Record and Constraints of the Eastward Advance of the Caribbean Plate in Northern South America

Joan F. Flinch and Veronica Castillo
Repsol USA, 2455 Technology Forest Blvd., The Woodlands, Texas 77381, U.S.A
(e-mails: jfflinch@repsol.com, mvcastillodeo@repsol.com).

ABSTRACT

A great variety of complex structures found in northern Colombia, northern Venezuela, the Lesser Antilles, Barbados, and Trinidad and Tobago record the eastward movement of the Caribbean plate relative to the South American plate through time. The development of these structures includes transtensional and foredeep basins as well as fold-and-thrust belts that become younger eastward since the Cretaceous. In northern Colombia, terrane accretion began in the Triassic and ended in the late Cretaceous, along the Gulf of Uraba, and the Sinu–San Jacinto Belt. Further east, the structure offshore Guajira, east from the Bucaramanga fault, is characterized by accretion involving the South American metamorphic basement. Well and seismic data in the Maracaibo Basin record the Paleogene flexure related to terrane collision and accretion. In the Gulf of Venezuela, offshore eastern Falcon, and La Vela, transtensional basins record the eastward movement of the Caribbean plate. Onshore northern Venezuela, the Villa de Cura subduction mélangé in the Cordillera de la Costa nappes represents the accretionary wedges involving ophiolites of Eocene age. The Guarico flysch records the flexure of the accretionary wedge during Oligocene time and fills the foredeep of the same age. The Cariaco, Carupano, and La Blanquilla are pull-apart basins related to a younger Oligocene–Miocene-stage strike-slip as the Caribbean plate advances toward the east. Ophiolitic obduction of the Caribbean oceanic domain onto the accreted terranes is represented by the thrusted ophiolites of Isla Margarita. The Monagas area or Serrania del Interior folded belt is a characterized Oligocene to Miocene thin-skinned thrusting involving the passive margin units of the South American plate and is overlain by the Carapita accretionary wedge. The Maturin Basin is the flexural basin associated with the loading of the Serrania del Interior thrust stack and extends to the east toward the Delta Centro and Punta Pescador areas, in the Orinoco delta and south of Trinidad. The Gulf of Paria pull-apart basin in eastern Venezuela and Trinidad developed since the late Miocene and is the easternmost strike-slip basin related to the eastward advance of the Caribbean plate, and terminates against the frontal accretionary wedge of the Caribbean plate of Barbados and Trinidad that is a Miocene to present-day shale-dominated accretionary wedge.
INTRODUCTION

Several ideas and studies propose that different structural features define the Caribbean plate boundaries. The South Caribbean plate boundary has been defined as a broad interaction zone between the South American and Caribbean plates (Burke et al., 1984). The Caribbean plate is moving in a right-lateral sense, with respect to the South American plate, while most of the eastward advance of this plate is accommodated in the north by the Cayman pull-apart and strike-slip systems of Motagua (Guatemala) and Jamaica. The southern boundary is characterized by several strike-slip systems, such as the Falcon–Aruba (Macellari, 1995), the Cariaco trough (Schubert, 1982; Mann and Burke, 1984), the Carupano–La Blanquilla (Ysaccis, 1997), and the Gulf of Paria (Flinch et al., 1999) (Figure 1).

The origin and age of the Caribbean Oceanic Plateau crust is still debatable. The radiometric age of flood basalts in offshore northern Colombia is used to date the age of the oceanic plateau, ranging from 90 to 75 Ma (Mauffret and Leroy, 1997) or 91 to 88 Ma (Sinton et al., 1998). Some authors indicate that the Caribbean Oceanic Plateau crust originated near the Galapagos Hot Spot in the Pacific (Mauffret and Leroy, 1997), and for others it has an intraplate in situ origin in Central America (Meschede and Frisch, 1998; James, 2003). The oceanic crust of the northern Colombian Basin is thought to be of pre-Coniacian age (Case et al., 1990) and is floored by a 4 to 8 km (2.5 to 5 mi) thick crust of the Caribbean Oceanic Plateau (Van der Hilst and Mann, 1994). This section consists of complex basalt flows and sills with inter-bedded sedimentary rocks (Driscoll and Diebold, 1999).

Figure 1. Plate tectonic map of the Caribbean and neighboring areas (modified from Pindell and Barret, 1990; Muehlberger, 1992; Flinch, 2003). 1000 km (621.4 mi)
Seismicity suggests an eastward-dipping subducting slab defined from 50- to 250-km (31 to 155.3 mi) depth that ends near the Santa Marta–Bucaramanga left-lateral strike-slip fault, which is associated with a cluster of deep-focus earthquakes. P-wave first arrivals reflect the change from subduction below the Plato–San Jorge Basin to strike-slip along the Santa Marta–Bucaramanga fault (Kellogg and Vega, 1984; Malave and Suarez, 1995). Seismic tomography shows two different segments of the Caribbean subducting slab: the southeast dipping southern Bucaramanga slab and the northern Maracaibo SSE dipping slab (Van der Hilst and Mann, 1994).

In the past, many geoscientists considered that the El Pilar fault represented the Caribbean–South American plate boundary (Schubert, 1982; Soulas, 1986). According to Vierbuchen (1984), right-lateral displacement of at least 150–300 km (93.2–186.4 mi) is required to explain the gravimetric field distribution. Nevertheless, the El Pilar fault (Figure 2) has an ambiguous surficial expression and shows no evidence of significant right-lateral displacement. According to Ball et al. (1971) and Gonzalez de Juana et al. (1980), the El Pilar fault is a steeply dipping normal fault that constitutes the southern boundary of the Cariaco trough and the Moron fault as the northern limit. Seismicity data do not support the continuity of the El Pilar fault through Trinidad (Speed, 1985). Moreover, Burke (1988) suggests that the plate boundary is at least 200 km (124.2 mi) wide, and Robertson and Burke (1989) support that strike-slip motion is distributed among several faults, one of them being the North Coast fault zone, located north of Trinidad (Figure 2).

Based on the relative motion of the Caribbean plate, there are different proposals for the relative speed at which the plate is moving. The present rate of convergence between the Caribbean and South American plates is about 1.3 ± 0.3 cm/yr (Van der Hilst and Mann, 1994) or 1.5 cm/yr (Kellogg and Vega, 1995). In addition, there are large discrepancies in the present motion between the subducting Nazca and the South American plates: 6.8 ± 0.2 cm/yr according to Van der Hilst and Mann (1994) and 3.5 cm/yr according to Kellogg and Vega (1995). The diachronic age of flexural basins (i.e., foredeep basins); the timing of pre-, syn-, and post-growth strata on compressional, extensional, and strike-slip basins; geochronology of metamorphic terrane accretion; and apatite fission track analysis (AFTA) cooling ages were used to track the eastward advance of the Caribbean plate. Numerous previous studies from onshore–offshore northern Colombia (Flinch et al., 2000, 2003; Flinch, 2003; Montes et al., 2010; Martinez et al., this volume), onshore western Venezuela (Audemard, 1991; Lugo, 1991; Lugo and Mann, 1995; Castillo, 2001; Audemard and Audemard, 2002; Castillo and Mann, 2006; Mann et al., 2006), onshore central Venezuela (Ostos, 1990; Ave Lallemant and Sisson 2005; Sisson et al., 2005; Armas, 2005a; Perez de Ostos et al., 2005b), onshore eastern Venezuela the Gulf of Paria and Trinidad (Kugler, 1953, 1959; Di Croce, 1995; Flinch et al., 1997; Hung, 1997, 2005; Di Croce et al., 1999), and offshore Venezuela (Ysaccis, 1997) were integrated to date the deformation along the northern margin of the South American plate and the southern accretionary wedge of the Caribbean plate.

This chapter describes the structures and timing related to the eastward advance of the Caribbean plate from west to east, relative to the South American plate, from northern Colombia to Venezuela and finally Trinidad and Tobago.

**EASTWARD ADVANCE OF THE CARIBBEAN PLATE**

**Northern Colombia**

**Sinu–Lower Magdalena**

The Sinu–Lower Magdalena area is located in the Colombian Basin along the intersection between the Central American (Panama) and southern Caribbean accretionary wedges (Figure 3). The Panama accretionary wedge is characterized by the presence of northward-vergent imbricates (northeastward verging next to the Gulf of Uraba), mud volcanoes, minor directional faults, and gas hydrates (Reed et al., 1990; Westbrook et al., 1995).

The westernmost and oldest evidences of the eastward motion of the Caribbean plate are found in northern Colombia, more precisely along the Sinu–Lower Magdalena area. Tectonics in this area record magmatic arc migration from Jurassic to Paleogene, accretion of oceanic terranes (Jurassic and Cretaceous ophiolites), and possibly the formation of island arcs (Figure 3). The offshore Caribbean and the Lower Magdalena are occupied by the Sinu–San Jacinto accretionary wedge and associated piggy-back basins. Along the highest part of the wedge, the San Jacinto Mountains expose the older Cretaceous and Paleogene rocks (Figure 3). In addition a complex zone of inversion and strike-slip...
Figure 2. Structural map of northern South America from Panama to Trinidad and Tobago (modified from Ostos, 1990; Di Croce, 1995; Audemard, 1996; Flinch et al., 1997, 1999, 2003, 2004; Hung, 1997, 2005; Ysaccis, 1997; Di Croce et al., 1999; Castillo, 2001; Audemard and Audemard, 2002; Flinch, 2003; Ostos et al., 2005b; Perez de Armas, 2005a,b; Castillo and Mann, 2006; Mann et al., 2006; Montes et al., 2010; Barrios et al., 2011; Martinez et al., 2015). 500 km (310.7 mi)
structures called the Romeral fault zone separates the accretionary wedge from the Plato–San Jorge Basin (Figures 4 and 5). Further east and using the Jurassic strata as a reference marker, the Santa Marta–Bucaramanga strike-slip fault accounts for more than 100 km (62.1 mi) of left-lateral displacement offset. The basement of the Plato–San Jorge Basin, Ayapel, Balsamo, and Sucre areas is different...
Figure 4. Structural map of northern Colombia (modified from Flinch, 2003). Cross sections A–A’ and B–B’ are shown as Figure 5A and 5B. 60 km (37.3 mi)
from the oceanic basement of the Sinu–San Jacinto area. In this eastern domain, the basement is metamorphic and consists of Precambrian granulite, migmatite, amphibolite, and biotite gneiss. Paleozoic high-grade metamorphic rocks consisting of granitic orthogneiss, hornblende and biotite gneiss, and migmatite overlie the Precambrian. Greenschist facies consisting of amphibolite, micaceous and actinolitic schist, quartzite, and marble constitute the upper part of the Paleozoic section (Ingeominas, 1997). Lower Jurassic granodiorites and granitoids intrude these metamorphic terranes. In the southern part of the Sinu–San Jacinto area, the metamorphic and magmatic basement is overlain by lower Cretaceous serpentinitized peridotite, gabbro, pillow lava, and basalt. North of the Gulf of Uraba in the southern part of the San Jacinto Mountains, metamorphic basement is overlain by inter-bedded shale, sandstone, conglomerate, and limestone of Cretaceous age. These Cretaceous strata are strongly deformed and bounded by basement faults that can be attributed to the inversion of normal fault-bounded
Cretaceous basins. Jurassic sedimentary rocks, obducted ophiolitic and possibly island arc assemblages, and granites have been mapped in this area (Figure 4). Near the Santa Marta–Bucaramanga fault, the structure of the Middle Magdalena Valley consists of a set of inverted Oligocene–Miocene basins located at the front of the Cordillera Central. Further to the north, only Miocene to Pleistocene fluvial–alluvial sediments are exposed on the surface. The western part of the Plato–San Jorge area exposes large basement-involved inversion structures similar in age and geometry to those west of the Santa Marta–Bucaramanga fault in the Middle Magdalena Valley. North of the Monteria area (Figures 4 and 5), the contact between the Sinu and San Jacinto fold belts and the Plato Basin is the Romeral fault system (Duque-Caro, 1979). South of Uraba, the Cretaceous ophiolites are involved in the deformation and also intruded by Paleogene granites. The structure of this area is characterized by thrust imbricates and related folds (Duque-Caro, 1979). In the lower Magdalena area, granites are younger toward the west, indicating the westward migration of the magmatic arc as the South American continent was growing by lateral tectonic accretion (Flinch, 2003).

Offshore Guajira
The offshore Guajira area is occupied by the so-called South Caribbean deformed belt, which is an accretionary wedge and consists of north-verging thrust imbricates and possibly island arc assemblages, and granites have been mapped in this area (Figure 4). Near the Santa Marta–Bucaramanga fault, the structure of the Middle Magdalena Valley consists of a set of inverted Oligocene–Miocene basins located at the front of the Cordillera Central. Further to the north, only Miocene to Pleistocene fluvial–alluvial sediments are exposed on the surface. The western part of the Plato–San Jorge area exposes large basement-involved inversion structures similar in age and geometry to those west of the Santa Marta–Bucaramanga fault in the Middle Magdalena Valley. North of the Monteria area (Figures 4 and 5), the contact between the Sinu and San Jacinto fold belts and the Plato Basin is the Romeral fault system (Duque-Caro, 1979). South of Uraba, the Cretaceous ophiolites are involved in the deformation and also intruded by Paleogene granites. The structure of this area is characterized by thrust imbricates and related folds (Duque-Caro, 1979). In the lower Magdalena area, granites are younger toward the west, indicating the westward migration of the magmatic arc as the South American continent was growing by lateral tectonic accretion (Flinch, 2003).

Western Venezuela

The Merida Andes, Perija, and the Maracaibo Foreland
Western Venezuela is formed by several structurally complex blocks, which were later overlain by the Cretaceous to early Paleocene passive margin facies. The Merida Andes are characterized by the presence of basement-involved thrust sheets of Paleozoic and Precambrian rocks and inverted Jurassic grabens (Audemard, 1991; Audemard and Audemard, 2002). The basement and grabens are overlain by Cretaceous to Paleogene strata, which represent a passive margin setting. The Maracaibo Basin is structurally bounded to the north by the Oca-Ancon right-lateral strike fault system (Audemard, 1996), to the west by the left-lateral Santa Marta–Bucaramanga fault system and the late Miocene–Recent thrust and strike-slip faults within the Sierra de Perija. To the south-southeast the Maracaibo Basin is limited by Pliocene–Recent thrust and strike-slip faults within the Sierra de Perija. To the south-southeast the Maracaibo Basin is limited by Pliocene–Recent thrust and strike-slip faults in the Merida Andes and to the east-northeast by Eocene-age thrust faults in the Trujillo range and the right-lateral Bocono fault (Kellogg, 1984) (Figure 2).

The structural configuration of the Maracaibo Basin is the result of multiple tectonic phases that also help to understand the tectonic advance of the Caribbean plate toward the east, relative to the South American plate. These tectonic phases have been previously described in a more regional scenario along the northern margin of South America (Burke et al., 1984; Lugo and Mann, 1995; Pindell et al., 1998; Villamil and Pindell, 1998; Di Croce et al., 1999) and are finally grouped into three major events that support the idea of the eastward advance of the Caribbean plate:

1. Pre-Cretaceous rifting phase related to the separation of North and South America, which imprinted a strong NNE-trending structural grain to the area of the Maracaibo Basin, which is defined by three large half-grabens related to El Tigre, Urdaneta, and Pueblo Viejo faults (Figure 2). These half-grabens have been interpreted in the subsurface of the Maracaibo Basin using two-dimensional (2-D) seismic data and wells that penetrated the basement (Audemard, 1991; Lugo, 1991; Lugo and Mann, 1995). It is important to note that the large mountain ranges adjacent to the present-day Maracaibo Basin (Merida Andes and Sierra de Perija) have been and can be interpreted as inverted half-graben structures because rift-related redbeds are locally thicker in these mountains than in adjacent areas (Gonzalez de Juana et al., 1980) (Figure 6).
Figure 6. (A) Faults developed during the late Jurassic rifting phase that were later inverted during the Eocene and middle to late Miocene. The number identifies the following faults: 1) Tigre, 2) Cerrejon, 3) Cuiba, 4) Urdaneta, 5) Lama–Icotea, 6) Bachaquero, 7) VLE, 8) Uribante, 9) Angaraveca, and 10) San Lazaro. (B) Main faults that are active during Eocene. Middle Eocene structures correspond with NW-striking thrust faults, possibly related to the distal thrust sheets of a major thrust belt in the northeastern part of the Maracaibo Basin (Lugo, 1991). During middle to late Eocene, fault activity was related to NW-striking normal faults, possibly related to flexural extension associated with the advancing thrust belt during the oblique collision between the Caribbean and South American plates. In addition, NNE–SSW thrust faults were developed in the Sierra de Perija area. (C) Major faults that are active during late Neogene. Two interpretations for the Oca fault have been included: 1) The Oca fault as a Pliocene normal fault interpreted from seismic reflection profiles by Audemard (1991), and 2) the Oca fault as an Holocene right-lateral strike-slip fault interpreted from field data by Audemard (1995) (modified from Castillo, 2001). 100 km (62.1 mi)
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