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# Active fault recognition in northwestern Venezuela and its seismogenic characterization: Neotectonic and paleoseismic approach

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**RESUMEN**

Los tiempos de recurrencia obtenidos de trincheras en el NW de Venezuela son 1752 ± 133 años para la falla de Ancón y 4300±1000 años para la falla de Oca, con magnitudes de Ms 7.4-7.5. Las fallas menores en el norte del estado de Falcón pueden generar sismos de Ms 6.2 a 7.0 cada 1,500 años o más.

**PALABRAS CLAVE:** Neotectónica, parámetros sismogénicos, paleosismología, Falla de Oca, Venezuela.

**ABSTRACT**

Northwestern Venezuela lies within the interaction zone of the Caribbean and South America plates and is being subjected to a stress field characterized by a NNW-SSE maximum horizontal stress and a ENE-WSW minimum horizontal stress (strike-slip regime). This stress tensor, calculated from microtectonic data collected at various sites in Plio-Pleistocene formations of northern Falcón state, is responsible for present kinematics and activity of five sets of faults: east-west right-lateral faults, NW-SE right-lateral faults (synthetic to the east-west faults), NNW-SSE normal faults, north-south to NNE-SSW left-lateral faults and ENE-WSW reverse faults (sub-parallel to fold axes).

The most conspicuous tectonic feature of northwestern Venezuela is the east-west, right-lateral Oca-Ancón fault system which extends for 650 km from Santa Marta (Colombia) to Boca de Aroa (eastern Falcón state). It is also the greatest seismogenic source of this region, as paleoseismic trenching carried out on the Oca and the Ancón faults revealed the occurrences of earthquakes of magnitudes Ms 7.4 to 7.5 on both faults. The recurrence time of such events is 1752 ± 133 yr. on the Ancón fault and 4300 ± 1000 yr. on the Oca fault. Magnitude assessment of maximum credible earthquakes for those fault segments from trench data coincides fairly well with magnitude estimates by means of segmentation criteria.

Minor faults of northern Falcón state can generate maximum credible earthquakes ranging between Ms 6.2 and 7.0 and their recurrence time is longer than 1500 yr. due to their rather slow (generally ≤ 0.5 mm/yr) slip rate.

**KEY WORDS:** Neotectonics, seismogenic parameters, paleoseismology, Oca fault, Venezuela.

## INTRODUCTION

Northern Venezuela lies in the interaction zone between the Caribbean and South America plates. Although it is generally accepted that the Caribbean plate moves eastward with respect to South America (Bell, 1972; Malfait and Dinkelman, 1972; Jordan, 1975; Pindell and Dewey, 1982; Sykes, McCann and Kafka, 1982; Wadge and Burke, 1983; among others), this plate boundary is not of the simple dextral type; but is instead, a broad active deformation zone resulting from a long-lasting oblique-collision process. Nevertheless, a large portion of this right-lateral motion seems to take place along the dextral Boconó-San Sebastián-El Pilar fault system (Molnar and Sykes, 1969; Minster and Jordan, 1978; Perez and Aggarwal, 1981; Stephan, 1982; Aggarwal, 1983, Schubert, 1984; Soulas, 1986; Beltrán and Giraldo, 1989).

Seismicity in northern Venezuela has been moderate in magnitude since installation in 1964 of the first Venezuelan seismological station belonging to the World Wide Standard Seismographic Network (WWSSN). However, if a longer time span is considered, several destructive earthquakes have been described in historical chronicles since the settlement by Spaniards in America at the beginning of the sixteenth century (Centeno-Graü, 1940; Grases, 1980), proving that this Caribbean-South America boundary is presently active. Moreover, northern Venezuela is characterized by diffuse seismicity. This suggests that plate margin deformation does not occur along a single fault zone even though major historical earthquakes have been related to the Boconó-San Sebastián-El Pilar fault system. Several other minor faults are responsible for intermittent moderate seismicity in this active deformation belt. In fact, northwestern Venezuela is cross-cut by several active faults, among which the Oca-Ancón fault system stands out for its total length in excess of 600 km.

In northwestern Venezuela, as in many other seismic active areas of the world away from main subduction zones, seismicity has been useful mainly to confirm the recent tectonic activity of some structural features, and, in the most favorable cases, to propose some focal mechanisms (*cf.* Dewey, 1972; Malave, 1992; Audemard and Romero, 1993) that are in agreement with the regional stress tensor obtained by Audemard (1991; 1993a). Nevertheless, the rather poor seismological data of this region, a direct consequence of low recurrence of earthquakes, is insufficient to assess the regional seismic hazard exclusively by means of a seismological approach (Gutenberg-Richter law, frequency/magnitude relationship). Rather, seismogenic-parameter assessment of the active or potentially active faults should rely on neotectonic data and include a paleoseismic approach.

## METODOLOGY

Seismic hazard assessment based on a neotectonic approach relies largely on the comprehension of the coseismic behaviour of every single active or potentially active fault in any particular region. It is a general consensus that seismogenic faults only break along a segment of their total length during a major earthquake (Wallace, 1970; Swan *et al.* 1980; Schwartz and Coppersmith, 1984; Soulas, 1988). Moreover, such segments seem to have their own seismic history and seem to be bounded by fixed barriers, either in time or space (concept of characteristic segment), that prevent rupture propagation beyond that segment (Smith and Bruhn, 1984; de Polo *et al.*, 1991; Machette *et al.*, 1991; Stewart and Hancock, 1991; Zhang *et al.*, 1991). However, Crone and Haller (1991) consider that some of those barriers can allow rupture propagation to a contiguous segment. Those barriers are called "leaky boundaries".

This concept of characteristic segments has triggered the development of several empirical relationships that relate maximum magnitude of earthquakes to certain geometric parameters of the fault plane that characterize the coseismic rupture: length of surface rupture and width of fault-plane rupture. In this work, we have used one of the first proposed relationship of this type; namely, that of Utsu and Seki (1954) which is of the following general form:

$$M = a \log A + b \quad ,$$

where

M = Ms magnitude,
A = area of rupture in $km^2$,
$a$ and $b$ = specific constants of each single seismic fault or of a given region.

For Utsu and Seki (1954), $a$ and $b$ values are close to 1 and 4 respectively. Therefore:

$$M = \log A + 4. \qquad (1)$$

Other similar relationships have been subsequently proposed by several authors (Berckhemer, 1962 *in* Chinnery, 1969; Wyss, 1979). As equation (1) indicates, magnitude is estimated from the area of rupture (A=length x width of rupture along fault plane). After Crone and Haller (1991), such a relationship allows earthquake magnitude to be calculated more accurately than other empirical relationships based only on rupture length, coseismic displacement or combination of such parameters, as proposed by Wyss and Brune (1968), Krinitzsky (1974), Slemmons (1977) or Bonilla *et al.* (1984).

In this work, coseismic displacement is estimated from the Aggarwal (1981) relationship, also based on rupture area (A); namely,

$$D = 4\,A^{1/2} \quad , \qquad (2)$$

where

D = coseismic displacement in cm,
A = area of rupture in $km^2$.

Knowing the average slip rate of the fault calculated on deformed-and-dated geological markers, the return period is estimated from

$$T = D/V \quad , \qquad (3)$$

where

T = return period in years,
V = average slip rate in mm/yr.

Consequently, to assess the seismic hazard using the relationships presented above, besides the need of estimating the average slip rate of the fault from deformed geological markers, one must also know both the length and width of the rupture area for each single fault or fault segment in the region.

### Length of rupture

In regions of frequent and moderate-to-large-magnitude shallow seismicity, the length of fault rupture (surface rupture) can be observed and measured directly on the ground surface after large earthquakes. Conversely, in regions of rather low historical and instrumental seismicity, such as the Falcón region of scattered and low-to-moderate magnitude earthquakes, detailed neotectonic mapping and/or paleoseismic studies may be required.

In northwestern Venezuela, thorough neotectonic mapping (Figures 1 and 2) has established the seismogenic segments of active (or probably active) faults from which credible rupture lengths, considering typical barriers to seismic rupture propagation known from literature, can be estimated. Many authors agree that geometric discontinuities are the most common barriers to rupture propagation, although these can break later as a main aftershock (Soulas, 1988) or as an aftershock sequence (Sibson, 1989). On the other hand, such barriers can occasionally become the focus of a later large earthquake (Soulas, 1988; Crone and Haller, 1991). The most frequently used geometric criteria include the following:

(1) A single some-kilometer-wide overlap (Soulas, 1988; Sibson, 1989; Crone and Haller, 1991; de Polo *et al.*, 1991; Machette *et al.*, 1991; Turko and Knuepfer, 1991; Zhang *et al.*, 1991).

(2) Two or more narrow (3-to-4-km-wide) overlaps (Soulas, 1988).This is specifically for strike-slip faults as is the previous criterion.

(3) Double bend with long oblique segment (Soulas, 1988; Sibson, 1989).

(4) Single bend. In this case, as in the previous one, only sharp bends are significant. They need to be more than 30°-35° along strike-slip faults, where localized transpression or transtension is to occur. They must be more than 50° to 60° along dip-slip faults (Soulas, 1988; Sibson, 1989; Crone and Haller, 1991; Machette *et al.*, 1991; Turko and Knuepfer, 1991; Zhang *et al.*, 1991). Wheeler (1987, *in* de Polo *et al.*, 1991) consid–

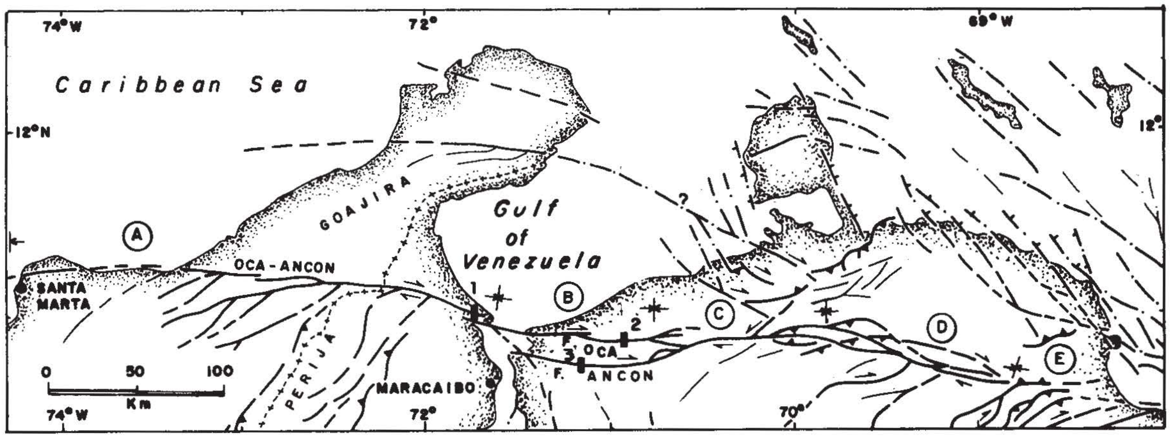


Fig. 1. Neotectonic map of northwestern Venezuela and northern Colombia. The most relevant tectonic feature of the region is the east-west right-lateral strike-slip Oca-Ancón fault system. Capital letters identify fault sections and small boxes identify trench sites: 1 Cluff and Hansen (1969), 2 and 3 Audemard (1991). Map sources: Miller (1960), Tschanz *et al.* (1969), Kellogg and Bonini (1982), Soulas (1986), Soulas *et al.* (1987), Audemard (1991) and Audemard *et al.* (1992).

ers that bends along strike of normal faults is not a criterion of segmentation (converse to Zhang *et al.*, 1991). Moreover, Machette *et al.* (1991) mention that a certain polarity is to be taken into account and whenever the bend is concave in the roofwall of the normal fault, a barrier is then formed. This criterion coincides with what other authors call a salient (Crone and Haller, 1991; de Polo *et al.*, 1991; Machette *et al.*, 1991). For strike-slip faults, Sibson (1989) considers that single bends may or may not be barriers to the rupture propagation and mentions that a certain directivity has to be considered.

(5) Interception of faults (Soulas, 1988; Crone and Haller, 1991; de Polo *et al.*, 1991; Machette *et al.*, 1991; Turko and Knuepfer, 1991; Stewart and Hancock, 1991). It is very likely that many cases of barriers considered as overlaps actually correspond to sealed basement faults normal to the seismogenic fault trace.

(6) Bifurcation or convergence of faults (Soulas, 1988; de Polo *et al.*, 1991; Machette *et al.*, 1991; Zhang *et al.*, 1991).

(7) Complex configuration of many short fault traces in a "knot-like" shape, among which the horse-tail structure (transtensive or transpressive) is a particular case (Soulas, 1988; King, 1986; Bruhn *et al.*, 1987 *in* Machette *et al.*, 1991; Zhang *et al.*, 1991).

Soulas (1988) also identifies two criteria of kinematic type: sudden change of motion type along the fault trace and considerable variation of slip rate, usually combined with geometric barriers.

### Width of rupture

Width of fault rupture can be established by means of the seismicity associated with each seismogenic source. In the Falcón region, seismicity typically is less than 20 kilometers deep (Figure 3).

## NEOTECTONIC APPROACH

The detailed neotectonic study carried out in northwestern Venezuela has resulted in identification of five sets of active faults according to strike and kinematics (Audemard, 1993a) (Figure 2): (1) east-west right-lateral faults (Oca-Ancón fault system, Adícora fault); (2) NW-SE right-lateral faults, synthetic to the east-west faults (Lagarto, Urumaco, Río Seco, La Soledad and Santa Rita faults, among others); (3) NNW-SSE normal faults (Paraguaná Western Coast, Cabo San Román, Puerto Escondido and Los Médanos faults); (4) north-south to NNE-SSW left-lateral faults (such as Carrizal and El Hatillo faults) and (5) ENE-WSW reverse faults, sub-parallel to fold axes (Taima-Taima, Chuchure, Matapalo and Araurima faults). Configuration of these tectonic features suggests that this region is undergoing a strike-slip tectonic regime characterized by maximum ($S_H$) and minimum ($S_h$) stresses contained in the horizontal plane and oriented NNW-SSE and WSW-ENE, respectively. This stress tensor has been confirmed by means of an automated evaluation, after the method of Etchecopar *et al.* (1981), of the microtectonic data collected by Audemard *et al.* (1992) in Plio-Quaternary deposits cropping out in the north-central sector of Falcón state. In addition, this microtectonic evaluation indicates that the present tectonic regime is of the compressive-strike slip (transpressive) type, with $S_H$ striking NNW-SSE (Figure 2).

Neotectonic mapping of northwestern Venezuela has identified the prominence of the Oca-Ancón fault system among the tectonic features of this region (Figure 1); it is the second longest fault system of the deformation belt of the southern boundary of the Caribbean plate after the Boconó fault. Both faults define the northern and southeastern boundaries of the triangular Maracaibo block

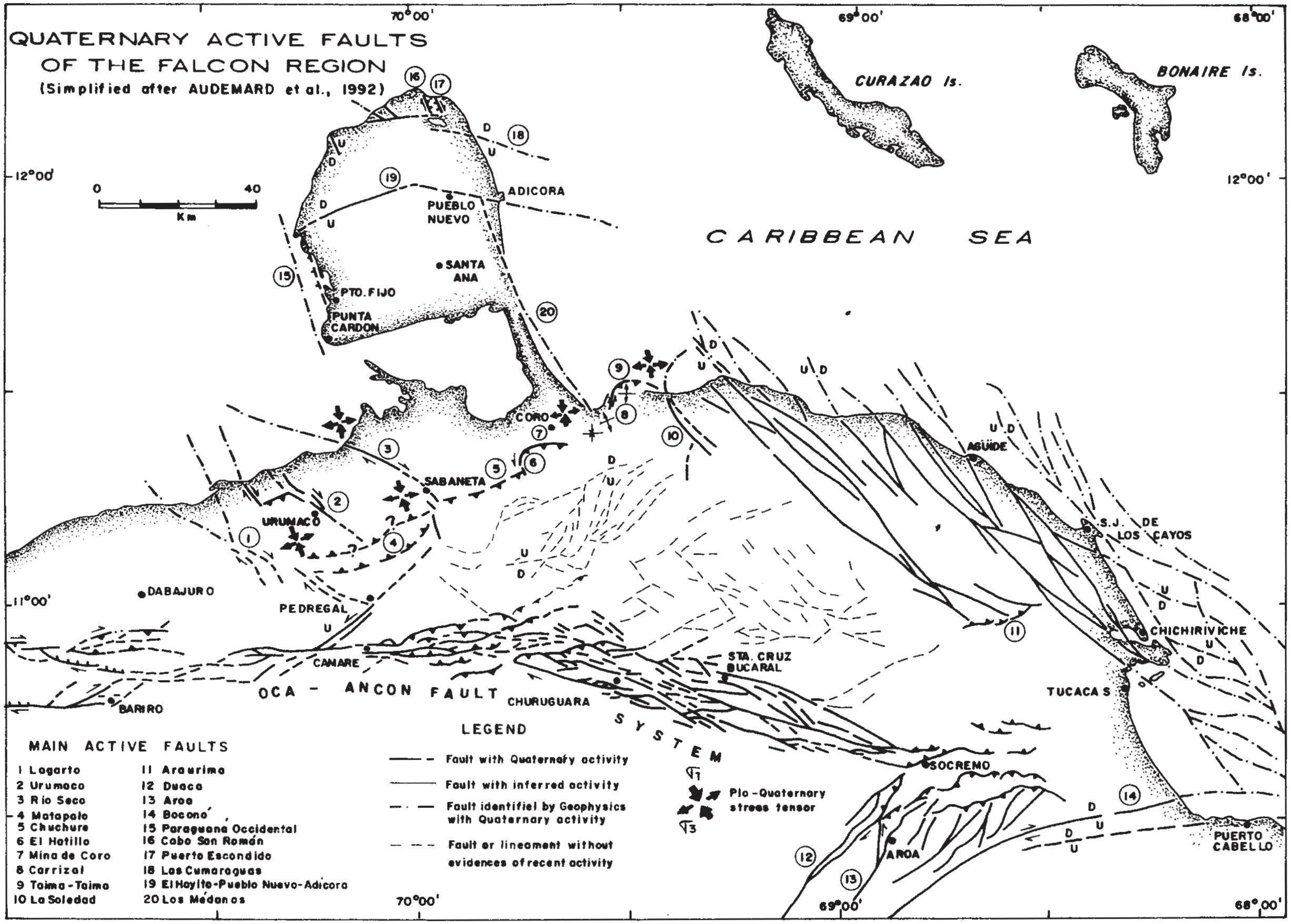


Fig. 2. Neotectonic map of the Falcón region (after Audemard *et al.*,1992). Five different sets of faults are interpreted as active under a transpressive stress field characterized by NNW-SSE maximum horizontal stress and ENE-WSW minimum horizontal stress.

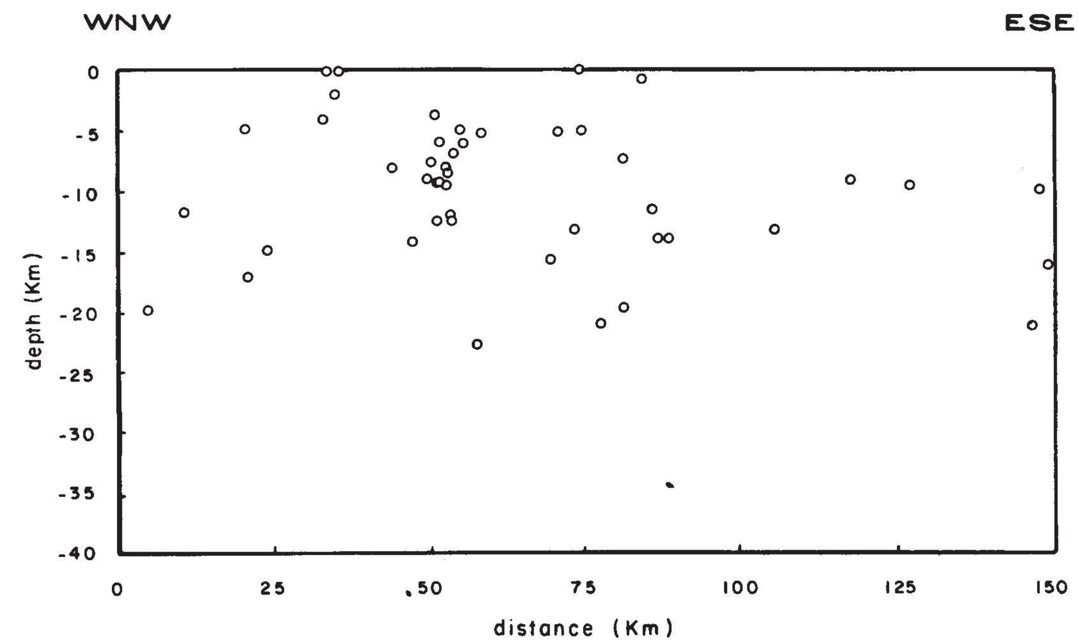


Fig. 3. Depth of seismicity associated to section D of the Oca-Ancón fault system, after a microseismicity survey carried out by Intevep *et al.* (1992).

(northwestern Venezuela and northern Colombia), which is also bounded by the Santa Marta-Bucaramanga fault on the west. The east-west, right-lateral Oca-Ancón fault system extends for 650 km from Santa Marta (Colombia) to Boca de Aroa (eastern coastlands of Falcón State). It crosses the Goajira peninsula, the outlet of lake Maracaibo, the coastal plains of northwestern Falcón State and the central Falcón range. It sharply truncates the north ends of the Santa Marta block (northern Colombia) and Perijá range (its summits constitute the Colombian-Venezuelan border). The Oca-Ancón system converges with the Boconó-San Sebastián-El Pilar system on the Aroa-Golfo Triste depression (Figures 1 and 2). It can be neotectonically subdivided into the following 5 different sections (Audemard *et al.*, 1992; Audemard, 1993a) (Figure 1):

A) *between the city of Santa Marta and the outlet of lake Maracaibo (Toas island)*: this section is the simplest among the others as it is comprised of a single trace that truncates the northern end of the Perijá range. Westward, it seems to control the linear northern coast of the Sierra Nevada de Santa Marta in Colombia; and farther west, it seems to connect to the east-west striking Jordán fault, mapped east of Santa Marta;

B) *between Toas island and the village of Mene de Mauroa*: the fault trace of the system in this section is divided into two sub-parallel strands: the east-west striking Oca and Ancón faults. Both traces are defined by several-kilometer-long fault scarplets in Quaternary alluvial terraces (Voorwijk, 1948) that limit a large area of probable recent subsidence, interpreted as an active pull-apart basin (Audemard *et al.*, 1992; Audemard, 1993a);

C) *between the villages of Mene de Mauroa and Paraiso*: the fault trace is very complex, as several strands converge on or diverge from the main fault in an anastomosing manner. The eastern portion of this fault section, between the villages of Camare and Paraiso in central Falcón state, coincides with the Camare-Paraiso range. This portion has been interpreted as a flower structure since the inner deformation in the fault zone is of the 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 the village of Paraiso and the Aroa valley*: This section of the fault system strikes WNW-ESE and comprises several sub-parallel fault strands of shorter length than in other sections. The seismic activity near Churuguara in central Falcón state, which is characterized by small-to-moderate but persistent earthquakes, is clearly associated with this WNW-ESE section of the Oca-Ancón fault system. The relatively high frequency of such seismic activity could be due to the large number and short lengths of the fault strands that comprise the system in that region (Audemard and Romero, 1993);

E) *between Socremo and Boca de Aroa* : The fault system regains its original nearly east-west strike along the northern margin of the Aroa valley. The fault along this section shows geomorphic features of reverse faulting where Quaternary alluvial ramps are flexed.

In summary, neotectonic studies to date in northwestern Venezuela have established the following features of the potentially-active faults:

(1) Geometry of each single fault that comprises its active trace (length, bends, stepovers, bifurcations, convergences, etc.), strike and dip.

(2) Kinematics of each single fault by means of slickensides. Whenever slickensides were not observed, microtectonic evaluation has allowed indirect estimates of the sense of slip by considering the present regional stress tensor.

(3) Value of cumulative displacement along each fault and age of this deformation, thus allowing estimates of slip rate for each fault*.

### Paleoseismic approach

The Oca-Ancón fault system is the largest potential seismic source in this region because of the probable rupture length of its seismogenic segments. Therefore, the seismic potential of this fault was evaluated further by excavating two paleoseismic trenches across the individual active traces of the Oca and Ancón faults on Section B (Figure 1). Both trench sites were located on fault scarplets (2 and 3 in Figure 1) and trenches were excavated by bulldozer down to 7 or 8 m in depth. They were cut perpendicular to the scarplet strike. Width of trenches decreased from 8 m at the top to 4 m at the bottom in order to stabilize trench walls and length varied between 80 and 85 m. Thus, removal of some 2,500 to 3,000 $m^3$ of material per trench was required. The paleoseismic results of both trenches are presented later in this paper.

## RESULTS OF THE SEISMIC HAZARD ASSESSMENT

### Neotectonic approach

Based on the neotectonic data, such as segmentation of potentially seismogenic faults, width of the coseismic rupture based upon the associated seismicity, and average slip rate of each fault calculated on deformed geological markers, characteristic seismogenic parameters (maximum credible earthquake and return period) have been estimated for each fault or each seismogenic fault segment by means of the empirical relationships of Utsu and Seki (1954) and Aggarwal (1981). These results are summarized in Table 1.

Let us demonstrate how the seismogenic potential assessment of any of the active faults included in Table 1 is carried out by discussing the Urumaco fault case. It is obvious from the neotectonic map shown in Figure 2 that this fault can hardly break along its entire length due to the restraining bend that divides the fault into two similar seismogenic segments. So, the maximum credible earthquake for the Urumaco fault estimated from Utsu and Seki's relationship (equation 1) may be generated by a 30-km-long fault rupture (Table 1). Assuming a fault width of about 12 km, since this fault is secondary to the major Oca-Ancón fault system whose width is about 20 km (Figure 3), the maximum-credible-earthquake magnitude is calculated as Ms 6.6 (= log 360+4). In addition, the coseismic slip corresponding to a Ms 6.6 earthquake can be calculated as some 70 cm from equation (2). Taking into account the Urumaco-fault slip rate of ≤ 0.1 mm/yr, calculated on a post-Pliocene right-lateral offset of 2 km (Soulas *et al.*, 1987), the return period can be estimated at ≥ 7000 yr for each single 30-km-long seismogenic segment. Consequently, the return period of the maximum credible earthquake for the entire Urumaco fault is reduced by half (≥ 3500 yr) because the Urumaco fault comprises two equivalent seismogenic segments. This reasoning is valid for all other active faults shown in Table 1.

### Paleoseismic approach

As mentioned previously, sector B of the Oca-Ancón fault system has been evaluated paleoseismically by means of two trenches placed across each of the two parallel strands known as the Oca and the Ancón faults (Audemard, 1991; 1993b; 1994). The paleoseismic study based upon interpretation of these trenches reveals earthquakes of magnitude Ms 7.4 to 7.5 on both faults along this section of the system. The recurrence of such events is 1752 ± 133 yr. on the Ancón fault, whereas it is 4300 ± 1000 yr. on the Oca fault. Other conclusions from this study (Audemard, 1991; 1996) are: (a) The Oca and Ancón faults are both right-lateral and the Oca fault also has a significant reverse component of displacement. The Oca-Ancón fault system is transpressive along section B, and behaves similarly along all the east-west striking sections; (b) Three earthquakes have been identified on the Oca fault at the Hato-El Guayabal trench (2 in Figure 1), dated at 7755 ± 320, 6240 ± 390 and 1945 ± 630 yr. B.P. (Table 2). Since the youngest deformation observed in the Hato-El Guayabal trench and in the Sinamaica trench (1 in Figure 1) is astonishingly similar in age (1920 ± 780 yr. B.P.), we believe that the most recent earthquake along this fault was associated with a 120-to-130-km-long surface rupture, equivalent to the distance between these two trenches.

* According to the used geological marker, we have established a "quality factor" that indicates the degree of confidence in estimates of the average slip rate and consequently in the estimated return period:
a- identifies displacement rates estimated from measured and dated deformations observed in paleoseismic trenches, in natural outcrops or from very young geological markers that have undergone just the latest tectonic regime;
b- corresponds to displacement rate along a fault that could have only been calculated partially on an tectonic feature structurally complex or composed by several traces. In some cases, the rate has been estimated by analogy with other faults of similar kinematics or by considering that the seismogenic fault is contiguous to a well-studied sector of the same feature. In other cases, the rate could have been established by means of a marker dated exclusively of relative manner;
c- implies that displacement rates have been calculated using very weak criteria: vague age of deformation; cumulative displacement resulting from several different tectonic regimes (superimposed extension and compression; superimposed strike-slip displacements of opposite directions along a single fault); relative significance of displacement components unknown (particularly when seismic profiles were used).

## Table 1

Seismogenic parameters of northwestern Venezuelan faults (after Audemard *et al.*, 1992). Explanation of (*) is given in text.

| ACTIVE FAULT | Rate of displacement (mm/yr) * | Total length (Km) | Maxim. possible quake (Ms) | Possible return period (years) | SEISMOGENIC SEGMENT | Credible rupture length (Km) | Maxim. credible quake (Ms) | Credible return period (years) | Type of faulting | Relative significance of displacement components |
|---|---|---|---|---|---|---|---|---|---|---|
| OCA-ANCON (total) | ≈ 2,0 b | 650 | ≈ 8,0 | very unlikely | --- | --- | --- | --- | dextral | H >> V |
| OCA-ANCON SYSTEM: OCA Sect. A+B | ≈ 0,45 a | 400 | 7,9 | very unlikely | 3 segments of equal length | 130 | 7,4 | ≈1430+330 | reverse dextral | H > V |
| OCA-ANCON SYSTEM: ANCON Section B | ≈ 1,55 a | 140 | 7,5 | ≈ 1900 | Ancón | 140 | 7,5 | ≈ 1900 | dextral | H >> V |
| OCA-ANCON SYSTEM: Section C | ≈ 2,0 b | 75 | 7,1 | ≈ 670 | Section C | 75 | 7,1 | ≈ 670 | reverse dextral | H >> V |
| OCA-ANCON SYSTEM: Section D | ≈ 2,0 b | 110 | 7,3 | very unlikely | 25 Km-long segments | 25 | 6,7 | ≈ 390 | dextral to normal dextral | H >> V |
| OCA-ANCON SYSTEM: Section E | <2,0 b | 40 | 7,0 | >560 | Section E | 20 | 6,7 | >390 | reverse with dextral comp. | V > H |
| LAGARTO | 0,2-0,3 c | 80 | 7,0 | unlikely | northern segment | 40 | 6,7 | ≥2650 | normal dextral | H >> V |
| URUMACO | ≤0,1 b | 68 | 7,0 | very unlikely | 2 segments of equal length | 30 | 6,6 | ≥3500 | dextral - reverse dextral | H >> V |
| RIO SECO | ≈ 0,35 a | 110 | 7,3 | 5000-6000 | 2 segments of equal length | 50 | 7,0 | ≈ 1500 | reverse dextral | H >> V |
| PARAGUANA W | ≤0,2 c | 80 | 7,0 | unlikely | central section | 35 | 6,6 | ≥3400 | normal, with sinistral comp.? | V > H |
| ADICORA | ≤0,05 c | 90 | 7,1 | ≥24000 | west Adícora | 30 | 6,6 | ≥14000 | normal, with dextral comp.? | V > H |
| | | 220? | 7,4 | unlikely | east Adícora | 60 | 6,9 | ≥19000 | | |
| LOS MEDANOS | ≤0,2 c | 55 | 6,8 | ≥ 4700 | Los Médanos | 55 | 6,8 | ≥ 4700 | normal, with dextral comp.? | V > H |
| TAIMA-TAIMA | ≈ 0,1 b | 30 | 6,9 | ≈ 10000 | Taima-Taima | 30 | 6,9 | ≈10000 | reverse | V >> H |
| LA SOLEDAD | ≈ 0,3 c | 40 | 6,7 | ≈ 2650 | La Soledad | 40 | 6,7 | ≈ 2650 | normal dextral | H > V |
| SAN ROMAN | ≈ 0,2 b | 14 | 6,2 | ≈ 2300 | San Román | 14 | 6,2 | ≈ 2300 | normal, with dextral comp. | V > H |
| FALCON NE COAST FAULTS | ≈ 0,3 b | 185 | 7,3-7,4 | very unlikely | 30 Km-long segments | 30 | 6,6 | ≈ 2300 | normal dextral | H > V |
| ARAURIMA | ≈ 0,1 b | 25 | 6,8 | ≈ 9000 | Araurima | 25 | 6,8 | ≈ 9000 | reverse, with dextral comp.? | V >> H |
| PEDREGAL | ≈ 0,5 c | 40 | 6,7 | ≈ 1600 | Pedregal | 40 | 6,7 | ≈ 1600 | sinistral, with reverse comp.? | H > V |

**Table 2**

Results of the Oca fault paleoseismic evaluation at the Hato-El Guayabal trench (after Audemard, 1991).

| Occurrence (yr B.P.) | Vertical throw (m) | Vertical rate (mm/yr) | Total displacement (m) | Rate of displacement (mm/yr) | Magnitude (Ms) | Time elapsed inter-events (yr) |
|---|---|---|---|---|---|---|
| 1945 ± 630 | 0.9 | 0.22 ± 0.05 | 1.80 | 0.42 ± 0.08 | 7.4 | 4295 ± 1020 |
| 6240 ± 390 | 0.4 | 0.34 ± 0.16 | 0.80 | 0.57 ± 0.22 | 6.9 | 1515 ± 710 |
| 7755 ± 320 | 0.5 (estimated) | ------ | 1.00 | ----- | 7.0 | ----- |

Based upon equation (1) and a 20-km-deep rupture width (Figure 3), such a rupture could be responsible for earthquakes of magnitude (Ms) 7.4, which is in agreement with the magnitude calculated empirically, by combining equations (1) and (2), from the total displacement measured at the Hato-El Guayabal trench (1.8 m). Thus, seismogenic segments of the Oca fault have been defined as being a third of the total fault length along section A+B. Consequently, the Oca-fault recurrence has also been reduced. Based on these interpretations, the next Ms 7.5 earthquake on the Oca fault for the Maracaibo region should not be expected within 2500 years; (c) One surface-rupture event has happened on the Ancón fault between 3125 ± 185 and 1770 ± 145 yr. B.P. (2467 ± 843 yr. B.P.). Comparing this latest occurrence of such Ms 7.5 earthquakes to the estimated recurrence of 1752 ± 133 yr., it is clear that the 100% likelihood of a Ms 7.5 earthquake on that segment is being reached; (d) The Holocene slip rate of the fault system is about 1.885 ± 0.325 mm/yr. This slip rate is roughly partitioned along segment B: a fourth along the Oca fault and three fourths on the Ancón fault. The Oca-Ancón fault system has the fastest fault slip rate in the region, and also is the most prominent seismogenic source zone.

## CONCLUSIONS

Although historical and instrumental seismicity is rather scarce, low in magnitude and diffuse in the Falcón region, northwestern Venezuela is an active tectonic area, that is part of the transpressive margin between the Caribbean and South American plates. The lack of large earthquakes in this region as observed in either historical or instrumental records is meaningless for assessing seismic hazard in this region, as demonstrated by paleoseismic studies in section B of the Oca-Ancón fault system. Recurrence of such large earthquakes is longer than the time span of any local seismic record. Because of the long recurrence intervals, a neotectonic-paleoseismic approach is appropiate to assess the seismic hazard of northwestern Venezuela.

This neotectonic approach has resulted in identification of five sets of active faults according to fault strike and kinematics: (1) east-west right-lateral faults; (2) NW-SE right-lateral faults, synthetic to the east-west faults; (3) NNW-SSE normal faults; (4) north-south to NNE-SSW left-lateral faults, and (5) ENE-WSW reverse faults, subparallel to fold axes. Configuration of these tectonic features suggests that the Falcón region is undergoing a strike-slip tectonic regime, characterized by maximum and minimum horizontal stresses oriented NNW-SSE and WSW-ENE, respectively. This stress tensor has been confirmed by evaluating the microtectonic data collected in Plio-Quaternary deposits cropping out in the north-central region of Falcón state. In addition, this microtectonic evaluation defined the present tectonic regime as a compressive-strike slip (transpressive) plate boundary.

This neotectonic mapping has determined that the Oca-Ancón fault system stands out as a major tectonic feature of northwestern Venezuela, due to its 650-km-long active fault trace. Consequently, the Oca-Ancón fault system is also interpreted as the greatest potential seismic source of this region, because of the probable rupture lengths of its seismogenic segments. This system is the second longest and most active fault system of the Caribbean-South America plate boundary, after the Boconó-San Sebastián-El Pilar fault system. Paleoseismic studies carried out on section B of the Oca-Ancón fault system revealed the occurrence of earthquakes of magnitude Ms 7.4 to 7.5 on both the Oca and Ancón faults. The return period of such an earthquake is 1752 ± 133 yr. on the Ancón fault, and is 4300 ± 1000 yr. on the Oca fault.

Other conclusions from this study are: (a) The Oca and Ancón faults are both right-lateral and the Oca fault also has a reverse component of slip. The Oca-Ancón fault system is transpressive along section B, and is interpreted to behave in a similar manner along other sections that strike east-west; (b) Three earthquakes have been identified on the Oca fault at the Hato-El Guayabal trench, dated at 7755 ± 320, 6240 ± 390 and 1945 ± 630 yr. B.P.; (c) One surface-rupture event has been documented on the Ancón fault between 3125 ± 185 and 1770 ± 145 yr. B.P. (2467 ± 843 yr. B.P.). Comparing this latest occurrence of such Ms 7.5 earthquakes to the estimated recurrence of 1752 ± 133 yr., it is clear that we appear to be entering the window of opportunity for recurrence of such an earthquake on that segment; (d) The Holocene slip rate of the fault system is about 1.885 ± 0.325 mm/yr. Roughly speaking, a fourth of this slip rate occurs along the Oca fault, and the other three fourths along the Ancón fault.

The neotectonic approach also resulted in the identification of a large number of minor active faults associated with the Oca-Ancón fault system. These minor faults are capable of generating maximum credible earthquakes of magnitude Ms between 6.2 and 7.0, with return periods generally longer than 1500 yr. based upon their displacement rates that are typically slower than 0.5 mm/yr.

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