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ABSTRACT

BOW-WAVE MODEL FOR DEFORMATION AND FOREDEEP DEVELOPMENT SINCE 10 MA, EASTERN VENEZUELA AND TRINIDAD

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The SE Caribbean is commonly perceived as a site of ongoing dextral oblique collision or transpression involving a component of N-S contraction (eg., Speed, 1985). This perception is caused by the recognition of widespread SE-ward folding and thrusting across the region (eg., Case and Holcome, 1980), as well as by the ongoing subsidence in the large, asymmetric Maturín-Southern [foredeep] Basin (eg., Di Croce et al., 1999). However, the perception is not strictly true, because the relative motion between the Caribbean and South American plates in the SE Caribbean region is actually dextral slip at 20 mm/yr along azimuth 085° (N85E). The 085° azimuth derives from structural styles (eg., Robertson and Burke, 1989), seismicity (Deng and Sykes, 1995), and GPS motion studies (Perez et al., 2001; Saleh et al., in press). Further, Algar and Pindell (1993), Pindell (1994), Pindell et al. (1998), and Pindell and Kennan (2001) point to a change in structural style and seismic geometries to suggest that the 085° azimuth of relative motion has been occurring since about 10 or 12 Ma, which extends the problem back through the Late Miocene.

In order to account for this first order discrepancy, we first review several aspects of the primary structure of the SE Caribbean plate boundary zone (SCPBZ), and then consider the geological history. Aspect 1: reviewing gravity, GPS, and seismic data, we show that Caribbean crystalline lithosphere continues at depth beneath the Northern Range and Araya-Paria peninsulae metasediments to the trace of the El Pilar-Caroni Fault. We have detected the Caroni portion of this fault in Northern Basin seismic; the fault continues E-W down the center, not the northern flank, of Caroni Basin, and merges in the eastern offshore with faults of the Central Range. The buried (blind) edge of Caribbean crust may be considered as the primary petrologic plate boundary east of Gulf of Barcelona, and it is on this fault where most of the relative plate motion since 10 Ma has occurred. Further offshore, the Caroni Fault bends northward to become the crystalline edge of Caribbean crust deep within the Barbados Ridge.

Aspect 2: in the Gulf of Barcelona, wells have penetrated Pliocene-?Late Miocene section and entered Cretaceous basaltic basement, south of the Cariaco Basin/El Pilar Fault. In the Serranía Oriental, Passalacqua et al. (1995) modelled a gravity profile to show that a high density (3.0 g/cc) layer must exist at depth within the NW Serranía del Interior. Although most workers (eg., Ysaccis, 1997) have presumed that the basaltic basement in Gulf of Barcelona overththrust the Serranía, we argue instead that it is wedged into the Serranía at a Neocomian sub-Barranquín Fm level that was possibly evaporitic, like Couva Marine in the Gulf of Paria. We call this wedge the Barcelona Volcanic Wedge (BVW), and consider that prior to 10 Ma it represented like the Villa de Cura complex the leading edge of Caribbean crystalline plate; drove much of the deformation in the Serranía del Interior Oriental; and was laterally and vertically offset from Villa de Cura along the Urica Fault (dextral transtensive tear fault at that time) during oblique collision in this area between the Caribbean and South American margin. This basaltic BVW in this position (1) satisfies gravity, (2) fills the "space problem" in balanced cross sections that was discussed by, but not resolved by, Hung (2005), and (3) was isolated from the rest of the Caribbean Plate at about 10 Ma when the Cariaco-El Pilar fault system was initiated. The detachment level in the Serranía was thus defined by the level at which the BVW wedged into the stratigraphy; given this wedge of material, we see no necessary need to involve South American basement in balanced cross sections of the Serranía. One exception to this rule may be that the Dragon Gneiss of Paria Peninsula was backthrusted, along with the entire known Serranía stratigraphic section, some 30 km onto the BVW/Caribbean edge in the Middle Miocene as the latter drove southeastward into the South American stratigraphy.

Aspect 3: the foreland shortening history east of Urica Fault is as follows. In the Serranía Oriental, Middle Miocene shortening was perhaps 80 km, but since 10 Ma has been less than 5 km, and even this is probably post-4 Ma. Oblique collision thus ended at 10 Ma, with minor reactivation since the Pliocene. Likewise, at the longitude of Pedernales, Gulf of Paria and the Soldado marine area, shortening was strongest in the Middle Miocene, and again has been reactivated since the Pliocene to form the Pedernales structure, the southern diapiric trend, and the western Southern Range. In onshore Trinidad, shortening was again strongest in the Middle Miocene, followed by Late Miocene-Early Pliocene trantensional detachment of the pre-existing fold-thrust belt, which was in turn followed by transpression since the Pliocene. In the SE Trinidadian offshore and Columbus Basin, shortening has been continuous since 10 Ma, although gravitational collapse within the normal fault province has hindered the assessment of this compressive history. Taking the above observations altogether, it is clear that the N-S component of shortening between the Caribbean and South American plates largely terminated at about 10 Ma. This is supported, in the NE Caribbean, by a corresponding increase in N-S contraction between the Caribbean and North American plates since about 10 Ma.

We distinguish between a Middle Miocene Caribbean-South America dextral oblique collisional orogen, and the subsequent development of a Late Miocene-Recent E-W transcurrent plate boundary zone. Structures pertaining to each have often been lumped into a single basket from which models for steady-state deformation have been erroneously proposed. In Trinidad and Eastern Venezuela, the commonly cited "10.5 Ma unconformity" marks the boundary of these two distinct phases, although this “unconformity” is as often a low angle extensional fault detachment plane as it is an unconformity. This is because transtensional deformation within the pre-existing fold-thrust belt is a prime characteristic of the transcurrent phase. The basal strata overlying what is better called the “10 Ma surface” include La Pica and Morichito fms in Eastern Venezuela, and the Lengua, Cruse, and Manzanilla fms in Trinidad. Depending on the severity of low angle detachment where this surface is the footwall of a fault, usually shown in seismic as low angle extensional growth wedges, the basal strata on it may be as young as latest Miocene or even earliest Pliocene.

The relative motion history between the Caribbean and South America is a left-bending dog-leg in which ESE Middle Miocene oblique convergence gave way to E-W (ie, 085°) transcurrence at 10 Ma. The 085° azimuth cannot be extended further than 10 Ma, or else the basement of the SE Caribbean would improbably begin to restore onto the South American basement of central Venezuela. In addition, there is no younger time at which this change may have occurred, as regional structural development changes from folding and thrusting to widespread transtensional detachment and renewed sedimentation (requiring new accommodation space) on an eroded surface at 10 Ma (Lengua, Cruse, Manzanilla fms).

We propose a 10 Ma reconstruction that retracts the net effect of 200 km of post-10 Ma transcurrence (ie, 20 mm/yr toward 085° for 10 Ma) between the Caribbean and South America lithospheres. Because we believe the Caribbean crust extends southward to the El Pilar-Caroni Fault, the Araya-Paria and Northern Range restore westward along with the Caribbean Plate. These ranges ride passively ON the edge of Caribbean crust, which is why GPS studies show they move at full Caribbean velocity. The 10 Ma reconstruction is supported by the realignment of the blind toe of the Tobago terrane with the truncated eastern limit of the Barcelona Volcanic Wedge in the Serranía, which together defined the leading edge of the Caribbean crystalline lithosphere prior to 10 Ma. Thus, in Venezuela, the majority of relative plate motion since 10 Ma has occurred on the El Pilar Fault, with only minor motions on fault splays and bulk shear strain occurring to the north and south of that fault. One such fault to the south is the Anaco thrust, which may indicate that the pre-existing Jurassic Espino Graben hs inverted transpressionally since Late Miocene Freites deposition.

In Trinidad, the 200 km of plate motion has been shared at the surface on additional faults, not just the El Pilar-Caroni. This is due to the E-W opening of the Gulf of Paria low-angle transtensional detachment basin, perceived by many as a pull-apart basin. The Gulf of Paria Basin has its “head” (first transtensional detachment fault, which happens to be counter-regional) in the San Juan Graben of the eastern Serranía, from which the detachment deepens eastward from 6 seconds depth beneath the Guanoco High. The detachment is the same as that which had emplaced the fold thrust belt in the eastern Maturín foothills, and thus the Gulf of Paria marks a primary break in the original Middle Miocene fold-thrust belt. This has been achieved primarily under gravitational collapse of the thrust belt toward the Atlantic, possibly assisted by ramping of the fold-thrust wedge down a step at the Bohordal transfer zone, and possibly assisted by dextral shear along the El Pilar-Caroni Fault on the basin’s north side. N-S cross sections of the basin show half-graben geometry where the master fault is the North Marine Ridge footwall, which dips north beneath a foundered hanging wall of collapsed Middle Miocene fold-thrust belt comprised at least by Couva Marine, Cuche, “Chimana”, Paleocene/Chaudiere, and Brasso fms (Domoil, Gulf, Avocado, Gopa Highs). Ultimately, the master fault merges with the N-dipping El Pilar-Caroni Fault, and since late Manzanilla or Springvale time strike slip motion has shifted from the North Marine footwall to the high-angle South Boundary Fault, thereby splitting the original half graben fill into two parts. The amount of E-W extension across Gulf of Paria Basin can be estimated in two ways, the first by realigning the two sandy portions of Nariva Formation at Brighton and Nariva Hill (Eggertson, 2000), and the second by E-W balancing of transtensionally-created accommodation space above the 10 Ma surface; both give 50 to 60 km E-W offset. Faults carrying that transcurrence eastward from the basin since 10 Ma include (1) the San Fernando-Point Radix fault zone, with perhaps 40 km of motion when measured below the sub-10 Ma surface (but not above it due to supra-10 Ma surface extensional faulting south of Pt Radix fault zone); (2) the NE-dipping low angle Los Bajos “Deep” Fault, with 5 km of Late Miocene eastward transtension through the Middle Miocene fold-thrust belt, followed by 10 km of Pliocene-Early Pleistocene dextral strike slip motion on the Los Bajos Fault sensu-stricto, which cuts upward from the trailing edge of the Late Miocene hanging wall; and (3) beginning in Pliocene time, the Central Range Fault Zone with 10-15 km of dextral transpression due to its 070° orientation. The majority of motion has thus occurred on the Caroni Fault beneath Caroni Basin.

To synthesise, we apply and refine a “bow-wave” model to describe the deformations of the post-10 Ma transcurrent phase. Because the SE limit of Caribbean crystalline crust is curvilinear, veering from E-W beneath Barbados to E-W in the Caroni Basin and westward, this analogy is highly applicable. Along the “bow of the boat”, transpression occurs, like the waves generated by the boat (ie, offshore SE Trinidad). Along the flanks of the boat, N-S convergence is minimal since 10 Ma (ie, Serranía, Gulf of Paria). In addition: (1) the point defining the boundary between the bow and the flank of the “boat” has migrated east by 200 km since 10 Ma, beginning near El Pilar village in Venezuela, and now in the eastern Caroni Basin. This is why the Gulf of Paria has not been shortened during its opening; (2) the Caribbean Plate, which does NOT converge with South America, nevertheless has moved into a position where it can progressively load the Maturín-Southern Basin, albeit laterally. The lateral loading has steadily increased in both the Maturín and the Southern foredeep sub-basins because the thickness of the Caribbean forearc lithosphere increases from about 25 km below Tobago to about 100 below Margarita, which must be accommodated by progressively increasing South American flexure and hence foredeep accommodation space; (3) the small amount of N-S shortening that IS observed since the Pliocene west of central Trinidad (western Southern Range, Maturín diapir trend/Pedernales, Pirital Fault) is likely the result of 5 to 10 km of eastward reactivation of a deep (deepest?) Middle Miocene thrust plane. Such a thrust likely dips toward 330°-340° on average; thus, the reactivation is transpressional and drives up to 5 km of young N-S shortening on certain structures of the orogen. The involvement of the Central Range Fault Zone in this phase may relate to this too, caused perhaps by the initiation of South American basement involvement, whose grain matches the trend of the Central Range, or by northern Trinidad ramping up over the NW dipping basement surface of the Trinidad re-entrant.

Finally, this minor, late transpressional reactivation appears to have involved the Anaco Thrust which lies outside the Serranía Oriental re-entrant, west of the Urica Fault, and which is an inverted normal fault along the southern flank of the Espino Graben. Inversion of the Anaco Fault is thought to have occurred during Late Miocene deposition of the Freites Formation as marked by Freites onlap (Banks and Driver, 1957). However, GPS results (Perez et al., 2001) show that the El Baúl Massif is presently moving east by perhaps 3 mm/yr relative to the South American base station, which lies near the Orinoco River to the southeast of the Anaco Thrust. Because we are aware of no other structure in the interior plains that could accommodate the eastward motion of the El Baúl High to the east, we conclude that the eastward motion of El Baúl is driving the Anaco inversion. And because El Baúl resides on the hanging wall of the Jurassic Espino [half] Graben, we consider that the half graben may be inverting as a whole. Inversion on this huge scale likely relates to the crust reaching all the way west to the basement-involved Mérida Andes. A dextral transfer zone extending from near the Colombian border to Anaco is expected. Returning to the Serranía and Trinidad re-entrants, it is possible that the Anaco reactivatation trend continues eastward along the Maturín diapir trend, through Pedernales, thee Southern Range, and eastward along Galeota. If so, this entire trend may mark basement-involved reactivation of an Espino half-graben that trends farther west and east than is commonly thought.

Whether or not this late reactivation represents the onset of a third phase, acknowledging and understanding the details of the oblique collision and subsequent transcurrence in the SE Caribbean is paramount for hydrocarbon exploration, affecting interpretations of structural timing and style, maturation mechanisms and timing, and the relationship between sedimentation (provenance) and tectonics (driving causes). Further, individual components of various petroleum systems in the region have been amalgamated by the juxtaposition of terranes of quite different origin. Trinidad is not a place that can be neatly summarised by only local models of evolution; the bigger picture involving Venezuela and Barbados as well as a detailed understanding of Caribbean kinematics is absolutely required.

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