

# QUATERNARY FAULTS AND STRESS REGIME OF VENEZUELA

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## ABSTRACT

Spatial configuration of Quaternary active tectonic features along the southern Caribbean plate boundary suggests that the region is subject to a compressive strike-slip (transpressional *sensu lato*) regime, characterized by a NNW-SSE maximum horizontal stress ( $\sigma_{H1}=\sigma_1$ ) and/or an ENE-WSW minimum ( $\sigma_h=\sigma_3$  or  $\sigma_2$ ) horizontal stress. Stress inversion applied to fault-plane kinematic indicators measured essentially in Plio-Quaternary sedimentary rocks confirms this tectonic regime. Accordingly, this stress regime is responsible for the Quaternary activity and kinematics of six sets of brittle features along northern Venezuela (from Colombia in the west to Trinidad in the east): (1) east-west right-lateral faults, (2) NW right-lateral faults -acting as synthetic Riedel shears-, (3) ENE to east-west dextral faults -P shears-, (4) NNW normal faults, (5) almost north-south left-lateral faults -antithetic Riedel shears- and (6) mostly subsurface ENE reverse faults associated with folding of the same orientation. Brittle deformation conforms to the simple shear model, although not all the deformation can be accounted for it since strain partitioning is also taking place because regional folding and thrusting are due to the normal-to-structure component of the relative slip vector between the Caribbean and South America plates. On the other hand, the maximum horizontal stress in western Venezuela, particularly in the Maracaibo block and south of the Oca-Ancón fault, progressively turns counter-clockwise to become more east-west oriented, producing left- and right-lateral slip along the north-south striking and NE-SW striking faults, respectively. The orientation and spatial variation of this regional stress field in western Venezuela results from the superposition of the two major neighboring interplate maximum horizontal stress orientations ( $\sigma_{H1}$ ): roughly east-west trending stress across the Nazca-South America type-B subduction along the Pacific coast of Colombia and NNW-SSE oriented stress across the southern Caribbean boundary zone.

Keywords: *Quaternary tectonics, fault-slip data, stress tensor, Caribbean, Venezuela.*

## RESUMEN: Fallas y campo de esfuerzos cuaternarios de Venezuela.

La configuración espacial de los rasgos tectónicos activos cuaternarios en el Caribe meridional sugiere que esta región está sujeta a un régimen tectónico transcurrente compresivo (transpresivo *sensu lato*), caracterizado por un esfuerzo horizontal máximo ( $\sigma_{H1}=\sigma_1$ ) de dirección NNO-SSE y un mínimo ( $\sigma_h=\sigma_3$  or  $\sigma_2$ ) orientado ENE-OSO. La aplicación de métodos de inversión a datos microtectónicos determinados sobre planos de fallas afectando rocas sedimentarias esencialmente de edad plio-cuaternarias confirma este régimen tectónico. Consecuentemente, este régimen es responsable por la cinemática y actividad cuaternaria de seis familias de estructuras tectónicas frágiles a lo largo del norte de Venezuela (desde Colombia en el oeste hasta Trinidad en el este): (1) fallas dextrales este-oeste, (2) fallas dextrales NO que actúan como "Riedels" sintéticos-, (3) fallas dextrales ENE a este que se comportan como fracturas P, (4) fallas normales NNO, (5) fallas sinestrales submeridianas consideradas como fracturas "Riedels" antitéticos y (6) fallas inversas ENE - sub-paralelas al plegamiento de la misma orientación. En esta región en particular, la deformación frágil obedece el modelo de cizalla simple, aunque no toda la deformación puede atribuírsele porque simultáneamente ocurre partición de la deformación porque el plegamiento y fallamiento inverso se debe esencialmente a la componente ortogonal a las estructuras del vector de desplazamiento relativo entre las placas Caribe y Suramérica. Por otra parte, el esfuerzo máximo horizontal en Venezuela occidental, particularmente en el bloque de Maracaibo y al sur de la falla de Oca-Ancón, progresivamente tuerce en sentido anti-horario para orientarse este-oeste, permitiendo la activación simultánea de fallas sinestrales y dextrales de orientación norte y NE respectivamente. La orientación y variación espacial del campo de esfuerzo regional en Venezuela occidental resulta de la superposición de las orientaciones de los dos esfuerzos horizontales máximos imperantes en el norte de Suramérica ( $\sigma_{H1}$ ): el esfuerzo de orientación este-oeste producto de la subducción de la placa Nazca por debajo de la costa pacífica de Colombia y el esfuerzo orientado NNO-SSE a través del límite de placas del Caribe meridional.

Palabras clave: *Tectónica cuaternaria, microtectónica, tensores de esfuerzos, Caribe, Venezuela.*

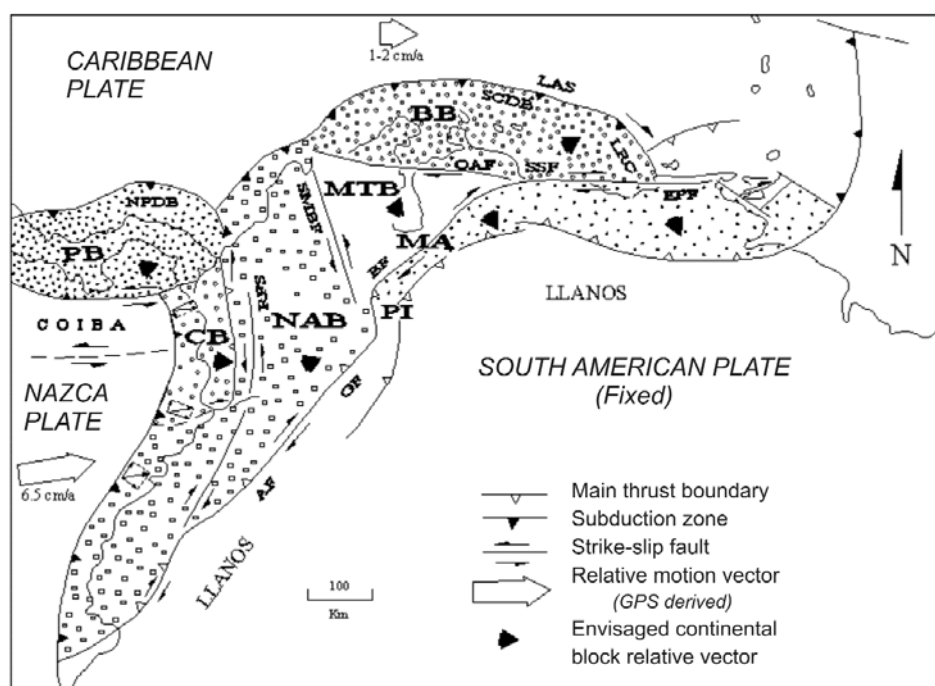
## INTRODUCTION

This paper presents an updated compilation of the Quaternary faults of Venezuela,

generated in the frame of an ILP II-2 project, "Major Active Faults of the World", led by Michael Machette of the USGS, responsible for the Western Hemisphere, and

Vladimir Trifonov of Russia, responsible for the Eastern Hemisphere. The South American maps and data compilation efforts were coordinated by Carlos Costa of

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**Figure 1:** Simplified general geodynamic setting of the southern Caribbean (modified from Audemard, 2002). Region is subject to a complex block tectonics. Vector decomposition of the convergence vector at the Nazca subduction may explain the along-strike slip change of the Romeral fault system. Equivalence of used acronyms is as follows: Bonaire (BB), Chocó (CB), Maracaibo (MTB), North Andean (NAB) and Panamá (PB) blocks; Mérida Andes (MA) and Pamplona indenter (PI). Some major faults are also reported: Algeciras (AF), Boconó (BF), El Pilar (EPF), Guaicaramo (GF), Romeral (RFS), Santa Marta-Bucaramanga (SMBF), San Sebastián (SSF) and Oca-Ancón (OAF); and other features as well: Leeward Antilles subduction (LAS), Los Roques Canyon (LRC), North Panamá deformation belt (NPDB), and Southern Caribbean deformation belt (SCDB).

the University of San Luis in Argentina. The Quaternary fault map data of Venezuela, updated until 1998, are compared to stress tensors derived from fault-plane kinematic indicators measured essentially in sedimentary rocks of Plio-Quaternary age and compiled by Audemard *et al.* (2005). In this paper these will be discussed in terms of their significance with respect to the interactions among the Caribbean, South America and Nazca plates and the smaller continental blocks of northwestern South America.

## GENERAL GEODYNAMIC SETTING

Western Venezuela and northern Colombia are situated in a very complex geodynamic setting involving a number of tectonic blocks or microplates. Conversely, northern Venezuela essentially lies in the direct interaction zone between the South America and Caribbean plates (Fig. 1) and there is a general consensus on the eastward motion of the Caribbean plate relative to South

America (Bell 1972, Malfait and Dinkelman 1972, Jordan 1975, Pindell and Dewey 1982, Sykes *et al.* 1982, Wadge and Burke 1983, among others). Lately, this has been strongly supported by results of recent GPS surveys (Freymueller *et al.* 1993, Kaniuth *et al.* 1999, Weber *et al.* 2001, Pérez *et al.* 2001, Trenkamp *et al.* 2002). Nevertheless, this Caribbean-South America plate boundary -which drives and defines active tectonics along northern Venezuela (from Colombia to Trinidad)- can not be classified solely as being of the simple dextral type (Soulas 1986, Beltrán 1994) since it comprises a more than 100 km wide active transpressional zone occurring partly offshore and partly onshore northern Venezuela (Audemard 1993, Singer and Audemard 1997, Audemard 1998, Ysaccis *et al.* 2000). Important positive relief features within the onshore portion of this plate boundary zone, such as the Coastal and Interior ranges (I, J and Q in Fig. 2), line the entire northern and part of the eastern Venezuelan coast. This would seem inconsistent with the Caribbean plate motion vector

in a direction  $086^\circ \pm 2^\circ$  with respect to the Central range of Trinidad predicted by Weber *et al.* (2001), and  $N084^\circ \pm 2^\circ E$  with respect to South America (Canoa site) by Pérez *et al.* (2001) from GPS data, which suggest almost pure wrenching with only slight transtension in eastern Venezuela, an issue which shall be discussed in more detail later in this paper. This wide transpressional boundary (in its widest definition, signifying coexistence of strike-slip and compression but not necessarily accommodated jointly on one single structure) extends southwestward into the Mérida Andes (MA in Fig. 1). The plate boundary in western Venezuela covers a 600 km wide zone and comprises a set of discrete tectonic blocks or microplates (Fig. 1), which move independently among the surrounding larger plates (Caribbean, South America and Nazca). The Maracaibo block (MTB in Fig. 1) which stands out among those blocks for its perfect triangular shape, is bounded by the left-lateral strike-slip Santa Marta-Bucaramanga fault (SMBF) in Colombia and the right-lateral strike-slip

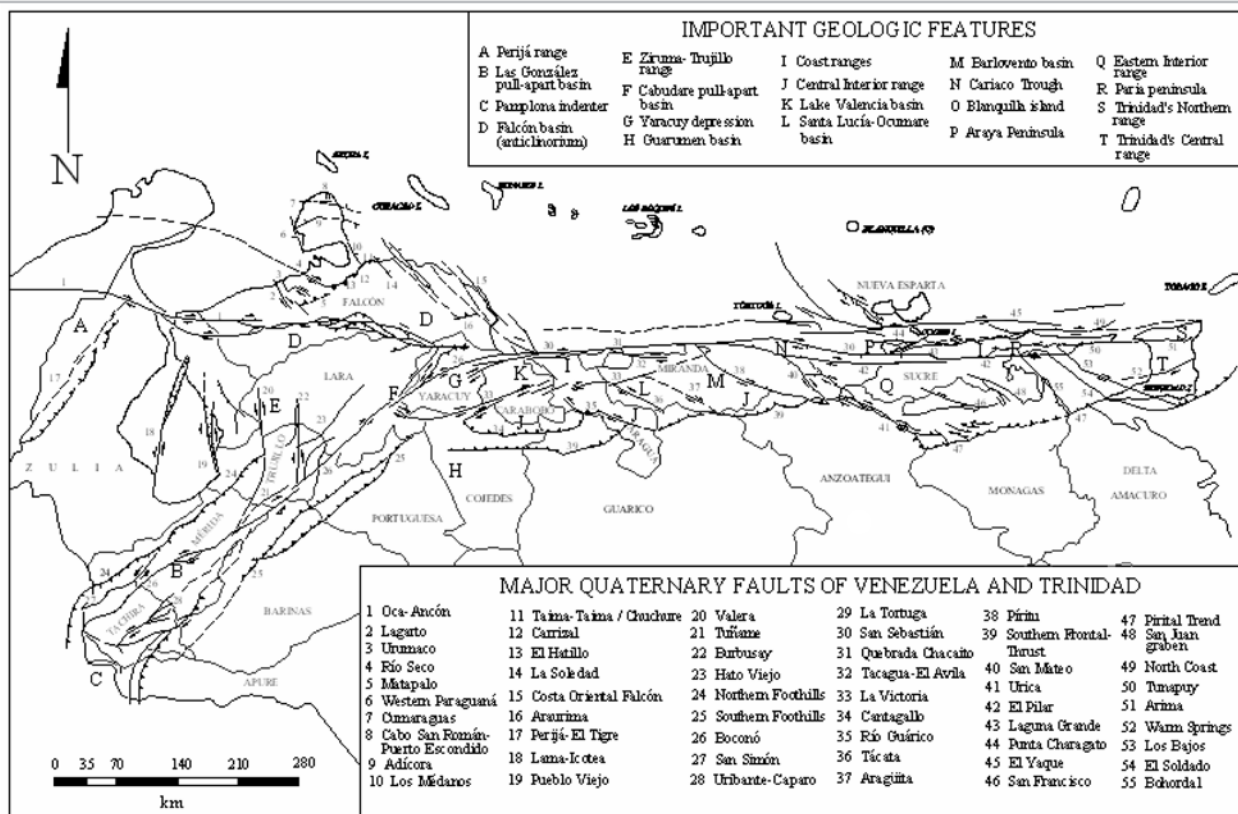


Figure 2: Schematic map of Quaternary faults of Venezuela (simplified from Audemard *et al.* 2000). Faults and toponyms used throughout this contribution are identified. Very few localities are only reported in figure 4.

Boconó fault (BF) in Venezuela and separated in the north from the Bonaire block (BB in Fig. 1) by the right-lateral strike-slip Oca-Ancón fault (OAF). Besides, both the Maracaibo and Bonaire blocks are being extruded northward with the Bonaire block moving slightly east. Together they are overriding the Caribbean plate north of the Leeward Antilles islands, where a young south-dipping, amagmatic, flat subduction (LAS) has developed in recent times (mainly during the last 5 ma). The tectonic extrusion of these blocks is induced by the collision of the Panamá arc (PB in Fig. 1) against the Pacific side of northern South America and its subsequent suturing (Audemard 1993, 1998). Recent results from GPS plate motion studies (Frey Mueller *et al.* 1993, Kellogg and Vega 1995, Kaniuth *et al.* 1999, Trenkamp *et al.* 2002), such as the CASA project, confirm this northeastward escape of both blocks, which in the process generate the Southern Caribbean Deformation Belt (SCDB) north of the Netherlands Leeward Antilles. The present Caribbean-South American

geodynamic configuration results from a transpressive evolution that has occurred throughout the Tertiary and Quaternary, initiated as an oblique type-B subduction. The NW-dipping oceanic lithosphere, attached to northern South America, subducted obliquely under Caribbean plate island arc. This plate boundary zone later evolved into a long-lasting east-younging oblique-collision, where Caribbean-affinity nappes overrode towards the SSE, thus scrapping off passive-margin-affinity nappes and incorporating them into the tectonic pile, which in turn was all overthrust onto the undeformed South America passive margin. More recently, this plate boundary converted into a partitioned transpression when and where collision became unsustainable (for more details refer to Audemard 1993, 1998). Its latest evolutionary stage is still active in Eastern Venezuela and Trinidad and marks the shift from oblique subduction to present-day partitioned oblique collision. This east-younging oblique convergent margin has acted diachronically throughout the evolution of this entire nor-

thern portion of the plate boundary (Audemard 2000) and clearly indicates that, through time, the plate boundary zone has progressively changed from a predominant compressive to a more wrenching type. This change started at around 17-15 Ma in northwestern Venezuela (Audemard 1993, 1998). The tectonically complex southeastern Caribbean is undergoing two major geodynamic processes: (a) strain partitioning characterized by NNW- trending shortening across the entire region from north of La Blanquilla island (O in Fig. 2) to the southernmost active thrust front of the Interior range and right-lateral strike-slip along the main east-west striking El Pilar and NW-SE striking Los Bajos-El Soldado faults, as well as along other minor parallel and/or synthetic Riedel shear faults (Fig. 2); and (b) slab detachment associated with an incipient type-A subduction (e.g., Russo and Speed 1992, Russo 1999; responsible for the largest onshore negative Bouguer anomaly of the world, located south of the southern edge of the Interior range). These processes concur with a plate boundary

geometry such as the present one, where the El Pilar fault transfers its slip eastward to one of its synthetic Riedel shears (Los Bajos and El Soldado faults), which is acting as a "lithospheric tear fault", thus separating the transpressional boundary on the west from the conventional type-B Lesser Antilles subduction zone on the east. These two distinct seismotectonic domains were originally identified by Pérez and Aggarwal (1981). The different seismicity patterns support contrasting geodynamic contexts (oblique collision and oblique subduction roughly west and east of the Los Bajos-El Soldado fault system, respectively). Recent GPS findings by Weber *et al.* (2001) indicate that most of the strike-slip motion of the El Pilar fault is transferred onto the Warm Springs fault system of the Central Range of Trinidad rather than onto a fault south off Trinidad (Fig. 2). This would imply that the Paria gulf is functioning at present as a pull-apart basin bounded by the El Pilar and Warm Springs faults on the north and south respectively, at a releasing stepover. Both faults exhibit a similar slip rate, in the order of 8-10 mm/a (compare Audemard *et al.* 2000 and Saleh *et al.* under review). However, this crustal deformation does not exclude that a major plate boundary is underlying this region, as evidenced by the instrumental seismicity, a conclusion originally drawn by Pérez and Aggarwal (1981) and later confirmed by Sobiesiak *et al.* (2002).

As in eastern Venezuela, strain partitioning is also a common feature along the rest of the transpressional boundary zone. In the Mérida Andes, strain is nicely partitioned between the right-lateral strike-slip Boconó fault (BF) running slightly oblique along the axis of the chain and thrust faults bounding the chain on both flanks (Audemard and Audemard 2002). The north-central coastal ranges also exhibit strain partitioning, where dextral slip in the range core is accommodated by both the San Sebastián and La Victoria faults and other minor synthetic Riedel shears whereas transverse shortening is mainly taken by uplift and the frontal thrust faults bounding the chain along its southern edge, such as in the Guaramen basin (Cojedes state; Audemard 1999a).

A large portion of the dextral slip along this complex boundary seems to be presently accommodated by the major right-lateral strike-slip Boconó-San Sebastián-El Pilar-Los Bajos fault system or segments of it (Molnar and Sykes 1969, Minster and Jordan 1978, Pérez and Aggarwal 1981, Schubert 1980a and b, 1982, Stephan 1982, Aggarwal 1983, Schubert 1984, Soulas 1986, Beltrán and Giraldo 1989, Singer and Audemard 1997, Audemard *et al.* 2000, Weber *et al.* 2001, Pérez *et al.* 2001). This slip is now known to be transferred farther east onto the Warm Springs fault system of central Trinidad (after Weber *et al.* 2001's results). It is still matter of debate whether this is either a transcurrent or transform system and depends on the authors and their proposed geodynamic models. Most authors accept or postulate this major right-lateral strike-slip fault system to be the plate boundary between the Caribbean and South America plates (e.g., Hess and Maxwell 1953, Schubert 1979, Aggarwal 1983, among many others), whereas few others propose different plate boundary models along this right-lateral strike-slip plate boundary zone: (a) orogenic float type for the Andes (Audemard, 1991, Jácome, 1994, Audemard and Audemard 2002, Fig. 3) or eastern Venezuelan Coastal and Interior ranges (Ysaccis *et al.* 2000), thus being flanked by both an A- and B-type subductions; and (b) SE-directed A-subduction or underthrusting of the Maracaibo block under the Mérida Andes (Kellogg and Bonini 1982, De Toni and Kellogg 1993, Colletta *et al.* 1996, 1997). However, the incorporation of the Boconó fault into this major right-lateral strike-slip fault system is a rather recent event, that relates to the northward extrusion of the Maracaibo block, because the former transcurrent boundary used to comprise the east-west-striking Oca-Ancón fault system (OAF) located farther north in northwestern Venezuela (Audemard 1993, 1998). Therefore, the Oca-Ancón fault system belonged to this major right-lateral strike-slip plate boundary zone along the southern Caribbean from when transpression started at around 17-15 Ma to when essentially ceased or considerably slowed down at around 5-3 Ma. Although the Caribbean with res-

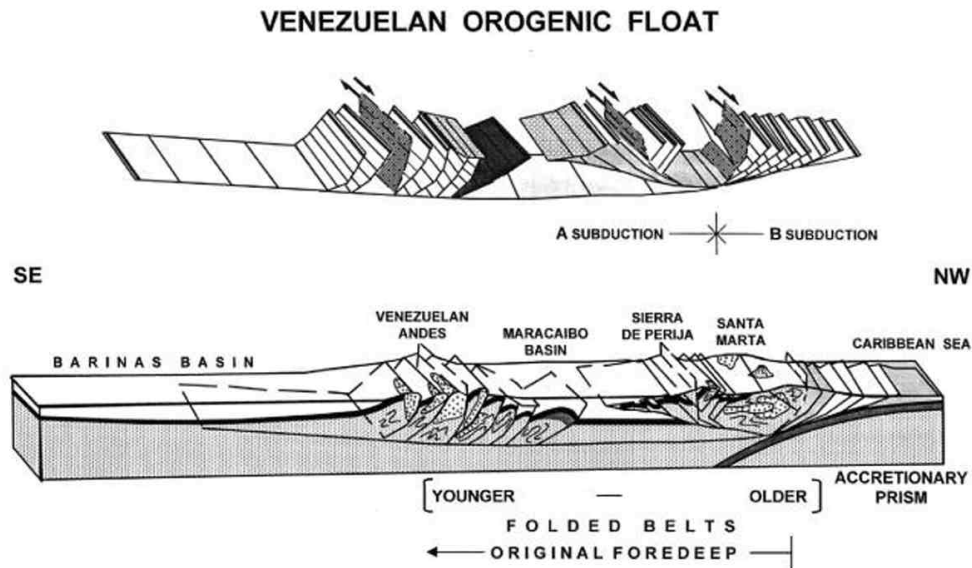
pect to South America is moving at rates between 12 mm/a in the west (geologic slip rate from Nuvel 1-A model) and  $18 \pm 2$  mm/a in the east (GPS-derived slip rate by Weber *et al.* 2001), the present major strike-slip (Boconó-San Sebastián-El Pilar-Warm Springs faults) boundary slips at  $\approx 1$  cm/a (Pérez and Aggarwal, 1981; Soulas, 1986; Freymueller *et al.*, 1993; Audemard *et al.*, 2000; Pérez *et al.*, 2001, Weber *et al.* 2001, Trenkamp *et al.* 2002). Secondary faults however have slip rates one order of magnitude less and in fact most of them exhibit slip rates under 0.5 mm/a, with the exception of the Oca-Ancón (2 mm/a, estimated from a paleoseismic assessment performed by Audemard, 1996), the Burbusay ( $\leq 3$  mm/a), Valera and La Victoria ( $\leq 1$  mm/a) faults (for more details, refer to Audemard *et al.* 2000, and to figure 2 for relative location).

## NEOTECTONIC MAPPING IN VENEZUELA

Active tectonics in Venezuela at present are driven by tectonic plate and microplate interactions, as explained in the introduction. Knowledge about the southern Caribbean plate boundary zone has much evolved from the original ideas of Hess and Maxwell (1953), when a rather simple dextral wrenching system had been proposed. Over twenty years of neotectonic analysis comprising studies in the disciplines of surface geology, geomorphology, microtectonics, seismotectonics and paleoseismology, combined with data from conventional geologic studies and seismic reflection surveying both onshore and offshore, now give us a more complete understanding of the complex active geologic setting in Venezuela and surrounding areas.

Neotectonics in Venezuela, as for everywhere else in the world, is defined as the tectonics resulting from the most recent and still active stress field. On this basis, Venezuelan neotectonics refer to the tectonics of the Quaternary (after Soulas 1986), implying that tectonic features that either show no evidence of activity during that timeframe or have an orientation not susceptible to reactivation in the near future under the present stress regime, are not in-





**Figure 3:** The orogenic float model applied to the Mérida Andes. Cross-section extends from the northwestern tip of the Santa Marta Block (SMB; location in Fig. 2) to the Llanos Basin, across the southernmost Mérida Andes, at the Pamplona indenter. Bottom figure displays major geologic units and structures, whereas top figure only exhibits major structures -brittle thrust and strike-slip faults, detachments and triangle zones- to give a more legible view of their interplays (after Audemard and Audemard 2002).

cluded in this compilation. The latest version of the neotectonic (Quaternary) fault map depicted in figure 4 is the third version of this type of maps (Audemard *et al.* 2000), the first version having been elaborated by Soulas in 1985, and published in 1986 (Soulas 1986), which was later updated by Beltrán (1993) as the second version. The latest version differs from the previous ones in three important aspects: (a)- New neotectonic data corresponding to onshore areas studied by Funvisis between 1993 and 1999 have been incorporated. They include data on the southern frontal thrusts of the Interior range in eastern Venezuela and the southern foothills of the Mérida Andes, as well as a preliminary assessment of the inner active deformation of the triangular block defined by the Oca-Ancón, Boconó and Valera faults; (b)- A reinterpretation of the San Sebastián-El Pilar relay at the Cariaco trough in accordance with the interpretation of Blanco and Giraldo (1992); and (c) The map has been simplified in terms of the number of faults (imposed by the aim of the ILP-II-2 project), particularly in the Colombia-Venezuela border area, known as the Pamplona indenter -PI-. On the other hand, faults exhibit more detail both with respect to their Quaternary kinematics as to their discrimination by age

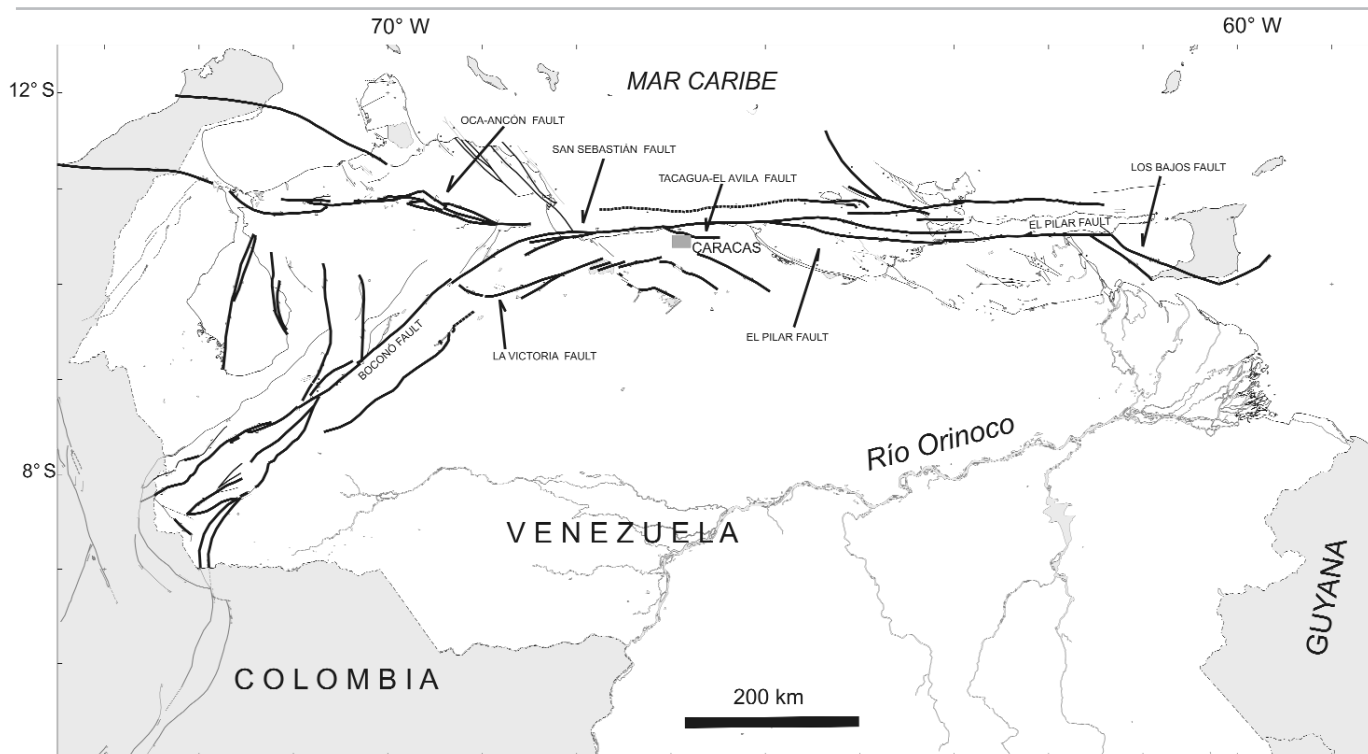
of latest activity and slip rate, which allows easy and quick identification of the major active features. The map is complemented with a database that contains relevant information about each fault and/or fault section (length, attitude, age, sense of slip, slip rate, geomorphic expression, latest activity from geologic data, and so on) and its seismogenic potential (maximum credible earthquake and its recurrence). For more details, the reader is referred to the USGS web page.

#### QUATERNARY TECTONICS OF VENEZUELA

As mentioned earlier, most of northern and western Venezuela is situated in a complex plate boundary zone. Due to this complexity, we shall discuss in this paper only the most relevant aspects of the Quaternary Venezuelan tectonics. Figure 2 portrays all names of the active tectonic features used throughout this paper, while figure 4 (Audemard *et al.* 2000) represents the version of the map of the ILP project and gives further details on the Quaternary activity and relevance of only the major Quaternary features of Venezuela. In the following, we shall present the main issues drawn from these two figures.

The Quaternary deformation does not occur all over the country. Instead, strain is concentrated along localized strips or belts (Singer and Audemard 1997); all of them located in western and northern Venezuela. Most of these mobile belts exhibit high positive relief, implying an important amount of shortening along the plate boundary. It does not exclude however that some belts show negative relief but such features are always of more local extent.

The most conspicuous mobile belt is at least 100 km wide and runs over 1200 km in length from the Colombian border near San Cristobal in the southwest into Trinidad in the east. This major belt -which seems to be the prolongation of the Eastern Cordillera of Colombia- corresponds to an alignment of mountain chains that comprises from southwest to east: the NE -trending Mérida Andes and the E-W-oriented Coast and Interior ranges both in north-central and northeastern Venezuela. This belt exhibits a first-order dextral fault system that mostly runs along the chain's backbone over a distance of more than 1200 km and comprises the NE-trending Boconó fault in the Andes section (VE-06 in Fig. 4), and both the E-W-striking San Sebastián fault (VE-16 in Fig. 4) in central Venezuela and the El Pilar fault (VE-13 in Fig. 4) in eastern Venezuela



**Figure 4:** Map of Quaternary faults of Venezuela (after Audemard *et al.* 2000). Also accessible as a pdf file from the USGS web page in open file reports (ofr-00-0018). Line thickness is proportional to fault slip rate: the thickest indicates  $> 5$  mm/a and the thinnest  $< 1$  mm/a. Shown faults have proven Quaternary activity.

(Singer and Audemard 1997). Most of the dextral slip between the Caribbean and South America plates is accommodated by this fault system. In fact, this fault system moves at about 1 cm/a when most other faults slip slower than a 1 mm/a (Audemard *et al.* 2000, Pérez *et al.* 2001). The combination of this rather fast slip rate and the significant length of the Boconó-San Sebastián-El Pilar fault system translates into an associated seismicity of moderate frequency and magnitude and is considered to be responsible for most large ( $M_s > 7$ ) historical earthquakes that have struck the country since the first ever reported event in 1530. Fault rupture is concentrated in some particular segments of this plate boundary (e.g., Rod 1956, Cluff and Hansen 1969, Aggarwal 1983, Audemard 1997a, Pérez *et al.* 1997, Audemard 1999b, Audemard 2002). Some secondary mobile zones branch off from the major one. The most important of these are: the E-W-striking dextral Oca-Ancón fault system (VE-01 in Fig. 2) in northwestern Venezuela and three NW trending normal-dextral fault systems respectively located from west to

east in eastern Falcón, along the submarine canyon of Los Roques and in the gulf of Paria. The three latter ones constitute the principal areas of negative relief due to the significant normal component involved. Another deformation belt is the NNE-trending Perijá range in westernmost Venezuela, whose crestline defines the borderline with Colombia.

The major Boconó-San Sebastián-El Pilar fault system displays several structural complexities of kilometric to several-kilometre scale, either in transtension (pull-apart basins such as those of La González/San Juan de Lagunillas -south of Mérida-, Cabudare, Cariaco trough and the gulf of Paria among others; refer to Fig. 2 for relative location), or in transpression (Caigüire hills at Cumaná, and Las Manoas and Guarapiche -west and east of the 1997 epicentre, respectively, in Fig. 4-; all in Sucre state, in eastern Venezuela and related to the El Pilar fault). In fact, this major wrenching fault system has no major complication of regional scale, except for both ends (Singer and Audemard 1997). In the west, at the Colombia-Venezuela border, the Bo-

conó fault bends into the Pamplona indenter (as defined by Boinet 1985). Here, the Boconó fault sharply changes orientation to connect with the N-S-striking Chitagá fault, which shows a strong reverse slip when joining the Boconó fault, but progressively becomes a dominant left-lateral fault towards the south. Farther south, slip is transferred to the NW-trending sinistral Pamplona-Chucarima-Morro Negro fault system (CO-37 in Fig. 4). On the other extreme in the east, in the Paria gulf and Trinidad, the major right-lateral strike-slip fault system also bends rather sharply, 45° clockwise this time. The fault system splays into several NW-striking offshore faults - among which are the Los Bajos (VE-15 in Fig. 4), El Soldado and Bohordal faults (in Fig. 2)- that exhibit both normal and dextral components. Los Bajos-El Soldado fault system is claimed to link the major transcurrent fault system to the southern tip of the type-B Lesser Antilles subduction; hypothesis that is not necessarily shared by Weber *et al.* (2001), who postulate that slip transfer takes place along the Warm Springs fault of the Central Range of Trinidad from repea-

ted GPS measurements. At this eastern tip, the El Pilar fault also shows a splay in the north compartment that branches off towards ENE. This splay, named the Tunapuy fault, exhibits a dominant reverse component with minor dextral slip. Beltrán (1998) proposes that the reverse Tunapuy fault in the Paria peninsula prolongs into the reverse Arima fault of northern Trinidad that bounds the southern foothills of the Northern range of Trinidad (Fig. 2). Weber *et al.* (2001b) have demonstrated that the Arima fault, based on calcite and quartz geothermometry applied to south-dipping shear bands and cataclastic zones studied along the southern border of the Northern range in Trinidad, is a south-dipping range-bounding normal fault, whose activity as such could only be constrained between 12 and 1 Ma. However, the results of studies by Saleh *et al.* (under review), based on geodetic data (triangulation and GPS data merging), argue for a reverse slip along the Arima fault. This would seem to confirm the Arima fault slip determined from aerial-photo interpretation based on landforms of Quaternary activity performed by Beltrán (1998).

Several second-order faults of considerable length diverge obliquely from the major right-lateral strike-slip fault system. Many of these are considered to function simply as large synthetic Riedel shears related to the principal deformation zone marking the direct Caribbean-South America plate interaction in north-central and northeastern Venezuela. The best known faults of this type are: the Río Guárico (VE-09 in Fig. 4), Tacagua-El Avila (VE-10 in Fig. 4), Táchata (VE-11 in Fig. 4), Píritu (VE-12 in Fig. 4), San Mateo (Jose; VE-14 in Fig. 4), Urica and San Francisco faults, among several others. In the Mérida Andes, along the Boconó fault, there is no manifestation of such large Riedel shears, although there are many branching faults. Among them deserve mention the north-south-striking sinistral Valera (VE-04 in Fig. 4) and Burbusay faults and the subparallel dextral Caparo fault (SE of San Cristobal; Fig. 2). The presence of R shears, in this case in association with the Oca-Ancón fault system, also happens in the Falcón range. Dextral slip is also accommodated by sub-parallel-trending

faults to the main right-lateral strike-slip fault system. For instance, the San Simón and Caparo faults in the Andes run parallel to the Boconó fault. In north-central Venezuela, the La Victoria fault acts as a P shear with respect to the San Sebastián fault. The North Coast in eastern Venezuela is also dextral and runs north of and parallel to the el Pilar fault.

In the north-central and eastern mobile belts, few faults exhibit left-lateral strike-slip. The Quebrada Chacaito fault trends almost north-south, north of Caracas, but other slightly oblique faults to the main dextral system in northeastern Venezuela also exhibit sinistral motion. A case in point constitutes the Punta Charagato fault in the Cubagua island, and the Laguna Grande fault in the Araya peninsula (Giraldo and Beltrán 1989). The orientation and slip of these left-lateral strike-slip faults seem atypical with respect to their tectonic setting in northeastern Venezuela. These ENE-striking faults, in combination with the east-west striking dextral faults, bound wedge-shaped tectonic blocks, whose acute angle points to between ENE and east. Some blocks in this region show a slip vector that slightly diverges to ENE ( $N084^\circ \pm 2^\circ E$  after Pérez *et al.* 2001), which matches rather well with the orientation of the bisecting line between both fault trends. This could argue for the occurrence of block extrusions to some extent in this complex southeastern corner of the Caribbean in order to reduce mass excess. This would give a satisfactory explanation to the apparent transtension postulated by other authors from GPS vectors (e.g., Weber *et al.* 2001), when transpression is actually the operating mechanism at plate-boundary scale.

Active thrust faults are present along most chain fronts, although they may be blind or hidden behind triangular zones or intracutaneous wedges. They have been detected onshore along the northern edge of the presently inverted Falcón basin (south of Coro), along the foothills on both flanks of the Mérida Andes and along the southern front of the Interior range both in central (e.g., Cantagallo overthrust) and eastern (e.g., Pirital and sub-parallel thrusts) Venezuela (Figs. 2 and 4). Other manifestations

of compression are chain uplift and build-up, and intense folding in sedimentary sequences like in the Falcón basin ("D" in Fig. 2), the eastern Interior range ("Q" in Fig. 2), the Andes foothills, and even in the Neogene-Quaternary foreland sequence of the central Interior range.

Normal faults are also common and widespread within the deformation belts. Tuñame in the Mérida Andes (VE-05 in Fig. 4), Los Médanos (north of Coro), Cabo San Román and Puerto Escondido (north tip of the Paraguaná peninsula in northwestern Venezuela) and the Río San Juan graben (in eastern Venezuela) faults are some examples of normal faulting (refer to Fig. 2 for location). Except for the Tuñame fault located in the Andes (Figs. 2 and 4), all other normal faults in northern Venezuela strike NNW. Instead, the normal slip of the Tuñame fault -that roughly strikes ENE and is located at the convergence of the Valera and Boconó faults- is a consequence of a void effect induced by a bookshelf rotation mechanism produced by simple shear between the Oca-Ancón and Boconó faults. Dhont *et al.* (2005) propose instead that the axial extension within the central Andes, involving the Tuñame fault, responds to the northward escape of the Trujillo block, bounded between the north-south-striking left-lateral Valera fault on the west and the NE-SW-trending right-lateral Boconó fault on the east (Figs. 2 and 4).

In western Venezuela, the mobile belt is much wider than in northern Venezuela, reaching up to 600 km in width, and comprising the entire Maracaibo block (MTB) that covers also part of northern Colombia (Audemard, 2000; Audemard *et al.*, 2000). This block is bounded by the sinistral Bucaramanga fault (SMBF in Fig. 1) on the southwest and the dextral Boconó and Oca-Ancón faults. Other authors consider the northern boundary of the block to be the flat subduction (LAS in Fig. 1), responsible for the Southern Caribbean Deformation Belt (SCDB) established from seismic tomographic studies by Van der Hilst (1990), rather than the Oca-Ancón fault system (OAF in Fig. 1). In Venezuelan territory, this block contains two deformation belts with positive relief: the Perijá range and the western part of the Mérida Andes,

between which the Maracaibo basin is being squeezed and shortened in NW-SE direction. The Perijá range happens to be the least studied area until the present-day in terms of active tectonics because of poor accessibility and personal security problems.

The triangular Maracaibo block (MTB) shows an intense internal fragmentation where blocks are individualized by north-south to NE-SW trending faults. Most of these faults are essentially left-lateral in slip, with a minor thrust component in many cases, such as from west to east: Icotea, Pueblo Viejo, Valera, Burbusay, among others. This structural and geometrical configuration may result from a bookshelf rotation mechanism induced by simple shear generated between the dextral Boconó and Oca-Ancón faults (Audemard *et al.* 1999, 2005). But the two faults are not parallel and are at an angle of 45°, which is an atypical configuration that must result in particular complex deformations, as well as switching the sense of slip along faults through time.

The spatial configuration of the faults and folds at regional scale and their kinematics, as deduced solely from the neotectonic mapping, points out that the Northern Falcón basin (northwestern Venezuela) is undergoing a stress tensor with a NNW-SSE to N-S maximum horizontal stress and an ENE-WSW minimum (or intermediate) horizontal stress (Audemard 1993, 1997b, 2001; Audemard *et al.* 2005). This would mean that the simple shear model associated with strike-slip faulting proposed by Wilcox *et al.* (1973) applies. Regional folding in this region does not only result from wrenching, as proposed by many authors (e.g.: Stephan 1982), but also from regional compression. Both folding due to wrenching in close association with the Oca-Ancón fault system (transpression s.s.) and to regional compression occur together (transpression s.l.). The neotectonic mapping in this region also permits the determination of active brittle structures in five distinguishable families based on their orientation and kinematics (Audemard, 1993, Audemard and Singer 1996, Audemard 1997b, 2001; Figs. 2 and 4): (1) East-West right-lateral faults (Oca-Ancón Fault System -VE-01-, Adícora Fault); (2) NW-SE

right-lateral faults, as synthetic Riedel shears to the east-west faults (Urumaco -VE-02-, Río Seco -VE-03-, and La Soledad faults); (3) NNW normal faults (Western Paraguaná, Cabo San Román, Puerto Escondido and Los Médanos faults, all fault-bounding the Paraguaná peninsula); (4) North to NNE left-lateral faults, antithetic to the east-west faults (Carrizal, El Hatillo and other minor faults); and (5) ENE reverse faults, parallel to fold axis of similar orientation (Araurima, Taima-Taima/Chuchure and Matapalo faults). In terms of slip rate, most Quaternary tectonic features in Northern Falcón are rather slow, showing slip rates generally below 0.4 mm/a. The major Oca-Ancón fault system is the exception to this, with a maximum slip rate close to 2 mm/a (Audemard 1993, Audemard and Singer 1994, Audemard *et al.* 1994, Soulas and Giraldo 1994, Audemard 1996, Audemard and Singer 1996, Audemard *et al.* 2000).

The Coast and Interior ranges of north-central and eastern Venezuela is the only portion of the plate boundary zone to result from rather simple direct interaction between the Caribbean and South America plates. The same applies to northwestern Venezuela as registered in the Falcón basin and applicable at larger scale to the Bonaire block confined between the Leeward Antilles subduction and the Oca-Ancón fault system. Therefore, this region also complies with the simple shear model, at least as far as the brittle tectonics is concerned, with strain partitioning also occurring along this plate boundary segment. Within the Mesozoic metamorphic SSE-overthrust nappes of central Venezuela, six families of active tectonic features are distinguishable on the basis of their orientation and present kinematics (Figs. 2 and 4): (1) East-West right-lateral faults (San Sebastián, La Tortuga and El Avila faults); (2) NW right-lateral faults, synthetic to the east-west faults (Río Guárico -VE-09-, Táchata -VE-11- and Aragüita faults); (3) NW to NNW normal-dextral to dextral-normal faults (Píritu -VE-12- and Tacagua -VE-10-faults); (4) North to NNE left-lateral faults, antithetic to the main east-west faults (Quebrada Chacaito faults); (5) ENE reverse faults, parallel to fold axis (Nappe fronts,

among which the Cantagallo overthrust); and (6) ENE to E dextral faults -P shears- (La Victoria fault -VE-08-). This is actually the only case of active P faulting recognized in the plate boundary zone.

For eastern Venezuela, the configuration of the active structures is as follows (Figs. 2 and 4): (1) East-West right-lateral faults (El Pilar -VE-13-, El Yaque and North Coast faults); (2) NW right-lateral faults, synthetic to the main east-west faults (San Mateo -VE-14-, Urica and San Francisco faults); (3) NW to NNW normal-dextral to dextral-normal faults (San Juan Graben, Bohordal, Los Bajos and El Soldado -VE-15- faults); (4) ENE left-lateral faults, which do not obey the simple shear model (Laguna Grande and Punta Charagato faults; issue discussed earlier in this paper); and (5) ENE reverse faults, parallel to fold axis orientation (frontal thrust of the Interior range, among which the Pirital thrust stands out).

All present deformations along northern Venezuela are related to the WNW oriented oblique convergence vector of the Caribbean plate with respect to South America (e.g.: N 75° W, after Minster and Jordan 1978; later confirmed by many others from GPS data, as indicated earlier). Meanwhile, western Venezuela presents a more complex scenario that shall be discussed later in this paper that reflects the influence of the convergence vector between the Nazca and South America plates to the southwest in Colombian territory.

#### QUATERNARY STRESS TENSORS OF VENEZUELA

Audemard *et al.* (2005) have recently published a nationwide stress tensor compilation derived from fault-plane kinematic indicators. In order to ascertain the characterization of the latest and still active tectonic phase, this compilation has only integrated stress tensors derived from Plio-Quaternary sedimentary rocks (refer to Table 1 in Audemard *et al.* 2005). This approach has relied on an inversion method, through which the stress tensor has been obtained from the measured strain. Those tensors were calculated with either the Etchecopar



*et al.* (1981)'s method or the right dihedral method designed by Angelier and Mechler (1977). This latter method is less accurate than that of Etchecopar *et al.* (1981), which is also capable of establishing the qualitative shape of the stress tensor ellipsoid through the value of "R", being R defined as  $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ . The principal stress in vertical position indicates the dominant tectonic regime but R helps to better define it (refer to Ritz 1991, for more details). From this tectonic stress inversion, Audemard *et al.* (2005) reach the following general conclusions:

(1)- northern Venezuela -covering the Falcón basin and the central and eastern Coast and Interior ranges from west to east- is characterized by a Plio-Quaternary stress tensor of rather uniform and constant orientation throughout. The prevailing orientations of this tensor are NW to NNW (145° to 170°) for the maximum horizontal stress ( $\sigma_H$ ) and NE to ENE for the minimum horizontal stress ( $\sigma_h$ ). Therefore, there is a good consistency among stress tensors at regional scale. This geologically derived tensor mostly represents a transcurrent regime (intermediate stress in vertical position). Where the Etchecopar *et al.*'s method was applied, as in the case of the Falcón region, the stress regime can be constrained better and is of the compressive transcurrent type (Audemard 1991, 1993, 1997c and 2001). Some authors describe this tectonic regime as transpressive and refer to the enlarged sense of the term and do not restrict its use only to the localized stress changes introduced by strike-slip motion in proximity of or along the wrench fault. This stress tensor is highly oblique to the general east-west trend of the major wrench faults of northern Venezuela (Oca-Ancón, San Sebastián and El Pilar faults). This strong obliquity is responsible, on the one hand for the occurrence of strain partitioning (right-lateral strike-slip along east-west trending faults and transverse shortening in NNW-SSE direction). On the other hand, it is also responsible for simultaneous left-lateral strike-slip motion on faults that are slightly oblique to the east-west trending dextral faults, as is the case of the WSW-ENE-striking Punta Charagato and Laguna Grande faults in eastern

Venezuela (Fig. 2). The consistency of the stress-tensor orientation along northern Venezuela from west to east (from north-western Colombia to Trinidad) permits the identification of local variations of the stress regime. Most of these local stress changes coincide with known transtensional geometries, or occasionally with transpressional geometries (refer to Audemard *et al.* 2005 for further details). These changes are easily identifiable because the stress tensor orientation remains essentially constant but their principal stress magnitudes vary (stress tensor permutation, where maximum and intermediate stresses may interchange positions).

(2)- The stress tensor calculated by either the Etchecopar *et al.* (1981)'s automated method or the right dihedral method of Angelier and Mechler (1977) well represents the stress field for the present-day kinematics of seven major families of active faults along northern Venezuela: (a) east-west right-lateral faults; (b) NW right-lateral faults, synthetic to the east-west faults; (c) NNW normal faults; (d) NW to NNW normal-dextral to dextral-normal faults; (e) North-South to NNE-SSW left-lateral faults, antithetic to the east-west faults; (f) ENE to east-west right-lateral faults -P shears-; and (g) ENE reverse faults, paralleling the axis of active folds. Spatial configuration of these brittle tectonic structures indicates that the region is undergoing a transpressional s.l. (compressive-transcurrent) regime that complies with the simple shear model proposed by Wilcox *et al.* (1973). Therefore, this regional configuration is related to the slightly oblique convergence between the Caribbean and South America plate in the west and almost perfect wrenching in eastern Venezuela with some "apparent" transtension (Pérez *et al.* 2001 and Weber *et al.* 2001), that is directly responsible for east-west trending dextral wrenching along northern Venezuela. On the other hand, in northwestern Venezuela there is convergence between the Bonaire block (BB) and the Caribbean plate in a process of flat subduction located offshore of the Leeward Antilles islands (LAS), which operates in concurrence with the NNE directed extrusion of the Maracaibo and Bonaire blocks. Overall there is good

agreement between stress tensors obtained from microtectonic data and large scale neotectonic mapping.

(3)-  $\sigma_H$  in the northern Mérida Andes (Lara state), in proximity to the Boconó fault, tends to become east-west oriented, which allows the simultaneous functioning of the NE-striking dextral (e.g.: Boconó, Caparo, San Simón) faults, the equally-trending thrust faults along both Mérida Andes foothills and the north-south striking sinistral faults (e.g., Valera and Burbusay, among several others; Fig. 2).

(4)- As a result of this, the stress field on the Maracaibo block (MTB) progressively turns counterclockwise from a NNW trend in the north (Beltrán and Giraldo 1989, Audemard 2001, Audemard *et al.* 2005) to east-west oriented to the south (Audemard *et al.* 1999), making it resemble a folding fan with vertex pointing to the SE (Giraldo 1990, Audemard and Audemard 2002). The orientation of this regional stress field in western Venezuela results from the superposition of the two major neighbouring interplate maximum horizontal stress orientations ( $\sigma_H$ ): (1) a roughly east-west trending stress across the Nazca-South America type-B subduction along the pacific coast of Colombia and (2) a NNW-SSE oriented stress across the southern Caribbean plate boundary (Audemard 2000, Fig. 1). As a result, the Maracaibo block is simultaneously being shortened along the NW direction (expressed by the vertical growth of the Santa Marta block and Perijá and Mérida ranges) and extruded to the NNE (Audemard 1993, 1998, 2000b, Audemard and Audemard 2002).

## DISCUSSION AND CONCLUSIONS

The stress tensors derived from microtectonic data collected in Plio-Quaternary rocks and those derived from the spatial configuration of Quaternary active faults are in good agreement. On the one hand, deformation along the southern Caribbean coast results from a compressive strike-slip (transpressional s.l.) regime characterized by a NNW-SSE maximum horizontal stress ( $\sigma_H = \sigma_1$ ) and/or an ENE-WSW minimum

( $\sigma_1 = \sigma_3$  or  $\sigma_2$ ) horizontal stress. This configuration gives rise to the present activity and kinematics of seven sets of brittle and ductile features: (1) east-west right-lateral faults, (2) NW right-lateral faults or synthetic Riedel shears, (3) ENE to east-west dextral faults or P shears, (4) NNW normal faults, (5) almost north-south left-lateral faults or antithetic Riedel shears, (6) ENE reverse faults -sub-parallel to fold axes and mostly in the subsurface- and (7) associated ENE trending folds (well-developed in the Falcón basin -northwestern Venezuela- and the Interior range in the east). The main exceptions to this general configuration are found in eastern Venezuela: the Punta Charagato and Laguna Grande faults that display left-lateral slip along the ENE direction. This "apparent" inconsistency may be explained by using a ENE-directed block escape model. In most of northern Venezuela, brittle deformation obeys the simple shear model.

On the other hand, the stress field on the Maracaibo block progressively turns counter-clockwise to become more east-west oriented, allowing left- and right-lateral slip along north-south and NE-SW striking faults, respectively. This regional stress field in western Venezuela results from the superposition of the two major neighbouring interplate maximum horizontal stresses ( $\sigma_{H1}$ ) related to the Nazca plate type-B subduction and NNW-SSE oriented stress across the southern Caribbean plate boundary. This results in the Maracaibo block simultaneously being shortened on the NW direction and extruded roughly towards the NNE.

Wrenching is the dominant geodynamic process, but it is always accompanied by compression of variable magnitude along strike of the major strike-slip fault system, proving that stress (or strain) partitioning is the actuating mechanism. Only locally, transtension becomes significantly important, such as in the Cariaco trough and gulf of Paria in association with the El Pilar fault. It can now be firmly established that the GPS slip vectors do not only support the hypothesis of ongoing transpression along most of this complex plate boundary zone, but also tend to confirm most of the active fault slip rates derived from geologic

and neotectonic studies carried out in Venezuela for almost 25 years by the Funvisis staff.

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