MAJOR ACTIVE FAULTS OF VENEZUELA.

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Introduction

Northern Venezuela essentially lies in the interaction zone between the South America and Caribbean plates, whereas western Venezuela shows a more complex geodynamic setting. A wide consensus establishes that the Caribbean plate moves eastward relatively to South America (Bell 1972; Malfait and Dinkelman 1972; Jordan 1975; Pindell and Dewey 1982; Sykes *et al.* 1982; Wadge and Burke 1983; Freymueller *et al.* 1993; among others), but this active plate boundary is not of the simple dextral type (Soulas 1986; Beltrán 1994) since it is an over 100 km wide active transpressional zone (Audemard 1993; Singer and Audemard 1997; Audemard 1998), that has important reliefs associated (the Coastal and Interior ranges along the northern coast). This wide transpressional boundary extends southwestard into the Mérida Andes, where strain is nicely partitioned between the right-lateral strike-slip (RLSS) Boconó fault running along the axis of the chain and thrust faults bounding the chain on both flanks (this configuration both in the Andes and in the Interior range was described by Rod in 1956b and some others, much before the concept of "partitioning" was put forward). As a matter of fact, the plate boundary in western Venezuela is eventually up to 600 km wide and comprises a set of discrete tectonic blocks, independently moving among the surrounding larger plates (Caribbean, South America and Nazca), among which the triangular Maracaibo block stands out. This independent block is bounded by the LLSS Santa Marta-Bucaramanga fault in Colombia and RLSS Boconó fault in Venezuela and separated on the north from the Bonaire block by the RLSS Oca-Ancón fault. Besides, both Maracaibo and Bonaire blocks are roughly being extruded northward and are overriding the Caribbean plate north of the Leeward Antilles islands, where a young south-dipping, volcanicless, flat subduction has been forming in recent times (mainly in the last 5 ma). Extrusion of these blocks is to be related to the collision of the Panamá arc against the Pacific side of northern South America and its later suturing (Audemard 1993, 1998).

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 (NW-dipping, South American-attached oceanic lithosphere under Caribbean plate island arc), which later evolved into a long-lasting oblique-collision (SSE-vergent Caribbean-affinnity nappes overriding South America passive margin) and in turn has shifted to 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, which recreates how this east-younging oblique collision has acted diachronically throughout the evolution of this entire northern portion of the plate boundary. Strain partitioning (RLSS along the east-west striking El Pilar and NW-SE striking Los Bajos-El Soldado faults and NNW-SSE-oriented shortening across the Interior range) and slab detachment (responsible for the largest onshore negative Bouguer anomaly of the world south of the southern edge of the Interior range) are two of the major involved processes, combined with a plate boundary geometry such as the present one, where the El Pilar fault transfers its slip to one of its synthetic Riedel shears (Los Bajos-El Soldado fault), which is acting as a "lithospheric tear fault", thus separating the transpressional boundary on the west from the Lesser Antilles subduction zone on the east.

At present, strain along northern Venezuela is also being partitioned in both the west (Audemard 1993) and the east (Rod 1956b; Passalacqua *et al.* 1995). Deformation along the southern Caribbean coast results from a compressive strike-slip (transpressional) regime characterized by a NNW-SSE maximum horizontal stress ($\sigma_H=\sigma_1$) and/or an ENE-WSW minimum ($\sigma_h=\sigma_3$) horizontal stress (Audemard 1985, 1993, 1997b; Beltrán and Giraldo 1989), which is responsible for present activity and kinematics of five sets of structural features: east-west right-lateral faults (Oca-Ancón, San Sebastián, El Pilar, Northern Coast), NW-SE right-lateral faults –synthetic Riedel shears- (Urumaco, Río Seco, La Soledad, Costa Oriental de Falcón, Río Guarico, Tácata, Aragüita, Píritu, Urica, San Francisco, Los Bajos-El Soldado) NNW-SSE normal faults (Costa Occidental de Paraguaná, Los Médanos, Río San Juan Graben, Bohordal), almost north-south left-lateral faults –antithetic Riedel shears- (Carrizal, Quebrada Chacaito), ENE-WSW reverse faults –sub-parallel to fold axes and mostly in the subsurface- (Matapalo, Taima-Taima, Cantagallo, Tala, Interior range frontal thrusts, Tunapuy) and associated ENE-WSW trending folding (well-developed in the Falcón basin –Western Venezuela- and the Interior range in the east). On the Maracaibo block and south of the Oca-Ancón fault, the stress field progressively turns counterclockwise (Beltrán and Giraldo 1989) to become more east-west oriented (Audemard *et al.* 1999b), allowing left- and right-lateral slip along the north-south striking (e.g.: Valera and Burbusay) and NE-SW striking (e.g.: Boconó, Caparo, Queniquéa, San Simón) faults, respectively. This regional stress field in western Venezuela results from the vectorial addition of the two major neighboring interplate maximum horizontal stresses (σ_H): east-west trending stress across the Nazca-South America type-B suduction along the pacific coast of Colombia and NNW-SSE oriented one across the Caribbean southern boundary. Therefore, the Maracaibo block is simultaneously being shortened on the NW-SE direction (expressed by the vertical growth of the Santa Marta block and Perijá and Mérida ranges) and extruded roughly towards NNE.

Within the transpressional boundary zone, a large portion of the dextral motion seems to take place along the major RLSS Boconó-San Sebastián-El Pilar-Los Bajos fault system (Molnar and Sykes 1969; Minster and Jordan 1978; Pérez and Aggarwal 1981; Stephan 1982; Schubert 1984; Soulas, 1986; Beltrán and Giraldo 1989; Singer and Audemard 1997). This major boundary slips at ≈ 1 cm/yr (Soulas 1986; Freymueller *et al.* 1993), whereas secondary faults at least slip one order of magnitude less faster; as a matter of fact, most of them exhibit slip rates under 0.5 mm/yr, except for: Oca-Ancón (2mm/yr), Burbusay (≤ 3 mm/yr), Valera and La Victoria (≤ 1 mm/yr) faults.

Major active faults

Active structures in Venezuela may be geographically gathered in three main transpressive belts running within major positive fisiographic units: (1)- the SW-NE trending Mérida Andes, (2)- the east-west Falcón, Coast and Interior ranges and (3)- the Perijá range, which happens to be the least studied area in terms of active tectonics. Among the numerous faults in Venezuela which have been recognized as active features by means of surface geology, geomorphology, microtectonics, seismotectonics and/or paleoseismology, only the fastest faults with onshore expression shall be discussed In this paper: the Boconó and El Pilar faults –both belonging to the transforming Caribbean-South America plate boundary zone-, and the Oca-Ancón fault which holds the second fastest slip rate (Audemard 1993, 1996) and used to be part of the initial and former southern Caribbean transform plate boundary, between 17 and 5-3 myr, before strike-slip shifted onto the Boconó fault (Audemard 1993, 1998).

Boconó fault

The NE-SW trending RLSS Boconó fault runs slightly oblique to the main Venezuelan Andes axis and bounds the Caribbean Coast range of northern Venezuela on the west, thus extending for about 500 km between the Tachira depression, at the border between Colombia and Venezuela, and Morón -on the Caribbean coast of Venezuela-. At its north end at the coast, the Boconó fault exhibits a 45° clockwise bend that allows prolongation into the east-west striking San Sebastián-El Pilar system. To the south, the Boconó fault connects with the colombian llanos-foothills bounding system through the Chinacota-Bramón fault system, after undergoing two opposite right-angle bends; structure known as the Pamplona indentor (Boinet, 1985). It seems to extend as far south as the Jambeli graben (Guayaquil gulf, Ecuador), thus disconnecting the northwestern corner of South America from the rest of the continent (Stephan 1982). At least five different portions or seismogenic segments have been identified along the Boconó fault based on past seismic activity and potential geometric barriers or complexities to rupture propagation (see Audemard *et al.* 1999a, for more details).

The Boconó fault has been identified and mapped rather easily by the excellent quality and large quantity of along-strike exhibited geomorphic evidence, among which: continuous series of aligned 1-5 km wide valleys and linear depressions, passes, saddles, trenches, sag ponds, scarps and sharp ridges (e.g., Rod 1956b; Schubert 1980a, 1980b, 1982; Giraldo 1985; Soulas 1985; Soulas *et al.* 1986; Soulas and Singer 1987; Casas 1991; Ferrer 1991; Singer and Beltrán 1996). As much as 75 km of dextral offsets in Mesozoic rocks have been measured, although a more reliable value is probably about 30 km (Giraldo 1989; Audemard and Giraldo 1997). Offset of Quaternary features, such as: mountainous ridges, drainages, alluvial deposits and shutter ridges, ranges between 60 and 1000 m depending on their age. These data yield a Quaternary slip rate between 3 and 14 mm/yr (for a complete review see Schubert 1982). However, recent studies in the Mucubají area (Schubert 1980a; Soulas 1985; Soulas *et al.* 1986) obtained average slip rate of about 5 to 9 mm/yr, based on 60 to 100 m of dextral offset (measurement diversity depends on authors) of Los Zerpa moraines, which are radiocarbon-dated at a minimum of about 13.000 yr old. These rates are essentially consistent with those predicted by plate motion models of about 1 cm/yr, assuming that the Boconó fault is part of the main boundary between the Caribbean and South American plates (e.g., Molnar and Sykes 1969; Minster and Jordan 1978; Soulas 1986; Freymueller *et al.* 1993).

the Boconó fault slip rate decreases towards both end. South of where the fault is the fastest (near Mucubají), average slip rate decreases to 5.2 ± 0.9 mm/yr between Mérida and San Cristobal (Audemard 1997a) and as little as a 1 mm/yr at the Venezuela-Colombia border (Singer and Beltrán 1996). Complexity of the Boconó fault system in the southern Andes (three active strands at least, in some cases), combined with existence of other sub-parallel active faults, such as: Queniquéa, San José, Uribante-Caparo, Seboruco among others, may account for such rate reduction that is expressed in a longer return period between equivalent earthquakes on the Boconó fault near Cordero (Audemard 1997a). Similarly, Subparallel and branching faulting along the northernmost portion of the Boconó fault may explain the slip rate drop (1.5-3 mm/yr) reported by Casas (1991), along the Yaracuy valley.

As mentioned earlier, strain partitioning is taking place throughout the Venezuelan Andes and significant thrusting also occurs subparallel to the RLSS Boconó fault on both sides that is considered to accommodate important compression across the Andes (Gonzalez de Juana 1952; Rod 1956b; Hospers and Van Wijnen 1959; Schubert 1968; Kellogg and Bonini 1982; Henneberg 1983; Soulas 1985; Audemard 1991; De Toni and Kellogg 1993; Jácome, 1994; Sánchez *et al.* 1994). As Rod (1956a) has initially observed, the Boconó fault zone along with El Pilar fault zone are responsible for most of the largest Venezuelan earthquakes. The present-day seismicity along the Boconó fault occurs within a broad zone that generally comprises the entire width of the Mérida Andes, suggesting that also other faults may be also seismogenic, such as the thrust structures building up the chain. For instance, the Guanare March 05, 1975 and the Ospino December 11, 1977 earthquakes of magnitude mb 5.5 and 5.6 respectively are the most recent and largest events associated to the southern Andean Foothills thrust system (Piedemonte Oriental fault).

Several large historical earthquakes have been ascribed to the Boconó fault zone, such as those of 1610, 1812, 1849, 1894, 1932 and 1950. Two of them, 1610 and 1894, have been recently directly associated to the southern segment of the fault, by mean of paleoseismic studies (Audemard, 1997).

El Pilar fault

In northeastern Venezuela, El Pilar fault extends eastward for some 350 km, from the Cariaco trough –located south of La Tortuga island- to the Gulf of Paria, exhibiting an about 80 km long onshore portion between the gulfs of Cariaco and Paria – State of Sucre-. As frequent, nice and fresh geomorphic features have been mapped along this fault as along Boconó. El Pilar fault has been subdivided by Beltrán *et al.* (1996) in four different sections: (**A**)- a submarine trace west of Cumaná that bounds the Cariaco trough (pull-apart basin) on the south and dies out at the Caigüire hills, at Cumaná, in a restraining stepover; (**B**)- the second portion extends from the north side of the above-mentioned stepover to the Casanay-Guarapiche restraining bend. This portion has been ruptured in this century by the combination of the January 17, 1929 Cumaná and July 09, 1997 Cariaco earthquakes (Audemard 1999a); (**C**)- a 30 km long section that slightly diverges to the ENE and extends between Casanay and El Pilar; and (**D**)- a fourth east-west trending portion that cuts across the swampy areas of the Sabanas de Venturini and runs offshore south of the Paria peninsula, before connecting and transfering its kinematics to the NW-SE striking Los Bajos and Soldado faults. These three faults are considered as the eastern portion of the major RLSS plate boundary fault sytem between the Caribbean and South American plates.

El Pilar fault is the most important sesimogenic source of northeastern Venezuela, as proven by the recent Cariaco July 09th, 1997 Ms 6.8 earthquake. This event was associated to surface rupturing along a significant (≈ 36 km long) portion of the onshore section of the dextral El Pilar fault, extending between the gulfs of Cariaco and Paria (Audemard 1999a). In addition, northeastern Venezuela has been struck by several destructive earthquakes since the spanish conquest, in the early 16th century. The first recorded event in this area, and in Venezuela, was the 1530 earthquake that heavily destroyed Cumaná. This city has been repeatedly damaged since by the 1684, 1766, 1797, 1853, 1929 and the recent 1997 events. A re-assessment of the seismic history of this fault (Audemard 1999b) has yielded that: a) the 1766 event seems to have generated in a source different from El Pilar fault because the size of the felt area suggests that it is an intermediate-depth earthquake; b) damage to Cumaná produced by the 1797 event suggests that this was a local earthquake, perhaps equivalent to the 1929 earthquake, which ruptured just east of Cumaná into the Gulf of Cariaco for some 30 km in length; and c) seismogenic association of the 1530 and 1853 earthquakes still remains unclear but it is very likely these ruptures occurred offshore, as implied by the tsunami waves that both events have generated, placing their hypocenters west of Cumaná in the Cariaco trough.

Oca-Ancón fault system

The east-west, right-lateral Oca-Ancón fault system extends for 650 Km from Santa Marta (Colombia) to Boca de Aroa (eastern coastlands of the State of Falcón). This fault used to be part of the plate boundary, before being relayed at about 5-3 myr by the Boconó fault (Audemard 1993, 1998). It can be structurally subdivided into five different sections (Audemard *et al.* 1994): **(A)**- *between Santa Marta in Colombia and the outlet of lake Maracaibo (Toas island)*: this segment is the simplest as it comprises a single trace that truncates the northern end of the Perija range. Westward, it seems to control the linear northern coast of the Sierra Nevada de Santa Marta, and farther west it seems to connect to the east-west striking Jordán fault, mapped east of Santa Marta; **(B)**- *between Toas island and Mene de Mauroa*: this segment is composed of two subparallel strands: the east-west striking Oca and Ancón faults. Both traces are defined by several-kilometer-long fault scarplets in Quaternary alluvial terraces that limit a large area of probable subsidence that is interpreted as an active pull-apart basin; **(C)**- *between Mene de Mauroa and Paraiso*: this segment is geometrically complex as several strands converge on or diverge from the main lineament, displaying an anastomosing character. The eastern part of the segment, between Camare and Paraiso in central Falcón, coincides with the Camare-Paraiso range. This part has been interpreted as a flower structure since the inner deformation in the fault zone is of strike-slip type whereas the outer deformation is characterized by reverse faults affecting early to middle Pleistocene alluvial ramps rooted in both flanks of the east-west linear range; **(D)**- *between Paraiso and the Aroa valley*: this segment strikes WNW-ESE and it comprises several subparallel fault strands of relatively short length in comparison with other segments. Seismic activity near Churuguara in central Falcón, which is characterized by small-to-moderate but persistent earthquakes, is clearly associated with this segment of the Oca-Ancón system. The relatively high frequency of such earthquakes could be related to the large number and short length of fault strands that comprise the system in this region; and **(E)**- *between Socremo and Boca de Aroa*: this segment of the fault system regains its original strike along the northern margin of the Aroa valley (about east-west). The fault shows geomorphic features of south-vergent reverse slip where Quaternary alluvial ramps are tilted and flexed.

The Oca-Ancón fault system is the greatest potential seismic source of northwestern Venezuela: two trenches dug across the individual active traces of the Oca and Ancón faults on segment B revealed evidence of Ms 7.4 to 7.5 earthquakes on both faults (Audemard 1996). The recurrence of such events is 1752 ± 133 yr on the Ancón fault and 4300 ± 1000 yr on the Oca fault. Probability of occurrence of a 7.5 event on the Ancón fault is extremely high at present.

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