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ABSTRACT

CENOZOIC CARIBBEAN-SOUTH AMERICA TECTONIC INTERACTION: A CASE FOR PRISM-PRISM COLLISION IN VENEZUELA, TRINIDAD, AND BARBADOS RIDGE

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Enormous effort by the collective geological community has been devoted to the description and characterisation of the Caribbean-South American plate boundary zone. Less but still considerable effort has gone into understanding the history of the Caribbean-South American plate collision, and still less effort has gone into trying to understand the nature of the South American margin prior to Caribbean collision. Was it a passive margin as the Caribbean progressively collided with it from the west, as many have come to believe, or was it already active during the Caribbean collision? If active, how so? Understanding the answer to this question is important for understanding the history of the collision itself and the structure of today's plate boundary zone, as well as for better understanding the paleo-environments and distribution of source and reservoir rocks in various petroleum systems along the margin.

Prior to the advent of plate tectonic theory, workers envisioned an end-Cretaceous-Eocene northern marginal high that provided detritus with an orogenic signature to various clastic depocenters such as the Scotland Formation in Barbados (eg., Senn, 1940). With the advent of plate tectonics, but prior to accurate plate kinematic control, came the idea that arc-continent collision caused tectonism and metamorphism in the Caribbean Mountains and Margarita of Late Cretaceous age, followed by some thin-skinned thrusting or gravity sliding in the Guarico foreland basin in the Paleogene (eg., Maresch, 1974). With (1) the definition of accurate circum-Caribbean plate kinematics as allowed by early SEASAT and GEOSAT data, and (2) the realisation that northern South America's foreland basin subsidence history youngs diachronously eastward (Pindell, 1985), came the realisation that the predominantly Cretaceous metamorphic and igneous rocks must be Pacific-derived allochthons that were not emplaced onto the margin until the Paleogene, and that the northern South American shelf was passive at least until the Maastrichtian and possibly to the time of Caribbean collision, facing onto the Proto-Caribbean Seaway, an arm of the Atlantic (Pindell, 1985;

Dewey and Pindell, 1986; Pindell et al. 1988). But the arc-passive margin collision model was always hostage to one major problem: N-S convergence between North and South America since the Maastrichtian was significant (ie, hundreds of km) and convergence began before the arrival of the Caribbean allochthons in Venezuela and Trinidad.

Thus, suspicion of a “pre-Caribbean-arrival” convergent boundary between the North and South American plates, somewhere in the Proto-Caribbean Seaway, clouded our confidence in the margin remaining passive until the time of Caribbean collision (ie, during the Paleogene). It was not until the first seismic tomographic work in the Caribbean (Van der Hilst, 1990) that the geological community had good evidence that South American continental lithosphere had been severed from the Proto-Caribbean lithosphere which had been subducted beneath the Lesser Antilles. Driven by the suspicion of convergence since the Maastrichtian, Pindell et al (1991) honoured the Cenozoic inter-American relative motion history by proposing that the northern South American Cretaceous passive margin was converted in the Late Maastrichtian-Paleocene to a south-dipping “Proto-Caribbean” subduction zone along the toe of the margin. Further, it was suggested that this structure drove N-vergent accretion of South American continental slope and rise strata to South America’s northern edge (eg, Caracas Group, Paria, and Northern Range strata), PRIOR to the eastwardly diachronous collision of the Caribbean Plate, and associated emplacement of the Cretaceous allochthons, with Venezuela and Trinidad. In such a model, the term “trench-trench collision” is a more accurate description of Caribbean-South American interaction during Cenozoic time than is “arc-passive margin collision”, although convergence at the Proto-Caribbean thrustbelt or subduction zone has been too small for a magmatic arc to develop.

Evidence for this Proto-Caribbean subduction zone is geologically subtle in the onshore, but defining the Paleogene existence of the plate boundary (Pindell and Kennan, 2001; Pindell et al., 2006) is critical for understanding the origin and distribution of Paleogene reservoir clastics and burial/unroofing histories of Cretaceous source rocks, and thus deserves our full attention. Evidence for the Proto-Caribbean subduction zone/thrustbelt now includes the following items.

(1) Atlantic plate kinematic history requires about 150±50 km of North America-South America convergence to have already occurred at the longitude of Late Eocene Caribbean collision in western Venezuela, and at the longitude of Early Miocene Caribbean collision in Eastern Venezuela (Pindell et al., 1988; Muller et al., 1999), which must have had a pre-Caribbean-arrival geological expression within or at the margins of the Proto-Caribbean Seaway.

(2) Mantle seismic tomography beneath the Caribbean and northern South America (Van der Hilst, 1990) shows a subducted Proto-Caribbean slab beneath the Caribbean Plate, and this subducted slab is both severed from, and overthrust by, the northern edge of South American continental lithosphere. The Caribbean slab also underthrusts northern South America, through the severed tear between the Proto-Caribbean and South American lithospheres. However, because the Proto-Caribbean slab continues some 150 km south of the southern limit of subducted Caribbean lithosphere, overthrusting of the Proto-

Caribbean by South America must have started earlier; ie, there was a S-dipping Proto-Caribbean trench or thrust zone along northern South America *before* the arrival of the Caribbean Plate along northern South America.

(3) ENE of Barbados on the Atlantic floor, a paired basement ridge/trough (south side/north side, respectively) projects ENE into the Atlantic from beneath the Barbados accretionary ridge, which we interpret as the eastward continuation of the N-facing Proto-Caribbean subduction zone's hanging wall (ridge) and trench (trough), not yet overthrust in this area by Caribbean lithosphere or Barbados Prism (Pindell et al., 2006). This ridge/trough pair extends out to about magnetic anomaly 31 (Late Maastrichtian), which is the age when convergence between the Americas began, hence the Proto-Caribbean subduction zone may have initiated simply as a third arm extending from a triple junction between it and the Maastrichtian mid-Atlantic spreading center. Assuming rigid plates, the 150 km of shortening which had already occurred at a given longitude of Caribbean collision theoretically should have diminished eastward from that longitude to zero at the effective pole of rotation for the convergence. However, the observable geological manifestation of this shortening may appear to have propagated eastward through Paleogene time.

(4) Paleogene uplift and erosion of section along the South American shelf was once interpreted as being due to the passage of the Caribbean forebulge (Dewey and Pindell, 1986; Pindell et al., 1988), but our field studies in Eastern Venezuela and Trinidad now show that subaerial erosion reached at least Turonian levels (note: prime source rock interval), and possibly Albian levels locally, and thus often exceeds that predictable by forebulge uplift alone. Further, seismic records in Central Venezuela (eg., PDVSA 1995 bid round samples) show normal fault offsets at the basal foredeep unconformity that are often larger than those predicted by lithospheric forebulge flexure alone. This erosion and faulting may better be related to slow but progressive hanging wall uplift as the Cretaceous passive margin was converted into the "Proto-Caribbean" subduction zone (Pindell and Kennan, 2001). Local occurrences of extensional faulting in the basement and/or the passive margin section (northward slumping) may owe their origin to gravitational relaxation of hanging wall elements toward the free face of the new trench.

(5) Fission track cooling ages in apatite grains from the Barranquín Fm of the Serranía Oriental are mostly Miocene and Oligocene, but some are as old as Eocene. (Perez et al., 2005; Locke and Garver, 2005). These authors speculate an Eocene onset of uplift in the Serranía Oriental, which pre-dates the Late Oligocene onset of Caribbean collision first suggested by Dewey and Pindell (1986) in that area, and may relate, if not due to partial annealing, to the hanging wall uplift noted above.

(6) Post-orogenic cooling of the "Caribbean Series" metasediments through 350°C, as shown by Ar-Ar dating of first foliation micas, was underway in the Caracas Group by 42 Ma (Middle Eocene), and in the Paria Peninsula and Northern Range by about 26 Ma (Oligocene) (Sisson et al., 2005; Foland and Speed, 1992). A zircon fission track age of 29 Ma from Paria Peninsula (Cruz et al., 2004; in press) suggests that uplift and cooling locally may have begun even earlier. These ages predate the time of Caribbean collision at these places as judged from adjacent initial foredeep development (Oligocene in

Guarico Basin; mainly Miocene in Maturín Basin), suggesting that the primary metamorphism in these ranges pertains not to the collision of the Caribbean, but to an earlier event or process which may be the accretion of these strata at the Proto-Caribbean trench/foldbelt prior to the arrival of the Caribbean. If anything, the arrival of the Caribbean forearc at the margin triggered the cooling, not the heating, of these rocks.

(7) Speed (2002 and many earlier references) built a comprehensive model for the depositional and deformational history of the Scotland District, Barbados, employing a single trench model in which Eocene-earliest Miocene forearc pelagic strata overthrust, in the Miocene, Eocene-?Oligocene fine to coarse grained clastic accretionary prism strata that originally lay trenchward of the forearc basin. However, there are several apparent inadequacies in this model, some of which are: 1) fold and thrusts trend ca. 070°, not 010°-030° as expected in a single, ESE-migrating prism model; 2) much of the Scotland District deformation is NW-vergent, as opposed to the expected ESE-vergence (trenchward), thereby requiring special structural dynamics or backthrusting during initial accretion to explain; and 3) there is no gradation in lithology or composition between the Oceanics (pelagic forearc) and Basal Complex (clastic prism) strata, except for some radiolarites in the lower Basal Complex that could, but do not appear to, relate to the Oceanics; this raises doubt over whether the two units were ever adjacent enough to form parts of the same forearc-subduction complex. In contrast, a prism-prism collision model appears to explain the geology of the Barbados Ridge better, although such a model is the subject of ongoing work by us. Much of the Basal Complex may pertain to the Proto-Caribbean Prism, rather than the Caribbean Prism, whereas the Oceanics may correspond to the Caribbean Prism. If so, N-vergence with fold-thrust trend 070° in the Basal Complex is precisely that predicted for the Proto-Caribbean prism along northern South America. Furthermore, in this model, tectonic juxtaposition between the Oceanics of the Caribbean Forearc (?Prism) and the Basal Complex of the Proto-Caribbean Prism should not have happened along Barbados' migration path until the Middle Miocene, which is the age proposed by Speed for the thrusting of the Oceanics onto the Basal Complex. Speed also concluded that the juxtaposition of the Oceanic and the Basal complexes was E-directed, in keeping with collision of two pre-existing prisms driven by Caribbean migration. The first overlap sequence lying on both is the Conset Marl of Middle Miocene age, marking the completion of this process. Finally, the backthrusting of Prism material into the Tobago Trough forearc strata (Torrini et al., 1989) would be seen in this model as the Caribbean crystalline forearc wedging into the pre-existing Proto-Caribbean Prism. Since this Middle Miocene tectonic juxtaposition and accretion of Proto-Caribbean Prism to the leading edge of the Caribbean, the two prisms have moved eastwards, only 20° different to the Basal Complex's original 070° fold trend (ie, 70° change in bulk shortening direction), by some 200-300 km relative to South America as a composite accretionary prism terrane.

The Paleogene development of the Proto-Caribbean subduction zone/thrustbelt caused progressive shallowing of the South American hanging wall margin as it was telescoped [homoclinally?] northwards onto the Proto-Caribbean lithosphere. Uplift of this hanging wall was then reversed to foredeep subsidence as the Caribbean arrived from the WNW diachronously, due to the loading effect of the Caribbean lithosphere on first the

Proto-Caribbean lithosphere immediately ahead of the Proto-Caribbean trench and then the South American lithosphere itself once the trench had been crossed by Caribbean lithosphere. Thus the culmination of uplift and onset of Caribbean load-induced subsidence on South America is predicted to, and does (Pindell et al., 1991), young eastward with the migration of the Caribbean Plate. In the eastern Serranía Oriental, the hanging wall uplift culminated in the Late Eocene and/or earliest Oligocene, producing such redeposited slope facies as the Plaisance Conglomerate of Trinidad. But the uplift was homoclinal over the whole of the Serrania, and the resulting angular discordance of only 2 or 3 degrees is not observable in the field. In addition, South American hanging wall uplift produced a Cenozoic paleobathymetric ridge projecting and plunging ENE from the northern flank of the Serranía del Interior out to about lat/long 15N/53W in the Atlantic, passing under the present position of Barbados. This submarine ridge probably was not buried by abyssal plain sedimentation until the Middle or Late Miocene, and thus separated the Paleogene clastic dispersal pattern from South America into 2 realms: (1) a deep water Proto-Caribbean realm whose complex heavy mineral signature reflects Eocene-Oligocene orogenesis in western and Central Venezuela (eg., Barbados, Tiburon ODP cores), and (2) a Guyana-Trinidadian realm on the backside (south) of this ridge that remained entirely cratonic and mineralogically mature until the Upper Oligocene onset of Nariva Formation deposition, marking the closure of the Proto-Caribbean Trough at the longitude of the Serrania/Trinidad, such that orogenic minerals could finally reach Trinidad. This underlying Atlantic basement ridge, with about 3 km of relief at the basement level, is also responsible for Barbados' present, unique subaerial exposure on the E-wardly migrating Barbados Ridge.

Establishment of the Proto-Caribbean subduction zone likely provided additional first order controls on deposition in western Venezuela, but these will be harder to identify because the effects of Caribbean-South America collision there are more coeval with those of Proto-Caribbean hanging wall uplift, and the two may interfere. But the issue is large enough for us to question past suggestions of the down-dip continuation of the Misoa depositional system. From central Venezuela to Trinidad and possibly to Barbados, the Proto-Caribbean subduction zone produced a N-vergent fold-thrust belt at the foot of the South American Plate's Paleogene hanging wall margin. We have found no evidence whatsoever that any of this accreted continental slope and rise material was thrust tectonically or shed depositionally southward onto the South American shelf margin until after it was first incorporated into the migrating Caribbean accretionary belt, and thus obducted diachronously from west to east with Caribbean elements. This occurred at about 15 to 20 km/my back to the Paleocene: Paleocene in Guajira, Late Eocene in Falcon, Oligocene in Guarico Basin, and Middle Miocene in the Maturín-Southern Basin, as shown by cooling ages on obducted terranes and foredeep subsidence history ahead of the allochthons (Pindell et al, 1991).

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