Colombia-Venezuela-Trinidad Prolific Oil Province: Revised Triassic-Recent Depotectonic History*

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Introduction

In the popular Caribbean-South America dextral oblique collision model (e.g., Pindell et al., 1998, summarizing interpretations of Pindell and co-authors since 1982), a three-stage evolution for northern South America is invoked: (1) Jurassic rifting (Pangea breakup); (2) Late Jurassic to Cenozoic passive margin subsidence, beside the spreading (until Campanian) Proto-Caribbean Ocean; and (3) Caribbean Arc oblique collision from the west, driving a diachronous, landward-verging thrust belt and foreland basin that youngs eastward from western Venezuela (Paleocene start) to Trinidad (Miocene).

Long-Lived Rifting

Following Pindell and Dewey (1982), most workers accept that Pangean rifting in Colombia, Venezuela, and Trinidad gave way to Proto-Caribbean spreading in Late Jurassic time. However, rifting in fact continued much longer, as shown by syn-tectonic features in the Neocomian-Coniacian succession of northern South America (Higgs, in review, a, b), and by deposition of source-rock Villeta-La Luna-Querecual-Naparima Hill anoxic mud for much longer (10-15 m.y., Cenomanian-Coniacian; Erlich et al., 2003) and at faster subsidence rates (100- 200 m/m.y. decompacted) than is possible on a passive margin, where oceanic wind- and wave-driven circulation prevents long-term thermohaline stratification. This long time span included Oceanic Anoxic Event 2, but this event was too brief (< 2 m.y.; Tsikos et al., 2004) to explain the longevity of source-rock deposition in northern South America. A rift interpretation for this suite of formations recalls the old idea (Hedberg, 1950) that the Querecual reflects restricted circulation behind a northern barrier sill. The barrier was interpreted by Maresch (1974) as a continental-margin arc, although the Querecual lacks tuffs, despite probable NE prevailing "trade" winds. Active faulting during La Luna deposition has been postulated previously (Erlich et al., 1999; Macsotay et al., 2003).

The rifting is interpreted here to reflect two Mesozoic hemiglobal superplume events:

(A) A Late Triassic-Early Jurassic event (227-183 Ma), responsible for initial fragmentation of Pangea (Vaughan and Storey, 2007).

(B) A mid-Cretaceous event (120-80 Ma), responsible for the Caribbean Plateau (90-75 Ma) overthickened oceanic crust (Larson, 1991), which formed nearby (Meschede and Frisch, 1998). During the intervening tectonically quieter period, deposition in the rift graben (Carib Graben of Higgs, 2006) included thick halite (max. 2-3 km; Carib Halite of Higgs, 2006), corresponding to a Berriasian- Valanginian extreme eustatic low (Haq et al., 1988), which caused halite deposition by cutting off the Carib Graben from the world ocean. The halite was later largely dissolved underground due to increased rainfall beginning in the middle Miocene (Panama barrier completion, initiating the modern Gulf Stream beside Trinidad and Venezuela; Mullins et al., 1987; Coates et al., 2004). Deep penetration of meteoric water into the mountain belts built by graben inversion (see below) caused syn-orogenic halite-dissolution subsidence, resulting in Neogene supraorogen basins, like the Gulf of Barcelona, Gulf of Paria, and Carupano-North Coast Basin (Higgs, 2006; Higgs, in review, b). Abundant regional evidence for dissolved halite in Venezuela and Trinidad includes a near-absence of Berriasian-Valanginian fauna, and a sharp contrast in grade of induration or metamorphism between now-adjacent formations that formerly bracketed the halite (e.g., La Quinta-Rio Negro; Chancellor-Laventille; Higgs, 2006; Higgs, in review, b).

Also interpretable as rift-related (Higgs, in review, a) are Cretaceous granitoid plutons in the Central Cordillera of Colombia (124-68 Ma, K-Ar; Aspden et al., 1987), including the Antioquia Batholith. This plutonic eposide and a Jurassic one (Aspden et al., 1987) are generally attributed to subduction (Aspden et al., 1987; Cooper et al., 1995; Pindell and Kennan, 2007), despite their generally inconclusive geochemical signature (Aspden et al., 1987; Gonzalez, 2001) and the failure to produce an emergent continental-margin arc (Cooper et al., 1995). On the contrary, the Cretaceous plutons are coeval with overlying shallow-marine deposits (Cooper et al., 1995; Gonzalez, 2001), indicating that the plutonism occurred in a subsiding basin, interpreted here as a rift (Carib Graben), as suggested by Aspden et al. (1987) for some of the Jurassic plutons, based on geochemistry. The Cretaceous plutonism is attributed (Higgs, in review, a) to the same mid-Cretaceous superplume responsible for the Caribbean Plateau. The Jurassic plutons may have formed in the previous, Late Triassic-Early Jurassic event; their younger apparent age spread (183-142 Ma K-Ar; Aspden et al., 1987), spanning Early through Late Jurassic time, could reflect partial resetting by the Cretaceous event. A "Colombia superplume" may have underlain NW Colombia.

Proto-Caribbean Spreading

Following the protracted rifting, Proto-Caribbean Ocean spreading began. Spreading is interpreted here to have begun in Santonian time, rather than 70 m.y. earlier in the Oxfordian (Pindell and Kennan, 2001b), with important implications for petroleum exploration in Colombia, Venezuela, and Trinidad. Proto-Caribbean spreading ended in Campanian time (Pindell et al., 1988) due to a plate reorganization (Higgs, 2008a, the Caribbean Arc) that also caused the onset of slow, amagmatic subduction of Proto-Caribbean lithosphere under Venezuela and Trinidad, likewise in Campanian time (72 Ma; see below), rather than Eocene (Pindell et al., 1991) or Maastrichtian (Pindell et al., 2006). Thus, the Venezuela-Trinidad passive margin lasted just 10-15 m.y. (Santonian and most of the Campanian), rather than about 100 m.y. in eastern Venezuela for example (Erikson and Pindell, 1993).

The much later, Santonian start of Proto-Caribbean spreading, compared to the conventional model (Oxfordian), requires that another ocean opened before the Proto-Caribbean, to accommodate more than 2000 km of NW-SE divergence between North and South America from Middle Jurassic until Campanian time, interpreted from Atlantic magnetic anomalies and fracture zones (Pindell et al., 1988). A vanished (subducted), Jurassic-Cretaceous "Inter-Americas Ocean" is proposed (Higgs, in review, a), separating the Yucatan-Bahamas margin of North America from a "Chortis-Greater Antilles Superterrane" (CGA), then still joined to South America (Figure 1, Higgs, 2008a). The superterrane consisted of two elements that later became separated:

(A) the Chortis Terrane (summary in Mann, 1999), comprising Nicaragua, Honduras, and the Nicaragua Rise, and considered here to include Jamaica (discussion in Pindell et al., 2005).

(B) A Greater Antilles Terrane (Higgs, in review, a), comprising the metacontinental terranes of Cuba and Hispaniola (summary in Pindell et al., 2005), and probable similar basement under Puerto Rico.

Spreading of the Inter- Americas Ocean was synchronous with the long-lived, Carib Graben rifting that eventually detached CGA from South America. The northern "missing half" of the Carib Graben, likely to contain (dissolved?) halite and La Luna-equivalent source rocks, is predicted to underlie the current southern fringe of CGA, raising petroleum potential there.

Proto-Caribbean Subduction

Inter-Americas convergence (Pindell et al., 1988; Müller et al., 1999) gave rise to Proto-Caribbean subduction (Pindell et al., 1991), beginning under Venezuela and Trinidad in latest Campanian time (chron 32, 72 Ma), based on stratigraphic evidence from those countries (Higgs, in review, a). The direction of convergence changed from WSW to SSE in late Paleocene time (chron 25, Müller et al., 1999, fig. 9), initiating oblique subduction under Colombia too (Figure 1). The longer-lived and more orthogonal subduction in Venezuela and Trinidad, compared to Colombia, drove two continental-margin upper crustal nappes landward (Figure 2). The nappes are assumed to have detached at the base of the seismogenic upper crust, typically 15-20 km thick (Jackson, 2002; Afonso and Ranalli, 2004). In Maastrichtian-Paleogene time the Outer Nappe overrode and metamorphosed the Inner Nappe rift deposits (up to greenschist grade), represented by the Caracas and Caribbean groups of the modern coastal ranges of Venezuela and Trinidad. Inboard of the Inner Nappe, a thrust belt occupied the southern fringe of the former Carib Graben. The nappes fed Campanian-Miocene olistostromes and turbidites southward into a Proto- Caribbean flysch trough reaching from western Venezuela to Trinidad (Figures 1, 2, and 3; Higgs, 2006, note former Slope Nappe-Shelf Nappe terminology). Trough deposition was terminated progressively later eastward by the arrival of the Caribbean Arc (see below). Previous authors similarly invoked northern derivation of latest Cretaceous to Miocene olistostromes and turbidites in central Venezuela and Trinidad (Kugler, 1953; Suter, 1960; Bell, 1967, 1971, 1972). Northern derivation in Trinidad was disputed by Pindell and Kennan (2001a, 2007).

Subduction was too slow (< 1 cm/yr) for the downgoing Proto-Caribbean slab ever to reach sufficient depth for arc magmatism (Pindell et al., 1991). The restricted subduction reflects the limited N-S inter-Americas convergence, totaling only 300 km (Campanian to Recent) at the longitude of western Venezuela and 100 km at Trinidad nearer the rotation pole (Müller et al., 1999). These values are consistent with the total N-S shortening envisaged for the Outer Nappe, Inner Nappe, and thrust belt, in the order of 100-200 km (Figure 2), prior to the arrival of the Caribbean Arc. Lesser N-S convergence in Trinidad was compensated by the later arrival there of the Caribbean Arc (see below). Given faster or longer subduction, an arc would have formed. Thus the Proto- Caribbean foreland basin is of a little known "pre-arc" type, seldom preserved, usually obliterated or modified beyond recognition by arc magmatism.

The advancing Proto-Caribbean nappes caused a Proto-Caribbean forebulge to migrate southward ahead of the foreland basin, as indicated by an unconformity in eastern Venezuela. A putative Late Eocene unconformity at outcrop (Hedberg, 1950), between the Caratas and Los Jabillos formations, is conventionally thought to increase in duration southward into the subsurface, where it supposedly separates S-onlapping Oligo-Miocene strata above (Los Jabillos-Capiricual equivalent) from N-dipping, erosionally truncated Upper Cretaceous (Tigre) through Vidoño-Caratas equivalents (e.g., Parnaud et al., 1995, fig. 4, after Perez de Mejia et al., 1980, fig. 1-13a). However, the outcrop unconformity is doubtful: no angularity has ever been proven (LEV, 1997), and microfossil studies have revealed no missing Eocene or Oligocene faunal zones (Gonzalez de Juana et al., 1980; LEV, 1997). Instead, the Caratas and Los Jabillos at outcrop can be interpreted in terms of uninterrupted deposition of N-derived turbidites and shales (Figure 3), including high-density calciturbidites forming the Tinajitas Member of the Caratas, not to be confused with Tinajitas-bearing olistostromes in the overlying Areo Formation, reflecting cannibalization by thrust-front advance (Higgs, in review, a). The subsurface unconformity, difficult to pinpoint because the entire section is sand-rich (Parnaud et al., 1995, fig. 4), is reinterpretable as a Campanian-Miocene diachronous basal sand onlapping the (sandy) Tigre Formation southward, reflecting the S-advancing forebulge.

Caribbean Arc Eastward Migration

Coeval with Proto-Caribbean subduction, the Caribbean Arc initially migrated relatively eastward after its Campanian birth (Higgs, 2008a). This eastward motion caused oblique obduction of a forearc nappe onto the NE-trending Ecuador-Colombia margin (Figures 1, 3). The Caribbean Arc passed "Guajira corner", in the far north, much later (latest Eocene, 35 Ma; Figure 3) than in the established model (Paleocene, c. 60 Ma; e.g., Pindell et al., 1998), again with major consequences for petroleum exploration in Colombia, Venezuela, and Trinidad. The Arc then changed its relative motion to SE (Higgs, 2008a) and migrated along and sub-parallel to the SE-trending Falcon margin, forming the Gulf of Venezuela-Falcon Basin, a transform-related transtensional basin complex (Oligocene-Lower Miocene), whose basement in the east locally consists of Jurassic and Cretaceous metasediments and metavolcanics (Siquisique; Bartok et al., 1985), interpretable as Proto- Caribbean Inner Nappe rift strata (Higgs, 2006; Higgs, in review, a). Beyond Falcon, the Caribbean Arc encountered the central Venezuela-Trinidad margin, whose ENE trend caused a second episode of oblique obduction of a forearc nappe (Villa de Cura-Margarita-Tobago). The Villa de Cura klippe rests on the erosionally exhumed, relatively in situ Inner Nappe, popularly interpreted instead as having come far (100s km) from the west in the Caribbean accretionary prism, after Algar and Pindell (1993). Loading by the Caribbean nappe on either side of Falcon drove a Caribbean foreland basin, both in Ecuador-Colombia (NE-younging start of subsidence, Paleocene-Eocene) and in central Venezuela- Trinidad (E-younging, middle Miocene-Pliocene). These basins diachronously supercede the Proto-Caribbean foreland basin in both regions. Caribbean relative motion switched from SE to E near 2.5 Ma (Higgs, 2008b, 5-0 Ma development).

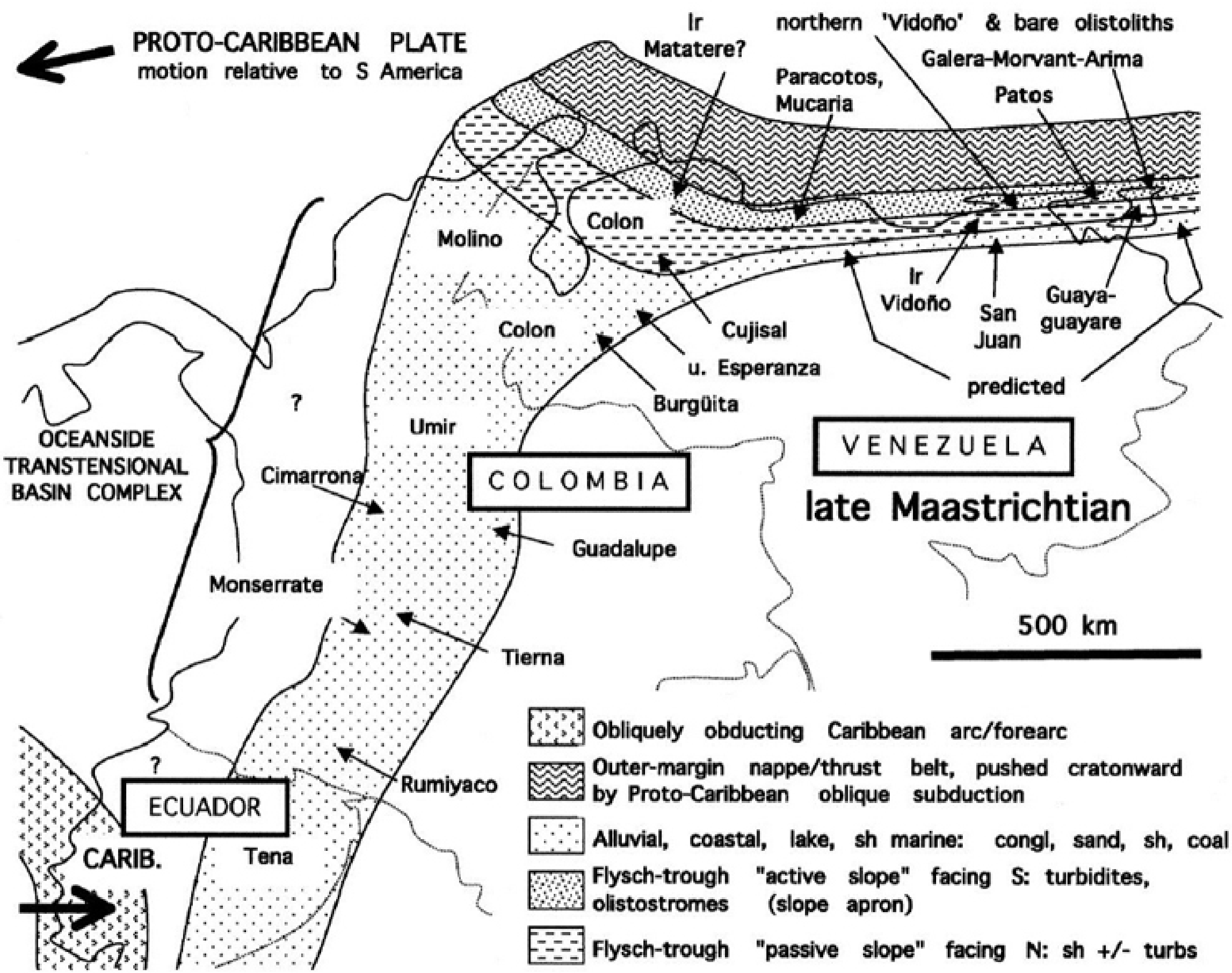

Figure 1. Late Maastrichtian paleogeographic map of northwestern South America. The Proto-Caribbean foreland basin, then largely confined to Venezuela and Trinidad, comprised a northern flysch trough flanked in the S by a N-facing slope and shelf. Solid arrows reflect approximate sediment-supply direction. Insignificant at this scale is palinspastic restoration for: (1) shortening of the foreland basin by thrust-front advance, greater in the E (basin now narrower in Central Venezuela-Trinidad sector) because Proto-Caribbean plate convergence here was more orthogonal for longer time(see text); (2) distributed NW-SE shortening in Colombia and Western Venezuela (Higgs, 2008b, 5-0 Ma development); and (3) since 2.5 Ma, 50 km of eastward relative movement of the "Northern Andes Block", including the "Maracaibo block" (Higgs, 2008b). "Predicted" means non-exposed, either buried in thrust sheets, or deeply buried under (or immediately ahead of) the present-day frontal thrust.

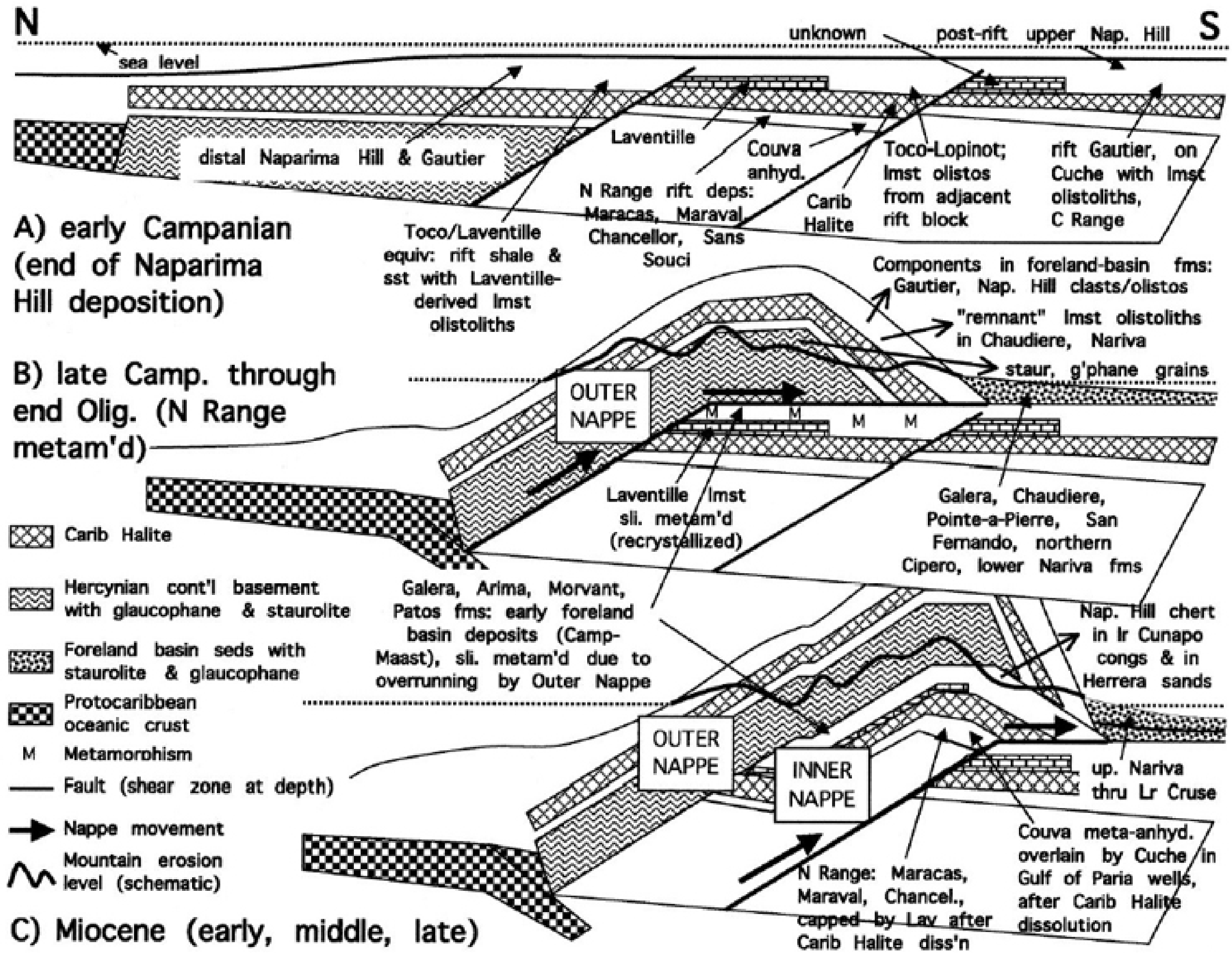

Figure 2. Schematic N-S paleo-section across northern South America continental margin at longitude of Western Trinidad, at three different times, showing development of Outer Nappe and Inner Nappe. Equally applicable to Western, Central, and Eastern Venezuela, except formation names differ and Inner Nappe was uplifted earlier (Paleocene) in Western and Central Venezuela (Higgs, in review, a). For simplicity, this figure neglects (a) halokinesis (Carib Halite; see text), (b) cannibalization and nappe-overriding of early foreland-basin deposits, and (c) advance of a thrust belt beyond the nappe front.

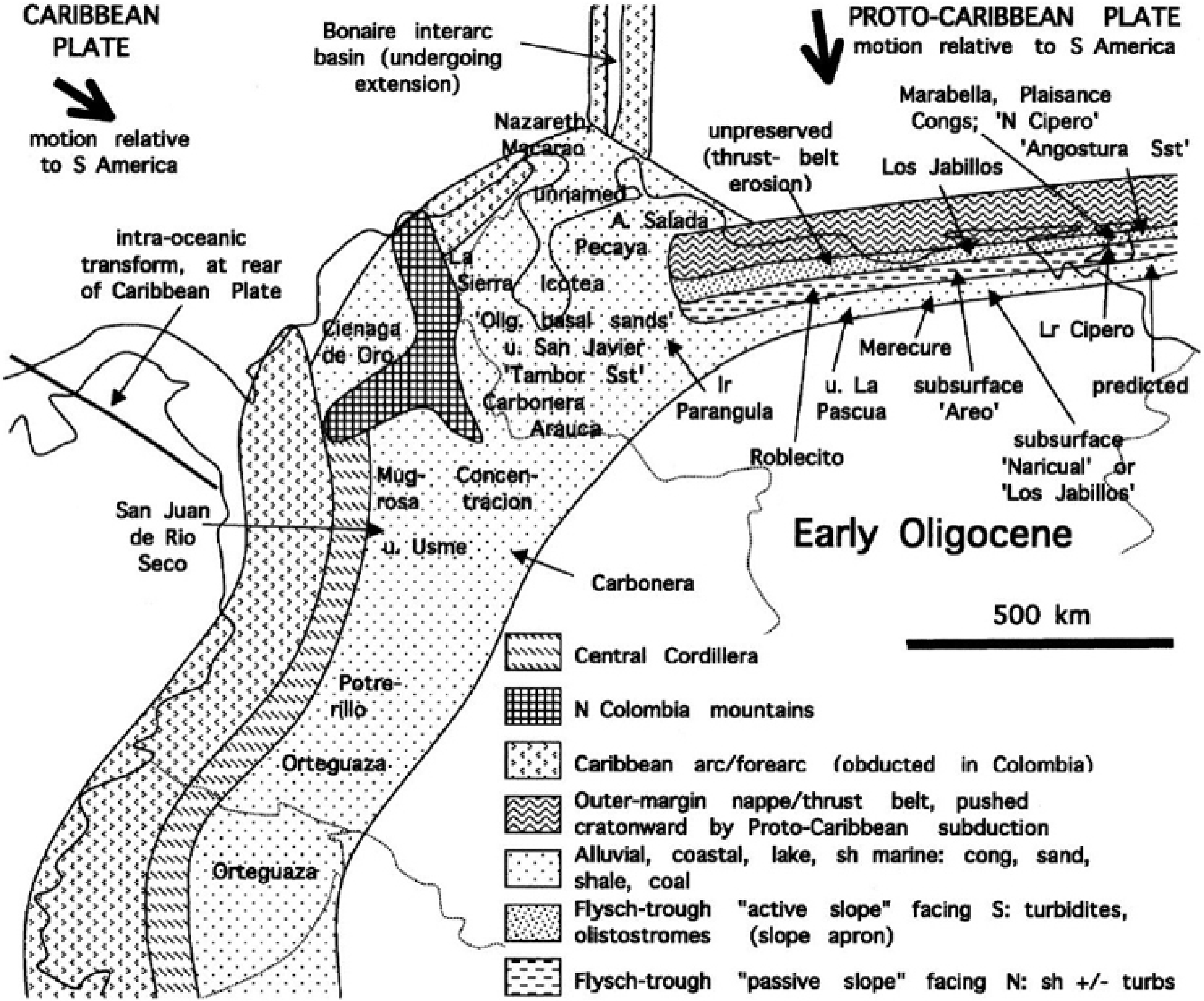

Figure 3. Early Oligocene paleogeographic map of northwestern South America.

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