ACTIVE BLOCK TECTONICS IN AND AROUND THE CARIBBEAN: A REVIEW

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Abstract. The knowledge of the Caribbean and its plate boundaries has largely improved along the last 35 years despite getting progressively much more complex. The borders of the Caribbean plate are actual plate boundary zones –PBZ-, in which many tectonic blocks of different size, composition, origin and geometry, are amalgamated. These blocks somehow surround the Caribbean large igneous province or oceanic plateau. The identification of tectonic blocks along the southern Caribbean border happened first, boosted by the fact that the plate boundary was much less conspicuous compared to the others. This was favored to a great extent by the boundary cutting across continental areas. Instead, the northern boundary of the Caribbean plate became a natural laboratory for GPS Geodesy because of the apparent simpler geometry of the PBZ. Surprisingly, GPS networks have not solved all targeted kinematic issues because most of the networks are on small islands, sitting within the deformation zone. Several of these islands in fact exist because the contractional deformation made them crop out, such as Jamaica and Hispaniola. This problem is also common to the Caribbean-Atlantic PBZ. Stable reference points inside the Caribbean Sea, such as San Andrés, Providencia and Aves islands, are needed to resolve the motion between North America and Caribbean plates. From recent GPS results, the inner Caribbean plate appears as a single, almost rigid body, at least under the current 2-3 mm/a resolution of the approach. The Hess Escarpment, which exhibits a non-negligible seismic activity along its southwestern submarine termination close to Costa Rica, may be slipping in that order. Nevertheless, in the frame of the Neogene Caribbean geodynamic evolution, this submarine feature, which cuts the Caribbean ocean floor into two large pieces, juxtaposes two different Caribbean regions at naked eye. Finally, strain partitioning at different scale is common to all Caribbean plate boundaries. Block indentation-extrusion and induced subductions are also common.

Keywords: Block Tectonics, Escape, Indentation, Induced Subduction, Buoyancy, Oblique Convergence, Hess, Caribbean

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Resumen Extenso. La comprensión del Caribe y sus bordes de placa en los últimos 35 años ha definitivamente mejorado, a pesar de hacerse progresivamente mucho más complejo. De hecho, las fronteras de la placa Caribe son zonas de borde de placa –ZBP-, en las cuales bloques tectónicos de diverso tamaño, composición, origen y geometría están amalgamados (Figuras 1 y 2). Estos bloques de cierta forma rodean la meseta oceánica del Caribe. El reconocimiento de estos bloques tectónicos ocurrió primero a lo largo de su frontera sur, como consecuencia que el límite de placa era menos sobresaliente. Ello se vio ampliamente favorecido por estar la frontera en áreas continentales (Figuras 1 y 2). Por el contrario, el borde septentrional de la placa Caribe se convirtió en un laboratorio natural de geodesia satelital por GPS, como consecuencia de su aparente simplicidad estructural. Sin embargo, las redes GPS no resolvieron las incógnitas cinemáticas planteadas, dado que las redes están instaladas en pequeñas islas, las cuales están inmersas dentro de la propia zona de deformación (Figuras 1 y 2). Varias de estas islas de hecho existen por los procesos contraccionales que las han elevado fuera del mar, tal como Jamaica y Española. Igual situación se presenta a lo largo del borde de placa entre las placas Caribe y Atlántica. Puntos de referencia estable dentro del mar Caribe, tales como las islas de San Andrés, Providencia y Aves, son necesarios para resolver el movimiento relativo entre las placas Norteamericana y Caribe.

El proceso de partición de las deformaciones de distintas escalas es común a las cuatro fronteras de la placa Caribe (Figuras 3 y 4). En América Central, una franja costera, limitada por la trinchera mesoamericana y el arco volcánico activo, escapa hacia el NO, aprovechando el debilitamiento de la corteza continental de la placa Caribe por el volcanismo activo a nivel de la América Central. Igual situación es reportada en la porción norte de las Antillas Menores, donde el antearco de este sector de las Antillas se desplaza hacia el norte relativo al resto del arco volcánico. En el límite de placas Norteamérica-Caribe, la franja más septentrional de la isla Española, limitada entre las fallas Española Norte y Septentrional, al norte

y sur respectivamente, se desplaza hacia el oeste con respecto al resto de Española. En el margen sur de la placa Caribe, el bloque de Bonaire, asi como el bloque que contiene las napas Caribe sobrecorridas en el norte de Venezuela (aflorantes en Cordillera de la Costa y serranías del Interior central y oriental), hacen lo propio (Figuras 5 y 9), aunque a tasas de movimiento más lento que en los otros bordes de placa.

Por otra parte, la indentación y expulsión de bloques, así como subducciones inducidas, son procesos igualmente frecuentes en los bordes de la placa Caribe. La indentación por altos o relieves submarinos de alta flotabilidad (ej., Carnegie y Cocos), como motor de expulsiones de bloques tectónicos, ha sido invocado para el bloque Norandino y la franja costera de América Central que se extiende entre Costa Rica y Guatemala, respectivamente (Figuras 2 a 5). En otros casos, tales particiones de deformaciones han sido atribuidas a la covergencia oblicua entre la placa subductante y la sobrecorrida, como para el caso del antearco de las Antillas Menores del norte y el bloque septentrional de Española (Figura 8). No obstante, el mejor ejemplo regional de indentación-expulsión lo conforma la colisión y posterior suturación del bloque del Chocó (originalmente perteneciente al Arco de Panamá) contra la fachada occidental suramericana, que induce la expulsión de una gran porción de Suramérica, que se extiende entre el golfo de Guayaquil o graben de Jambelí, en Ecuador, y las Antillas Holandesas de Sotavento, al norte de Venezuela, incluyendo toda Colombia montañosa (Figuras 1, 5 y 9). Este proceso es relativamente joven, probablemente iniciado en el Mioceno superior, con el cierre parcial del canal del Caribe, pero hecho efectivo ya en el Plioceno (5-3 Ma), cuando ocurre el paroxismo tectónico más reciente de la Cordillera Oriental de Colombia y de los Andes de Mérida en Venezuela, al igual que la transcurrencia dextral del sistema que se extiende entre las fallas de Dolores (Ecuador) y Boconó (Venezuela). Parte del retardo en el acoplamiento efectivo del bloque de Chocó contra Suramérica, además de la oblicuidad entre los bloques en confrontación, puede deberse a la baja rigidez del indentor (Arco de Panamá), el cual sufre fuertes deformaciones internas (flexión oroclina y fallamiento sinestral de orientación NO-SE; Figura 6). El choque efectivo del bloque Chocó conlleva a la expulsión de los bloques Norandino, Maracaibo y Bonaire hacia el NNE. La subducción que conlleva a esta colisión está hoy día parcialmente fosilizada entre el bloque Chocó y Suramérica, en asociación al sistema de fallas de Romeral. Esta colisión tiene expresión superficial hasta la latitud de 4° N en Colombia, y se expresa en superficie por el alineamiento ENE-OSO de las fallas de Garrapatas, Río Verde, Ibagué y el cambio de estilo estructural del piedemonte llanero de la Cordillera Oriental de Colombia de transcurrencia dextral al sur al de transpresión dextral al norte, aproximadamente a la latitud de Santa Fé de Bogotá. En profundidad, tal cambio estructural al nivel de la losa de subducción de afinidad caribeña (y fuertemente suturada contra el bloque Chocó al sur del golfo de Urabá), coincide con el desgarre de Caldas, ubicado algo más al norte (5,6° N) que su expresión superficial que llega hasta la latitud de 4° N. Esta losa de subducción ha sido muy bien definida recientemente con base en anomalías de velocidades de ondas P, la cual se hunde hacia el ESE, bajo el bloque triangular de Maracaibo y los Andes de Mérida, hasta profundidades de 700 km, pero no alcanza extenderse más al norte de la falla de Oca-Ancón (Figuras 7, 10 y 11), la cual debe funcionar como su desgarre norte, para separarla de la subducción inducida de las Antillas de Sotavento, a la cual se asocia el cinturón de deformación surcaribeño. A partir de vectores GPS, el bloque Norandino senso stricto puede ser subdividido en hasta 13 bloques tectónicos menores (Figura 12), tal como a fines del Proyecto GEORED del Servicio Geológico Colombiano; pero a fines de modelación de deformación rígida se ha fragmentado de manera conservadora en sólo 3 subbloques (Figura 13).

Por su parte, el interior de la placa Caribe parece ser una única unidad rígida, al menos hasta la resolución de los resultados GPS del orden de 2-3 mm/a. El escarpe de Hess, el cual presenta una actividad sísmica no despreciable en su extremidad suroeste (Figuras 14 y 15), parece moverse en ese orden de velocidad. No obstante, en términos de la evolución geodinámica neógena del Caribe, este rasgo mayor submarino que corta en dos el piso oceánico Caribe en dirección NE-SO, yuxtapone dos entidades caribeñas muy dispares a simple vista. Proponemos que este accidente puede haber jugado un rol muy importante en la migración relativa hacia el este de la parte meridional caribeña, la contentiva del LIP o meseta oceánica, en el Mioceno medio y el Mioceno superior. Actualmente, se estaría iniciando una reactivación moderna, igualmente con movimiento predominantemente sinestral con componente subordinada normal;

pero esta vez ligada a la subducción del alto de Cocos de alta flotabilidad.

Palabras clave: Tectónica de Bloques, Escape, Indentación, Subducción Inducida, Flotabilidad, Convergencia Oblicua, Hess, Caribe.

INTRODUCTION

The original concept of a Caribbean plate –CA- sliding eastward with respect to the Americas in a simplistic but very creative drawer-like manner (Hess, 1962), has much evolved in the last 50 years. This model postulated early on that the very small CA plate was sort of squeezed among larger surrounding plates, and escaping like an orange pip to the east relative to the others. Said in another way, four rigid lithospheres in the Caribbean and Middle-America regions could be defined from the recorded earthquakes, active calc-alkaline volcanoes and spreading ridges: The Caribbean –CA-, Cocos –CO-, Northern America –NA- and Southern America –SA- plates (Molnar & Sykes, 1969; Figure 1). This geometry required that the northern and southern CA plate boundaries were of the roughly east-west-trending transform type, whereas the borders on the west and east were type-B subduction zones (Figure 1). From carefully observing a digital topographic-bathymetric map of the Caribbean region, three of the four CA plate boundaries are easily recognizable and traceable, in a rough manner. However, this is not the case for the southern border. The topographic expression of the Boconó fault –BF- in Venezuela is in no way comparable to that of the Motagua-Polochic Fault System –MPFS- in Guatemala. Regarding this issue, Kafka & Weidner (1979), among many others, found difficult to analyze northwestern SA using the concept of plate tectonics. Nevertheless, Molnar & Sykes (1969) already sketched rather well the major tectonic features to be taken into account in that SW corner. In the late 70s and early 80s, for instance, Schubert (1979; 1980; 1982a; 1982b; 1984) postulated that the CA-SA plate boundary in Venezuela ran along the transform Boconó, San Sebastián and El Pilar faults. Very early on, this led to the fact that several tectonic blocks (or microplates) had to be defined or identified along this southern CA plate boundary to trace the possible connection between the southern tips of the CO-CA subduction on the west and the Atlantic-CA subduction on the east. As a matter of fact, as Mann & Burke (1984) indicated, the concept of Plate Boundary Zones (PBZ) had to be applied to those two transform boundaries because of the diffuse and spread Neogene deformation over across-strike widths of hundreds of kilometers, which was first highlighted by Burke *et al.* (1980), Kafka & Weidner (1981) and Sykes *et al.* (1982). This concept was taken from that of Dewey & Sengör (1979), who adapted it from the original application developed by Luyendyk & MacDonald (1976) for deformation zones at mid-ocean ridges. As predicted by Mann & Burke (1984), only the gathering and integration of more seismic and geologic studies, in which satellite geodesy could not be considered because not yet born, had led to a better knowledge of the current Caribbean plate boundaries. This paper intends to discuss how the concept of PBZ along the Caribbean borders has been generalized not only to the transform boundaries but has been enriched by geo-scientific studies over the years. Very particularly, the definition and identification of tectonic blocks have been boosted in recent years by "unexpected" GPS-derived vectors that have led to the individualization of some of such blocks. This has been very true to the four corners of the CA plate where very complex tectonic settings are imaged at the transfer zone or connection between transform boundaries and typical subduction zones; yet not well understood at every of these four corners. To simplify the description of the four CA plate borders, this paper will present each of the borders separately in a clockwise way, starting from the western border corresponding to the CO-CA subduction.

WESTERN CARIBBEAN PLATE BOUNDARY

Most of Central America is located in the northwestern corner of the CA Plate. The western CA plate boundary is essentially a type-B subduction zone running along the Pacific coast of Central America (Molnar & Sykes, 1969), very well imaged in the Pacific ocean bathymetry by the Middle-America trench, which extends farther northwestward offshore along the Pacific coast of Mexico into the Gulf of California (Figures 1 and 2). To the southeast, the Middle-America trench and its related NE-dipping subduction extends to a transform fault, the N-S trending Panamá Fracture zone, which puts in contact the CO and Nazca –NZ- oceanic plates to the west and east of the transform respectively. The CO Plate subducts under the CA plate at a convergence rate of 70-80 mm/a, and at an azimuth of about 20-22° (DeMets *et al.* 1990; DeMets, 2001). Recently, this slip rate has been bracketed at 78 ± 1 mm/a, following the construction of a GPS station at Cocos Island, being the only current permanent station sitting on the CO plate (Protti *et al.* 2012). The subducted slab plunges at a fairly steep and average angle of about 45° (Bevis & Isacks, 1984; Burbach *et al.* 1984), although, for instance, Protti *et al.* (1994), as well as DeShon *et al.* (2006), discuss that the subducting slab may locally exhibit considerable changes in shape (dip and orientation) along southern Costa Rica, in association to the Cocos ridge (Figure 2), to which they bring a wealth of seismologic data as supporting evidence.

This convergent plate boundary drives different tectonic behaviors in the overriding (CA) plate north and south of the Cocos ridge. Its effects can be even followed to the northeast as far as into the Caribbean plate interior, affecting the Caribbean oceanic floor, as shall be discussed later in this paper. The major change in the overriding plate, as could be expected, does not coincide with the change in plate at the Panamá Fracture zone. Therefore, the subduction of the Cocos Ridge along with the CO plate is a major geodynamic process that defines the current configuration not only under the Nicoya Peninsula but also of this plate boundary, as well as the tectonic processes occurring within the overriding CA plate at larger scale.

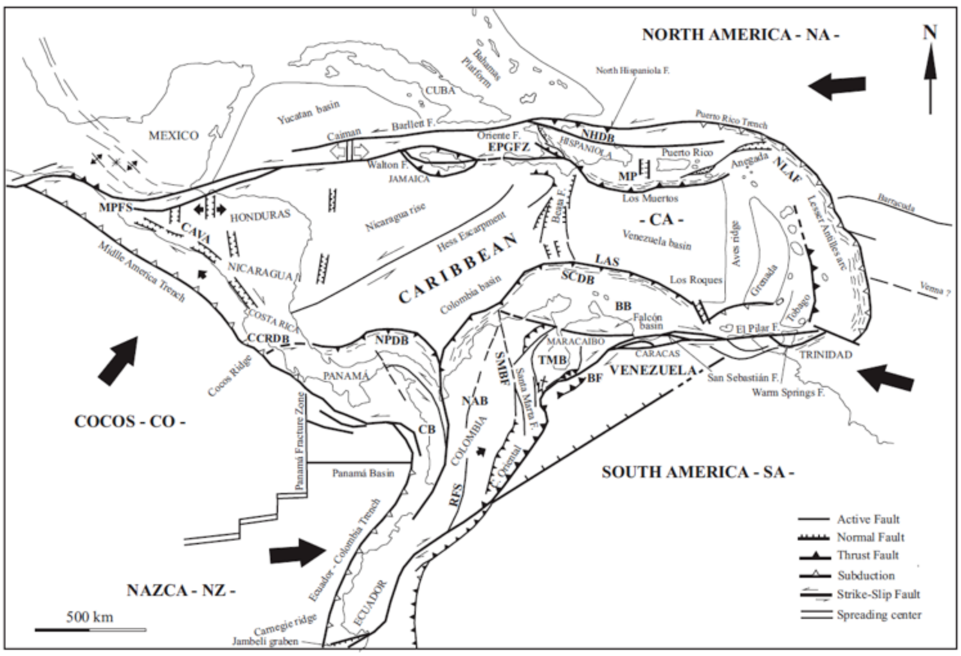

Figure 1. Major tectonic features of the Caribbean region (modified from Stephan, 1982). Abbreviations (same as in text): BB Bonaire block; BF Boconó fault; CAVA Central America volcanic arc; CB Chocó block; CCRDB Central Costa Rica deformed belt; EPGFZ Enriquillo-Plantain Garden fault zone; LAS Leeward Antilles subduction; MP Mona Passage; MPFS Motagua-Polochic fault system; NAB North Andes Block; NHDB North Hispaniola deformed belt; NLAF Northern Lesser Antilles forearc; NPDB North Panamá deformed belt; RFS Romeral Fault System; SCDB Southern Caribbean deformed belt; SMBF Santa Marta-Bucaramanga fault; TMB Triangular Maracaibo block.

Figura 1. Rasgos tectónicos mayores de la region caribeña (modificado de Stephan, 1982). Abreviaturas (iguales al del texto): BB Bloque de Bonaire; BF Falla de Boconó; CAVA Arco volcánico de América Central; CB Bloque Chocó; CCRDB Cinturón de deformación de Costa Rica Central; EPGFZ Zona de falla de Enriquillo-Plantain Garden; LAS Subducción de las Antillas de sotavento; MP Paso de la Mona; MPFS Sistema de falllas de Motagua-Polochic; NAB Bloque Norandino; NHDB Cinturón de deformación de Española Norte; NLAF Antearco de las Antillas Menores del Norte; NPDB Cinturón de deformación Nor-Panameño; RFS Sistema de Fallas de Romeral; SCDB Cinturón de deformación Sur-Caribeño; SMBF Falla de Santa Marta-Bucaramanga; TMB Bloque Triangular de Maracaibo.

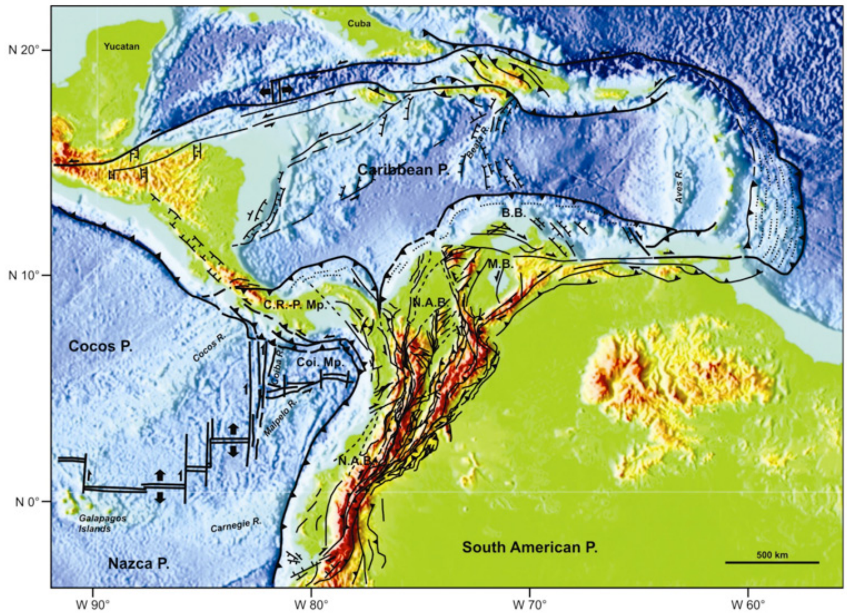

Figure 2. Major tectonic features of the Caribbean region on relief map (from López, 2010). Submarine features are well expressed.

Figura 2. Rasgos tectónicos mayores de la region caribeña en mapa de relieve (según López, 2010). Los rasgos submarinos se expresan muy bien.

Northwestern Caribbean corner north of Cocos Ridge

The northwestern Caribbean corner is wedge-shaped between the roughly NW-SE trending CO-CA subduction trench and the ENE-WSW-trending transform fault, which cuts across Central America through Guatemala (Figure 1). Here, the NA Plate juxtaposes against the northern edge of the CA Plate along a left-lateral transform fault system, known offshore as the Swan Fault Zone that bounds on the south the Cayman spreading center (Case & Holcombe, 1980), and extends westward onshore Central America as the Motagua-Polochic Fault System –MPFS- (Molnar & Sykes, 1969; Malfait & Dinkelman, 1972; Figure 1). Relative NA-CA plate motion is about 2 cm/a (Sykes *et al.* 1982; Dixon *et al.* 1998; DeMets, 2001).

Corner extension at acute fault junction

The volcanic arc associated to the CO plate subduction comprises 75 basaltic to dacitic volcanoes with documented Holocene activity, 31 of which have been active in historic times (Simkin *et al.* 1981; Carr & Stoiber, 1990). They lie along a line closely paralleling the Middle America trench, some 150 km inside the overriding Caribbean plate (Figure 3). This supports an average dip of the subduction slab of about 45° along this subducting slab stretch. The volcanic arc extends from the MPFS to central Costa Rica, onshore of where the Middle America trench looses its surface expression, down south to the Central Costa Rica deformed belt (CCRDB) as defined by Marshall *et al.* (2000). Volcanoes are closely spaced, 12-30 km apart, with elevations ranging from 100 m to more than 4000 m (Carr, 1984). In general, the volcanic front is 10-15 km wide (Carr & Stoiber, 1990).

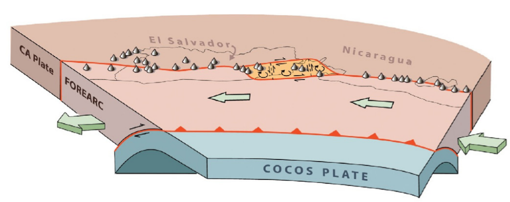

Figure 3. Strain partitioning along the Middle America trench. Cartoon showing trench parallel sliver escaping towards the NW, between CAVA and CO-CA subduction (from Alvarado *et al.* 2011).

Figura 3. Partición de deformaciones a lo largo de la trinchera mesoamericana. Bloque esquemático mostrando el escape hacia el noroeste del bloque limitado por el CAVA y la subducción de Cocos bajo el Caribe (según Alvarado *et al.* 2011).

Just south of the MPFS and east of the volcanic arc, in the mass wedge defined by the two former features, lies a system of several N-S oriented grabens (Figure 4; Dengo, 1968; Dengo & Bohnenberg, 1969; Weyl, 1980; Mann *et al.* 1990; Gordon & Muehlberger, 1994; Guzmán-Speziale *et al.* 2005; Lyon-Caen *et al.* 2006). These grabens are seismically active. In fact, Guzmán-Speziale *et al.* (2005) have derived an ongoing east-west trending extension from focal mechanism solutions resulting in N-S trending normal faulting, which in turn bounds the abovementioned grabens.

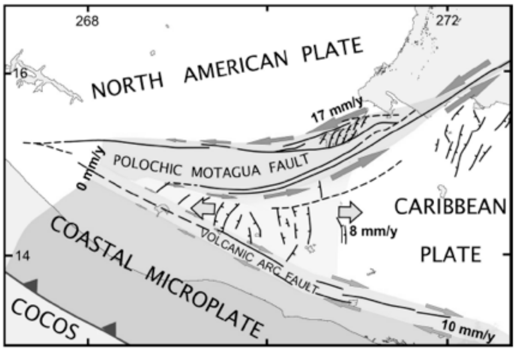

Figure 4. Corner effect between the MPFS and CAVA (from Lyon-Caen *et al.* 2006), where east-directed escape of the wedge-shaped corner induces E-W extension.
Figura 4. Efecto esquina entre el MPFS y CAVA (según Lyon-Caen *et al.* 2006), donde se aprecia que el escape hacia el este de la esquina definida por el MPFS y CAVA induce extensión con fallas normales submeridianas.

Guzmán-Speziale (2001) had previously calculated a maximum rate of opening (stretching) of 8 mm/a. This extension accounts for the CA-NA slip reduction in Guatemala from 20 to 12 mm/a near longitude 269.5° E, calculated by Lyon-Caen *et al.* (2006). On the other hand, Guzmán-Speziale *et al.* (2005), also using published CMT solutions, show that a right-lateral strike-slip system parallels the CO plate subduction and runs along the volcanic arc axis extending from México to the CCRDB. This behavior may be explained by the fact that silica and feldspar-rich rocks of continents and island arcs deform more easily at low temperatures than oceanic basalts do, as proposed by McKenzie (1972). In this case, being rocks hot at volcanic centers, regardless of their mineralogical composition, they definitely constitute a preferential weakness plane in the overriding plate.

Parallel-to-trench escaping sliver

Several authors (Fitch, 1972; Harlow & White, 1985; Guzmán-Speziale, 1995a; DeMets, 2001; La Femina *et al.* 2002; Lyon-Caen *et al.* 2006; Alvarado *et al.* 2011) have proposed that earthquakes along the Central America Volcanic Arc –CAVA- are due to oblique subduction of the CO Plate. This implies that slip partitioning takes place, in which the normal-to-subduction component of CO-CA convergence is taken by pure subduction along the Cocos slab itself, while parallel-to-trench right-lateral component is taken by a forearc sliver, named Central American coastal microplate by Lyon-Caen *et al.* (2006). This upper plate block is bounded by the CAVA and Middle America trench on the north and south, respectively (La Femina *et al.* 2002; Lyon-Caen *et al.* 2006; Alvarado *et al.* 2011; Figures 3 and 4). This microplate is moving right-laterally with respect to stable CA at 10 mm/a (Lyon-Caen *et al.* 2006). However, still in 2002, Guzmán-Speziale & Gómez (2002) pointed out that this model presented several problems, such as very small along-arc components of relative plate motion, seismogenic fault planes perpendicular to the volcanic arc for some of the earthquakes, and buttressing of the supposedly detached forearc at its northwestern end. This issue has essentially been resolved by satellite geodesy (Lundgren *et al.* 1999; La Femina *et al.* 2002; Lyon-Caen *et al.* 2006; Alvarado *et al.* 2011). The driving mechanism of such parallel-to-trench motion can be imputed to stress transfer applied by the buoyant Cocos Ridge during its subduction along with the CO plate under the CA plate, which acts as a sort of a rigid indenter into the overriding plate (Jacob *et al.* 1991; Montero, 1994a y b; Kolarsky *et al.* 1995; Silver *et al.* 1995; Suarez *et al.* 1995; Tajima & Kikuchi, 1995; Trenkamp *et al.* 2002; La Femina *et al.* 2009). Shallow subduction of the Cocos Ridge beneath the CA plate results in six major tectonic effects (Kolarsky *et al.* 1995). These effects are: a) a volcanic gap in the Costa Rican volcanic arc chain, b) a shallowing of the dip of the subducted CO plate beneath Costa Rica, c) forearc indentation of the Pacific margin of Costa Rica (between Nicoya and Osa peninsulas), d) structural inversion of forearc (Terraba) and backarc (Limon) basins, e) arching of on- and offshore acoustic basement in a direction parallel to plate convergence between Costa Rica and the CO plate, and f) a radial stress pattern around the underthrust area of the Cocos Ridge as inferred from earthquake and geologic indicators. This last effect has been recently confirmed from GPS-derived slip vectors (La Femina *et al.* 2002; Lyon-Caen *et al.* 2006; La Femina *et al.* 2009; Alvarado *et al.* 2011).

NA-CA-CO triple junction

NA-CA-CO triple junction has been classically been defined as the intersection between the MPFS and the Middle America trench in the Gulf of Tehuantepec, offshore southeastern Mexico (White & Harlow, 1993). Conversely, most workers (Muehlberger & Ritchie, 1975; Plafker, 1976; Burkart, 1978; Sánchez-Barreda, 1981; Burkart, 1983; Guzmán-Speziale *et al.* 1989; Guzmán-Speziale, 2001) agree that this triple junction is not a trench-trench-fault triple point in the classical view of McKenzie & Morgan (1969). Instead, it is a very broad zone of deformation. In that particular respect, north of the MPFS in the NA plate, the deformation zone includes the strike-slip faults of Southeastern México tectonic province (after Guzmán-Speziale *et al.* 1989; Guzmán-Speziale, 2010) as well as the Reverse-Faults tectonic province (Guzmán-Speziale & Meneses-Rocha, 2000; Guzmán-Speziale, 2010). This implies that the left-lateral slip of the MPFS on the northern side of its western fault tip is partly taken by both shortening and lateral escape inside the NA plate (Figure 1). To the south of the MPFS in the CA plate, Lyon-Caen *et al.* (2006) show that the triple junction is also complex and the deformation is distributed over a wedge-shaped, 400 km-wide area (Figure 4). This kinematic model is entirely consistent with that proposed by Plafker (1976). Besides, the extension expressed by N-S trending grabens at the acute corner between the MPFS and MAVA can be imputed to the "escape" effect imposed by the strike-slip motion of both bounding faults: left-lateral along the MPFS and right-lateral on MAVA (Figure 4). In that respect, DeMets *et al.* (2010) indicate that distributed east-west extension of at least 5 ± 1 mm/a occurs in areas of western Central America. The result is consistent with geologic and seismic observations of east-west extension across central and western Honduras and Guatemala (Manton, 1987; Guzman-Speziale, 2001; Lyon-Caen *et al.* 2006).

Central America south of Cocos Ridge

Panamá microplate

The tectonic regime of the southern Caribbean region in southern Central America is dominated by the interaction of four major plates (CA, SA, CO, and NZ; Figure 1). An added level of complexity is introduced by the Isthmus of Panamá, which acts as a separate Panamá or Chocó-Panamá microplate (Adamek *et al.* 1988; Kellogg & Vega, 1995; Lundgren *et al.* 1999; Taboada *et al.* 2000; Trenkamp *et al.* 2002). The Panamá block is considered a broad zone of deformation (Pennington, 1981) with diffuse boundaries. A suture zone between the Chocó and the North Andes Block –NAB- defines the eastern boundary. The Uramita fault zone in the north and the Istmina fault zone in the south (Taboada *et al.* 2000; Suter *et al.* 2008) mark an island arc-continental collision of Neogene age (Figure 5; Keigwin, 1978; Lonsdale & Klitgord, 1978; Keigwin, 1982; Keller *et al.* 1989). Offshore southern Panamá, the boundary between the Panamá microplate and the NZ plate is delimited by the Southern Panamá fault zone or Southern Panamá deformed belt, a diffuse left-lateral fault zone that accommodates the eastward motion of the NZ plate, and north-south convergence (Jordan, 1975; Hey, 1977; Adamek *et al.* 1988; Silver *et al.* 1990; Kolarsky & Mann, 1995; Mann & Kolarsky, 1995; Westbrook *et al.* 1995). The western boundary is a broad zone of distributed left-lateral shear in central Costa Rica (Montero-Pohly & Dewey, 1982; Fan *et al.* 1991; Protti & Schwartz, 1994; Montero-Pohly, 1994a y b; Montero *et al.* 1998; Lundgren *et al.* 1999; Marshall *et al.* 2000; Montero-Pohly, 2001), between the CA and the Panamá microplate, named the Central Costa Rica Deformed Belt –CCRDB. This belt seems to act as a crustal (lithospheric?) left-lateral lateral ramp, accommodating shortening and left-lateral slip simultaneously but not necessarily on the same tectonic features.

North Panamá deformed belt –NPDB-

The north Panamá deformed belt –NPDB- defines the northern boundary of the Panamá microplate (Silver *et al.* 1990; (Figures 1 and 5). Convergence at the NPDB is a consequence of: a) slow southwestward convergence of the CA plate with the Panamá microplate (Kellogg & Vega, 1995; Trenkamp *et al.* 2002); b) ductile buckling deformation (oroclinal bending) generated by eastward motion of Panamá against the North Andes microplate –NAB- (Wadge & Burke, 1983; Silver *et al.* 1990; Montes et al, 2012); c) escaping deformation along NW-SE trending left-lateral strike-slip faults from the collision with the SA plate (Wadge & Burke, 1983; Mann & Burke, 1984; Mann & Corrigan, 1990), and d) the NE-directed stresses (backarc thrusting) transferred from the subduction of the buoyant, aseismic Cocos Ridge beneath southern Costa Rica, between Nicoya and Osa peninsulas (Jacob *et al.* 1991; Kolarsky *et al.* 1995; Silver *et al.* 1995; Suárez *et al.* 1995; Tajima & Kikuchi, 1995; Trenkamp *et al.* 2002).

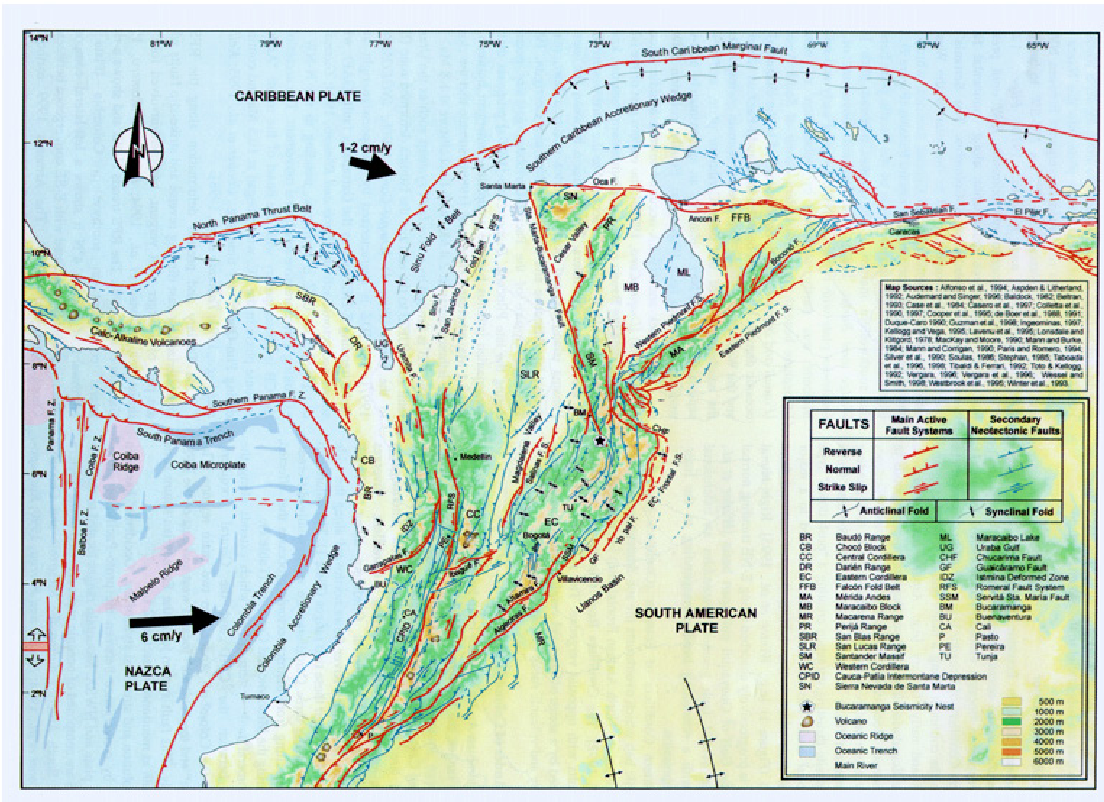

Figure 5. Structural map of the northwestern corner of South America (from Taboada *et al.* 2000), showing the collision and suturing of the Chocó block (CB, corresponding to the southern part of the original Panamá Arc) against SA. Major faults in Colombia and Venezuela are shown.

Figura 5. Mapa estructural de la esquina noroeste de Suramérica (según Taboada *et al.* 2000), donde se muestra la colisión y suturación del bloque del Chocó (CB, correspondiente al sector sur del Arco de Panamá original) contra América del Sur. Se identifican las fallas principales en territorio colombiano y venezolano.

The convergent nature of the NPDB has long been recognized (Bowin, 1976; Pennington, 1981; Wolters, 1986; Adamek *et al.* 1988; Silver *et al.* 1990; 1995). GPS measured convergence rates between the Panamá microplate and the CA plate are to the southwest at 7 mm/a (Trenkamp *et al.* 2002). Substantial evidence for active convergence along this boundary includes the 1991 (Ms 7.5) Valle de la Estrella earthquake in eastern Costa Rica (Jacob *et al.* 1991; Soulas, 1991; Plafker & Ward, 1992; Goes *et al.* 1993; Protti & Schwartz, 1994; Suárez *et al.* 1995), active folding in the NPDB (Silver *et al.* 1990; 1995), a possible subduction zone boundary marking the shallow subduction of the CA plate beneath the Panamá microplate (Bowin, 1976; Wolters, 1986), and intermediate-depth earthquakes delineating a slab (Adamek *et al.* 1988; Camacho *et al.* 2010).

True subduction or pseudo-subduction?

The controversy centers on the existence (or lack) of a Wadati-Benioff zone depicting the subducted slab of the CA plate beneath the Panamá microplate. Although Adamek *et al.* (1988) show a cross section of relocated hypocenters that images a subducting slab, they reject the NPDB as a subduction zone due to the lack of volcanism and absence of events below 70 km. Given the slow convergence rate and the recent initiation of subduction (probably < 10 Ma old) along the NPDB, in addition to the fact that the CA plate is more rigid than a typical oceanic crust because of being a thickened crust (Reflector B"; Large Igneous Province –LIP- or oceanic plateau; Edgar *et al.* 1971; Donnelly, 1973; Case, 1975; Houtz & Ludwig, 1977; Biju-Duval *et al.* 1978; Burke *et al.* 1978; Sinton *et al.* 1998; Hauff *et al.* 2000), the slab has not yet sunk enough to produce dehydration and subsequent volcanism. Furthermore, it may never produce any volcanism since it will keep as a shallow subduction while the subducting CA slab corresponds to a thickened –more rigid and buoyant- oceanic crust. The same situation and ongoing controversy is posed for the Southern Caribbean deformed belt –SCDB- along northwestern Venezuela.

Several previous studies (Adamek *et al.* 1988; Silver *et al.* 1990) concluded that the oblique convergence between the CA plate and the Panamá block had not formed a Wadati-Benioff zone but merely demonstrated an amagmatic overthrusting of the Panamá microplate onto the CA plate. Although the NPDB in central Panamá is an area of moderate seismicity, previous studies using teleseismic data from earthquakes in the NPDB were limited by the dearth of events of magnitude >5.0. Camacho *et al.* (2010), using data from local and regional networks, present credible evidence of a Wadati-Benioff zone rather than simple underthrusting for the Caribbean margin of Panamá. Earthquakes locate below the Moho depth of 28 km, within the mantle, and to depths of 80 km. Although Silver *et al.* (1990) point out that the subduction of the CA plate under Panamá is a nonself-sustaining subduction zone in the sense described by McKenzie (1977), there is evidence of a subducted slab to a depth of at least 80 km.

To exacerbate this discussion, Stephan (1982) and Stephan *et al.* (1986) proposed to call these festoons of the NPDB and SCDB, as well as the one of Hispaniola-Puerto Rico (corresponding to the Los Muertos trench) pseudo-subductions, arguing that they exhibit little intermediate seismicity to none, and absence of volcanism. These authors proposed that the festoons were just produced by plate-scale bending, across the CA plate in the E-W direction in their view, and subsequent overriding over the CA plate. It is worth mentioning that this proposal is far ahead in time of inception of the flat subduction concept. Rather, we consider them as incipient induced subductions (Audemard, 1993; 1998; 2009), thus justifying their youth and shallow depth into the mantle, as supported by the absence of generalized intermediate seismicity and the lack of volcanism. This second aspect can be well explained by the flat slab geometry by itself. So could shallow seismicity if the subduction is very young. In our view, these two "alleged" subductions are induced from other major geodynamic processes, rather than driven by mantle convection. In the case of the NPDB, the Panamá microplate is overriding the CA plate because of the northward diachronic and progressive collisional and later suturing processes of the southern part of the original Panamá block (known as the Chocó-Baudó block, in Colombia) against the NW corner of SA and subsequent progressive internal (oroclinal-type?) bending of the non-rigid Panamá microplate. The bending, as alleged by Stephan *et al.* (1996), in our view, should account for a significant part of the shortening taken in by the NPDB, which has not stopped yet while the NPDB and SCDB festoons do not collide. In the case of the SCDB, the festoon is produced by the NNE-directed escape of the North Andean Block (NAB; in the sense of Ego *et al.* 1995), which adds to the N-S shortening affecting the CA plate, due to the weak (~4 mm/a) SSE-directed convergence between the Americas since the Oligocene (Ladd, 1976; Sykes *et al.* 1982; Burke *et al.* 1984). Audemard (2009) proposes that the Leeward Antilles Subduction –LAS- is rather young and is different from the subduction that led to collision of the Panamá Arc against western South America along the Chocó Block and San Jacinto terranes.

Panamá microplate rigidity

As to the internal deformation of the Panamá microplate, Montes *et al.* (2012)'s reconstruction requires that the Panamá microplate used to be broken down on smaller blocks that rotated around vertical axes. They also conclude that the current "S" shape of the Isthmus may have been achieved by oroclinal bending where discrete faults separated relatively rigid blocks and helped their rotation. Left-lateral offset of the Campanian to Eocene belt between 38 and 28 Ma, opening of the Canal Basin at ~25 Ma (Farris *et al.* 2011), and initiation of the NPDB (Silver *et al.* 1990) at 15 Ma (Montes *et al.* 2012), as the Panamá-Chocó Block was first thrust to the NW onto the CA plate (Kellogg & Vega, 1995; Camacho *et al.* 2010) are all results of oroclinal bending of the arc. From their restoration, Montes *et al.* (2012) agree with Farris *et al.* (2011), that the gap between the former Panamá-Chocó block and continental SA narrows at about 25 Ma and effectively disappears at about 15 Ma. This would coincide with the onset of shortening along the NPDB estimated by Montes *et al.* (2012). This would also place the age of effective collision of the Baudó-Chocó block against the Pacific continental edge of the SA plate not earlier than late Miocene. The final suturing of both blocks is actually still underway at the Uraba gulf (Caribbean Colombian coast), implying that effective stress transfer of the collision from the Baudó-Chocó block to the future NAB may well have happened in the Pliocene, as suggested by Audemard (1993; 1998; 2009) and supported by a wealth of geologic data collected in Venezuela (Audemard, 1993; Audemard & Audemard, 2002; Audemard, 2003; 2009). Such a delay of several millions years between first stages of collision and effective suturing, responsible for the NNE-directed escape initiation of the NAB, can be accounted for by: a) acute angle of attack between the former Panamá Arc and the Pacific coast of South America, with a first impact zone tending to the southern tip of the arc; b) Oroclinal bending of the Panamá Arc (mainly preserved in the current Panamá microplate) attests to the low rigidity of the arc, which should surely retard the effective stress transfer of the Panamá Arc collision against continental South America while the indenter is internally deforming itself; and c) N-S diachronism of the effective suturing of the Chocó-Baudó block against northwestern South America, and freeing itself from the Panamá Arc. Certain refinements in the chronology of the escape of the North Andes Block at regional scale can be proposed. The onset has occurred at some time between the beginning of Chocó accretion (Middle Miocene; Duque-Caro, 1990), the effects of this in the Eastern Cordillera of Colombia (10.5 Ma, Cooper *et al.* 1995), similar to the Mérida Andes (Audemard & Audemard, 2002), and development of the Middle America land bridge, showing coupling of Chocó with South America. First Caribbean-Pacific planktonic faunal divergence occurred by 6.2 Ma (Keller *et al.* 1989), mammal exchange occurred by 3.3 Ma (Gingerich, 1985), planktonic faunas show Caribbean-Pacific separation by 3.1 Ma (Keigwin, 1978) and final gateway closure occurred by 1.8 Ma (Keller *et al.* 1989).

From the above discussion, it remains clear that the Panamá microplate is not a rigid block. Rather, it amalgamates a set of NW-SE elongated slivers at least in Panamá (Figure 6); split apart by equally trending left-lateral active faults (Silver *et al.* 1990; Rockwell *et al.* 2010). Furthermore, the microplate progressively bends through time, becoming a more tightly bent orocline, with an apex pointing roughly to north. Many of the major faults of Panamá have long been recognized in the geology and geomorphology (Jones, 1950; Woodring, 1957; Stewart *et al.* 1980), although they were not considered Holocene (Cowan *et al.* 1998; Cowan, 1999; Schweig *et al.* 1999; Petersen *et al.* 2005). Among these, the Pedro Miguel, Limón, and related faults comprise a zone that extends from the southern flank of the Sierra Maestra in north-central Panamá southward for at least 40 km, crossing the Panamá Canal between the Miraflores and Pedro Miguel Locks, and extending southward offshore into the Gulf of Panamá (Figure 6; Rockwell *et al.* 2010).

Timing of North Andes Block escape

Further constraint on the North Andes Block – NAB- escape is provided by the dextral-slip onset of the Dolores-Pallatanga-Algeciras-Guaicáramo-Boconó fault system. This brittle system is responsible for allowing the free NNE-directed escape of the NAB (Case *et al.* 1971; Dewey, 1972;

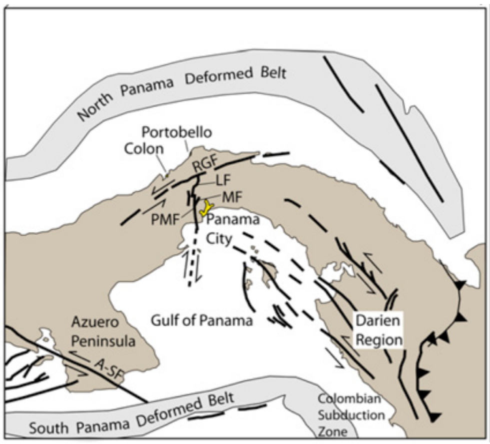

Figure 6. Structural Location map of central Panamá, showing the Pedro Miguel (PMF), Limón (LF), Rio Gatún (RGF), Miraflores (MF), and Azuero-Sona (A-SF) faults (from Rockwell *et al.* 2010). This significant brittle deformation in NW-SE trending slivers, attests to the low rigidity of the Panamá microplate.

Figura 6. Mapa de ubicación estructural de Panamá central, mostrando las fallas Pedro Miguel (PMF), Limón (LF), Rio Gatún (RGF), Miraflores (MF), y Azuero-Sona (A-SF) (según Rockwell *et al.* 2010). La importante deformación frágil en bloques elongados NO-SE, atestiguan la baja rigidez de la microplaca de Panamá.

Pennington, 1981; Stephan, 1982; Audemard, 1993, 1998; Freymueller *et al.* 1993; Ego *et al.* 1996). Opening of the pull-apart Jambelí Graben in the Gulf of Guayaquil, Ecuador, is related to this northward escape of northwestern South America (Audemard, 1993, 1998; Figure 1). This author attributes basin formation to localized transtension in a horsetail splay structure at the SW termination of that very long fault system, nearing the Nazca trench at the NZ-SA-NAB triple junction. Basin fill began in the Late Miocene (Benítez, 1986). If SCDB is a result of the NE escape of the North Andes Block as proposed by Audemard (1993; 1998; 2009), this major feature may shed additional light on the escape onset. Indications that SCDB is relatively young come from: (1) seismic profiles and bathymetry (Silver *et al.* 1975; Talwani *et al.* 1977; Mascle *et al.* 1979; Kellogg & Bonini, 1982; Ruiz *et al.* 2000); (2) Pliocene-Pleistocene deformation of the accretionary prism west of Santa Marta (Ruiz *et al.* 2000); (3) lack of significant sedimentation in Los Roques canyon in the last few tens of millions years; (4) paucity of intermediate thrust earthquakes, up to 200 km deep, under the Maracaibo Basin (Orihuela & Cuevas, 1992; Malavé & Suárez, 1995); and (5) Recent tomographic images from Bezada (2010) and Bezada *et al.* (2010) show that no cold discontinuity goes beyond 100 km deep north of the Oca-Ancón Fault system, while a very large anomaly is south of this fault (Figure 7), which deepens in ESE direction instead, and to which the seismic Bucaramanga nest seems related.

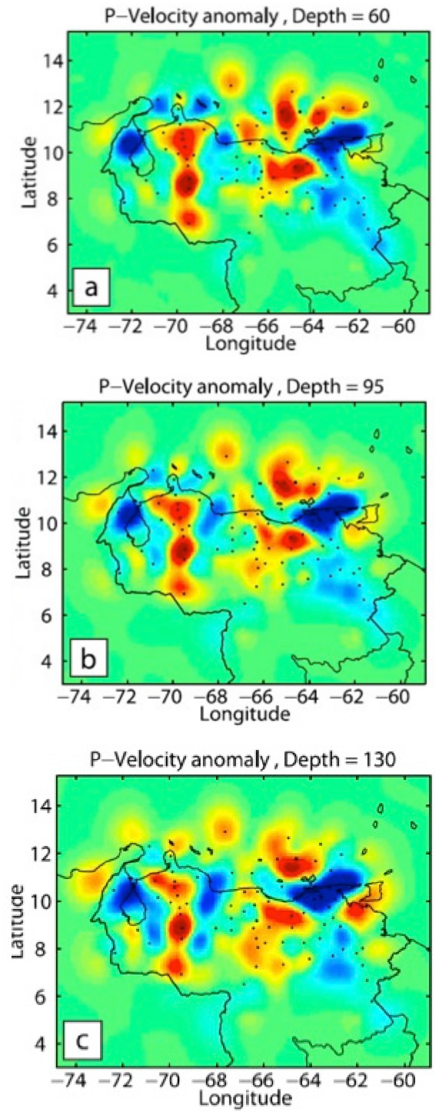

Figure 7. P-wave velocity anomalies in the shallowest 130 km of the model (from Bezada *et al.* 2010). The blue areas are considered colder than the mantle and the red ones hotter. North of the Oca-Ancón fault –OAF, the colder areas do not show beyond 130 km in depth. Then, there is no evidence of a deep cold oceanic slab in association with the SCDB.

Figura 7. Anomalías de velocidad de la onda P en los primeros 130 km de profundidad del modelo (de Bezada *et al.* 2010). Las áreas azules se consideran más frías que el manto circundante y las rojas más calientes. No hay áreas frías al norte de la falla de Oca-Ancón –OAF- a profundidades superiores a los 130 km. Entonces, no hay evidencia de una losa de subducción fría profunda asociada al SCDB.

Forces driving NAB escape

Other driving mechanisms than the Panamá-Chocó collision against the SA Pacific face have been invoked or put forward to induce escape of the NAB. Pennington (1981) and Gutscher *et al.* (1999) proposed that the arrival of the aseismic Carnegie Ridge at the Ecuador-Colombian trench initiated the escape, very similar to Cocos Ridge under Costa Rica (Figure 2), while Kellogg & Mohriak (2001) proposed that the rapid oblique subduction of the NZ plate and the Carnegie Ridge might be driving together the northeastward escape. Elastic modeling of observed horizontal displacements in the Ecuador forearc is consistent with partial locking in the subduction zone and partial transfer of motion to the overriding SA plate (Trenkamp *et al.* 2002; White *et al.* 2003). Gutscher *et al.* (1999) and Bourdon *et al.* (2003) noted an apparent shallowing in the subduction of the NZ plate in NW Ecuador based on the distribution of hypocenters obtained from a local seismic network as well as the nearly complete absence of intermediate depth seismicity between 2.5° N and 1° S. They hypothesized that this shallow subduction zone was the subducted extension of the Carnegie Ridge. Pennington (1981), Gutscher *et al.* (1999), Kellogg & Mohriak (2001), and Trenkamp *et al.* (2002) proposed that the subduction of the thick buoyant crust of the Carnegie Ridge resulted in increased coupling with the overriding South American plate. Scholz & Small (1997) proposed that even the subduction of a large seamount would increase the normal stress across the subduction interface, thereby increasing seismic coupling. The inferred continuation of the Paleo-Carnegie Ridge beyond the trench (Gutscher *et al.* 1999) has a NE orientation and is compatible with the displacement direction of the North Andes. GPS measurements of ENE rapid subduction (58 ± 2 mm/a) of the NZ plate and Carnegie Ridge under South America at the Ecuador trench are also consistent with the northeastward displacement of the North Andes (Trenkamp *et al.* 2002).

Egbue & Kellogg (2010) propose that stable SA (Guyana shield) is acting mechanically as a rigid buttress for the margin-normal component of NZ-SA convergence, while the margin-parallel component of the NZ-SA America convergence is driving the North Andes northeastward toward the relatively free CA-North Andes boundary. For extrusion tectonics to occur, the block being impinged on cannot be bilaterally confined (Tapponnier *et al.* 1982). The escape direction is always toward the free boundary, which in the northern Andes is towards the Caribbean, as previously indicated for the NAB by Audemard (2003) after applying the same concepts.

As a matter of fact, we are still inclined to support the Baudó-Chocó block collision against NW SA as the main driving cause for the NAB escape. However, the buoyant Carnegie ridge subduction, as well as the convergence obliquity between the NZ plate and the SA freeboard, may substantially add to it. From the time of initiation of the Carnegie ridge collision, discussed just after this, it would seem that this collision comes into the escape story somehow late, at the Plio-Pleistocene boundary. In the same way, NZ-SA convergence obliquity cannot be the driving force of the NAB escape because the latter would be a process as old as the own NZ plate subduction.

Gutscher *et al.* (1999), based on examination of the basement uplift signal along a trench-parallel transect, and adakite volcanism along the Ecuador arc, proposed that the ridge reached the trench and has been colliding with South America for at least 2 Ma and most likely for the last 8 Ma. Rather, Spikings *et al.* (2001) from plate convergence rate calculations, suggest the Carnegie Ridge collided with the Ecuador Trench at ~15 Ma. Subsequently, Garrison & Davidson (2003) among others, documented that adakites in the Andes can be explained by the state of equilibrium that exist between the mantle wedge derived arc magma and the thickened garnet-bearing continental crust and therefore do not require melting of subducted oceanic slabs. Pedoja (2003) and Cantalamessa & Di Celma (2004), based on analyses of marine terrace uplift, independently postulated that ridge subduction began at the Pliocene-Pleistocene boundary (1.8 Ma). Long before, Lonsdale & Klitgord (1978) proposed that the Carnegie Ridge arrived at the trench about 1 Ma, based on interpretation of magnetic anomalies and bathymetry of the CO and NZ plates.

NA-CA PLATE BOUNDARY

This PBZ is the one that best images how the definition of faults, and later identification of discrete blocks, have evolved through time, recognizing step by step the very large complexity of the PBZ. Due to the fact that this PBZ slaloms through islands of diverse size and varied geology, satellite geodesy was sought and put in practice rather early, compared to the rest of the Caribbean region, to bring insights in the active tectonics of this NA-CA plate boundary. Nevertheless, the different block entities are still being (re-)defined with the help of GPS networks while the others in larger continental areas or blocks are roughly better known at present because major active bounding tectonic features are better and/or more exposed. As clearly expressed by Dixon *et al.* (1991), over the past two decades, a fundamental objective of neotectonic research in the Caribbean region has been to determine the present motion of the CA plate using Global Positioning System (GPS) technology.

Prior to the use of GPS for measuring present plate motions, CA-NA plate velocities were estimated from conventional marine geophysical and seismologic observations. The predictions of the latter estimates varied widely, ranging from 11 ± 6 mm/a of sinistral strike-slip motion (Jordan, 1975; Stein *et al.* 1988; DeMets *et al.* 1990; 1994) to 37 ± 10 mm/a (95% uncertainty) of oblique convergence (Sykes *et al.* 1982) along much of the CA-NA plate boundary. The wide range of predicted motions resulted from disagreements about which, if any, data constituted reliable measures of CA plate motion, including whether earthquake slip vectors from the Middle America and Lesser Antilles trenches are systematically biased by strain partitioning (Sykes *et al.* 1982; Stein *et al.* 1988; DeMets, 1993; 2001; Deng & Sykes, 1995) and whether magnetic anomalies from the Cayman spreading center record the full CA-NA rate (Sykes *et al.* 1982; Rosencrantz & Mann, 1991). The first unambiguous geodetic determination of present day CA plate motion was reported by Dixon *et al.* (1998) from GPS measurements made at three sites during the early to mid-1990s. Relative to sites on the NA plate, all three stations moved 18-20 mm/a, ~80% faster than predicted by the NUVEL-1A model (DeMets *et al.* 1994), widely used at the time. Subsequent geodetic measurements at additional sites in the eastern Caribbean confirmed this result (MacMillan & Ma, 1999; DeMets *et al.* 2000; DeMets, 2001; Sella *et al.* 2002) and further demonstrated that CA-SA plate motion significantly exceeds that predicted by NUVEL-1A (Weber *et al.* 2001; Sella *et al.* 2002). DeMets *et al.* (2010) stress that it is thus now well established that the CA plate moves significantly faster than predicted by NUVEL-1A. On top of this, these authors express, and largely discuss, that all previous geodetic models of Caribbean plate motion have had two significant, though unavoidable, drawbacks related to their underlying geodetic data.

Structure of the NA-CA PBZ

In terms of plate boundary structural complexity, the understanding of the NA-CA plate boundary evolved from a simple fault system (Molnar & Sykes, 1969; Jordan, 1975; Ladd, 1976; Plafker, 1976; Pennington, 1981) to the complex PBZ as recently defined, for instance, by Benford *et al.* (2012 a and b; Figure 8), but was already rather well depicted by the review of Mann & Burke (1984), which was slightly improved in that of Mann *et al.* (1990). This NA-CA plate boundary zone consists of a 100-250-km-wide seismogenic zone of mainly left-lateral strike-slip deformation extending over 2000 km along the northern edge of the Caribbean Sea. The dominant structural element in the central plate boundary zone is the Cayman trough (Figures 1 and 2), a submarine pull-apart basin formed by at least 1100 km of oceanic spreading at the Mid-Cayman spreading center, a 100-km-long jog between left-lateral faults of the plate boundary (CAYTROUGH, 1979). The spreading center has been active since the Middle Eocene and is currently spreading at a rate of about 15 mm/yr (Rosencrantz *et al.* 1988). In the western Cayman trough, the plate boundary appears to be a single, active strike-slip fault exhibiting locally complex restraining bends (Mann *et al.* 1991a). To the east of the Cayman trough in Jamaica, Hispaniola, and Puerto Rico, the plate boundary is especially wide with a seismogenic zone up to 250 km wide at the longitude of the island of Hispaniola. In addition, the NA-CA PBZ is essentially left-laterally transforming west of Central Hispaniola (west of the Beata ridge longitude), while it functions as an oblique subduction from eastern Hispaniola eastward up to its connection to the Lesser Antilles subduction, near the Virgin Islands (Dolan *et al.* 1998; Mann *et al.* 2002). Ten Brink *et al.* (2009) define this PBZ along Hispaniola and Puerto Rico as a "bivergent crustal wedge".

A PBZ of two-parallel fault zones

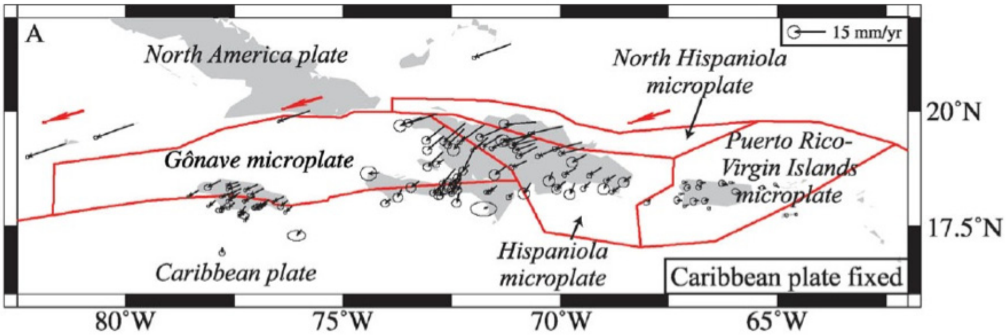

Figure 8. Tectonic blocks in the CA-NA PBZ defined by Benford *et al.* (2012b) from GPS data.

Figura 8. Bloques tectónicos definidos en la zona de frontera de placas CA-NA por Benford *et al.* (2012b) a partir de datos GPS.

Discrete strike-slip fault zones, which are throughgoing or mappable for hundreds of kilometers, have been recognized along this PBZ. They are linked by either transpressional (push-up or restraining bend) segments or transtensional (pull-apart basin) segments. In this respect, the NA-CA transform boundary somewhat resembles California (Allen, 1981). In the NA-CA PBZ, these faults are (Mann and Burke, 1984; their Figure 4) from west to east: (1) the Chixoy-Polochic Fault Zone of Guatemala and southern Mexico (Burkart, 1978, 1983, Erdlac & Anderson, 1982); (2) the Motagua Fault Zone of Guatemala (Plafker, 1976); (3) the Swan Fault Zone of the Cayman Trough (Case & Holcombe, 1980); (4) the Oriente Fault Zone of the Cayman Trough (Case & Holcombe, 1980); (5) the Duanvale Fault Zone of Jamaica (Horsfield, 1974; Mann & Burke, 1980); (6) the Enriquillo-Plantain Garden fault zone –EPGFZ- of Jamaica and Hispaniola (Mann *et al.* 1983); (7) the Septentrional fault zone of the Dominican Republic (Bowin, 1975; Mann *et al.* 1984); and (8) the Puerto Rico trench fault zone (Perfit *et al.* 1980; Case & Holcombe, 1980). These Neogene faults are arranged into two distinct but rather parallel left-lateral strike-slip zones. A northern strike-slip zone strikes westward from the Puerto Rico trench and passes through: (1) Northern Hispaniola (Septentrional fault zone); (2) along the southern margin of Cuba (Oriente Fault Zone) and (3) into a zone of sea-floor spreading (Mid-Cayman spreading center) at the center of the Cayman trough. On the other hand, the southern strike slip zone extends westward from Central Hispaniola (Enriquillo fault zone) and passes through: (a) the southern peninsula of Haiti ("Décrochement senestre sud Haïtien" of Calmus, 1983, and Bizon *et al.* 1985; also known as Plantain Garden fault zone, which extends westward into Jamaica across the Jamaica passage); (b) Jamaica as a series of reverse and thrust faults, which conforms a transpressional bend. The main left-lateral strike-slip fault through this bend, as revealed by GPS vectors, runs east-west across Jamaica axially or in the southern half of the island (DeMets & Wiggins-Grandison, 2007) or offshore south of the island (Benford *et al.* 2012b); (c) the southern boundary of the Cayman trough (The Walton and Swan fault systems, east and west of the spreading center, respectively) and (d) the onshore prolongation of the Swan Fault system across onshore Guatemala (Motagua-Polochic fault system –MPFS-). This second southern left-lateral strike-slip fault system connects to the east to the N-dipping Los Muertos trench that runs south offshore of Hispaniola and Puerto Rico islands. This in turn transfers slip to the Anegada Passage fault system. In an implicit manner, the first block ever defined in this NA-CA PBZ corresponds to the one bounded by the two previously described largely left-lateral transcurrent fault system. This block thus extends, in a west-east direction, from the Cayman sea-floor spreading center to the junction of the Anegada Passage fault system with the Puerto Rico trench.

Microplates within the PBZ

In spite of the active tectonics of the NA-CA PBZ being well identified and characterized as early as the 1980's, the fragmentation of the PBZ in discrete smaller blocks has happened much later with the inception of the GPS technology and progressive installation of numerous networks of rather small aerial coverage in the various islands by different groups (Calais *et al.* 2002 in Hispaniola, Jansma & Mattioli, 2005 in the Lesser Antilles, and DeMets & Wiggins-Grandison, 2007 in Jamaica). Slip vectors of local/regional coherence in tendency have definitely helped define the boundaries of the different tectonic blocks conforming this PBZ.

Several groups of workers have proposed that the fault bounded region extending eastward from the Cayman sea-floor spreading center to the transfer zone of the Puerto Rico oblique subduction-Lesser Antilles frontal subduction, may reflect the existence and active movement of intervening microplate(s) within the NA-CA PBZ. For example, Byrne *et al.* (1985), Mauffret & Jany (1990), and Masson & Scanlon (1991) proposed the existence of an active fault-bounded Hispaniola-Puerto Rico microplate on the basis of active, submarine fault boundaries present on both the north and south sides of the Virgin Islands, Puerto Rico, and eastern Hispaniola. Heubeck *et al.* (1991), Mann *et al.* (1991b), Rosencrantz & Mann (1991) and Mann *et al.* (1995) have all emphasized the presence of an adjacent but discrete microplate to the west of the Hispaniola-Puerto Rico microplate, stretching westward from central Hispaniola to the Cayman spreading center. Rosencrantz & Mann (1991) have named this fault-bounded area, the "Gônave microplate" after Gônave Island, one of the larger landmasses entirely within the proposed microplate boundaries in western Hispaniola. The 190,000-km2, rectangular-shaped microplate is bounded to the west by the Mid-Cayman spreading center, to the north and south by the two continuous and discrete northern and southern left-lateral strike-slip fault zones earlier described, that extend from the Mid-Cayman spreading center to the about longitude 71 ° W in central Hispaniola (around the meridian of Beata ridge), and to the east by a complex thrust zone in central Hispaniola (Heubeck & Mann, 1991b; Mann *et al.* 1991c).

Hispaniola-Puerto Rico and Gônave microplates

Consequently, the Hispaniola-Puerto Rico and Gônave microplates, in that chronologic order, are the two first tectonic entities to be defined within the NA-CA PBZ. The two microplates together conform the entire block extending from the Cayman spreading center to the Virgin Islands, previously described within the NA-CA PBZ. They are contiguous on the east-west direction, being the Gônave microplate the one sitting to the west. The limit between the two microplates has been subject of live debate. It may lie west of Hispaniola, within central Hispaniola or may be diffuse (Manaker *et al.* 2008; Calais *et al.* 2010; Benford *et al.* 2012a). As a matter of fact, while Heubeck *et al.* (1991), Mann *et al.* (1991b), Rosencrantz & Mann (1991) and Mann *et al.* (1995) place the eastern boundary of the Gônave microplate in the western flank of the Central Range of Hispaniola, Pubellier *et al.* (1991; 2000) place this transpressional boundary in the "trans-Haitian faults", within the Haitian Fold-and-Thrust belt, and particularly indicate that the slip along the Los Muertos trench is transferred to the 120° trending Chaîne des Matheux-Montagnes du Trou d'Eau fault. The latter lies in a more southwestern position with respect to the Central range of Hispaniola. Pubellier *et al.* (2000) claim that the limit proposed by previous authors used to be the active boundary but this microplate boundary has migrated in SW direction and taken the present configuration since the Pliocene instead. Shortening through the Neogene in the eastern part of the Gônave microplate was thus accommodated slowly by ramp anticilines propagating and migrating southwestward. Benford *et al.* (2012a) test several elastic block models for various Gônave microplate geometries, from a Gônave microplate extending between the Cayman spreading center and the Mona passage, which was rejected at a high confidence level, to a likely diffuse boundary within or offshore from western Hispaniola (western coast of Haiti), trying to fit to the eastern boundary proposed by Pubellier *et al.* (2000).

The southern limit of the Gônave microplate runs along the Walton and Plantain Garden-Enriquillo Fault Zones, which are connected by a very large transpressional bend, resulting in the uplift and growth of the island of Jamaica (Mann *et al.* 1985; 2007). From a dense GPS network in Jamaica, DeMets & Wiggins-Grandison (2007) determine that the kinematic and seismic data thus indicate that deformation on the island is dominated by left-lateral shear along largely E-W-trending strike-slip faults. In addition, relative to the CA Plate, the Jamaican GPS velocities calculated by these authors exhibit a nearly monotonic increase in site velocities from south to north along a transect orthogonal to the island's major east-west faults. However, velocities that they calculated along a transect orthogonal to the island's numerous NNW-striking faults, also increase monotonically from the WSW to ENE, being supportive of an interpretation of those faults as restraining bends. In other words, Jamaica definitely sits in the boundary between the Caribbean and the Gônave microplate. On top of that, it is very likely that the 8 ± 1 mm/a estimated by DeMets & Wiggins-Grandison (2007), represents a minimum value for the rate of Gônave-CA Plate motion. Besides, they also estimate a firm upper limit of 13 ± 1 mm/a for Gônave-Caribbean Plate motion assuming that additional elastic or permanent deformation occurs north of Jamaica beyond the reach of the existing GPS network. We add that part of that "unmeasured" deformation may also lie south of Jamaica, since most restraining bends tend to be bivergent.

Break-up of the Hispaniola-Puerto Rico microplate

In turn, the Hispaniola-Puerto Rico microplate appears otherwise to the rigid tectonic block proposed by Byrne *et al.* (1985), Mauffret & Jany (1990), and Masson & Scanlon (1991). The latter authors propose for the tectonic setting of Puerto Rico, major strike-slip movement on nearly east-west lines in the vicinity of the Puerto Rico trench coupled to a small counterclockwise rotation of a Puerto Rico block within the broader plate boundary zone. This simple model is attractive to these authors because it predicts the tectonic regime south of Puerto Rico (opening of the Anegada passage and overthrusting of this block onto the CA plate at the Los Muertos trench), and provides an explanation for a possible component of extension across the Puerto Rico Trench west of 65.5°W. This microplate has been broken down into 3 smaller blocks, where Hispaniola and Puerto Rico islands sit each in a different block – Hispaniola block and Puerto Rico block-, and are separated by the rift system of the Mona Passage (Figure 8). The extension of the Mona Passage, responsible for the tsunamigenic 1918 Mayagüez earthquake, results from a differential ENE motion relative to NA plate, where Hispaniola appears lagging behind Puerto Rico (Calais *et al.* 2002). Jansma *et al.* (2000) have shown that GPS data from Puerto Rico and Hispaniola are consistent with about 5 mm/a of east-west extension in the Mona Passage, the marine strait between the two islands. The same GPS study also revealed that the Puerto Rico-northern Virgin Islands microplate proposed by Masson & Scanlon (1991) on the basis of marine geophysical data is moving at a rate no faster than about 1 mm/a relative to the stable CA plate. In that respect, Mann *et al.* (2002) state that GPS velocities in the Puerto Rico, Virgin Islands and Lesser Antilles sites show that these areas are moving as part of the stable CA plate, at least at the 2-3 mm/a level. Mann *et al.* (2002) extend this conclusion to the entire Lesser Antilles volcanic arc and forearc area, at least in the area of Barbados Island. In the same way, the behavior of the Puerto Rico-Virgin Islands and Lesser Antilles as a single block indicates very slow (<1.5 mm/a) or no motion on the eastern part of the Los Muertos fault south of Puerto Rico and the Anegada Passage fault between Puerto Rico and St. Croix. These results do not support tectonic models involving present day rotation of the Puerto Rico-Virgin Islands block about a nearby vertical axis and/or eastward tectonic escape of a Puerto Rico-Virgin Islands microplate (Jansma *et al.* 2000).

As to the driving mechanism of the opening of the Mona Passage, Mann *et al.* (2002) invoke that northeastern Hispaniola during oblique subduction has collided against the Bahamas platform while Puerto Rico moved more freely, allowing even some 25° of counterclockwise rotation of Puerto Rico. Then, complex rifting in the Mona Passage (Grindlay *et al.* 1997; van Gestel *et al.* 1998) reflects both rifting and rotation as the uncollided area to the east (Puerto Rico and Virgin Islands) rotates in a counterclockwise direction. Paleomagnetic studies of the Neogene carbonate platform in Puerto Rico confirm 25° of counterclockwise rotation of the island in late Miocene-Pliocene time (Reid *et al.* 1991). In other words, Mann *et al.* (2002) express that this collided or ‘‘impeded’’ area of the CA plate to the west of the Mona Passage undergoes widespread shortening while the uncollided area to the east of the Mona Passage in Puerto Rico and the Virgin Islands is characterized mainly by counterclockwise rotation about a hinge point in the Mona Passage, broad arching of the Puerto Rico-Virgin Islands arch, normal faulting related to separation from the collided area, and strike-slip faulting.

North Hispaniola (Septentrional) microplate

In much the same way as Alvarado *et al.* (2011) have proposed a parallel-to-trench sliver for the Nicaragua-El Salvador forearc (see discussion above), a microplate has been defined in the northern Hispaniola region between the North Hispaniola fault (to which is associated the submarine North Hispaniola Deformed Belt –NHDB-) and Septentrional fault (Dolan *et al.* 1998; Dolan & Bowman, 2004). The best-fit elastic strain model by Mann *et al.* (2002) indicates strike-slip motion of 12.8 mm/a and 9 mm/a on those two faults, respectively. To the east, the North Hispaniola fault prolongs into the Puerto Rico trench, which shows clear evidence for low-angle thrust faulting. In turn, the Septentrional fault in Hispaniola appears to merge with active strike-slip faults been mapped on the inner wall of the Puerto Rico trench, the most prominent of these being the Bunce and Bowin faults (ten Brink *et al.* 2004; Grindlay *et al.* 2005b). Both, the North Hispaniola and Puerto Rico trench faults, mark the subduction of Atlantic lithosphere beneath Hispaniola and Puerto Rico, respectively. Dolan *et al.* (1998) express that highly oblique subduction of Atlantic oceanic lithosphere along the deformation front north of Hispaniola and Puerto Rico is partitioned onto two major structures: (1) the oblique left-lateral thrust fault along the south-to-SSW-dipping interface along the top of the underthrust Atlantic slab; and (2) the left-lateral Septentrional-northern Puerto Rico slope strike-slip fault system. This strain partitioning indicates that the part of Hispaniola north of the Septentrional fault constitutes a small microplate caught up within the plate boundary that is moving eastward relative to the NA plate at a much slower rate than the bulk of Hispaniola to the south (Figure 8). These authors propose that the Septentrional fault probably merges into the southwest-dipping decollement along the top of the subducted slab at a depth of ~15 to 30 km.

In Hispaniola, Manaker *et al.* (2008) confirm from GPS data that CA-NA oblique convergence is partitioned between plate boundary parallel motion on the Septentrional and Enriquillo faults in the overriding plate and plate-boundary normal motion at the plate interface on the Northern Hispaniola fault. East of the Anegada Passage, conversely, the CA-NA plate motion is accommodated by un-partitioned oblique slip on the faults bounding the Puerto Rico block to the north (Puerto Rico oblique subduction) and to the south (Los Muertos thrust). An increase of convergence obliquity, which is the case when moving westward from Puerto Rico into Hispaniola, is enough justification for inducing strain partitioning, as proposed by Fitch (1972) and McCaffrey (1992). Interestingly, the transition coincides with the subduction of the buoyant Bahamas platform under Hispaniola, whereas normal oceanic lithosphere descends obliquely beneath Puerto Rico. We believe that an increase of convergence obliquity, due to the change of orientation of the North Hispaniola and Puerto Rico trench at the Mona Passage, must add to a higher plate coupling introduced by the collision of the Bahamas platform against northern Hispaniola. This is supported by the following statement from Dolan *et al.* (1998): “Pronounced along-strike changes in structural style along the Hispaniola-Puerto Rico slope record an east-to-west transition from highly oblique, predominantly left-lateral underthrusting of Atlantic oceanic lithosphere (NA plate) along the 085° margin northwest of Puerto Rico, to oblique left-lateral contractional deformation along the 110° plate boundary off north-central Hispaniola.”

Four or five microplates within the NA-CA PBZ?

So far, four microplates (or blocks; Figure 8) have been defined from geological, seismological and geophysical marine data within the NA-CA PBZ, whose existence and definition have been progressively confirmed by numerous GPS studies carried out over the last 25 years. From west to east, the different entities that interact with the neighboring CA and NA plates are: the Gônave, Hispaniola, Septentrional and Puerto Rico-Virgin Islands blocks. As the GPS networks in the region have flourished and got denser, the modeling of the ever-increasing GPS data has become more refined. The most recently developed models are those of Manaker *et al.* (2008) and Benford *et al.* (2012a and b). As a matter of fact, Benford et al (2012a and b) were in need of even proposing a fifth block from GPS data results, inside the CA plate; incorporation that they have named the Nicaragua Rise block model. It would appear that, as suggested earlier by us in this paper, a significant portion of the bivergence of the Jamaica restraining bend lies offshore south of the island. A suggestive submarine promontory on the bathymetric chart southwest of Jamaica is much appealing to make this transpressional bend larger and wider than the actual portion above sea level. This would rule out the need of creating a fifth entity in this PBZ.

ATLANTIC-CA PLATE BOUNDARY

The Lesser Antilles Arc, comprising a score of islands, is 850 km long with a radius of curvature of 450 km. It stretches submeridionally from the SA continental margin to the eastern termination of the Greater Antilles (Puerto Rico and Virgin Islands), from which is separated by the Anegada Passage. The active island arc of the Lesser Antilles marks the eastern boundary of the CA Plate, which is underthrusted, in a westward-dipping subduction zone, by the old oceanic crust of the western central Atlantic Ocean. It is part of a wider island arc system (the eastern Caribbean) including, to the west, a back-arc basin (Grenada Basin) and a remnant arc (Aves Swell or Ridge). Farther to the west, the Venezuela Basin is one of the main oceanic basins, with abnormally thick crust, of the CA Plate. The Lesser Antilles trench is morphologically continuous with the Puerto Rico trench to the northwest, where subduction transitions from roughly trench-normal (Lesser Antilles) to highly oblique (Puerto Rico). The transition is marked in the upper plate by the Anegada Passage faults.

Bouysse & Westercamp (1990) provide a thorough review of the complex history of this island arc, which has probably been active since the Early Cretaceous. With the onset of the Early Eocene, a volcanic front settled upon this Mesozoic arc substratum. Its trace can be located from Grenada, in the south, to Anguilla, in the north, and constitutes the Older arc (Grenada-Grenadines-St. Vincent-St. Lucia-Martinique-Marie Galante-Grande Terre of Guadeloupe-Antigua-St. Bartholomew-St. Martin-Anguilla). This volcanic line later ceased its activity, and after several million years, the volcanism resumed along the Recent arc, which is still active today, and the locus of the "Volcanic Caribbees". Between Grenada and Martinique the two arcs are imbricated; but to the north, they diverge, and from Martinique northwards, they are split apart by a corridor some 50 km wide, the Kallinago depression (Bouysse, 1979). These two northern branches have been called the ***Outer arc*** to the east (from Marie Galante to Anguilla) and the ***Inner arc*** to the west (i.e. the northern half of the "Volcanic Caribbees"; Dominica-Les Saintes-Basse Terre of Guadeloupe-Montserrat-Redonda-Nevi-St. Kitts-St. Eustatius-Saba). A 110 km long submarine segment extends the Inner arc as far as the Anegada Passage. It has been extinct since the Late Pliocene and includes Luymes Bank and Noroit Seamount (Bouysse *et al.* 1985). La Desirade and Barbuda islands are located on the eastern rim of the northern Lesser Antilles Mesozoic basement. Together with the islands of the Outer arc, they have been called the ***"Limestone Caribbees"***.

To the west of the Lesser Antilles, the Grenada Basin, some 150 km wide, separates the former from the Aves Swell, a remnant arc extinct since the onset of the Cenozoic era (Bouysse, 1988). The surface contact between the Caribbean plate and the subducted Atlantic crust is underlined by a strong negative gravity anomaly (Bowin, 1976). The distance between the present volcanic front (Recent arc) and this anomaly is approximately constant and of some 150 km, implying that is a normal slab of intermediate dip (close to 40-45° W). Physiographi-cally, this contact corresponds to a classical subduction trench (more than 6000 m deep) only to the north of the latitude of Antigua, and constitutes the southeastern extension of the Puerto Rico trench. To the south, the trench is progressively filled in by sediments and passes to the Barbados accretionary wedge, which rises above sea level to form Barbados Island. The accretionary complex increases in width to the south (up to 300 km beyond the contact of the plates) and shows a maximum thickness of 20 km (Westbrook, 1975; 1982). The Barbados complex is one of the best examples of sedimentary accretionary wedges in the world, and has been thoroughly studied (Moore & Biju-Duval, 1984; Brown & Westbrook, 1987; ODP leg 110 Shipboard Scientific Party, 1987). It owes its importance to the huge longitudinal sedimentary input coming from the Orinoco and Amazon rivers.

A simple PBZ?

Feuillet *et al.* (2002) report active trench parallel extension in the northern half of the Lesser Antilles arc, north of about 15° N where the Tiburon Ridge is being subducted, and argue that it results from strain partitioning. López *et al.* (2006) report a systematic discrepancy between slip vectors of thrust fault earthquakes at the Lesser Antilles trench (LAT) and the predicted direction of NA-CA convergence. They mention that a possibility has been that the discrepancy resulted because neither was well constrained. Estimating CA motion has been challenging owing to the limited data along the plate's complex boundaries. Similarly, earlier studies had few slip vectors because interplate thrust events are infrequent. To address these difficulties, López *et al.* (2006) estimate a new CA-NA Euler vector using available GPS data from sites in the presumably stable interior of the Caribbean, and compare the predicted velocities to a larger set of slip vectors. The discrepancy persists, suggesting the Northern Lesser Antilles Forearc (NLAF) moves as a distinct entity from both the CA and NA. For simplicity, López *et al.* (2006) treat its motion as a coherent block, but because GPS sites are not within the NLAF, distributed deformation is also possible. Although there is no geologic evidence for the boundaries of the presumed NLAF block, López *et al.* (2006) conclude from the modeled GPS data that the motions of Martinique, Barbados, and Trinidad are similar to that of the Caribbean, suggesting that none are on the NLAF block, and the southern LAT is weakly coupled. Manaker *et al.* (2008) found that the discrepancies between earthquake slip vectors and GPS velocities were small and within the error limits of both data types. Also, the boundaries of a possible Lesser Antilles block are poorly defined and deformation could result from diffuse deformation within the arc rather than slip on a single fault zone, as shown by the broad distribution of mostly trench-perpendicular normal faulting within the arc (Feuillet *et al.* 2002). Manaker *et al.* (2008) therefore do not favor a separate Lesser Antilles Block in their model geometry, while recognizing that a denser and more precise data set may require it.

Later on, Feuillet *et al.* (2010) bring the missing geologic and geophysical supporting evidence. From a new high-resolution marine data acquired aboard R/V Le Suroît, these authors map active normal faults offshore Montserrat in greater detail. The main faults of the Montserrat-Havers fault zone have cumulative scarps up to 200 m high, and offset sedimentary layers by hundreds of meters. They are arranged in a righ-stepping, en echelon, transtensional array, which confirms, after Feuillet *et al.* (2010), that they accommodate the lef-lateral component of motion resulting from slip partitioning of oblique convergence along the volcanic arc. These N110°E-trending faults even cut across Montserrat's recent volcanic complex.

Consequently, the northern Lesser Antilles forearc, in much the same way as the northern sliver of Hispaniola, bounded by the North Hispaniola and Septentrional faults, and the terrane defined by the MAVA and the Middle America trench in the NA-CA and CO-CA PBZs, respectively, accommodates the trench-parallel component of oblique convergence at those PBZs. Furthermore, both, the Lesser Antilles forearc and the sliver in Central America, take profit of the presence of an active volcanic arc along one of its boundary, which weakens the upper plate (the CA plate in both cases).

SA-CA PLATE BOUNDARY

Hess & Maxwell (1953) proposed that the boundary was a simple dextral wrench system. Over 40 years of neotectonic analyses, integrating surface geology, geomorphology, microtectonics, seismotectonics and palaeoseismology, combined with data from conventional geological studies and on and offshore seismic reflection data, allow

a more precise view. The more we learn about the boundary zone, the more complex it seems.
There is wide consensus that the CA plate is moving east relative to SA and recent GPS results strongly support this (Freymueller *et al.* 1993; Pérez *et al.* 2001a and b; Weber *et al.* 2001). However, northern South America reflects interaction of the CA, SA and NA plates and the Panamá microplate. Deformation along the boundary is driven by oblique convergence (Silver *et al.* 1975; Pérez & Aggarwal, 1981; Speed, 1985; Lugo & Mann, 1992; Russo & Speed, 1992). Today this is more intense in the west than in the east where wrenching dominates.

Northern Venezuela lies in the interaction zone between the SA and CA Plate, while western Venezuela and northern Colombia comprise a number of interplaying tectonic blocks or microplates (Figures 1 and 9). The CA-SA Plate boundary from Colombia to Trinidad is over a 100 km wide active transpression zone on and offshore northern Venezuela (Audemard, 1993; Singer & Audemard, 1997; Pindell *et al.* 1998; Audemard *et al.* 2000; 2005; Ysaccis *et al.* 2000). Significant positive relief is present along the Coastal and Interior ranges of north-central and northeastern Venezuela. Further west, the southern Caribbean boundary broadens to as much as 600 km and includes several small tectonic blocks or microplates (Figures 1 and 9). The Triangular Maracaibo Block –TMB- is bounded by the left-lateral Santa Marta-Bucaramanga fault –SMBF- in Colombia and the right-lateral Boconó fault –BF- in Venezuela. The dextral Oca-Ancón fault –OAF- separates it in the north from the Bonaire Block –BB-. Both, the Maracaibo and Bonaire blocks, are being extruded northward. Extrusion is driven by the collision and suturing of the Chocó Block against the Pacific side of northern South America (Duque-Caro, 1978; 1990; Audemard, 1993; 1998; 2009), confirmed by GPS plate motion studies (Freymueller *et al.* 1993; Kellogg & Vega, 1995; Kaniuth *et al.* 1999; Trenkamp *et al.* 2002). The Maracaibo and Bonaire blocks override the CA Plate at the Leeward Antilles subduction –LAS. North of the Netherlands Leeward Antilles, south dipping, amagmatic, flat subduction has developed in the last 5 Ma. The onset of this escape tectonics is a key issue, which has already been discussed.

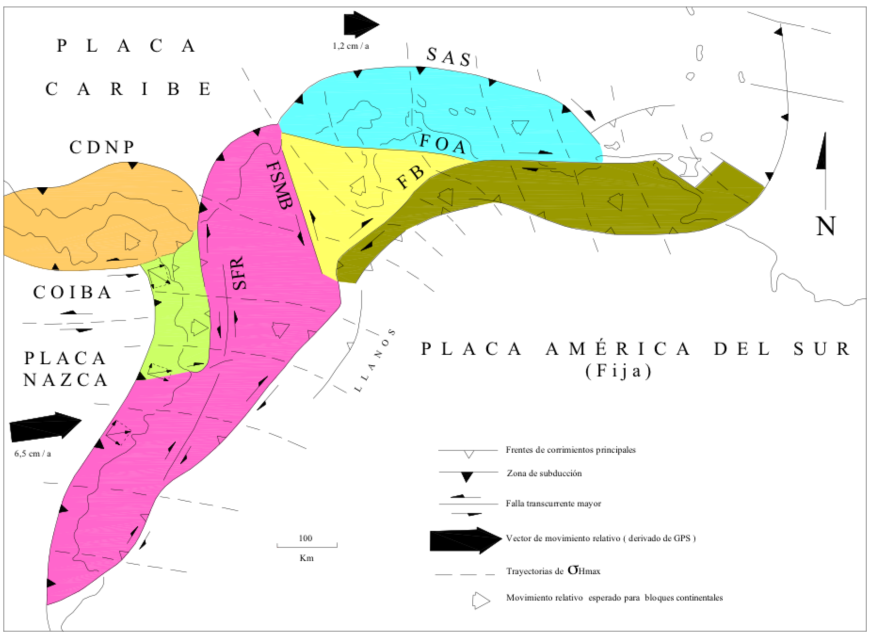

Figure 9. Tectonic blocks in the CA-SA PBZ defined by Audemard (2002) from geologic data and geodynamic criteria. Abbreviations and equivalences with Figure 1: CDNP = NPDB Northern Panamá deformed belt; FB = BF Boconó Fault; FSMB = SMBF Santa Marta-Bucaramanaga Fault; FOA = OAF Oca-Ancón Fault; SAS = LAS Leeward Antilles Subduction; SFR =RFS Romeral Fault System.

Figura 9. Bloques tectónicos definidos en la zona de frontera de placas Caribe-América del sur por Audemard (2002) a partir de datos geológicos y criterios geodinámicos. Abreviaturas: CDNP = NPDB Cinturón de deformación Nor-Panameño; FB = BF Falla de Boconó; FOA = OAF Falla de Oca-Ancón; SFR =RFS Sistema de Fallas de Romeral; SAS = LAS Subducción de las Antillas de Sotavento; FSMB = SMBF Falla de Santa Marta-Bucaramanga.

Along the CA coast of Venezuela

Much of present day dextral slip along the southern Caribbean boundary seems to be focused along the major Boconó-San Sebastián-El Pilar-Los Bajos-Warm Spring fault system where geological and geodetic data indicate a slip rate of 8-10 mm/a. Most authors see this system as the plate boundary (Hess & Maxwell, 1953; Schubert, 1979; Stephan 1985; Pérez *et al.* 2001a and b). Others note that deformation is distributed over a 100 km or more wide zone and interpret orogenic float in the Andes (Audemard, 1991; Jácome, 1994; Audemard & Audemard, 2002), across the Falcón Basin (Porras, 2000) and eastern Venezuela (Ysaccis, 1997; Ysaccis et al,. 2000). According to this understanding, the zone is flanked by both A and B-type subduction. Yet others recognize southeast-directed A-subduction or under-thrusting below the Mérida Andes (Kellogg & Bonini, 1982; De Toni & Kellogg, 1993; Colletta *et al.* 1996; 1997).

The PBZ exhibits strain partitioning from the Mérida Andes in the west to the Interior range in the east. In the Andes, partitioning occurs between the dextral Boconó fault and thrust faults on both mountain flanks (Audemard & Audemard, 2002). The north-central Coastal Range also exhibits strain partitioning. Dextral slip occurs in the core along the San Sebastián, La Victoria faults and minor synthetic Riedel shears while transverse shortening is accommodated by frontal thrust faults in the south (Guarumen basin; Audemard, 1999). A sub-sea, mirror thrust fault system may exist to the north and the easternmost portion of the LAS zone must account for some shortening as well. Farther east, strain partitioning involves NNW-SSE-trending shortening over a 250 km wide zone from north of La Blanquilla to the active thrust front of the Interior Range. Slab detachment (Russo and Speed, 1992; Russo, 1999; Bezada *et al.* 2010) associated with an incipient A-subduction, results in the largest onshore negative Bouguer anomaly in the world, south of the Interior Range. Dextral slip concurrently occurs along the main east-west striking El Pilar fault and along the NW-SE striking Los Bajos-El Soldado faults and minor parallel and/or synthetic Riedel shear faults. Partitioning might also occur on Trinidad.

Although transpression is the dominant process at plate boundary scale, transtension also occurs in two pull-apart basins, the Cariaco Trough (Schubert, 1979; 1984; Escalona *et al.* 2011) and the Gulf of Paria (Babb, 1997; Ysaccis, 1997) at the ends of the El Pilar fault. The age of opening of these basins constrains the timing of wrenching onset between 15 and 10 Ma in eastern Venezuela. Most of El Pilar fault strike-slip motion transfers via the Los Bajos and El Soldado synthetic Riedel shears to the Warm Springs fault of the Central Range of Trinidad (Weber *et al.* 2001). However, this shallow crustal deformation does not exclude a deeper plate boundary, as indicated by instrumental seismicity and as suggested by Pérez & Aggarwal (1981) and Sobiesiak *et al.* (2002; 2005).

Present day motion

Several authors have predicted that the CA Plate moves east at about 20 mm/a relative to South America (Jordan, 1975; Rosencrantz *et al.* 1988; Stein *et al.* 1988; Calais *et al.* 1992; DeMets *et al.* 2010) and GPS studies carried out in the CA-SA PBZ have confirmed this (Pérez *et al.* 2001a and b; Weber *et al.* 2001; Trenkamp *et al.* 2002; Jouanne *et al.* 2011). In the east, dextral slip along the plate boundary transfers to subduction in the Lesser Antilles, although the detailed tectonic setting remains still unclear.

GPS slip magnitudes remain rather constant from west to east but orientations change. ESE oblique convergence occurs between San Andrés Island, east of Honduras, and stable SA, confirming predicted N075°W convergence (Jordan, 1975; Minster & Jordan, 1978) and seismotectonic models (Pennington, 1981; van der Hilst & Mann, 1994). Data from eastern Venezuela indicate almost pure wrenching at the CA-SA PBZ [086° ± 2° with respect to the Central Range of Trinidad (Weber *et al.* 2001) and 084° ± 2°E with respect to South America (Pérez *et al.* 2001a)].

Vector orientations indicate transtension, as postulated by Robertson & Burke (1989), Algar & Pindell (1993) and Pindell *et al.* (1998), and inferred by Weber *et al.* (2001). Stress tensors of Colmenares & Zoback (2003) indicate the same. However, Choy *et al.* (1998) determined stress tensors indicating NW-SE compressive wrenching. Several authors came to this same result using geological data (Beltrán & Giraldo, 1989; Audemard, 1993; 2000; Audemard *et al.* 2000; 2005). Lately, Jouanne *et al.* (2011) derive slip vectors that show pure east-west dextral motion across eastern Venezuela with a minor component of shortening; all in perfect agreement with the geological tensors and focal mechanism solutions compiled by Audemard *et al.* (2005).

GPS results published by Pérez *et al.* (2001a, p. 70, Figure 1) indicate compression across the boundary south of the main dextral system (Audemard *et al.* 2005) where GPS rates are as high as 20-25% of the main dextral rate (18-20 mm/a), the same order of magnitude as those calculated from long-term geological criteria (Audemard, *et al.* 2000). In this area strain is partitioned between the major east-west dextral faults and ENE-WSW trending thrusts and folds of the Interior Range and the Margarita-Blanquilla platform.

Slip of 8-10 mm/a along the dextral Boconó-San Sebastián-El Pilar-Warm Spring faults, from the southern Mérida Andes to Trinidad, accounts for up to 50% of the 20 mm/a dextral relative motion at the CA-SA PBZ. A recent study (Jouanne *et al.* 2011) estimates that the other half of the entire PBZ slip rate, across the El Pilar Fault region, may take place as creep. Greatest slip along the Boconó fault from Late Quaternary geological markers is about 9-10 mm/a (Soulas, 1986; Audemard, 1997a; Audemard *et al.* 1999; 2008). The Warm Spring fault also accounts for half of the dextral motion across Trinidad.

Pérez *et al.* (2001a) indicate that strain is distributed across a zone at least 110 km wide, with 68% (almost 14 mm/a) of this occurring in a 30 km-wide fault zone involving the El Pilar fault and sub-parallel faults to the north. Weber *et al.* (2001) claim that the Warm Springs fault is the southern plate boundary in Trinidad. However, there is still 8 mm/a to be accommodated between southwestern most Trinidad and continental SA. This implies the presence of another major fault south of Trinidad, as proposed by many authors (Soulas 1986; Beltrán, 1993; 1994; Audemard *et al.* 2000; Audemard, 2002; Audemard & Audemard, 2002).

Recently, Pérez *et al.* (2011), from new GPS mea-surements, reveal that the 20 ± 2mm/a of eastward displacement of the CA plate relative to SA in northwestern and north-central Venezuela is partitioned into a dextral shear velocity of 12 ± 2 mm/a along a locking depth of 14 ± 4 km beneath the surface expression of the Bo¬conó Fault, with convergence normal to its northeast strike at 12 to 16 mm/a. Of this convergence, about a third concentrates in the Andean region close to the Boconó fault and manifests itself geologically as thrust slip on a narrow belt of thrust faults nearly parallel to it, running ~25 km away along both sides of the Boconó fault main trace.

North Andes Block

Northwestern SA is a broad convergent plate boundary zone characterized by active seismicity, a volcanic arc, subduction, and an on-going arc-continent collision. The North Andes Block –as originally defined by Pennington (1981); NAB- is bounded by the Colombian-Ecuador Trench and the Panamá Block to the west, the South Caribbean Deformed Belt –SCDB- to the north, and the Boconó fault and East Andean fault zones to the east (Figure 9). It is very likely that this eastern boundary will tend to simplify itself in the future, as suggested by the presence of Quaternary active faulting cutting across the Colombian and Venezuela Llanos, through the Meta fault in Colombia, which controls a very long strech of the river of same name, and Tala fault in eastern Venezuela, this latter resulting from tectonic inversion of the Espino graben southern bordering fault (Figure 1). Cenozoic deformation in this broad zone has been produced by the converging NZ, SA and CA plates and the Panamá microplate (Kellogg & Bonini, 1982).

Geodetic measurements using GPS from the Central and South American (CASA) GPS project show that the NZ oceanic plate is rapidly converging with stable SA (Freymueller *et al.* 1993; Trenkamp *et al.* 2002). The convergence direction is slightly oblique to the Colombia-Ecuador Trench. The aseismic Carnegie Ridge, produced by the passage of the NZ plate over the Galapagos hotspot, is being subducted in the Ecuador-Colombia trench. CASA measurements also suggest that a large part of the northern Andes is "escaping" to the northeast relative to stable SA at a rate of at least 6 ± 2 mm/a. Tapponnier *et al.* (1982), as already argued for by Audemard & Audemard (2002) and Audemard (2003), using plane rigid indentation experiments on unilaterally confined blocks of plasticine, were able to model intra-continental deformation and the evolution of strike-slip faults due to the collision of India and Asia. The faults that develop, allow the "escape" of the detached block in the direction of the free boundary. Proposed driving mechanisms for the "escape" of the NAB already discussed earlier, are: collision with the Panamá Arc, rapid oblique subduction of the NZ plate, and the subduction of the aseismic Carnegie Ridge at the Ecuador-Colombia Trench.

NAB: One or several blocks?

After regional Caribbean maps (Case & Holcombe, 1980; Stephan, 1982; Mann & Burke, 1984; Mann *et al.* 1990; Mascle & Letouzey, 1990; Audemard, 2002; 2003) and geodynamic models (Stephan *et al.* 1990; Audemard, 1993; 1998; 2009), it appears that the NAB as defined by Pennington (1981), in fact amalgamates several discrete blocks, which have a certain degree of kinematic independence, as shown by the GPS results of Freymueller *et al.* (1993) and Trenkamp *et al.* (2002). Audemard (2002), partly based on Freymueller's results, proposes a block individualisation (Figure 9).

As a matter of fact, the plate boundary in western Venezuela, Colombia and Ecuador is eventually up to 1000 km wide and comprises a set of discrete tectonic blocks, independently moving among the surrounding larger plates (CA, SA, NZ and Panamá microplate), among which the Maracaibo Block stands out for its triangular shape with one of its apexes pointing due south. The Triangular Maracaibo Block –TMB- is bounded just by rather rectilinear strike-slip (SS) faults: the left-lateral SS Santa Marta-Bucaramanga Fault –SMBFS- in Colombia and right-lateral SS Boconó Fault –BF- in Venezuela and separated on the north from the Bonaire Block –BB- by the right-lateral SS Oca-Ancón Fault –OAF-. In turn, the BB is bounded on the north by the Curacao Ridge; renamed more recently as the SCDB. The Leeward Antilles Subduction –LAS-, responsible for the SCDB, may well be an inherited structure of the Cretaceous active margin of the SA continent. Escalona & Mann (2011) instead consider this feature may have functioned as a back-thrust of the Caribbean nappes during their emplacement onto the SA margin, spanning the Eocene-Early Miocene and overriding then the back arc (towards the CA plate sea floor). Both TMB ans BB are being extruded NNE and are overriding the CA plate north of the Leeward Antilles Islands, where a young (mainly in the last 5 Ma), south-dipping, amagmatic, flat subduction (LAS) has been forming in recent times. Extrusion of these blocks is to be related to the collision of the Panamá Arc against the Pacific side of northern SA and its later suturing (Audemard 1993; 1998; 2009), although we do not completely rule out that the buoyant Carnegie Ridge may have partly contributed to the escape. Neither is ruled out that the LAS may have accommodated part of the Americas convergence since the Oligocene.

Besides the TMB and BB, Audemard (2002) also splits apart the Chocó Block from the Panamá microplate, both originally constituting the larger Panamá Arc; before the progressive clockwise docking of the southern part of the Panamá Arc (new Chocó Block –CB-) against the northwestern SA margin. Consequently, the new definition of the NAB refers to the rest of the original block defined by Pennington (1981) after individualizing TMB, BB and CB. But, is this NAB a single entity?

How many subductions under the NAB?

Since the NAB, as defined in this contribution, does not extend northward to the SCDB anymore, except for a short portion between the Baudó suture (Uraba Gulf) and the SMBFS (city of Santa Marta), this excludes the LAS, which shall be discussed apart later.

The NAB is for a very significant portion defined to the west by the Ecuador-Colombian Trench, under which plunges the oceanic NZ plate. In spite of changing from flat-slab to normal subduction, depending on whether the NZ plate brings along a ridge (i.e., Carnegie, Malpelo ridges) or not, the Ecuador-Colombian Trench is rather continuous up to Panamá. However, the NAB is limited on the west by the Choco-Baudó suture to the north of the ENE trending Garrapatas fault, which is the southern tip of the CB (Figures 5 and 9). Audemard (2002) indicates that the effect of the Chocó-Baudó suturing and indentation can be seen as far inland in Colombia as the Eastern Cordillera of Colombia. North of a line at 4º N latitude, comprising the right-lateral Garrapatas, Río Verde and Ibagué faults, which are the southern edge of the indentation at crustal levels, the following major changes are reported by Audemard (2002): (1) The Eastern Cordillera is significantly much wider to the north, as well as it exhibits higher relief; (2) the Llanos foothills of the Eastern Cordillera are more transpressional to the north and more wrenching to the south; (3) the Cauca Valley narrows significantly north of the Garrapatas Fault, squeezed between the Western and Central cordilleras, and the Cauca River has substantial difficulties to keep flowing north because the valley floor is being raised; (4) The axis of the Central Cordillera is shifted dextrally by the dextral Ibagué fault; and (5) The Cauca Romeral fault system (RFS) appears to change sense of slip at that latitude. The fault trend is arcuate with convexity to the east and tends to run parallel to the Ecuador-Colombian Trench. This major tectonic accident seems to accommodate the parallel-to-trench strike-slip component of strain partitioning, due to NZ-SA convergence obliquity (Audemard, 2002). To the north of latitude 4º N, the trench trends NNW-SSE. So do SS faults. This leads to left-lateral SS along the Cauca-Romeral Fault System, instead of right-lateral to the south of latitude 4º N. On top of that, the left-lateral sense of slip to the north is required to allow the NAB escape towards the NNE between the Cauca-Romeral fault system on the west and the EC Foothills System on the east, although not as fast as the TMB, which is not directly under the influence of the CB and is closer to the northern free boundary (to the SCDB). To some extent, the NAB moves slower to the north because it is more compressed and refrained by the CB indentation.

Although the Ecuador-Colombian Trench appears continuous along trend, the subduction slabs appear torn at the latitude of 5.6º N, as suggested by the eastward jump of the intermediate depth seismicity (Pennington, 1981; Taboada *et al.* 2000; Ojeda & Havskov, 2001; Mejía & Meyer, 2004; Corredor, 2003; Cortés & Angelier, 2005; Vargas & Mann, 2013). An east-west tear cutting the subduction slab has been proposed by Vargas & Mann (2013; Figure 10). They have named it the Caldas tear based on the location in the Caldas department of Colombia. The nearly 240 km long Caldas tear is a narrow, east-west trending boundary between two subducted slabs of different dip and nature. The northern zone is the down-dip extension of the Panamá Arc, has a shallower dip, and is not associated with active arc volcanism. It corresponds to a thickened oceanic crust, with the typical Caribbean oceanic plateau affinity. The southern zone has a steeper dip and is associated with an active volcanic front. This volcanic arc relates to the NZ slab. It is a normal subduction where the slab is conveying a normal oceanic crust. Earlier, using the distribution of earthquakes deeper than 80 km, Ojeda & Havskov (2001) proposed that such discontinuity represented a boundary between two subducted slabs with differing dips and strikes: the northern subduction zone, called the Bucaramanga subduction zone, has a shallower dip (27°) and more northeasterly strike, and the southern, called the Cauca subduction zone, has a steeper dip (35°-40°) and a more northerly strike.

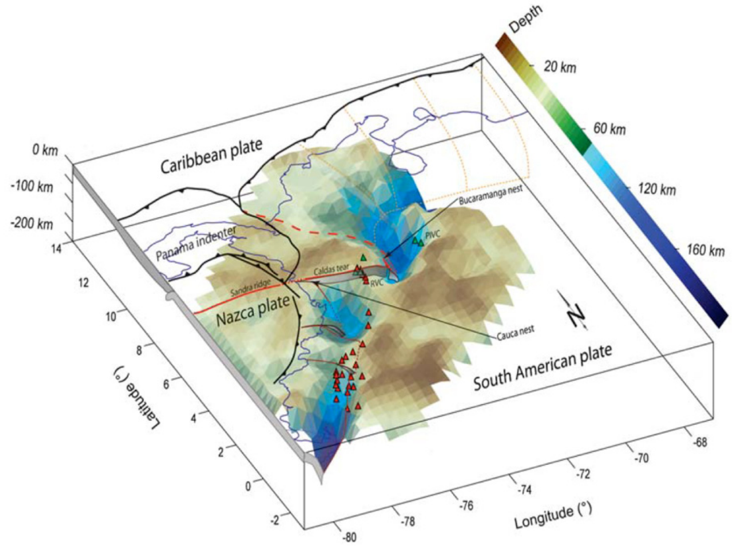

Figure 10. Block diagram showing seismic surface estimated by interpolation and filtering of local earthquakes (h ≥ 10 km; from Vargas and Mann, 2013). Blue lines, shore line. Bold black lines, limits of the convergent margins. Bold red lines, the southern border of the Panama indenter that includes the Sandra Ridge and the Caldas tear. Triangles, red (active) and green (inactive) volcanoes. Orange dashed lines, wireframe model suggested for indicating the subduction geometry of the Caribbean plate

Figura 10. Bloque 3D mostrando superficie sísmica estimada a partir de la interpolación y filtrado de sismos locales (h ≥ 10 km; según Vargas and Mann, 2013). Línea azul, línea de costa. Línea gruesa continua, fronteras de márgenes convergentes. Línea gruesa roja, el borde meridional del indentor de Panamá, que incluye el alto de Sandra Ridge y el desgarre Caldas. Triángulos: rojo (volcanes activos) y verde (volcanes inactivos). Línea naranja segmentada, línea de contorno para definir geometría de la losa de subducción caribeña

Although not matching perfectly, it would appear that all major changes at crustal levels mentioned at the latitude of 4ºN by Audemard (2002), with the rare exception of the volcanic arc, which is the surface expression of partial melting at around 100-120 km in depth and then tightly linked to the slab geometry at depth, are reflecting the same major geodynamic process as the Caldas tear: The collision and indentation of the southern tip of the Panamá Arc (CB) against northwestern SA. This process necessarily implied a backward jump of subduction from the east to the west board of the Baudó-Chocó Block sometime in the Pliocene. This implies in turn that at the latitude of the CB, there are two subduction slabs sinking in the mantle –an eastern flat slab of CA affinity dying out as CB-NAB suturing goes on, and a younger western slab taking the relay in activity-, while there is only one to the south of the southern tip of the CB: the normal NZ subducted slab. Also keep in mind there is a third slab in a more northerly position, offshore north of Venezuela. This subduction (or underthrsuting), induced by NNE escape of the BB and TMB, is to be presented next.

Leward Antilles Subduction –LAS-: True or induced subduction?

Earlier in this paper, we have introduced the discussion about the nature of this subduction, which displays a similar condition to the ones of the NPDB and the Hispaniola-Puerto Rico (Los Muertos) trench.

Many authors have postulated that subduction is occurring on the northern boundary of BB from the Uraba Gulf in the west to the Los Roques Canyon in the east. This subduction trends roughly east-west, has CA oceanic plateau affinity, dips south and is very young in age. Several evidences of geological, geophysical and seismological nature have been presented to support the existence of LAS: (1) Seismic profiling and bathymetric surveying across the Curacao Ridge image a typical accretionary wedge and its forearc basin (Silver *et al.* 1975; Talwani *et al.* 1977; Mascle *et al.* 1979; Kellogg & Bonini, 1982; Mascle *et al.* 1986); (2) An infrequent seismicity of intermediate depth below 50 km deep has been recorded, evidencing mainly southeast dipping thrusting (Malavé & Suárez, 1995; Audemard *et al.* 2005; Palma *et al.* 2010). The spatial distribution of these hypocenters allowed to delineating a south-dipping slab (Orihuela & Cuevas, 1992); and c) A cold slab, 450 km long and 16º southeast dipping, has been recognized from seismic tomography (van der Hilst, 1990; van der Hilst & Mann, 1993; 1994), plunging beneath northwestern Venezuela and northern Colombia. Kellogg & Bonini (1982), just from seismicity, had proposed a similar length (400 km).

But very recently, new findings have seen light. Bezada (2010) and Bezada *et al.* (2010), by analyzing teleseismic traveltimes with frequency-dependent kernels, produced a 3D P-wave velocity perturbation model. The model depicts the subduction of a section of the CA plate under SA with an east-southeast direction. The CA subducting slab penetrates, after these authors, the mantle transition zone, affecting the topography of the 410-km and 660-km discontinuities (Figure 11). However, the imaged cold slab considerably differs in geometry and lateral extent from the van der Hilst's proposal. In this new model, the slab at any depth –either at 95 km, 375 km deep or even deeper (Bezada, 2010)-, never appears north of the vertical projection of the Oca-Ancón fault system. In other words, it only exists beneath the Maracaibo block (TMB) at depth. Besides, it rather dips ESE, instead of SSE as early proposed.

From Audemard's geodynamic evolutionary models (Audemard, 1993; 1998; 2009), it seems clear that LAS keeps no relation with the subduction that led to collision-suturing of the Panamá Arc (the trailing edge of the CA plate) against western SA along the Chocó Block and San Jacinto terranes. This old Caribbean subduction, fully functioning prior to the Panamá Arc-SA collision, had to trend more sub-meridionally along the western coast of SA. This major plate boundary was rather straight and was as old as Cretaceous in certain models (Pindell & Dewey, 1982; Beck, 1985; Pindell *et al.* 1988; Stephan *et al.* 1990; Taboada *et al.* 2000). This old subduction still trends subparallel to both the Ecuador-Colombian Trench and the eastern border of the Chocó block. Instead, Audemard (1993; 1998; 2009) proposes that LAS must come much later into the regional evolution, sometime around 5-3 Ma ago, as a direct consequence of the NNE-directed BB-TMB escape. This two-subduction model is reutilized by Taboada *et al.* (2000), who show a 3-D model with two subduction slabs in this region, both composed of abnormally thick CA oceanic lithosphere, at different depths in asthenosphere. As advanced by Audemard (1993; 1998; 2009), this suggests that the slabs are of different age, being LAS at an incipient stage. Besides, this author proposes that LAS roots at the northern tip of the old Caribbean subduction (ending somewhere near the city of Santa Marta; at a clear v-shaped break in the LAS trench; see Mascle & Letouzey (1990) map and Figures 1, 2, 5 and 9) and extends progressively eastward around the northern border of the BB. By assuming that a 30º S-dipping slab has descended at 400-450 km in depth below northwestern SA (Kellogg & Bonini 1982), Audemard (2009) estimated a convergence not larger than 100 km (using 30º dip from Kellogg & Bonini, 1982) or 170 km (using 17º dip from van der Hilst & Mann, 1994). These estimates are certainly upper bounds, since they were imputed to the LAS, whose slab does not sink that deep. As a matter of fact, the study of Bezada (2010) and Bezada *et al.* (2010) can confidently illuminate this younger subduction only to a depth of about 100 km and only present north of the OAF (Figure 7).

Summarizing, this newly imaged geometry by Bezada (2010) and Bezada *et al.* (2010) of this slab (Figure 11) seems to reflect the shape at depth of the subduction that led to the collision of the southern end of the Panamá Arc against NW SA, still sinking into the asthenosphere. The surface trace of this extinct subduction must be squeezed onshore at present day between the CB and the NAB, corresponding to the Baudó-Chocó suture zone. Its northward extension should not go beyond the city of Santa Marta and die out against the OAF; which implies that this major feature at depth has acted as a tear between both subductions, as well as the boundary between the BB and TMB at shallower structural levels. As suggested by Audemard (1993; 1998; 2009), this long lived subduction is in no way the LAS. It is much older. Instead, LAS is an induced subduction due to escape tectonics occurring since the Pliocene. An additional argument favoring this is the LAS extent, from near the city of Santa Marta on the west to Los Roques Canyon on the east. These two localities are intercepted by the northward projections of the SMBF and the BF, respectively. However, this interpretation does not rule out a certain prior role in accommodating either convergence between the Americas since the Oligocene or shortening during the Caribbean nappe emplacement as a backthrust during between the Eocene and the Middle Miocene. In some way, we allow to inheritance of this LAS up to a certain extent.

Breakdown of the NAB

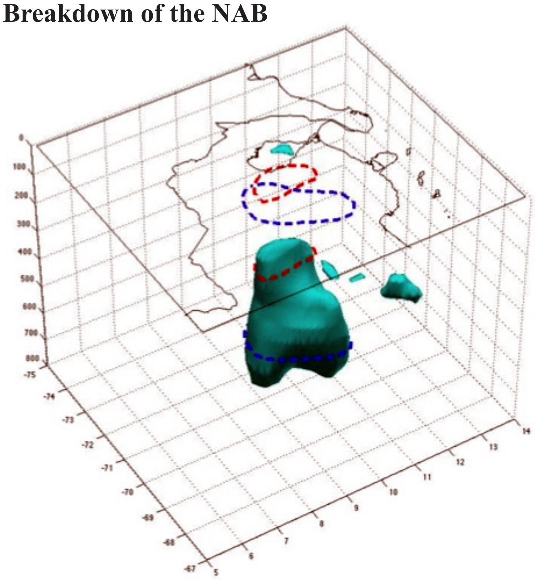

Figure 11. Block diagram showing shape of the Caribbean subducted slab under the Triangular Maracaibo block (modified by Maximiliano Bezada from Bezada, 2010 and Bezada *et al.* 2010). View from the SE. Contour lines of the slab are at 270 (red) and 480 (blue) km depth

Figura 11. Bloque 3D mostrando la geometría de la losa Caribe subducida bajo el bloque Triangular de Maracaibo (modificado por Maximiliano Bezada a partir de Bezada, 2010 y Bezada *et al.* 2010). Vista desde el SE. Se muestra líneas de contorno de la losa a 270 (roja) y 480 (azul) km de profundidad, para una mejor ubicación relativa bajo Venezuela

The original NAB proposed by Pennington (1981) already contains the Baudó-Chocó –CB-, Bonaire –BB-, Maracaibo –TMB- blocks, and the new NAB. The new NAB is defined by the Ecuador-Colombian Trench and the eastern limit of the CB on the west and a score of faults on the east, which comprises the Dolores, Pallatanga, Algeciras and Guaicáramo faults (Figures 5, 9).

For the development of the Servicio Geológico Colombiano's GEORED Project, Mora-Páez (2011) has discretized 20 tectonic blocks in Colombian territory surrounded by the larger NZ, CA, SA and Panamá Microplate, of which 2 are contained in the BB, 4 in the TMB and 1 corresponds to the CB (Figure 12). This implies that NAB on its own amalgamates 13 minor tectonic blocks in Colombia, following this block segmentation. This block individualization for the GEORED Project has been based on 3 assumptions (GEORED, 2009; López, 2010; Mora-Páez, 2011): (1) A tectonic sub-block represents a homogeneous crustal entity limited by main active faults, and it is thought to possess a characteristic pattern of internal deformation; (2) For some fault segments, current kinematics, rupture dimensions and terminations remains unclear; moreover, detailed palaeoseismological and neotectonic studies are yet scarce. Due to this, it has been necessary to make some general assumptions about fault extension, geometry and sense of slip from geophysical interpretation, geological maps and reports; and (3) Some regions at plate interface are expected to be more heterogeneous and to have higher sub-block segmentation. But, owing to the fact that some of those places have not been studied in depth and are difficult to access, the polygons of the sub-blocks are only approximately outlined.

More recently, for modeling the velocity vectors of the Panamá Microplate and neighboring larger plates (CO, NZ, SA and CA), a simplification of this model has been generated (Figure 13), adjusting the block geometries to comply with the vectors estimated by Trenkamp *et al.* (2002).

INTERNAL CA PLATE DEFORMATION: SINGLE OR SEVERAL BLOCKS?

Although the interior of the Caribbean plate is relatively aseismic in comparison to its boundaries, several indications of active deformation well within the plate interior include: (1) occasional intraplate earthquakes (Molnar & Sykes, 1969; Kafka & Weidner, 1979), with magnitudes as large as M 5.1; (2) intraplate N-S trending normal faulting affecting young sediments in the Nicaragua Rise seen on reflection profiles and displayed on the Case & Holcombe (1980) map (Holcombe *et al.* 1990); and (3) strike-slip mechanisms for intraplate earthquakes (Molnar & Sykes, 1969; Kafka & Weidner, 1979). In addition to this, DeMets *et al.* (2010) retake the issue once raised by many authors and use it as motivation: What is the role of the Beata Ridge in the internal CA plate deformation? Driscoll & Diebold (1998) pose the problem: One or two plates? but referring to the CA plate, with respect to the Beata Ridge role. We herein pretend to bring to live this discussion again on another major internal CA plate feature instead: The Hess Escarpment; without leaving aside the already existing one.

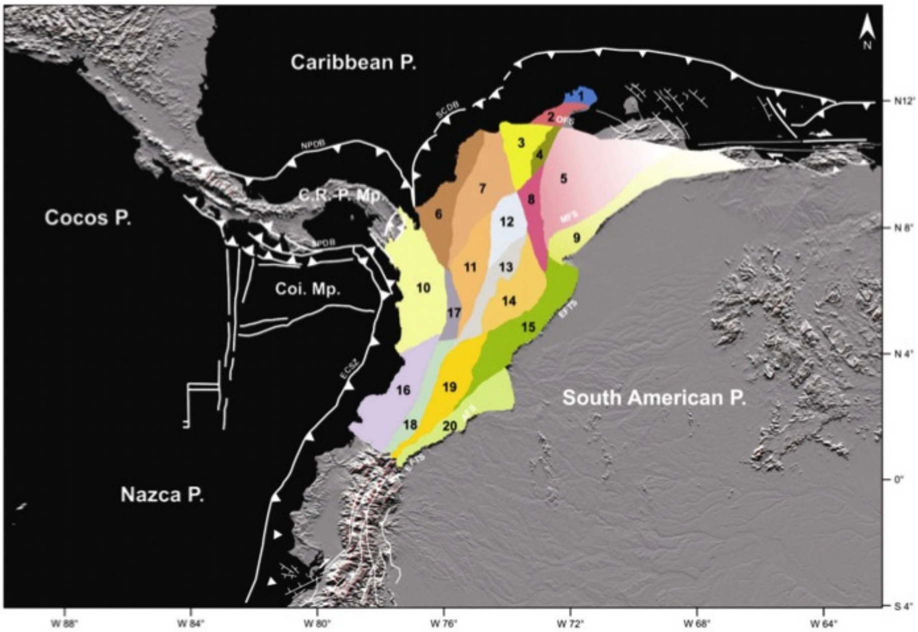

Figure 12. Tectonic blocks in NW South America defined by López (2010) in the frame of the Colombian GEORED Project. See discussion in text. Block labelling: 1. Alta Guajira; 2. Baja Guajira; 3. Santa Marta-Cuenca del Cesar-Ranchería; 4. Serranía de Perijá; 5. Cuenca de Maracaibo; 6. Sinú-San Jacinto; 7. Valle Inferior del Magdalena; 8. Macizo de Santander; 9. Pamplona; 10. Chocó; 11. Cordillera Central-Septentrional; 12. Serranía de San Lucas-Bajo Magdalena; 13. Valle Medio del Magdalena; 14. Cordillera Oriental-Flanco Oeste; 15. Cordillera Oriental-Flanco Este; 16. Cauca-Nariño; 17. Medio Cauca; 18.Valle del Cauca-Patía; 19. Valle Superior del Magdalena; 20. Macizo de Garzón-Serranía de La Macarena

Figura 12. Bloques tectónicos en el noroeste de América del sur definidos por López (2010), en el marco del proyecto colombiano GEORED. Referirse a discusión en el texto

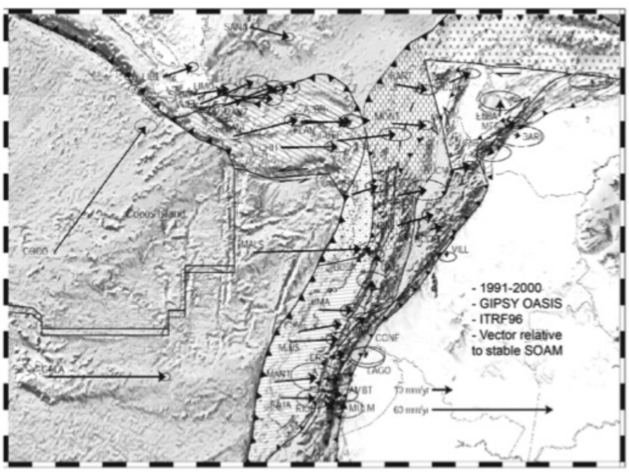

Figure 13. Tectonic blocks in the CA-NZ-SA PBZ and Panamá microplate, defined for GPS data modelling, as a simplification of block individualization of figure 12 and in agreement with figure 9. Basemap after Trenkamp *et al.* (2002)

Figura 13. Bloques tectónicos definidos en la zona de frontera de placas Caribe-América del sur-Nazca y microplaca de Panamá, a fin de modelaje de data GPS, como una simplificación de la definición de bloques de la figura 12 y en corcondancia con la figura 9. Mapa base de Trenkamp *et al.* (2002)

Hess Escarpment

The Hess Escarpment forms a prominent bathymetric break between the Nicaragua Rise to the north and the Colombian Basin to the south (Figures 1 and 2). It is poorly studied and is known mainly from bathymetric surveys and local seismic profiling. Despite the fact that the Hess Escarpment is not associated with any seismicity (issue that shall be argued against later in this paper), Mann & Burke (1984) predict that it may have a right-lateral oblique-slip component on the basis of: (1) its linear definition of the northern margin of an area of late Neogene deposition occupying the floor of the Colombian Basin; and (2) the stepping of offsets at 81° and 74°W (offset at 81° W steps left and appears to be a restraining bend, and offset at 74°W steps right and appears to be a pull-apart). The Hess Escarpment appears to terminate to the northeast along the western edge of the Beata Ridge, while its western end appears to terminate in Central America near an area of Quaternary alkaline volcanism (Wadge & Wooden, 1982) and near the southern end of the back-arc basin (Nicaragua Depression) behind the Middle America frontal arc. Continuous seismic profiling from the Venezuelan Basin across the Beata Ridge and Hess Escarpment to the Nicaragua Rise indicates that the prominent seismic reflectors A" (early Paleogene) and B" (late Cretaceous) are continuous across the Hess Escarpment (Moore & Fahlquist, 1976). Mann & Burke (1984) coincide in saying that the Hess Escarpment irrespective of any earlier history, appears to be a major late Neogene structural boundary in the Caribbean interior, although the amount of present-day displacement appears small.

Compartmentalization by the Hess Escarpment

In that sense, at very large scale, two conspicuously distinguishable uneven halves are noticeable at first sight in the Caribbean region (Figures 1 and 2). These two large units are split apart by the Hess Escarpment, which runs ENE-WSW in the CA plate interior. The northern unit shows simpler plate boundaries, whereas the rest is dominated by block tectonics around the entire periphery, except for the rather simple and normal Atlantic oceanic subduction beneath the eastern CA plate. In fact, the two PBZs of the northern unit correspond to: (1) on the north, the transform fault system that bounds the Cayman sea-floor spreading center; a major transtensional relay between two subparallel left-lateral strike-slip faults, with generation of oceanic floor; and (2) on the southwest, the CO-CA plate boundary, where normal ocean-floor subduction takes place. The only complication here is the presence of a trench-parallel sliver moving NW and parallel to the trench, which denotes that the PBZ is undergoing strain partitioning. On the contrary, the southern CA unit exhibits 3 areas where the continental or arc masses are overriding the thickened CA plate, namely the NPDB, SCDB and Muertos trench. These correspond to the 3 festoons described by Stephan *et al.* (1986): Panamá, Venezuela and Hispaniola-Puerto Rico psedosubductions, respectively. Different mechanisms have been evoked to explain the presence of these induced subductions, as discussed earlier in this paper.

Effects of the Hess Escarpment on the CA PBZs

In the PBZs themselves, the presence of the Hess Escarpment is also influential and noticeable. For instance, at its SW projection across the Middle America land bridge, north and south of its alignment, the size and width of Middle America drastically changes (Figures 1 and 2). North of the alignment, Middle America is large and appears robust (corresponding to Nicaragua, El Salvador and Guatemala) while to the south is in fact no more than a narrow land bridge along Costa Rica and Panamá. Geologically speaking, the juxtaposed blocks are also different. Baumgartner *et al.* (2008) propose that the Chortis (Mesquito)-Chorotega boundary is in the southwestward projection of the Hess Escarpment into central Costa Rica. Linkimer *et al.* (2010) express that this boundary does not conflict with geology and Vp/Vs estimates. In general, Vp/Vs is higher on the Chorotega side (south of the projection), although more Vp/Vs data will be needed to determine if its location is visible from Vp/Vs changes. These authors also suggest that this boundary continues on the western margin of the Nicoya Gulf, separating the Mesquito and Nicoya terranes and following the boundary suggested by Hauff *et al.* (2000), who consider the Nicoya Peninsula as part of the Chorotega Block and both the Tortugal and Santa Elena areas as part of the Chortis Block (i.e., Mesquito Terrane). Nor does the northeastern projection differ. This eventual northeastward prolongation roughly runs where the Mona Passage meets the North Hispaniola-Puerto Rico trench. In other words, where the North Hispaniola Fault bends 25° counterclockwise to continue eastward along the 75°N trending Puerto Rico oblique subduction. It coincides with the transition from a fully partitioned (Hispaniola) to non-partitioned (Puerto Rico) plate boundary. On top of that, it overlaps with where the surface expression of a buoyant Bahamas platform disappears. As discussed earlier, the incorporation of the buoyant Bahamas platform into the subduction zone results in the tectonic pinning of Hispaniola, whereas Puerto Rico moves eastwards at the full Caribbean plate velocity. This in turn requires extension between Hispaniola and Puerto Rico, consistent with GPS data (Jansma *et al.* 2000) and offshore observation of active normal faults in the Mona Passage (Grindlay *et al.* 1997; van Gestel *et al.* 1998). At scale of the entire NA-CA PBZ, this intersection also coincides with: (1) The double bend that this PBZ zone follows around northern Hispaniola; (2) The major change from pure transform on the west to (partitioned or not) oblique subduction on the east; and (3) Change in orientation of the Mesozoic Caribbean Arc (MCA in the sense of Bouysse, 1988) from its original NW-SE trend, before being bent 25° counterclockwise. Is it a coincidence that such a conspicuous and long feature tends to end where these major PBZ changes take place? If assumed that the Hess Escarpment in the Neogene allowed a significant eastward migration of the MCA, after colliding Cuba and Northern Hispaniola with the buoyant Bahamas platform, it would imply that this transform boundary used to slip left-laterally; conversely to Mann & Burke (1984)'s proposal (right-lateral slip of motion based on potential trasntensional and transpressional geome-tries). This would also account for the late Miocene-Pliocene rotation undergone by the Puerto Rico-Virgin Islands block, described by Reid *et al.* (1991) and the very slow oblique slip rate (or no relative motion) of the Los Muertos trench south of Puerto Rico, while the MCA kept migrating eastward and bending counterclockwise. It somehow came in help of the Cayman spreading center and its associated transform boundary faults, in accommodating left-lateral motion. If this assumption happens to be right, the left-lateral strike-slip rate of the Hess Escarpment fault system must have been similar to the opening rate proposed for the Mona passage of about 2-3 mm/a, and less than 5 mm/a, by Jansma *et al.* (2000) and Mann *et al.* (2002). More recently, model slip rates on the Mona Passage fault derived by Manaker *et al.* (2008), show SE-NW extension at 5.7 ± 4.3 mm/a trending ~N65° E, in good agreement with previously reported extension rate of 5 ± 3 mm/a between Hispaniola and Puerto Rico from GPS studies (Jansma *et al.* 2000; Jansma & Mattioli, 2005). This slip rate should be much the same as the one along the Los Muertos trench. This geometry would also support that the Puerto Rico block is attached to the Aves ridge and the stable CA plate, as proposed by Mann *et al.* (2002), thus implying that most of the Los Muertos trench and the Anegada passage features are inactive or below the current GPS threshold of 2-3 mm/a. These statements are confirmed by recent results from Manaker *et al.* (2008) as well. On one hand, slip on the Anegada Passage fault is 3 ± 3mm/a directed ~N43°W, implying NW-SE extension across this region. However, relative GPS velocities across the Anegada Passage are close to zero, suggesting that the actual slip rate may be closer to the lower end of the estimated model rate. On the other hand, these authors estimate that model oblique slip rate on the Los Muertos Thrust decreases to 1.7 ± 1.7mm/a east of the Mona Passage (south of the Puerto Rico block). Then, we could summarize that the most recent phase of eastward migration of the MCA may have essentially occurred through rotation of the northern and southern hinge zones of the Lesser Antilles subduction, being counterclockwise near the Virgin Islands on the north and clockwise in eastern Venezuela and Trinidad, while the CA plate was shortened in the north-south direction by the convergence between the Americas set on in the Oligocene and still ongoing, thus requiring a small amount of wrenching on both north and south PBZs, This is in agreement with the amount of late Cenozoic strike-slip motion in the southern PBZ estimated by Audemard & Giraldo (1997).

Beata Ridge and Aruba Gap

The Beata Ridge is marked by a triangular-shaped uplifted area at the place where the Caribbean is narrowest, between the Guajira Peninsula of Colombia and Hispaniola. It forms the boundary between the Colombian Basin and the Venezuelan Basin. Fox & Heezen (1975) suggested that the structure of the Beata Ridge consists of a steep fault scarp bounding its western edge and a series of fault blocks, which step down to the floor of the Venezuelan Basin. Using seismic profiles, Ladd *et al.* (1981) were unable to confirm whether the east flank of the Beata Ridge is a series of fault blocks or it consists of parallel volcanic ridges.

North-south seismic profiling in the Aruba Gap between the southern edge of the Beata Ridge and the Curacao Trench has revealed the presence of three fault profiles showing "flower structures", which Hopkins (1973) has interpreted as east-west trending strike-slip faults. This interpretation is consistent with strike-slip focal mechanisms for this general area from Molnar & Sykes (1969). From an age control established by Hopkins (1973) for the sedimentary sequence on the Beata Ridge, there is no record of any sediment younger than Late Pliocene, thus constraining the time of deformation.

A variety of geologic and seismic observations have been cited as evidence for deformation at the Beata Ridge, possibly driven by slow convergence of the SA and NA plates across the Caribbean region (Dixon & Mao, 1997; Müller *et al.* 1999). DeMets *et al.* (2010) list the following: (1) Heubeck & Mann (1991) suggest that the Caribbean plate consists of rigid subplates east and west of the Beata Ridge coinciding with the Venezuelan and Colombian basins; (2) Consistent with this interpretation, Leroy & Mauffret (1996) interpret apparently reactivated reverse faults imaged in marine seismic profiles that cross the eastern flank of the Beata Ridge as evidence for contraction across the Beata Ridge and hence deformation within the CA plate. Mauffret & Leroy (1999) further interpret compressional features along the Beata Ridge as evidence for NE-SW shortening between independently moving microplates flanking the Beata Ridge and estimate that the convergence rate across the Beata Ridge has averaged 9.0 ± 1.5 mm/a for the past 23 Ma.

After Driscoll & Diebold (1998), the timing and cause for the formation of the Beata Ridge remains controversial (Holcombe *et al.* 1990; Mauffret & Leroy, 1997). For example, recent studies have proposed that a renewed phase of deformation occurred in the Miocene and that deformation is still ongoing in the region of the Beata Ridge (Mauffret & Leroy, 1997). In the Mauffret & Leroy (1997) model, the Colombian plate is currently overthrusting the Venezuelan plate with the thrust front being located along the eastern flank of the Beata Ridge. Such a two-plate kinematic model for the Caribbean was first proposed by Dewey & Pindell (1985), and requires differential motion between the Venezuelan and Colombian basins. This plate kinematic model predicts that deformation across Beata Ridge accommodated the differential motion between the eastern and western Caribbean plates. On the basis of seismic reflection and dredge data, Fox *et al.* (1970) proposed that Beata Ridge was uplifted after the Eocene (i.e., post reflector A"). An alternative hypothesis, the single-plate model for the Caribbean, purports that the majority of the deformation observed across the Beata Ridge and Venezuelan Basin occurred early in the history of the Caribbean (i.e., Late Cretaceous) prior to large sediment accumulation. Minor fault reactivation along the eastern Beata Ridge and Venezuelan Basin is inferred to having been caused by the different styles of deformation in response to the north-south compres-sional stress (Holcombe *et al.* 1990; Diebold *et al.* 1995). Driscoll & Diebold (1998) seem to bring conclusive arguments to this debate. They conclude that the sediment thickness and stratal geometry of the overlying sedimentary successions across the Venezuelan Basin and Beata Ridge suggest that the majority of the observed deformation in this region occurred soon after the emplacement of the volcanics, and is best explained by the one-plate model. Minor fault reactivation in the Neogene along the eastern flank of the Beata Ridge is associated with an accommodation zone (i.e., tear fault) that records a change in the deformation style from subduction of the CA plate along the Los Muertos Trough to obduction of the CA plate onto the Bahamas platform along Hispaniola. We feel that the resumed tectonic activity across the Beata Ridge in the Neogene may be linked to left-lateral motion along the Hess Escarpment. More plausible is this if the Neogene deformation happens to be compressional.

GPS tests for CA plate internal deformation

DeMets *et al.* (2010)'s paper is largely motivated by the need of testing whether the CA plate undergoes internal deformation at present day. Simple, but rigorous numerical experiments with the GPS site velocities carried out by these authors indicate that any east-to-west deformation across the Beata Ridge and Lower Nicaraguan Rise is unlikely to exceed 2 mm/a, and within the uncertainties is zero. The kinematic evidence for insignificant east-to-west deformation agrees with results reported by Driscoll & Diebold (1998), who conclude that marine seismic data from the Beata Ridge do not require the occurrence of significant contraction across this structure since the Miocene. If such contraction has occurred, as suggested by Mauffret & Leroy (1999), results from DeMets *et al.* (2010) suggest that it has now ceased.

Mechanisms of CA plate internal deformation

Several mechanisms have been invoked to explain the internal deformations within the CA plate: (1) Convergence between the Americas since the Oligocene across the CA plate (Ladd, 1976; Sykes *et al.* 1982; Burke *et al.* 1984; Pindell *et al.* 1988), inducing the overriding of neighboring continental masses of either continental or oceanic affinity or N-S shortening at CA plate scale; (2) Plate-scale bending, across the CA plate in the east-west direction, and subsequent overriding over the CA plate (Stephan 1982; Stephan *et al.* 1986), responsible for the generation of several festoons (NPDB, SCDB, and Hispaniola-Puerto Rico); (3) Tectonic collision that deforms the overriding CA plate, such as those of the Cocos Ridge or the Panamá Arc; and (4) Tectonic escape of continental blocks, such as the NNE-directed escape of the North Andes Block –NAB- (Case *et al.* 1971; Dewey, 1972; Pennington, 1981; Stephan, 1982; Audemard, 1993; 1998; Freymueller *et al.* 1993; Ego *et al.* 1996); which in turn is to be also related to tectonic collision of either the Carnegie Ridge, the southern tip of the Panamá Arc or both jointly. Very little of the internal CA deformation has been attributed to major features lying within the plate interior except for the Beata Ridge; above discussed.

In addition, we propose a different mechanism of internal deformation, involving the Hess Escarpment. We believe that two plate boundary conditions in two different regions, in connection to both projections of the Hess Escarpment at PBZs, helped its development as well as its left-lateral strike-slip motion, probably in the late Miocene-early Pliocene, as bracketed by counterclockwise rotations in Puerto Rico measured by Reid *et al.* (1991): (1) on the northeastern projection of the Hess Escarpment, the collision and pinning of Northern Hispaniola against the buoyant Bahamas platform; and (2) on the southwestern end, the high coupling at CO-CA plate interface and simultaneous collision-incipient indentation of the buoyant Cocos Ridge. The buoyant Bahamas platform on one end acts as a buttress while the buoyant Cocos Ridge on the other tip acts much as an indenter. These two processes effectively added to each other to engine the relative faster "escape" of the southern unit of the CA plate with respect to the northern one. In addition, under the convergence between the Americas, which has induced N-S shortening across the shortest axis of the CA plate, the ENE-WSW orientation of the Hess Escarpment, in comparison to the east-west orientation of the current NA-CA PBZ, facilitates even more the migration and "escape" of the southern half of the CA plate, due to its wedge shape enlarging to the east, in the direction of the "escape". The 25° counter-clockwise rotation of the 500 km long Puerto Rico Block alone helps to accommodate some 200 km of N-S shortening in the Eastern Caribbean, east of the Mona Passage. In turn, this "escape" could also account for the decompression of the northern half of the CA plate, reflected in the opening of N-S trending grabens in the Nicaragua Rise, and even onshore Guatemala and Honduras, resulting in the N-S "flattening" of the Nicaragua Rise and contiguous continental Central America region.

An alternate driving mechanism could be advanced for the geometry and variable along-trend kinematics of the Los Muertos trench. Although it would keep contributing to accommodate the N-S shortening introduced by the convergence of the Americas, as proposed by many authors, it would incorporate it in a different manner. Under the assumption that the Hess Escarpment once slipped left-laterally, while the Puerto Rico Block was rotating counterclockwise and the Puerto Rico subduction along this block was progressively evolving from frontal to oblique subduction with time, the southern edge of the Puerto Rico Block had to be overthrusted onto the CA plate to accommodate part of the compression across the arc. This had to lead to the generation of the Los Muertos trench. Since the NE projection of the Hess Escarpment intersects the western tip of the Los Muertos subduction and forearc, we propose that the induced Los Muertos subduction (or overthrusting) can be regarded as a transpressional fault-tip thrust fault. In fact, it is a S-to-SSW-verging fold-and-thrust belt. The arguments favoring this alternate interpretation are: (1) the geometric angular relationship of the Los Muertos trench with the Hess Escarpment (~130°); (2) the widening of the Los Muertos sedimentary wedge towards the west (Granja *et al.* 2006); (3) its more pronounced arcuate shape to the west; and (4) the slip rate decrease from west to east. Most researchers agree on this. Motion on the low-angle Muertos thrust fault decreases from the west tip eastward to longitude 66° W where little or no active underthrusting is occurring (Masson & Scanlon, 1991). After Manaker *et al.* (2008), model oblique slip rates on the Los Muertos Thrust average 5 ± 2 mm/a, decreasing from 7.3 ± 1.0 mm/a west of the Mona Passage to 1.7 ± 1.7 mm/a east of the Mona Passage. Mann *et al.* (2002) estimate 6 to 1 mm/yr of thrust motion across the Los Muertos fault, also decreasing from west to east. Assuming that the Hess Escarpment has slipped left-laterally for some 10 Ma (since Late Miocene and coeval with the Puerto Rico Block rotation) at an average slip rate between 2 to 5 mm/a (in the same range as the slip on the Los Muertos trench or the Mona Passage extension), a minimum shortening of 20 to 50 km has been accommodated on the Los Muertos fold-and-thrust belt (sedimentary wedge) if fully coupled, related to transpression at the northeastern tip of the Hess Escarpment. In such a case, the Los Muertos trench would be linked to a pseudo- or induced subduction.

It must be kept in mind that this relative escape along the Hess Escarpment may have been arrested or substantially been slowed down more recently by the collision and later suturing of the Chocó block against the western border of NW SA, once attached to the trailing edge of the CA plate that effectively happened sometime in the Pliocene. In that sense, we can put forward that the Hess Escarpment has not been inactive in the past; and is not currently inactive either, as we shall discuss next.

Seismicity along the Hess Escarpment

Published maps, such as USGS-NEIC and MIDAS Consortium (1998) and Tarr *et al.* (2010), among others, suggest that the southwestern submarine expression of the Hess Escarpment, near the Caribbean shore of Coast Rica, exhibit an associated shallow seismicity, extending along its bathymetric expression. This seismicity is very sparse but well aligned along the trend of the Hess Escarpment. For instance, the plotted events on the USGS-NEIC-MIDAS map are above Mw 4.2. To better image this seismic activity, we show herein a map of the region with the plotted seismic data shallower than 33 km deep, available from the Global Earthquake Search of the USGS for the period January 1973 and June 2013 (Figure 14). The fewer (only 4) but larger dots represent shallow earthquakes of magnitude M ≥ 5.0 within the above mentioned time window.

What are the implications of this seismic activity? It is well expressed on all published maps, as well as on our figure 14, that the seismicity along the Hess Escarpment is restricted essentially to its southwestern termination. The rest of its extent appears deprived of any seismicity. It could be argued that this is biased by the low-density distribution of the seismographic stations in the Caribbean Sea region and particularly within the CA plate, but any event of magnitude M ≥ 5.0 should be recorded regardless of its hypocentral location inside the Caribbean. Then, the current seismic distribution should reflect the actual activity of the Hess Escarpment. If so, why is the crustal seismicity restricted to its southwestern termination then? As discussed earlier, this major tectonic feature may have played a fundamental role in the eastward migration of the southern uneven half of the CA plate sometime in the late Miocene-Pliocene, as suggested by the 25° counterclockwise rotation recorded in rocks of that age in Puerto Rico, but its left-lateral motion may have ceased, been arrested or slowed

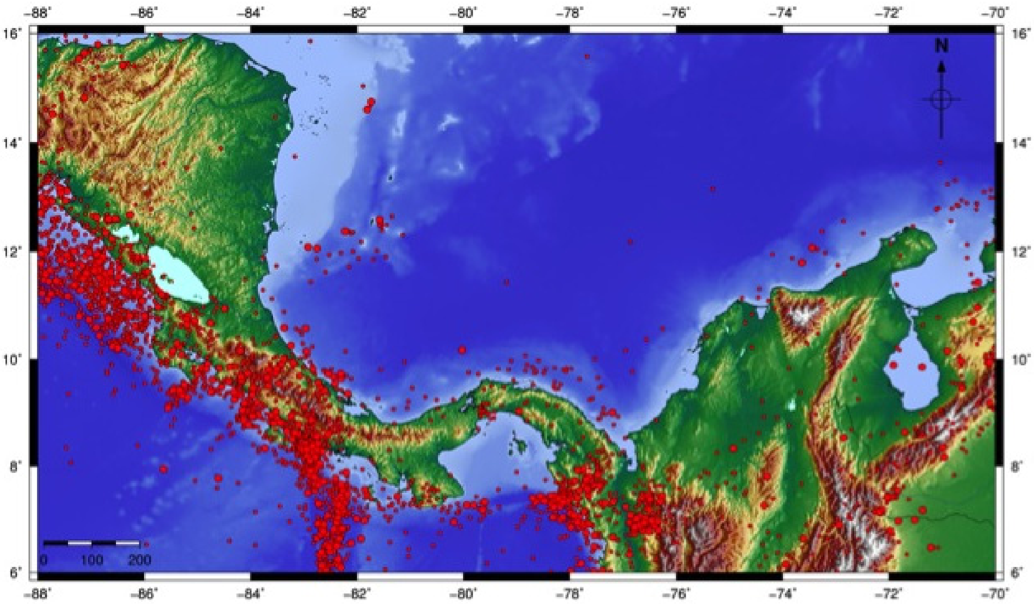

Figure 14. Seismicity shallower than 33 km deep, available from the Global Earthquake Search of the USGS for the period January 1973 and June 2013, plotted on GLOBE bathymetry-topography (GLOBE Task Team and others, 1999). Larger cricles are epicenters of events M ≥ 5.0. Note the seismic activity along the southwestern termination of the Hess Escarpment, off the Caribbean coast of Costa Rica

Figura 14. Mapa de sismicidad de eventos de profundidad inferior a 33 km, extraidos del Global Earthquake Search of the USGS para el período enero 1973 - Junio 2013, representados en la topografía-batimetría de GLOBE (GLOBE Task Team and others, 1999). Los círculos más grandes son de eventos de M ≥ 5.0. Obsérvese la actividad sísmica asociada a la terminación suoreste del escarpe de Hess, costa afuera de la costa caribeña de Costa Rica

down afterwards, sometime in the Pliocene. As suggested here, that motion break can be imputed to the suturing of the Chocó block, at the trailing edge of the CA plate, at that time. The present day seismicity of the Hess Escarpment close to Central America has then to be considered as a renewal or reactivation in seismic activity and a resume in motion of the Hess Escarpment in the Late (?) Quaternary, since four focal mechanism solutions herein presented attest to the left-lateral and normal components of slip along this major feature (Figure 15). It is very likely that this reactivation is a direct consequence of the collision-indentation of the buoyant Cocos Ridge against the Pacific board of Central America. The main argument in favor of this hypothesis is the nearness of this seismic activity to the southwestern termination of this very major tectonic feature, as well as the alignment of the Hess Escarpment along the northern edge of the paralleling Cocos Ridge. To some extent, the normal left-lateral slip along the Hess Escarpment is accompanying the overthrusting of the Panamá microplate onto the CA plate, just north of its northwestern termination along the CCRDB, which crosses Costa Rica and acts as a thrust left-lateral lateral ramp for the microplate emplacement. Both kinematics seem to result from the ongoing Cocos Ridge indentation.

It is worth mentioning that the major and current phase of dextral SS in northern Venezuela (CA-SA PBZ), which would necessarily be the southern boundary of this southern half of the CA plate, was set on around 17 Ma (Middle Miocene; Audemard, 1993; 1998; 2009). This strike-slip rupture propaga-tion was diachronic from west to east, starting at 17 Ma with Oca-Ancón fault –OAF- in western Venezuela and ending with the generation of the El Pilar fault at around 10 Ma in the Gulf of Paria (Audemard, 1993; 1998; 2009). In addition, the east-west trending OAF, which used to be part of that southern CA-SA boundary, transferred its dextral slip onto the Boconó fault sometime around 5-3 Ma (Audemard, 1993; 1998; 2009). Then, it is worth exploring whether the left-lateral Hess Escarpment and the right-lateral Oca-Ancón-San Sebastián-El Pilar fault system together, on the north and south respectively of the wedge-shaped southern half of the CA plate, did drive and ease the eastward migration and "escape" of that southern CA plate, between the Middle Miocene and Early Pliocene.

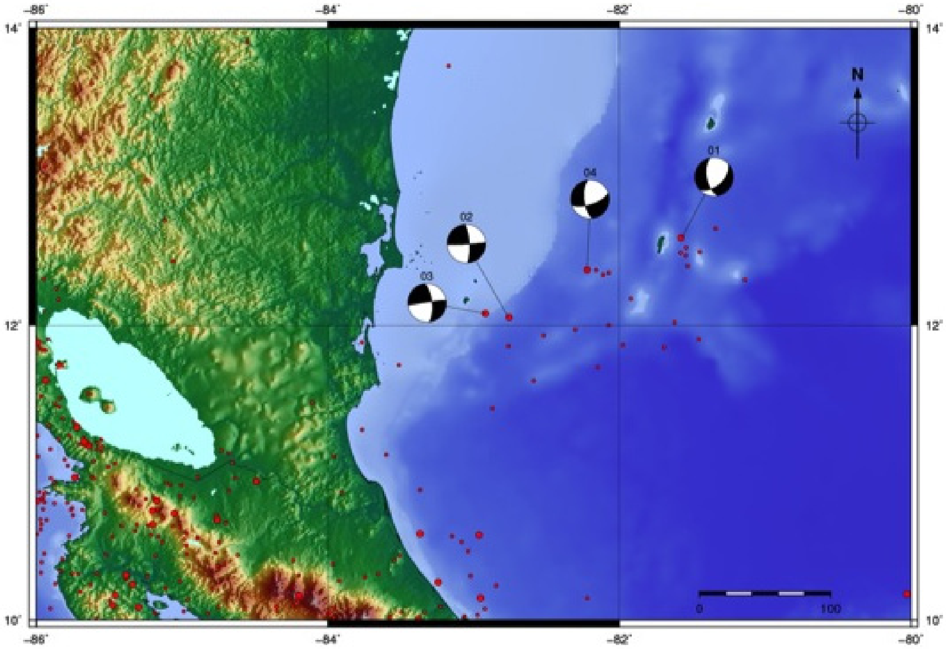

Figure 15. Focal mechanism solutions for earthquakes along the southwestern termination of the Hess Escarpment, off the Caribbean coast of Costa Rica, extracted from the Global CMT catalog (Dziewonski *et al.* 1981 and Ekström *et al.* 2012). They attest to normal and left-lateral components of slip along this tectonic feature

Figura 15. Soluciones de mecanismo focal de sismos asociados a la terminación suoreste del escarpe de Hess, costa afuera de la costa caribeña de Costa Rica, extraidas del Global CMT catalog (Dziewonski *et al.* 1981 y Ekström *et al.* 2012). Estos mecanismos atestiguan las componentes de movimiento normal y lateral izquierda de este accidente tectónico

CONCLUSIONS

With time and gathering of a wealth of geologic, geophysical, seismological and geodetic data in the last 3 decades, the knowledge of the Caribbean and its plate boundaries have become more complex and better understood. To speak of transform or subduction boundaries in the case of the Caribbean region appears very simplistic nowadays. These borders are real plate boundary zones –PBZ-, in which many tectonic blocks of very diverse and varied geometry and composition are taken in. In the southern Caribbean, the lack of a conspicuous boundary in comparison to other borders triggered first regionally the study of onshore major tectonic features and structures, whereas the northern boundary of the Caribbean plate became a natural laboratory for GPS studies, due to the limited extent of the geology in a score of islands. In this PBZ, GPS networks did not resolve all problems in terms of kinematics because most of the networks are on islands, sitting within the active deformation zone. This problem is also common to the Caribbean-Atlantic PBZ. The networks require of stable reference points inside the Caribbean Sea, such as San Andrés, Providencia and Aves islands. Although current and recent GPS results point to very little internal deformation in the Caribbean plate, probably below 2-3 mm/a, the Hess Escarpment has a non-neglegible seismic activity along its southwestern submarine termination, close to the Costa Rica Caribbean coast. Nevertheless, in the frame of the Caribbean geodynamic evolution, this major submarine feature cutting the Caribbean ocean floor into two uneven halves needs to be revisited and rethought. It splits the Caribbean plate into two parts, which exhibit very different geodynamic characteris-tics within the Caribbean plate and along its borders.

All Caribbean plate borders contain more than one tectonic block, and strain partitioning at different scale is common to all Caribbean plate boundaries. Trench-parallel slivers have been defined all over. Between the active volcanic arc and the oceanic trench, slivers have been proposed at the northern Lesser Antilles forearc, as well as along the Middle America trench north of Nicoya Peninsula in Central America. But they also happen along northern Venezuela (Bonaire block and Interior ranges of Venezuela) and north of the Septentrional fault in northern Hispaniola.

On top of that, indentation and indentation-extrusion processes are more frequent than ever thought in the PBZs. The best imaged of these processes is the collision and suturing of the Panamá block against NW South America, but the high buoyancy of different ocean-floor "anomalies" (Cocos and Carnegie ridges, and Bahamas carbonate platform) on oceanic plates have been held responsible for strain partitioning within the PBZ. In some occasions, convergence obliquity has been called upon as the driving force, such as at the northern Lesser Antilles forearc.

The refinement of tectonic block definition, as well as the identification of tectonic blocks, has been boosted by GPS Geodesy, and it still has plenty to provide in that sense. In some cases, small-scale spatial consistency of GPS vectors has led to the proposal of small tectonic blocks, such as that of the Nicaragua Rise, which incorporates the southern part of Jamaica.

Finally, blocks overriding the Caribbean plate have already been defined at three places. They seem not to be true subductions, but tectonic blocks, of composition different to oceanic crust, that thrust onto the Caribbean oceanic lithosphere, not driven by mantle convection. Coincidentally, all three festoons, interpreted as induced subductions, have been identified south of Hess Escarpment.

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