin, Gulf of Paria; Schubert 1980, 1982, 1988; Algar & Pindell 1993; Babb & Mann 1999; Flinch *et al.* 1999; Pindell & Kennan 2001a; Jaimes & Mann 2003), can be discounted due to lack of suitably positioned potential master faults and/or appropriate plate-motion vectors, both before and after the 1.5 Ma relative-motion change, and lack of associated pullapart volcanism. Pindell and Kennan (2001a) interpreted the Gulf of Paria as a pullapart caused

by a shift to Caribbean ENE transtensional relative motion at 12 Ma. Besides the lack of volcanics, this model conflicts with: (1) the lack of any range-parallel (SW-NE) fault in the Trinidad Central Range with sufficient continuity and linearity to be a strike-slip master fault, on which 100 km of dextral slip is supposed to have occurred since 12 Ma (Pindell & Kennan 2001a, fig. 15); and (B) the very thick (km) Upper Miocene-Recent interval in the Deltana-Columbus Basin (south side of supposed pullapart), suggesting relatively orthogonal nappe/thrust loading for most of the time since 12 Ma (*i.e.* Proto-Caribbean/Caribbean Foreland Basin, replaced at 1.5 Ma by shale-withdrawal- and compaction subsidence). Thus the 12 Ma shift to transtensional motion, Paria pullapart, and the resulting gross palinspastic (paleogeographic) distortion of Trinidad (*e.g.* Pindell & Kennan 2001a, fig. 15) are fallacies: in fact dextral slip in Trinidad is transpressive, and totals only 30 km (Caribbean relative motion 2 cm/yr since 1.5 Ma), distributed among the El Pilar and North Coast Fault Zones, rather than 240 km (2 cm/yr since 12 Ma), with 100 km of slip on the Warm Springs Fault.

Second, it was suggested that the Carúpano and North Coast Basins were formed by "local extension ... of topographic origin, the reduction of slope of a late Neogene high-mountain belt above a crustal detachment" (Speed & Smith-Horowitz 1998, p. 809). This extensional model, which implies crustal overthickening like that responsible for extension in the Mio-(?)Pliocene Tibet Plateau (Burchfiel *et al.* 1992), can be ruled out in northern Venezuela-Trinidad, because the crust is not abnormally thick (Pindell & Kennan 2001a, fig. 7; Boettcher *et al.* 2003, fig. 3; Vandecar *et al.* 2003, fig. 7). Elsewhere in the world, intra-orogen extension has alternatively been attributed to a severe reduction in plate convergence (Constenius 1996), and to "corner flow" above a retrograding subducting slab (Cavinato & Decelles 1999), but volcanics were produced in both cases.

The following supraorogen basins are special in that they lie above obducted Caribbean Nappe basement: Tuy, northern Gulf of Barcelona, Cariaco Trough, Tortuga-Margarita Shelf, Carúpano and North Coast Basins. The Tuy Basin unconformably overlies Villa de Cura metavolcanic forearc basement (*e.g.* Pimentel 1984). The other basins, except unproven Cariaco Trough (undrilled except shallow Quaternary cores; Schubert 1982), are known to lie unconformably on Eocene and younger strata (Castro & Mederos 1985; Pereira 1985; Goddard 1988) interpretable as forearc-basin deposits, as previously suggested for the Carúpano Basin (Speed & Smith-Horowitz 1998). Unconformably above this forearc interval is a package whose age is Late Miocene to Recent in the west (Barcelona Basin; Goddard 1988) and Pliocene to Recent in the east (North Coast Basin; Robertson & Burke 1989, fig. 8), interpreted here as dissolution-basin deposits, whose eastward younging reflects the diachronous emplacement of the Caribbean Nappe, onto the halite-bearing Slope/Shelf nappe pile. By the time the incoming Caribbean Nappe began advancing across the present-day Carúpano shelf region, in Pliocene time, the substrate (Slope Nappe) may have already been collapsing by halite dissolution (from 11 Ma) to form a dissolution basin, providing a low-relief surface for the Caribbean Nappe to advance across. This may explain why the Caribbean Nappe is now structurally low (buried) here in the east, unlike central Venezuela (Villa de Cura, mountains), where the Nappe was emplaced by Middle Miocene time, before any dissolution collapse of the substrate. Foundering of the substrate (in the east) would also imply that the Caribbean Nappe was collapsing while it advanced. Upper Miocene to Quaternary marine sediments have been uplifted above sea level in the far west of the Carúpano-North Coast Basin (Cubagua and Castillo de Araya Fms of Margarita and Araya Peninsula; LEV 1997), and Pliocene in the far east (Rockly Bay Fm of Tobago; Saunders & Muller-Merz 1985), suggesting that dissolution subsidence there has terminated (halite exhaustion), allowing the "background" tectonic uplift to take over.

Direct evidence for halite

In Colombia, Lower Cretaceous halite crops out and has been mined at several localities in the Bogotá area (McLaughlin 1972; López *et al.* 1991), including the former halite mine at Zipaquirá, now a subterranean cathedral. McLaughlin (1972) argued, contrary to most of the literature up to that time, that the halite masses are not diapirs but are in their correct stratigraphic position, an interpretation difficult to reconcile with his own cross sections that show the halite as local bodies confined to thrusted anticlinal cores and pinching out laterally into the supposed host stratum (McLaughlin 1972, figs 4, 6-8). López *et al.* (1991) reiterated the traditional diapir interpretation, in which case the stratigraphic base of the halite is unknown.

Halite diapirs or beds are unknown in Venezuela and Trinidad, but there are several reports of bedded anhydrite and gypsum (summary in Higgs, in review). The most notable occurrence is an anhydrite-dominated interval found in three wells in the Trinidad side of the Gulf of Paria, interbedded with subordinate shale and limestone and known as the Couva Marine Formation (Saunders 1997b). None of the wells reached the base of the formation; Couva Offshore-1 was abandoned after penetrating 6,120 feet of it (unpublished well file). The drilled anhydrite was interpreted as a possible diapir by Algar and Pindell (1993, p. 815-816 and fig. 2), an error rectified by Algar (1998, fig. 3) (anhydrite and gypsum are too dense for diapirism). According to Flinch *et al.* (1999), the Couva anhydrite reaches at least as far west as the Gopa High in Venezuelan waters of the Gulf of Paria, where a thrust-duplicated thickness of about 4 km was interpreted from seismic profiles (their fig. 4). The Couva anhydrite is Upper Jurassic or Lower Cretaceous, based on limited paleontological and radiometric data (Bray & Eva 1987;

Eva *et al.* 1989). The anhydrite is considered here to immediately predate the Carib Halite Formation (see below).

Outcropping gypsum beds 2-120 m thick are known in Jurassic and/or Cretaceous formations in Venezuela, namely the Cariaquito and/or Güinimita metasediments in the Paria Peninsula, Nirgua metasediments in the Cordillera de la Costa, and Río Negro Formation in the Mérida Andes (Bellizzia & Rodríguez 1976; González de Juana *et al.* 1968, 1972, 1980).

Indirect evidence for halite

There is abundant indirect evidence for buried halite in Venezuela and Trinidad, besides the inferred halite-dissolution basins. The evidence is summarized here; a fuller account is given by Higgs (in review). All of the features listed below can indicate present-day or former buried halite (*e.g.* Warren 1999). The evidence includes: (1) mud *diapirs* interpreted on seismic profiles (Escalona & Mann 2006a, fig. 10), more likely to be halite, because one of them roots in or below the Lower Cretaceous (their fig. 10D), a stratigraphic level not known for thick, undercompacted shales; (2) *saline springs*, common in all of the highland regions of Venezuela (Urbani 1977, 1989, 1991). In Trinidad, saline springs other than those associated with mud volcanoes (Higgins & Saunders 1974) are scarce, consistent with the suggestion that dissolution of the Carib Halite has finished in much of the country due to halite exhaustion, allowing tectonic uplift to reassert itself. Saline springs are also common in the Eastern Cordillera of Colombia (McLaughlin 1972; López *et al.* 1991); (3) local *gravity anomalies*, such as the Carúpano Low (Vierbuchen 1984); (4) *anomalously high geothermal gradients* (evaporites have high thermal conductivity) indicated by wells in several areas (*e.g.* Funkhouser *et al.* 1948, p. 1,891; Daal & Lander 1993, p. 323; F.E. Audemard & Serrano 2001, p. 362); (5) *"drowning coast" geomorphology* in eastern Venezuela and northern Trinidad (Paige 1930, p. 9; González de Juana *et al.* 1980, p. 738), characterized by deeply indented bays and alluviating valleys; (6) *exceptionally wide thrust belts*, reflecting evaporite decollement (Davis & Engelder 1985, 1987). A thrust belt about 350 km wide (across strike) propagated rapidly (Pliocene) northwestward across the Falcón-Gulf of Venezuela-Guajira region, prior to dissolution collapse of the Gulf and lower Guajira Peninsula; (7) an *intra-Cretaceous decollement* interpreted on seismic profiles at El Furrial, possibly a "conjectural infra-Cretaceous evaporite horizon" (Roure *et al.* 1994, p. 351); (8) a possible *rollover structure*, caused by halite lateral retreat (flow or dissolution), in the form of downlaps characterizing the Morichito Basin (Roure *et al.* 1994), similar to "apparent downlaps" or "rotated onlaps" in laboratory models of halite withdrawal (Ge *et al.* 1997; Guglielmo *et al.* 1998), and resembling halite-withdrawal rollovers in the Gulf of Mexico (Ge *et al.* 1997; cf. "pseudo-clinoforms" of Wu *et al.* 1990). Supporting the rollover interpretation, anomalously high paleo-temperatures are indicated in the Morichito Basin by sandstone petrography (Roure *et al.* 2003, fig. 3c, upper right), consistent with high paleo-heatflow due to halite formerly at depth; (9) *gypsum veins*, common in strata overlying dissolved or dissolving halite (Gustavson *et al.* 1994), occur in many Venezuela and Trinidad formations. Gypsum crystals, very common in Trinidad soils (Wall & Sawkins 1860, p. 90; Kugler 2001), are interpreted here as veins disaggregated by weathering; (10) *oils with evaporitic signatures* in eastern Venezuela (Goodman *et al.* 1982; Geomark 1993). In Colombia, the Bogotá halite contains ruptured interbeds or xenoliths of black laminated shale that are very rich in organic matter (López *et al.* 1991, p. 24); (11) *rauhwacke* (*i.e.* fault breccia along halite-lubricated thrusts after dissolution of the halite; Warren 1999), interpreted in the Cariaquito Formation in the Paria Peninsula Kugler 1953, p. 30); (12) *anomalous oilfield brine salinity*. For example, formation waters in Cretaceous limestone in La Paz Field near Maracaibo are "1.5 to 2.0 times more saline than modern seawater", and can contain much higher concentrations of sodium and chlorine ions than fractured-basement reservoir waters in the same field (Nelson *et al.* 2000, p. 1800), possibly due to contact with dissolving halite. A search of the reservoir-engineering literature would probably reveal further examples of abnormally high formation-water salinities in Colombia, Venezuela and Trinidad. In many cases, however, formation waters involved in halite dissolution may have been diluted by subsurface circulation of meteoric water; (13) *highly saline fluid inclusions*. Anomalously saline (224 ppt) fluid inclusions occur in a quartz-calcite vein filling a Miocene fracture in metamorphic rocks of the Cordillera de la Costa (Sisson *et al.* 2005b). "The source of the high salinity brine is unknown" (*op. cit.*, p. 169). The brine possibly acquired its high salinity by dissolution of halite, within the Shelf Nappe, after the 11 Ma start of deep subsurface circulation of meteoric water; and (14) *mineralization*. Azurite, fluorite, hematite, magnetite, malachite and silver, all of which can form in association with evaporite dissolution (Kyle 1991; Warren 1997, 1999), occur as minor ore deposits and shows in the Mérida Andes, the El Pilar region, and the Northern Range (Kugler 1959, sheet B; González de Juana *et al.* 1980, p. 171; Vierbuchen 1984, p. 210; Barr 1985, p. 120; Potter 1997, p. 17, 21). The emeralds of Colombia (Eastern Cordillera) were precipitated from halite-dissolving groundwater according to Giuliani *et al.* (1995).

Collapse breccias are also indicative of evaporite dissolution (Warren 1999). However, few sedimentary breccias interpretable as collapse breccias occur in Venezuela and Trinidad, despite the widespread dissolution of Carib Halite inferred here. Scarcity of collapse breccias would be consistent with (1) lack of non-evaporitic interbeds in the Carib Halite, and (2) dissolution of the halite over a broad horizontal front (from top down, or base upward), implying an aquifer immediately over and/or

under the halite (Warren 1999, p. 111), giving rise to a gradual letting-down of the overburden as dissolution proceeded, as opposed to focussed dissolution (*e.g.* edge-inward, or along cross-cutting faults), which can produce breccias by collapse of dissolution cavities (*op. cit.*). The Carib Halite is indeed inferred to have been under- and overlain by probable aquifers in some regions, as mentioned earlier.

Carib Halite distribution

Although halite is only known in one region (near Bogotá), its present and former distribution is indicated by the indirect lines of evidence discussed above. In summary, the halite is inferred to have accumulated in the following areas, from west to east.

In Colombia, halite was deposited in the Eastern Cordillera, Santander Massif, Santa Marta ranges, and Guajira Peninsula, as inferred from the Bogotá halite, saline springs, and distribution of supraorogen basins (Bogotá, Cesar-Ranchería, Lower Guajira).

In western Venezuela, halite accumulated throughout the region, based on saline springs, gypsum veins, an interpreted dissolution weld (see below), rapid thrust advance (Falcón-Gulf of Venezuela), supraorogen basins (*e.g.* Mérida, Carora, Gulf of Venezuela) and possible diapirs.

In central Venezuela, halite was deposited in the present-day Cordillera de la Costa and Central Serranía mountains, as shown by saline springs, gypsum veins, and supraorogen basins (La Victoria, Santa Lucía, Tuy). Halite also accumulated throughout the Gulf of Barcelona area, interpreted as a dissolution basin. Halite and/or anhydrite, unreached by drilling, is thought to underlie northern Guárico Basin, based on high heat flow.

In eastern Venezuela and Trinidad, halite accumulated in the region comprising the present-day Eastern Serranía, Araya-Paria Peninsulae, Gulf of Paria, island of Trinidad, and the entire Trinidad-eastern Venezuela northern shelf, based mainly on saline springs, gypsum veins and supraorogen basins (*e.g.* Morichito, Gulf of Paria, Caroni, South Trinidad, Carúpano-North Coast). With regard to the southern limit of the halite, the Maturín-Trinidad South Coast Thrust confronts backthrusts in Maturín, Pedernales and southern Trinidad (Kugler 1961 cross sections; Di Croce *et al.* 1999, fig. 8B; Flinch *et al.* 1999, fig. 6, profile II). This may mark the southern limit of the Carib Halite because, in thrust systems, backthrusts tend to develop "where a very efficient detachment horizon (*e.g.* salt) pinches out" (Vann *et al.* 1986, p. 226).

Carib Halite age

The age of the Bogotá halite was given as possibly Tithonian but mostly Berriasian and Valanginian (*i.e.* early

Neocomian) by McLaughlin (1972), based on fossils in nearby strata. McLaughlin (1972) considered the halite to belong to the Caqueza Group; his Tithonian(?) to Valanginian age range for the halite indeed falls within the Caqueza age range given in a recent compilation (Cooper *et al.* 1995, fig. 4). Shale inclusions in the halite, interpreted by López *et al.* (1991) as either ruptured interbeds or xenoliths, gave palynological ages of Hauterivian and/or Barremian (*op. cit.*). The xenolith interpretation is consistent with the (largely or entirely) Berriasian and Valanginian halite of McLaughlin (1972), which moreover coincides with a late Berriasian-early Valanginian eustatic lowstand, the lowest known for 200 million years (*i.e.* 200-11 Ma interval on Haq *et al.* 1988 chart; see also Hardenbol *et al.* 1998, chart 1). This temporal association suggests that the Carib Halite was deposited in a graben (see Carib Graben below), which is likely to have become isolated from the world ocean during the lowstand, favoring deposition of basin-central evaporites (Kendall & Harwood 1996, figs 8.7, 8.44), whereby the halite-precipitating water body, a saline lake below world sea-level, was separated from the ocean by an emergent sill across which ocean water percolated (and occasionally overspilled), at a rate insufficient to outweigh evaporation in the lake. The likely correlation between the eustatic low and the Bogotá halite was pointed out by López *et al.* (1991, p. 26).

In Venezuela and Trinidad, the same late Berriasian-early Valanginian age for the Carib Halite is consistent with all of the available biostratigraphic data. For example, in western Venezuela there is a "faunal gap": the youngest known Jurassic fossils are Kimmeridgian ammonites in Paraguaná (MacDonald 1968), while the oldest known Cretaceous fauna is Barremian, in the Río Negro Formation (González de Juana *et al.* 1980; LEV 1997). No halite has been encountered at outcrop or in wells, but a lithification discontinuity consistent with a halite-dissolution weld (see below) occurs between the La Quinta and Río Negro Formations; furthermore these formations almost certainly pre- and postdate the Berriasian-Valanginian age span of the Carib Halite respectively. In central Venezuela, fossils are scarce in the coastal and interior mountains and the Carib Halite Weld has not yet been identified, therefore this region provides no constraints on the age of the halite. The Weld probably crops out somewhere within the Caracas Group, given the reported Late Jurassic-Early Cretaceous age span of these poorly-dated metasediments (summary of age data in Benjamini *et al.* 1987). In Trinidad and eastern Venezuela, the youngest known Jurassic fossil is Tithonian (latest Jurassic), in Maraval Formation metasediments (Hutchison 1939; Spath 1939; Potter 1997), and the oldest known Cretaceous fossils are Valanginian, in the Cuche and Barranquín Formations (Macsotay *et al.* 1985; Vivas & Macsotay 1995b; LEV 1997; Saunders 1997a stratigraphic chart; review by Erikson & Pindell 1998a, p. 229). In Trinidad the Carib Halite is thought to lie stratigraphically between the Chancellor and the Cuche-equivalent Laventille Formations. (Note the still uncertain

stratigraphic order of Northern Range formations (Saunders 1997a stratigraphic chart).) The outcropping contact between these two formations is a metamorphic (thermal) discontinuity interpreted as the Carib Halite Weld (see below). In central and southern Trinidad and the Eastern Serranía of Venezuela, neither the Carib Halite nor the Weld are exposed, or reached by drilling. The oldest drilled or exposed formations are the Cuche and Barranquín.

Remarkably, no fossil taxa or fauna belonging indisputably to the Berriasian stage (spanning 7 m.y.; Hardenbol *et al.* 1998) have ever, as far as the author is aware, been found in Venezuela or Trinidad, with the possible exception of two faunas in the range Berriasian-Hauterivian and Berriasian-Valanginian reported from central Venezuela, confined to olistoliths in the Paleogene Los Cajones or Tememure Formation (Furrer, cited in González de Juana *et al.* 1980, p. 217; Furrer in Vivas & Macsotay 1995a, p. 99; Castro, cited in LEV 1997). However, based on the stated age ranges, these faunas could be as young as Hauterivian and late Valanginian, respectively. Thus a Berriasian-early Valanginian faunal gap throughout Venezuela and Trinidad is proposed here, in accordance with strata of this age being entirely (unfossiliferous) halite or dissolved halite. In contrast, Berriasian and Valanginian marine shales are well known in the Bogotá area (Campbell 1962). This suggests that the Carib Graben had a marine connection in that direction, consistent with (1) paleogeographic maps of Colombia showing increasingly marine conditions westward in earliest Cretaceous time (cf. Campbell 1962, fig. 1; Cooper *et al.* 1995, fig. 8), and (2) the paleocontinental reconstruction of Pindell and Kennan (2001b, fig. 4) showing the Colombian sector of the NW South America graben complex connecting westward to the adjacent Pacific Ocean, at least in late Jurassic time. Thus the Bogotá halite is probably just a thin tongue (within these marine shales), connecting northeast to the main body of Carib Halite in Venezuela.

Carib Halite thickness

Seismic profiles in those basins attributed here to halite dissolution reveal that the average thickness of the Upper Miocene to Quaternary syntectonic (growth-faulted) package is about 3 km (2 seconds two-way time). In the Gulf of Paria the thickness locally reaches about 4.5 km (Babb & Mann 1999, sum of isochron maps in figs 21B, 22B, 23B; Flinch *et al.* 1999, fig. 6). The greatest thickness is in Cariaco Trough, averaging about 6 km (4 secs; Goddard 1988, table 5 and figs 12, 13). Based on these values, and assuming that the accommodation was entirely provided by halite dissolution, the inferred average regional thickness of dissolved halite is about 3 km. In some basins, this thickness may reflect the aggregate of dissolved halite in two structurally separate Carib Halite intervals, for example the Shelf Nappe overlying the autochthon, as in the northern Gulf of Paria (Higgs, in review). The thicker (up to 6 km) basin-fill values may

reflect dissolution of thicker-than-normal halite, such as diapirs or intra-graben deeps. The highly variable thickness within individual basins (*e.g.* Flinch *et al.* 1999, fig. 6) thus mirrors the cumulative amount of (diapiric) halite dissolved in the nappe stack.

These values, taking into account that the halite is not completely dissolved (basins still subsiding), suggest that the average regional *depositional* thickness of the Carib Halite was approximately 4 km. This thickness is of the right order to explain the metamorphic discontinuity at the interpreted halite-dissolution weld in the Northern Range of Trinidad (see below). For comparison, in the Gulf of Mexico, reconstructions of the (upper Jurassic) Louann halite to its pre-halokinesis configuration suggest an average depositional thickness of 4-6 km (*e.g.* Humphris 1978, in Jackson 1995 fig. 15; Worrall & Snelson 1989, fig. 20b; Peel *et al.* 1995, figs 4d, 5e), and maximum present-day diapir heights are 10-15 km (*e.g.* Humphris 1978, in Jackson 1995, fig. 15; Martin 1978, in Worrall & Snelson 1989, fig. 12; Peel *et al.* 1995, fig. 1; Schuster 1995, fig. 20).

Carib Halite tectonic setting

The graben setting inferred from the coincidence with the Berriasian-Valanginian eustatic low, described above, is supported by the calculated subsidence rate. Given the estimated average Carib Halite depositional thickness of 4 km, and the eustatic-low span of about 3 m.y. (Hardenbol *et al.* 1998, chart 1), the calculated subsidence rate is 1.3 km/m.y.. This rate is much too fast for passive-margin thermal subsidence (*e.g.* Allen & Allen 1990), therefore the Carib Halite is inferred here to correspond to the rift phase of western Pangea breakup (Pindell & Dewey 1982; Pindell 1985). The halite can be assigned specifically to the *late*-rift stage, for two reasons: (1) the succeeding Barranquín Formation accumulated at subsidence rates of about 5-20 m/m.y. (Erikson & Pindell 1998b, fig. 4), compatible with a passive margin (*op. cit.*); and (2) no definite Cretaceous volcanics are known in Venezuela or Trinidad, near the age of the halite, whereas volcanics do occur in older, Jurassic rift deposits in the Espino Graben of central Venezuela (Middle Jurassic basaltic flow; Feo-Codecido *et al.* 1984), in the Perijá mountains (La Quinta Fm; LEV 1997), and at Siquisique (Bartok *et al.* 1985). Other interpreted Jurassic rift volcanics in Trinidad and north-central Venezuela are the Los Naranjos, Tiara, Las Hermanas and Sans Souci Formations (Higgs, in review).

Based on the interpreted late-rift setting of the Carib Halite, rifting in western Pangea lasted until Valanginian time, as interpreted previously for Colombia (Cooper *et al.* 1995). Sea-floor spreading, forming the Proto-Caribbean Ocean, began at the onset of (thermal) Barranquín Formation deposition, in the Valanginian, at about 135 Ma (Hardenbol *et al.* 1998). Similarly, in western Venezuela, the Río Negro Formation, whose oldest known fossils are Barremian (González de Juana *et al.* 1980), is generally

considered the first post-rift formation (*e.g.* Parnaud *et al.* 1995; Mann *et al.* 2006). In contrast, Pindell and co-workers interpreted Proto-Caribbean spreading to have begun in the late Jurassic, and to have been well advanced by 150 Ma, in the latest Jurassic (Pindell & Dewey 1982, fig. 14; Pindell 1985, fig. 12; Pindell & Tabbutt 1995, fig. 2; Pindell & Kennan 2001b, fig. 5). According to Pindell and Kennan (2001b, figs 4-6), sea-floor spreading started at about 160 Ma (Oxfordian), and the Proto-Caribbean was already more than 500 km wide by 130 Ma (Valanginian). Thus, the Pangea-breakup model of Pindell and co-workers is problematical, not only in terms of the palinspastic restoration of the Maracaibo Block described above, but also regarding the timing of breakup in Venezuela, where rifting continued about 25 m.y. later than claimed.

Carib Graben

The Carib Halite is interpreted to have been deposited in an interconnected graben complex, the Carib Graben, in which also accumulated the preceding Giron Formation of Colombia, the correlative La Quinta Formation of western Venezuela, and equivalents farther east (unspecified lower Caratas Group, lower Caribbean Group, and unexposed/undrilled formations of the Serranía del Interior and central/south Trinidad). The Carib Graben had previously been marine, at least locally, as shown by Middle and Upper Jurassic ammonites in western Venezuela (MacDonald 1968; Bartok *et al.* 1985). The Siquisique ammonites record the first marine connection between the Pacific and Tethys oceans, via the developing rift across Pangea ("Hispanic Corridor" of Smith 1983; Bartok *et al.* 1985).

The approximate extent of the graben complex is shown in Pangean paleocontinental sketch reconstructions by Bartok (1993, fig. 5) and Pindell and Kennan (2001b, fig. 3) (note incorrect large restorations of the Maracaibo Block in both cases). The graben complex covered much of NW Colombia and western Venezuela, connecting in the north to a graben running east from central Venezuela and embracing all of Trinidad. Lying adjacent to Venezuela at that time, prior to Proto-Caribbean spreading, was the Yucatán Block (Pindell & Dewey 1982, fig. 13; Pindell 1985, fig. 8; Maya Block of Bartok 1993, fig. 3), essentially comprising Yucatán Peninsula and Guatemala. A graben branched off from NW Venezuela and crossed western Yucatán Block (Pindell & Kennan 2001b, fig. 3), where evaporites including halite occur (Guatemala and southernmost Yucatán), whose age has been given as earliest Cretaceous (Viniegra 1971) and Early Cretaceous (Bishop 1980), suggesting contemporaneity and possible continuity with the Carib Halite. The southern margin of the Yucatán Block lay alongside the central Venezuela-Trinidad graben sector (Pindell & Kennan 2001b, fig. 3); the northern portion of the graben therefore probably underlies the present-day offshore margin of SE Yucatán (rotated anticlockwise during Proto-Caribbean opening; Pindell & Dewey 1982).

In central and eastern Venezuela, and in Trinidad, the Carib Graben encompassed both of the fault blocks later uplifted as the Slope and Shelf Nappes, and reached south into the autochthon, upon which the central Venezuela-to-Trinidad thrust belt developed.

Climatic implications of Carib Halite

Deposition of thick, extensive evaporites may seem incongruous, given that northern Venezuela, like today, was near the equator in earliest Cretaceous time (cf. Pindell & Kennan 2001b, fig. 4), where a humid, sub-equatorial climate might be expected, south of the northern hemisphere desert belt (but note present aridity in Falcón state and Guijira Peninsula). The explanation for this unexpected regional aridity is that equatorial winds at the western margin of Pangea blew from the western quadrant, as predicted by global paleoclimate models for Jurassic time (Chandler *et al.* 1992) and confirmed by cross-bedding orientations in Lower Jurassic eolian dune deposits in the southwestern USA (Loope *et al.* 2004). The westerly winds interacted with the coastal mountains along the western margin of Pangea (*e.g.* Late Jurassic map at www.Scotese.com) to produce a rain-shadow effect behind the mountains (Loope *et al.* 2004), suitable for precipitating halite in the Carib Graben in earliest Cretaceous time.

Carib Halite Weld, W Venezuela

In the Mérida Andes and Perijá mountains, and the Maracaibo Basin subsurface, the contact between the La Quinta and Río Negro Formations is conventionally interpreted as an unconformity (*e.g.* González de Juana *et al.* 1980; Parnaud *et al.* 1995; LEV 1997; "Sub-Cretaceous Unconformity" of Mann *et al.* 2006), based on: (1) probable missing time, the poorly defined age spans of these two sparsely fossiliferous formations being (A) undifferentiated Jurassic and (B) Barremian to Aptian (González de Juana *et al.* 1980); (2) the commonly observed slight angular discordance (*e.g.* Parnaud *et al.* 1995, fig. 4B seismic profile); and (3) a distinct difference in sandstone hardness, the La Quinta being harder. The contact is interpreted here as the Carib Halite dissolution weld, consistent with the faunal gap and with the induration discontinuity, reflecting the absence of a thick (c. 4 km) halite unit. The angular discordance separates La Quinta strata, tilted by half-graben-type rotational subsidence, from postrift Río Negro deposits. The discordance is exaggerated because rotational subsidence continued during deposition of the (missing) halite. A "breakup unconformity" (Falvey 1974; Lister *et al.* 1991) could additionally be present at the contact. At outcrop, the Río Negro Formation commonly shows intense fracturing (author's observations), but not brecciation, consistent with gradual foundering above a regionally dissolving layer, rather than focussed dissolution.

At the Siquisique inlier, (meta-) rift volcanics with shale interbeds containing Middle Jurassic ammonites are

associated with (meta-) Cretaceous sediments that have yielded Barremian fossils (Stephan 1980, cited in Bartok *et al.* 1985). These ages bracket the Berriasian-Valanginian age of the Carib Halite, suggesting that the Carib Halite Weld could be present there. The structural complexity of the outcrop (Bartok *et al.* 1985, fig. 4) could partially reflect dissolution collapse.

Carib Halite Weld, Trinidad

Cropping out in the Northern Range is a "sharp, east-west-trending major thermal discontinuity" in the petrographically determined deformation temperatures of the exposed low-grade metasediments (Weber *et al.* 2001b, p. 93). The discontinuity was deduced by Weber *et al.* (2001b) to be a steeply S-dipping normal fault, which they correlated with the supposed Arima Fault (Kugler 1961 map and cross sections; Saunders 1997a map), separating Chancellor Formation metasediments of lower greenschist grade (Frey *et al.* 1988) from Laventille Formation recrystallized limestone (Potter 1974). This strike-parallel contact can be interpreted instead as the Carib Halite Weld, with the thermal discontinuity reflecting about 4 km of missing halite. The "thick cataclastic zones ... pervasive along the southern foot of the Northern Range" considered by Weber *et al.* (2001b, p. 108) to support their fault interpretation may instead reflect intense fracturing caused by dissolution foundering.

Elsewhere in the Northern Range, the contact between the Sans Souci and Toco Formations (Kugler 1961; Saunders 1997a) might also be the Carib Halite Weld. The Sans Souci consists of volcanics of Santonian or older age (Wadge & Macdonald 1985), interpretable as Jurassic rift volcanics (Higgs, in review), consistent with their geochemistry (Wadge & Macdonald 1985); the metamorphic grade is prehnite-pumpellyite (Frey *et al.* 1988), attributed to burial under the Slope Nappe (Higgs, in review). The Toco Formation comprises Barremian-Aptian shales with subordinate sandstone, limestone and conglomerate (Barr 1962); metamorphism is too weak to have visually affected the shales, but the limestones have been recrystallized (Barr 1962, p. 396), and three samples were described as "metacarbonate" by Weber *et al.* (2001b, table 3). Thus, a metamorphic-grade discontinuity occurs between the two formations. The poorly exposed contact was interpreted as stratigraphic by Barr (1962), Kugler (1961) and Saunders (1997a), who all assumed the Sans Souci to be the younger formation (*e.g.* ?Aptian-Albian; Saunders 1997a stratigraphic chart), consistent with the mutual northward dip and with the Sans Souci lying in the north (Kugler 1961, cross section 1; Barr 1963, fig. 8, cross sections 3, 4; Wadge & Macdonald 1985, fig. 1). However, this age relationship is problematic as it would imply a reverse metamorphic gradient. In contrast, an older, Jurassic age for the Sans Souci explains the metamorphic relations, and is consistent with the presence of Jurassic rift volcanics in the Espino Graben (Feo-Codecido *et al.* 1984) and at Siquisique, the latter likewise

being slightly metamorphosed (Bartok *et al.* 1985) by burial under the Slope Nappe. If the Sans Souci indeed predates the Toco, the contact must be either a north-dipping thrust, or an overturned stratigraphic contact, consistent with upside-down Galera Formation nearby, as reported by Pindell (1998, p. vii) but in fact noted long before by Saunders (1972). A fault contact dipping steeply north was invoked by Wadge and Macdonald (1985, fig. 1), who believed the Sans Souci to post-date the Toco, therefore a normal fault was implied. Other authors considered the Sans Souci to intrude the Toco (Liddle 1946; Suter 1960; Algar & Pindell 1991), an untenable interpretation in view of the difference in metamorphic grade. The contact is interpreted here as the Carib Halite Weld. The weld interpretation implies that the Sans Souci immediately underlay the Carib Halite, and therefore could reach up to Berriasian age. The Sans Souci may thus be laterally equivalent to the Maraval and/or Maracas Formations (cf. Saunders 1997a stratigraphic chart), consistent with the presence in the Maracas of a metatuff bed of similar chemistry to the Sans Souci (Jackson *et al.* 1991).

Carib Halite Weld, E Venezuela

In the Paria Peninsula, along strike from the Northern Range of Trinidad, the Cariaquito Formation and the overlying Güinimita are separated by a supposed strike-parallel fault (González de Juana *et al.* 1968, p. 28 and fig. 2), reinterpreted here as the Carib Halite Weld. Here, too, consistent with the weld model, there is an apparent discontinuity in metamorphic grade, the Cariaquito being mainly schist whereas the Güinimita does not exceed "very low grade phyllites" (González de Juana *et al.* 1968, p. 27-28 and fig. 3).

Carib Halite Weld, Gulf of Paria

In the Gulf of Paria, the contact between the Couva Marine Formation (anhydrite) and the overlying Cuche, encountered in two wells, is interpreted here as the Carib Halite Weld, based on signs of slight metamorphism of shaly interbeds in the Couva (unpublished well files), whereas metamorphic effects are unreported in the Cuche shales throughout Trinidad. In a figure by Pindell and Kennan (2001a, fig. 3B), the Cuche is stated to be "metamorphic in Caroni Basin", but this is presumably an exaggeration; the accompanying text described the Cuche as only "overmature" (p. 165), as previously reported by Persad *et al.* (1993). The suggestion that the Couva-Cuche contact represents missing upper Berriasian-lower Valanginian halite is consistent with the imprecise age control for the Couva (Late Jurassic or Early Cretaceous; Bray & Eva 1987; Eva *et al.* 1989), and with the Valanginian age of the oldest known fossils in the Cuche (Saunders 1997a stratigraphic chart). Another well encountered Brasso Formation (Miocene) shales directly above the Couva anhydrite (well file), suggesting pre-Brasso erosional removal of the Carib Halite Weld.

Exploration implications

The Caribbean Model revisions and Carib Halite concept will affect petroleum prospectivity assessments and exploration strategy in Colombia, Venezuela and Trinidad, changing interpretations and predictions of subsidence history, paleogeography, structure/traps (decollement; dissolution collapse), seismicity (active transpression; collapse), paleo-heatflow effect on maturation (high halite conductivity), evaporitic source rocks, seals, *etc.*. Many new plays will arise. For example, the idea of a continentwide Proto-Caribbean Foreland Basin with dual, north- and south-derived sand fairways is new, replacing the single, pre-Caribbean passive-margin fairway of the old model. In Trinidad and eastern Venezuela, both fairways host large or giant oilfields (*e.g.* El Furrial in the south; Angostura, Brighton in the north), serving as analogues for future exploration. The El Furrial play is predicted low in the southern Trinidad thrust pile. The northern fairway, being confined to the thrust belt, was breached/eroded by uplift except where preserved by burial under a salt-dissolution basin, as in Trinidad (Angostura, Brighton); it is also preserved in the western Gulf of Paria (*e.g.* Posa), and is predicted in the Gulf of Barcelona, but is largely absent (eroded) in the intervening Eastern Serranía.

There are many other examples of the potential impact on exploration. For instance, the recognition that the Paleogene Maracaibo foredeep reflects Proto-Caribbean (not Caribbean) nappe loading has many exploration implications. The realization that there are four generations of foreland basin in Venezuela (Proto-Caribbean, Caribbean, Catatumbo, Mérida) will allow explorers to develop more sophisticated and reliable models of oil and gas generation, migration and entrapment.

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