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Tectonics, basin subsidence mechanisms, and paleogeography of the Caribbean-South American plate boundary zone

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ABSTRACT

Using a mega-regional dataset that includes over 20,000 km of on- and offshore 2D seismic lines and 12 wells, we illustrate three different stages of fault formation and basin evolution in the Caribbean arc-South American continent collisional zone. Transpressional deformation associated with oblique collision of the Caribbean arc migrates diachronously over a distance of ∼1500 km from western Venezuela in Paleogene time (∼57 Ma) to a zone of active deformation in the eastern offshore Trinidad area. Each diachronous stage of pre-, syn-, and post-collisional basin formation is accompanied by distinct patterns of fault families. We use subsidence histories from wells to link patterns of long-term basinal subsidence to periods of activity of the fault families.

Stage one of arc-continent collision: Initial collision is characterized by overthrusting of the south- and southeastward-facing Caribbean arc and forearc terranes onto the northward-subducting Mesozoic passive margin of northern South America. Northward flexure of the South American craton produces a foreland basin between the thrust front and the downward-flexed continental crust that is initially filled by clastic sediments shed both from the colliding arc and cratonic areas to the south. As the collision extends eastward towards Trinidad, this same process continues with progressively younger foreland basins formed to the east. On the overthrusting Caribbean arc and forearc terranes, north-south rifting adjacent to the collision zone initiates and is controlled by forward momentum of southward-thrusting arc terranes combined with slab pull of the underlying and subducting, north-dipping South American slab. Uplift of fold-thrust belts arc-continent suture induces rerouting of large continental drainages parallel to the collisional zone and to the axis of the foreland basins.

Stage two: This late stage of arc-continent collision is characterized by termination of deformation in one segment of the fold-thrust belt as convergent deformation shifts eastward. Rebound of the collisional belt is produced as the north-dipping subducted oceanic crust breaks off from the passive margin, inducing inversion of preexisting normal faults as arc-continent convergence reaches a maximum. Strain partitioning also begins to play an important role as oblique convergence continues, accommodating deformation by the formation of parallel, strike-slip fault zones and backthrusting (southward subduction of the Caribbean plate beneath the South Caribbean deformed belt). As subsidence slows in the foreland basins, sedimentation transitions from a marine underfilled basin to an overfilled continental basin. Offshore, sedimentation is mostly marine, sourced by the collided Caribbean terranes, localized islands and carbonate deposition.

Stage three: This final stage of arc-continent collision is characterized by: 1) complete slab breakoff of the northward-dipping South American slab; 2) east-west extension of the Caribbean arc as it elongates parallel to its strike forming oblique normal faults that produce deep rift and half-grabens; 3) continued strain partitioning (strike-slip faulting and folding). The subsidence pattern in the Caribbean basins is more complex than interpreted before, showing a succession of extensional and inversion events. The three tectonic stages closely control the structural styles and traps, source rock distribution, and stratigraphic traps for the abundant hydrocarbon resources of the on- and offshore areas of Venezuela and Trinidad.

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1. Introduction

The 1500-km-long and ~500-km-wide northern margin of South America is one of the most prolific hydrocarbon regions in the world and comparable in reserves with those of the Middle East (Fig. 1A). The northern South American region contains 38 giant oil fields with a daily production greater than 4 MMBO a day. Most giant fields of the region are concentrated in the Maracaibo foreland basin of western Venezuela (Mann et al., 2006), the Eastern Venezuelan foreland basin (Duerto and McClay, 2010; Parra et al., in press; Salazar et al., 2010), and the on- and offshore foreland basin of Trinidad (Garciacaro et al., 2010, in press, Soto et al., in press) (Fig. 1A).

The area of oil and gas fields of northern South America is the site of a diachronous and oblique collision between the Caribbean arc and the passive margin of South America (Pindell and Barrett, 1990; Lugo and Mann, 1995; Mann et al., 2006) (Fig. 2). This collision created deep (4–18 km) foreland basins that range in age from Eocene to present and become progressively younger to the east.

Despite the presence of mature oil and gas fields in the onshore foreland basins, offshore basins of the Caribbean and Atlantic coasts of Venezuela and Trinidad contain only few giant fields and in general remain insignificant in comparison to the more mature, onshore production areas located on the South American continental plate – including the heavy oil belt of Venezuela (Fig. 1B). This strong contrast in the distribution of hydrocarbons in the onland continental area and offshore areas of the Caribbean Sea indicates two possibilities that we discuss in this paper: 1) underexploration of the offshore area; or 2) offshore basins whose hydrocarbon systems are fundamentally different and less productive than the well-established petroleum systems of the mature onland basins (James, 2000a,b; Mann et al., 2006.

Significance and objectives of this paper

The complex distribution of basins and oil and gas fields offshore requires: 1) a complete understanding of the relation between large-scale plate interactions between the Caribbean and South American plates; 2) tectonic controls of fault families that control the patterns and phases of basin subsidence; 3) the effects of tectonics on the regional paleogeography; and 4) the distribution of source and reservoir rocks, traps, and migration history that make up the petroleum system itself (Fig. 1).

Previous studies in this region are topical and focused on a single basin like the Tobago and Carupano basins (e.g. Robertson and Burke, 1989; Ysaccis, 1997), Grenada basin (e.g. Saunders et al., 1985; Bird et al., 1999), eastern offshore Trinidad (Boettcher et al., 2003), La Blanquilla basin (e.g. Ysaccis et al., 2000), Cariaco basin (e.g. Schubert, 1982; Ysaccis, 1997), Guajira Peninsula-Gulf of Venezuela-Bonaire basin and Leeward Antilles (e.g. Biju-Duval et al., 1982; Macellari, 1995; Porras, 2000; Escalona et al., 2003; Gorney et al., 2007), the Orinoco delta platform (e.g. Di Croce et al., 1999; Sanchez, 2001), Paria peninsula (e.g. Babb and Mann, 1999; Flinch et al., 1999), the Barbados accretionary prism (e.g. Westbrook et al., 1988; Chaderton, 2005), Venezuelan basin (e.g. Driscoll and Diebold, 1999) and offshore Colombia (e.g. Wang, 1993; Hosie, 1994; Laverde, 2000; Ruiz et al., 2000; Kellogg et al., 2005) (Fig. 1). In comparison, only a few workers have studied the timing and subsidence mechanisms on a regional scale (Mascle et al., 1990; Pindell et al., 1998; Summa et al., 2003). The popularity of topical, single basin studies is related to data availability; none of these previous workers have had access to the mega-regional data set we have assembled as part of the Caribbean Basins, Tectonics and Hydrocarbons Industry consortium (http://www.ig.utexas.edu/research/projects/cbth/) of The University of Texas at Austin.

This mega-regional database is especially useful for constraining paleogeographic maps that are critical for petroleum exploration, in particular for the distribution of source rocks and high quality reservoir sandstone. For example, Dickey (1980), Kasper and Larue (1986), Diaz de Gamero (1996), and Driscoll and Diebold (1999) have all proposed that one or more of the major (4–18 km thick) clastic depocenters along the northern South America margin represent offshore deep-water depocenters and submarine fans deposited by a north-flowing, proto-Orinoco River. All of these workers propose that the location of the north-flowing proto-Orinoco River was in the Maracaibo basin in western Venezuela during Eocene time but that the river progressively shifted eastward to its present position in northeastern South America (Fig. 2). One hypothesis is that the leading edge of the Caribbean plate and the proposed positions of the proto-Orinoco River have moved from west to east in tandem (Diaz de Gamero, 1996) (Fig. 2). Driscoll and Diebold (1999) propose that the thick depocenter centered on the South Caribbean deformed belt (Edgar et al., 1971) represents the Eocene deepwater equivalent of well-studied shallow marine-deltaic rocks of the Maracaibo basin. Furthermore, Diaz de Gamero (1996) also proposes that the Miocene sediments in the Falcon basin were deposited by the proto-Orinoco River and that this drainage progressively moved eastward along with the deformation. However, none of these studies considered the complex paleogeographic setting and periods of main mountain uplift, the link between structural styles and basin formation along the margin that has formed barriers for sedimentation, and drainage diversion from the southern foreland basins and main continental land into the Caribbean basins.

2. Present tectonic setting of the Caribbean-South American arc-continent collision zone

GEOSAT gravity data compiled by Sandwell and Smith (1997) shows six elongate submarine to subaerial belts with distinctive gravity expression that can be traced from the front of the north-south-trending eastern edge of the Caribbean plate in the Lesser Antilles island arc to the east-west-trending southern edge of the plate along the coast of South America (Fig. 3). These belts correspond to tectonic terranes that include various components of the Great Arc of the Caribbean (GAC) and South American blocks that formed the eastern edges of the eastwardly-displaced Caribbean oceanic plateau located in the central Caribbean (Pindell and Barrett, 1990; Mann, 1999) (Fig. 3). These elongate tectonic terranes include: 1) the oceanic plateau core of the Caribbean plate with oceanic crustal thickness ranging from 8 to 20 km; 2) the Cretaceous-Eocene older part of the GAC that includes the Aves Ridge and the Leeward Antilles islands; 3) the elongate back-arc basins associated with the Caribbean arc that include the Grenada, Bonaire and Falcon basins; 4) the Lesser Antilles arc that trends to the south across the islands of Margarita and Tortuga and seems to extend into the Cordillera de la Costa terranes; 5) the Tobago and Carupano forearc basins; and 6) the Barbados accretionary prism and along-strike foreland basins of northern South America (Fig. 3).

GPS-based geodetic data show that the present-day Caribbean plate moves ~20 mm/yr to the east relative to South America along east-west-striking, right-lateral strike-slip faults in Venezuela and Trinidad (Perez et al., 2001; Weber et al., 2001; Trenkamp et al., 2002) (Fig. 3). In addition to large strike-slip faults, two subduction zones are shown in the study area on Fig. 3: 1) underthrusting of the Caribbean plate at low angles (~18°) to the east and southeast occurs beneath western and central South America and forms the accretionary prism along the South Caribbean deformed belt (van der Hilst and Mann, 1994; Taboada et al., 2000); and 2)