

# Surface rupture of the Cariaco July 09, 1997 earthquake on the El Pilar fault, northeastern Venezuela

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Received 1 December 2005; received in revised form 24 April 2006; accepted 28 April 2006

Available online 24 July 2006

## Abstract

This paper discusses the surface rupture of the Cariaco July 09, 1997 Ms 6.8 earthquake in northeastern Venezuela – located at 10.545°N and 63.515°W and about 10 km deep. The field reconnaissance of the ground breaks confirms that this event took place on the ENE–WSW trending onshore portion of the dextral El Pilar fault (between the Gulfs of Cariaco and Paria), which is part of the major wrenching system within the Caribbean–South America plate boundary zone. Dextral slip along this fault was further supported by the structural style of this rupture (en echelon right-lateral R shears connected by mole tracks at restraining stepovers) and by larger geometric complexities (pop-ups at Las Manos and Guarapiche), as well as by the focal mechanism solutions determined for the event by several authors. This 1997 surface rupture comprised two distinct sections, from west to east: (a) a main very conspicuous, continuous, 30-km-long, rather straight, 075°N-trending alignment of en echelon surface breaks, with a rather constant, purely dextral coseismic slip of about 25 cm, but reaching a maximum value of 40 cm slightly northwest of Pantoño; and (b) a secondary discontinuous, 10-km-long, boomerang-shaped rupture, with a maximum coseismic slip of 20 cm at Guarapiche. The onshore extent of the surface rupture totalled 36 km, but may continue westward underwater, as suggested by the very shallow aftershock seismicity. This aftershock activity also clearly defined the steep north dip of the fault plane along the western rupture, suggesting tectonic inheritance on this major fault.

From many locals' accounts, the rupture seems to have propagated from Pantoño to the west (highly asymmetric bidirectionality). This suggests that earthquake nucleation happened at or near the Casanay–Guarapiche restraining bend and rupture quickly propagated westward, allowing only a small fraction to progress eastwards beyond the bend. Additionally, the large fraction of after-slip (or creep) released is to be related to such restraining bend, which seems to have partly locked slip during rupture.

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*Keywords:* Cariaco earthquake; Surface rupture; Nucleation; After-slip; El Pilar fault; Caribbean

## 1. Introduction

Northeastern Venezuela was struck by a Ms 6.8 (Mw 6.9) earthquake on July 09, 1997, at 19:24:10.8 GMT. Its hypocenter was located at 10.545°N and 63.515°W and 9.4 km in depth (FUNVISIS, 1997; FUNVISIS et al., 1997; Pérez, 1998b; Romero et al., 1998; details on earthquake depth dispersion are given in Baumbach et

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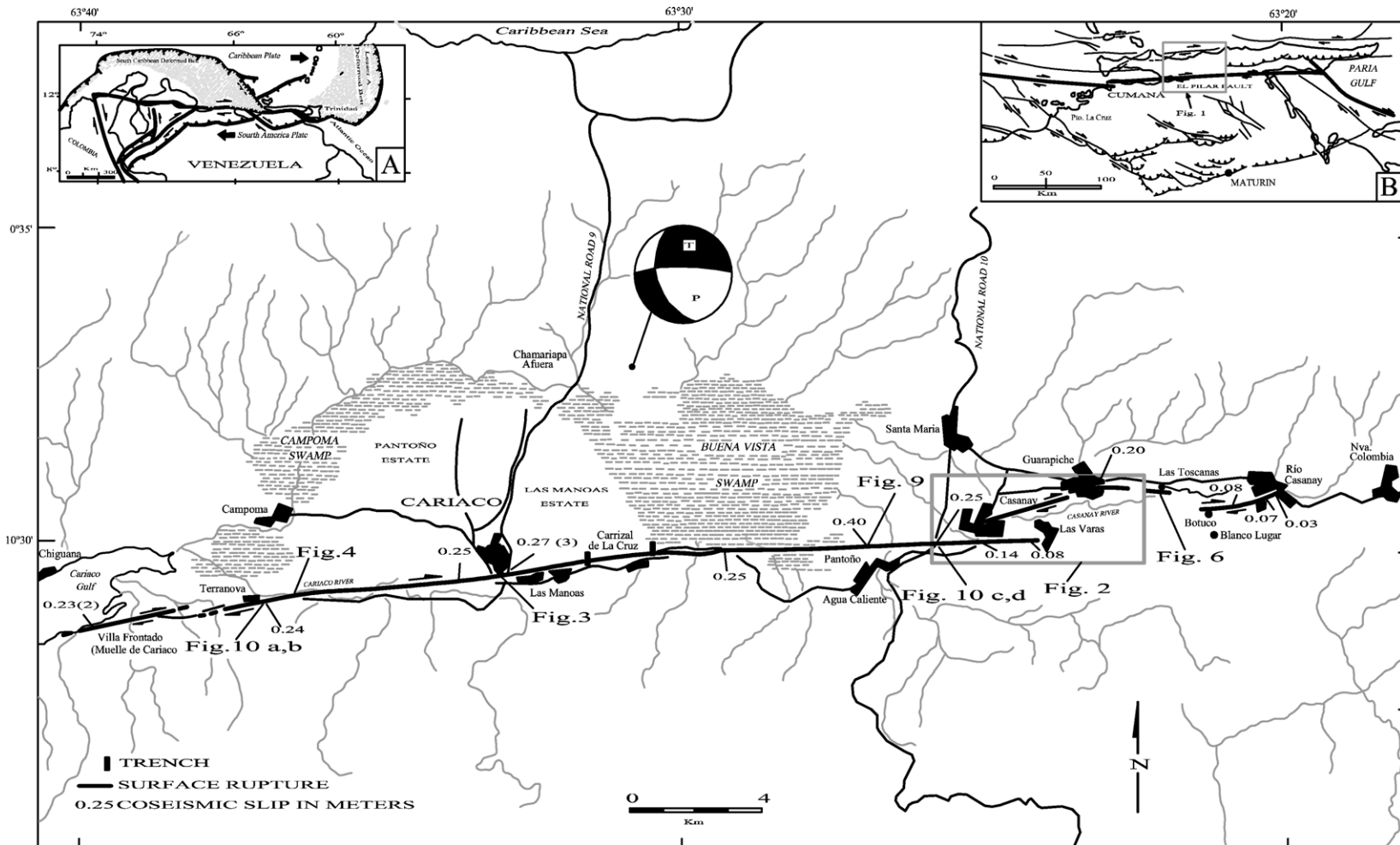


Fig. 1. Mapping of surface faulting during the Cariaco July 09, 1997 earthquake extending eastward along the El Pilar fault between Villa Frontado – on the seashore of the Cariaco Gulf – and Rio Casanay, state of Sucre. Coseismic slip measurements are reported along rupture, as well as the focal mechanism determination based on p-wave first arrivals recorded by the Funvisis national seismologic network (after Audemard et al., 2005). (A) Geodynamic setting of northern Venezuela (after Audemard et al., 2000). (B) Active transpressional tectonic setting of northeastern Venezuela, where the right-lateral strike–slip El Pilar fault plays a major role in strain partitioning (after Audemard et al., 2000, 2005). Box in (B) indicates coverage of Fig. 1. Locations of several other figures are also reported.

al., 2004), about 5 km north of the onshore section of the active El Pilar fault trace identified by FUNVISIS (1994) and Beltrán et al. (1996) and northeast of the town of Cariaco (Fig. 1). This settlement was the most severely damaged where collapse of two multistory school buildings was responsible for most casualties, but several other neighboring villages were also affected, such as: Chiguana, Casanay, Guarapiche and San Antonio del Golfo (Fig. 1). Cumaná, located 70 km west of the epicenter, also suffered damage, but all deaths there were due to a single building collapse. Total casualties were in the order of eighty people. In terms of magnitude, this is the largest earthquake felt in Venezuela during the 20th century, but not the most destructive one. The highest number of casualties – over 200 people – is associated to the Caracas (Ms 6.3; Mw 6.6) July 27, 1967 earthquake in central Venezuela.

Since strike–slip earthquakes of magnitude close to 7 commonly rupture the ground surface, and the Cariaco earthquake epicenter was on the land bridge between the Gulfs of Cariaco and Paria, a field reconnaissance in the state of Sucre, first airborne and later on ground, was launched 2 days after the main event. The initial survey was later complemented by two other campaigns carried out in December 1997 (5 months later) and March 1998 (8 months later). This paper summarizes our study of the 1997 earthquake ground ruptures, which contributes knowledge to the active tectonics and seismotectonics of the southeastern Caribbean, despite the associated casualties and the negative economic impact. It is only the second event in the 500-year-long seismic history of Venezuela, which has permitted recognition and documentation of surface rupturing (FUNVISIS, 1997; FUNVISIS et al., 1997; Audemard, 1999a). The Cumaná January 17, 1929 earthquake rupture was the first one, which was studied by Sidney Paige (1930). Both events were related to the El Pilar fault and affected the city of Cumaná in different degrees.

## 2. Southeastern Caribbean geodynamics

The relative eastward motion of the Caribbean plate with respect to South America is generally agreed upon (Bell, 1972; Malfait and Dinkelman, 1972; Jordan, 1975; Pindell and Dewey, 1982; Sykes et al., 1982; Wadge and Burke, 1983; Freymueller et al., 1993; Pérez et al., 2001; Weber et al., 2001; among others). However, this Caribbean–South America plate boundary – which drives and defines active tectonics along northern Venezuela – is not of the dextral simple type (Soulas, 1986; Beltrán, 1994) but instead it is a >100-km-wide active transpressional zone (Fig. 1A; Audemard, 1993, 1998; Singer and Audemard, 1997), along which a large fraction of wrenching is accommodated

by the RLSS Boconó–San Sebastián–El Pilar 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; Pérez et al., 2001; Weber et al., 2001).

The present Caribbean–South American geodynamic configuration results from a complex and evolving transpressive history 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 an east-younging long-living oblique-collision (SSE-vergent, Caribbean/passive margin affinity nappes overriding South America passive margin) and has later shifted to transpression when and where collision became unsustainable (for more details refer to Audemard, 1993, 1998). Its latest transpressional evolutionary stage is still active in Eastern Venezuela and Trinidad, which recreates how this east-younging geodynamic evolution has acted diachronically throughout the Cenozoic evolution of this entire northern portion of the plate boundary (Fig. 1A; Audemard, 1993, 2000). Two coeval geodynamic processes are taking place in this southeastern Caribbean corner at present day. On one hand, eastern Venezuela exhibits strain partitioning (Rod, 1956b; Soulas, 1986; Beltrán, 1994; Passalacqua et al., 1995; Audemard et al., 2000, 2005; among others). The El Pilar and NW–SE striking Los Bajos–El Soldado faults are accommodating RLSS motion while NNW–SSE-oriented shortening occurs across the Interior Range (Audemard et al., 2005), as attested by active folding and south-vergent thrusting (Fig. 1B; Singer et al., 1998; Wagner, 2004). On the other hand, slab sinking or detachment (e.g., Russo and Speed, 1992; Russo, 1999) is attested by the world's largest onshore negative Bouguer anomaly, which is located south of the southern edge of the Interior Range. These processes take place at a plate boundary geometry, where the El Pilar fault transfers its slip to one of its 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 conventional subduction domain of the Lesser Antilles on the east (Fig. 1A). These two distinct seismic domains were first defined by Pérez and Aggarwal (1981). Recent GPS results from Weber et al. (2001) indicate that slip motion from the El Pilar fault is mostly transferred eastward onto the Warm Spring fault located in the Central Range of Trinidad. This would then suggest that the gulf of Paria largely

coincides with a pull-apart basin at the right stepover between the two above-mentioned faults, as proposed, for instance, by Ysaccis (1997). Both faults exhibit a similar slip rate, in the order of 8–10 mm/a (compare Audemard et al., 2000 and Saleh et al., submitted for publication). The Warm Spring fault accounts for half of the dextral motion occurring across Trinidad (Saleh et al., submitted for publication). So does the El Pilar fault (Audemard et al., 2000), if the relative Caribbean–South America motion is in the order of 20 mm/a in eastern Venezuela, as published by Pérez et al. (2001) and Weber et al. (2001).

Present-day deformation along northern Venezuela results from a transpressional (compressive strike–slip) 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; Beltrán and Giraldo, 1989; Audemard, 1993, 1997; Audemard et al., 2005). This present stress tensor has been calculated from fault-plane kinematic indicators collected at various sites in Plio-Pleistocene formations of northern Venezuela (Audemard, 1985, 1993, 2001; Beltrán and Giraldo, 1989; Audemard et al., 2005) and additionally confirmed by focal mechanism solutions.

The 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 approximately 80-km-long onshore portion in State of Sucre between the gulfs of Cariaco and Paria (Fig. 1B). This fault has been source of controversy. No consensus was available as late as the early 1980s regarding its slip (refer to Schubert, 1979 and Giraldo, 1996), despite the large number of authors who consider the El Pilar fault as part of the major wrench-system within the Caribbean–South America transpressional boundary. Moreover, no agreement has been yet met on the cumulative RLSS displacement along this fault (for more details, refer to Schubert, 1979; Giraldo, 1996; Audemard and Giraldo, 1997).

The active trace of the El Pilar fault has been mapped rather thoroughly based on geomorphic evidence of tectonic activity by FUNVISIS (1994), which was later published by Beltrán et al. (1996). These authors report geomorphic features along the active fault trace such as: right-lateral offset drainages, fault trenches, pop-ups, pressure ridges, fault saddles, sag ponds and fault scarps (for more details, refer to Figs. 1 and 2 in Beltrán et al., 1996). This evidence unambiguously establishes the dextral slip character of this fault. This data bring supporting evidence to the

right-lateral slip on the El Pilar fault proposed by Pérez and Aggarwal (1981) based on few focal mechanisms. Quaternary fault mapping from that study matches well with the geologic fault trace originally reported by Metz (1968), and later compiled by Bellizzia et al. (1976) in the Venezuela geologic map. Based on the neotectonic mapping, the El Pilar active fault trace has been subdivided in four different sections (FUNVISIS, 1994; Beltrán et al., 1996; Audemard et al., 2000): (1) 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; (2) 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, 1999b); (3) a 30-km-long section that slightly diverges to the ENE and extends between Río Casanay and El Pilar; and (4) a fourth portion, also east–west trending, that cuts across the swampy areas of the Sabanas de Venturini and runs offshore south of the Paria Peninsula, before connecting and transferring its kinematics to the NW–SE striking Los Bajos and Soldado faults (Fig. 1B). The El Pilar, Los Bajos and El Soldado faults all together, as mentioned earlier, are considered as the eastern portion of the major RLSS plate boundary fault system between the Caribbean and South American plates. Weber et al. (2001), based on GPS results, extend this wrenching system farther east along the Warm Spring fault (WSF), which runs along the Central Range of Trinidad. However, a still very significant dextral motion is transferred farther south by Los Bajos fault (beyond the WSF) to a fault system running south of Trinidad offshore that should connect to the southern tip of the lesser Antilles type-B subduction.

Excluding the seismic contribution from the southern tip of the Lesser Antilles subduction, the El Pilar fault is the most important earthquake source within northeastern Venezuela, as initially noted by Rod (1956a). This region has particularly suffered from several destructive earthquakes since the Spanish conquest, which happened in the early 16th century. The first ever reported event in this area, and nationwide, was the 1530 earthquake that heavily destroyed Cumaná. This city has since been repeatedly damaged by the 1684, 1766, 1797, 1853, 1929 and the recent 1997 events (Audemard, 1999b), with ground shaking being highly influenced by the

significantly unfavorable soil conditions (thick saturated Holocene deposits of saltflat or delta plain origin), as discussed in detail by both Lang et al. (1999) and González et al. (2004). Except for the 20th century earthquakes, all other historical events have been ascribed to the El Pilar fault without any geological corroboration. Most previous macroseismic epicenter determinations for such historical earthquakes – the only available data at present – have underestimated or neglected by force such limitations, as well as the influence of population distribution and communication network at their time of occurrence. Taking into considerations such difficulties, a reassessment 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 the El Pilar fault because the size of the felt area suggests that it is an intermediate-depth earthquake (between 60 and 200 km deep); (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 these ruptures likely occurred offshore, as implied by the tsunami waves that both events generated, placing their hypocenters west of Cumaná in the Cariaco Trough. It should be stressed that there is no evidence in the 500-year-long historical record of any  $M \geq 7$  earthquake associated to the onshore portion of the El Pilar fault, implying that this fault must be somehow seismogenically segmented as proposed by FUNVISIS (1994).

Furthermore, the only geologic assessment of any prehistoric seismic activity along this fault before the Cariaco earthquake was carried out at Las Toscanas (Fig. 1), between Guarapiche and Río Casanay, by the Earth Sciences Department of Funvisis in 1994 by means of a trench excavation that confirmed the Holocene activity and sense of slip of this fault by revealing the occurrence of four prehistoric events of magnitude about 7 in the last 7 to 8 kyr (FUNVISIS, 1994; Beltrán et al., 1996, 1999). Slip was determined from kinematic indicators measured on fault planes exposed in trench walls.

### 3. Cariaco 1997 surface rupture

Despite unfavorable natural factors such as thick tropical vegetation and large swampy areas in the region between the Gulfs of Cariaco and Paria, state of Sucre,

northeastern Venezuela (Fig. 1), a thorough field survey carried out in the first 2 weeks after the main shock, allowed to map the surface faulting developed in association with the Cariaco July 09, 1997 earthquake.

#### 3.1. Surface breaks

Ground faulting could be traced for almost 37 km from the seashore town of Villa Frontado (also known as Muelle de Cariaco and located at the bottom of the Gulf of Cariaco) to Río Casanay in the east (Fig. 1). Though the surface rupture may essentially be considered as a single linear feature, it displayed two discrete sections (Audemard, 1999a): (1) a very conspicuous, continuous, rather straight,  $075^\circ\text{N}$ -striking surface break that extended eastward from Villa Frontado to Las Varas (slightly east of Casanay) for some 30 km (Fig. 1); thereafter named as the western rupture; and (2) another more segmented and complex surface rupture that branched off northeastward within the town of Casanay, extending east up to Río Casanay, for some 10 km (Figs. 1 and 2). This eastern rupture strand or section displayed an overall convex-to-the-north boomerang shape.

#### 3.2. Structural style

The structural style of surface faulting associated to the Cariaco 1997 earthquake was constant along the entire length of both sections. But size of associated structures varied between sections and also along strike within a single section, revealing that coseismic slip controlled their final size and geometry. The surface rupture was essentially composed of an echelon right-lateral R shears, eventually connected by mole tracks or mounds at restraining stepovers (Audemard, 1999a; Fig. 3). The ground crack pattern confirms the dextral slip along this rupture and, in turn, excludes any further debate on the sense of motion of the El Pilar fault. In addition, the rupture style is in agreement with the simple shear model in unconsolidated or poorly consolidated materials. Regardless of size of associated features, this style of rupture is well documented in the literature for dextral strike–slip faults. To some extent, surface rupture style on dextral faults during the following events is comparable to the Cariaco: the Seslund May 06, 1912 – South Iceland (Bergerat and Angelier, 2000), the Saros–Marmara August 09, 1912 – Western Turkey (Ambraseys and Finkel, 1987), the Varto August 19, 1966 – Turkey (Wallace, 1968), the Mudurnu valley July 22, 1967 – Western Turkey (Ambraseys and Zatopek, 1969), the Oroville August

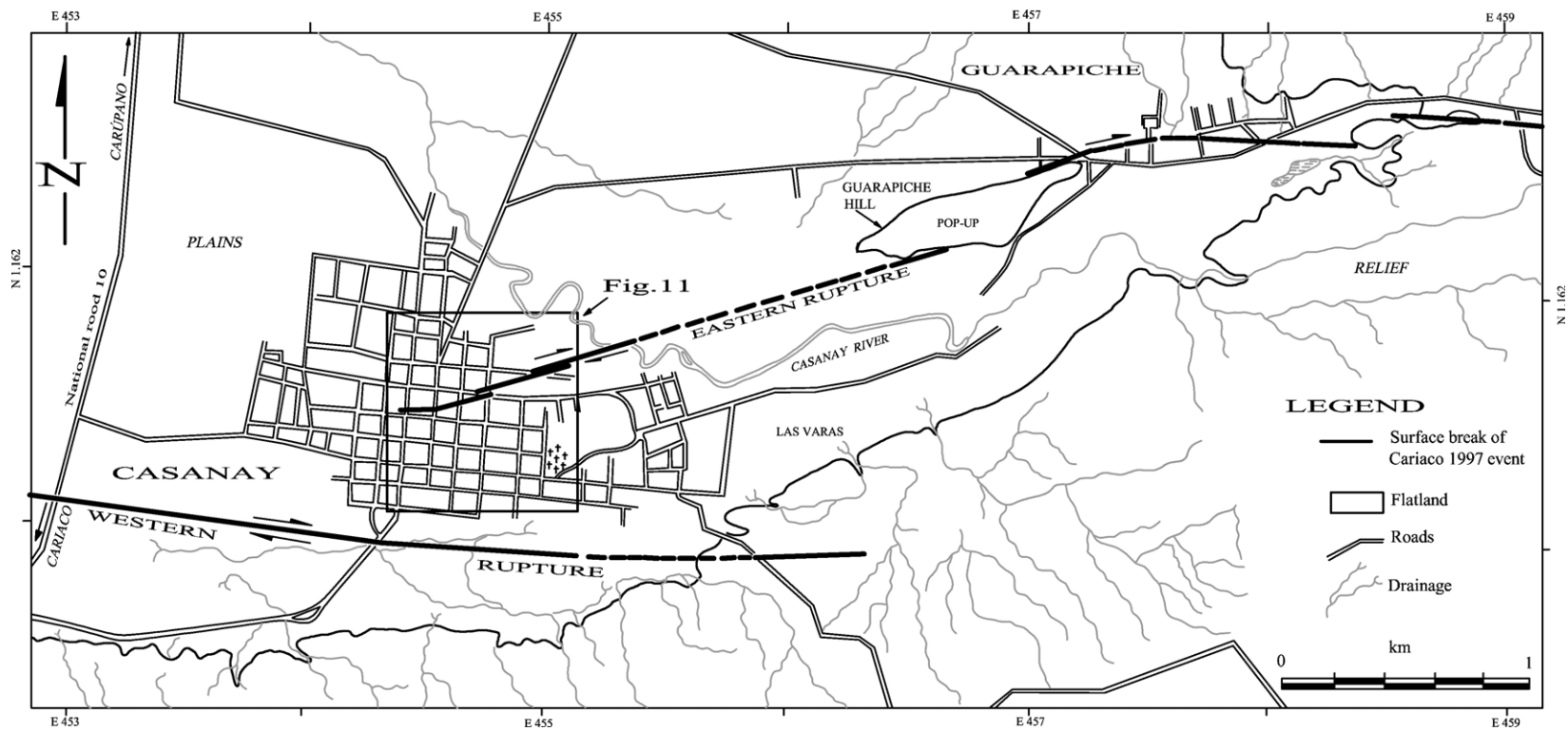


Fig. 2. Trace of the eastern rupture along the Casanay–Guarapiche restraining double bend. The Guarapiche Hill grows at a restraining overlap of this long oblique portion of the El Pilar fault. Relative location is shown in Fig. 1. Box of Fig. 11 is also shown.

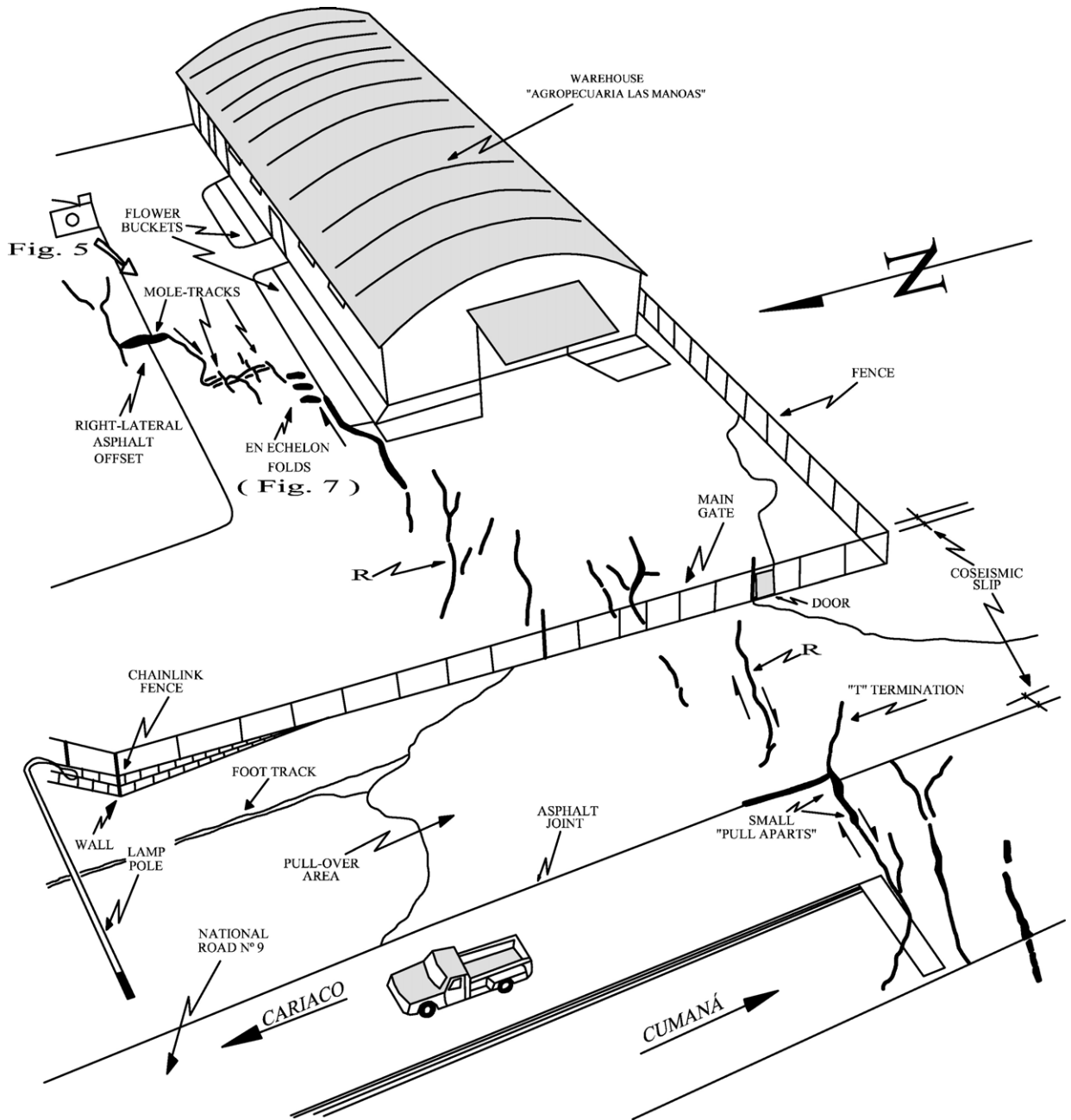


Fig. 3. Bird's-eye view of rupture style at Las Manos, across national road 9 and lateral yard of Las Manos hardware store (location given in Fig. 1). Notice that surface rupture entirely crossed chainlink fence through main gate, right-laterally displacing the fence alignment in 27 cm (measured on the western rupture within the first week after main shock).

01, 1975 – CA, USA (Hart and Rapp, 1975), the Westmorland April 26, 1981 – CA, USA (Sharp et al., 1986), few sections of the Spytak December 07, 1988 – Armenia (Philip et al., 1992), the Landers June 28, 1992 – CA, USA (USGS staff, 1992) and Izmit August 17, 1999 – Western Turkey (Barka et al., 1999), among many others.

#### 4. Western rupture

##### 4.1. Extent and location of western surface rupture

The western rupture, as indicated earlier, is oriented in WSW–ENE direction for some 30 km between the town of Muelle de Cariaco and Las Varas (village

located east of Casanay; Fig. 1). In a general sense, this western surface break could be observed at different sites, partly because the national roads zigzag along the rupture, and that many cultural features also interfered with the surface faulting (Fig. 1). The ground breaks cut dozens of cultural markers in several villages or towns (Figs. 1 and 2), from west to east: Villa Frontado, Terranova, Cariaco, Carrizal de la Cruz and Casanay. A detailed along-strike description of the ground ruptures is provided in Audemard (1999a).

The western portion of this rupture ran along the national road linking Villa Frontado–Cariaco–Casanay, between the towns of Muelle de Cariaco on the west and Carrizal de la Cruz on the east (Fig. 1). Here, the surface faulting was curiously not at the foot of the hills, and did not coincide with the geologic–topographic boundary between the Holocene low alluvial plains of the Cariaco River on the north and the relief on Mesozoic

sedimentary rocks on the south (Serranía del Interior or Interior Range). Instead, it was at mid-elevation of the north-facing slopes, only very few tens of meters at most above the plains of the northernmost hills of Serranía del Interior. Ground fractures were a combination of R and T cracks near the foot of the scarp (Fig. 4A and B). Farther east, the rupture was difficult to find, both from the air and on the ground, between the travertine pools at the Aguas Calientes farm and a rural road located west of Pantoño that heads north from the town of Aguas Calientes and services the Kokoland and La Piragua pools (Fig. 1). A large inaccessible swampy area covered by reeds (Laguna de Buena Vista) impeded observation of faulting, except for a short rupture stretch located slightly south of the Aguas de Moises pool. That stretch of surface break was under a thick thorny wood and ran along a few meter-high north-looking scarp. The surface rupture exhibited en-echelon, <2-m-long, 0.5-

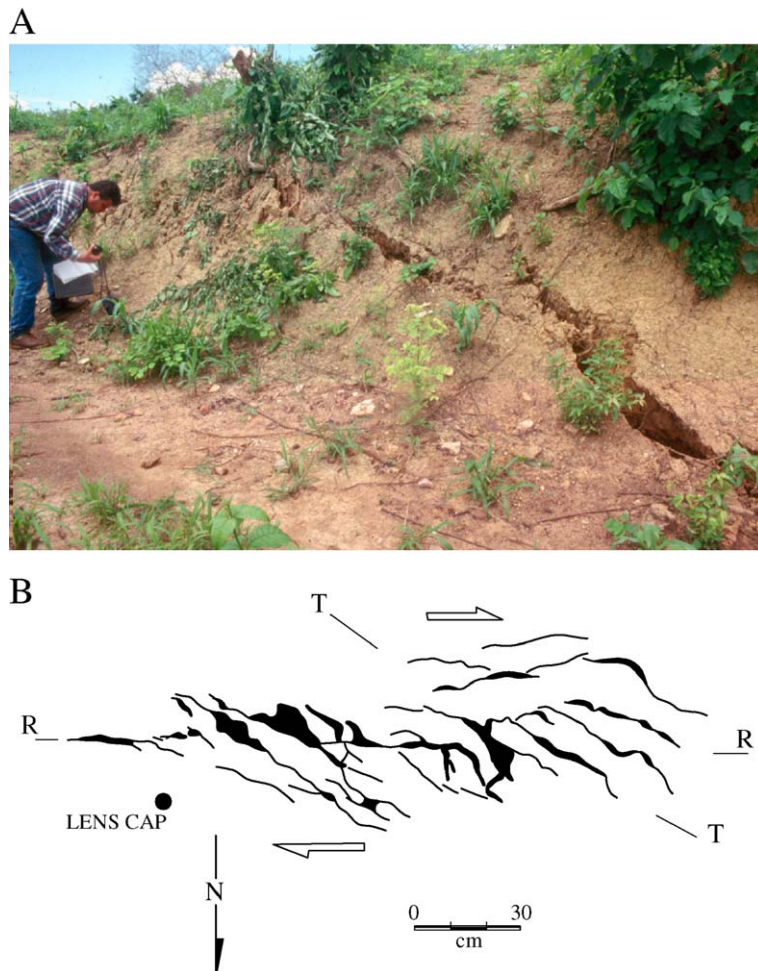


Fig. 4. Tension gashes opened on every inclined surface cut across by the surface faulting, as at Terranova. (A) E–W trending en echelon tension gashes on a north-facing fault scarp. (B) Fractures at the same scarp foot (couple of meters west of Fig. 4A) combine R shear and open crack features.

m-wide cracks. East of the Kokoland/Aguas de Moises access road, the surface rupture became visible again and could be followed east to Las Varas (Audemard, 1999a; Fig. 1).

This western break, although appearing rather simple, displayed two large geometric complications of several hundred meters in length. The first was located between Villa Frontado and Terranova. There, the western rupture exhibited a 400-m-wide relay (Fig. 1). The trace of the surface break disappeared on the northern side of the national road and jumped south over the road, reappearing just west of Terranova. Between both break strands and on two dirt tracks used for local access north of the main road, there were wide-open  $125^{\circ}\text{N}$  striking fish-shaped cracks. Mirroring these features across the road and behind a small hill located south of the road and west of Terranova, an echelon 3- to 4-m-long T fractures opened near the western tip of the southern strand. Their opening was as much as 88 cm along the  $075^{\circ}\text{N}$  direction (along which matching of both crack sides was perfect). All these open cracks result from local transtension at a dextral overlap between the two strands of the surface rupture, again indicating dextral slip along this fault. It should be underlined that direction of crack opening perfectly coincided with the general trend of the surface faulting observed in association with the Cariaco July 09, 1997 earthquake in this area.

At Las Manosas, the surface rupture also showed a slight inflection to the NE with respect to its general trend, before regaining its general  $075^{\circ}\text{N}$  trend near Carrizal de la Cruz. Associated with this gentle double bend is an elongated fish-shaped hill, known as Las Manosas hill. The western surface rupture only ran along the northern edge of this smooth relief. After crossing the grounds of the Las Manosas warehouse (Fig. 3) located at the western end of the Las Manosas hill, the ground breaks were found to the east on a dirt track running along the northern foot of the hill, as well as in the backyard of a goat cattler at the eastern hill tip (Audemard, 1999a). Las Manosas hill is then considered as a pop-up forming at a restraining bend; also proposed by FUNVISIS (1994). These two geometric complexities along the western surface rupture of the Cariaco 1997 earthquake confirm the dextral sense of slip of the El Pilar fault obtained from smaller-scale structural features.

#### 4.2. Structural style of western surface rupture

At regional scale, the western rupture was rather linear and continuous, except for the two aforemen-

tioned complexities. But the western rupture is composed of individual dextral R shears arrayed en echelon, at a small scale. These fractures were generally found in zones up to 4- to 5-m-wide (Fig. 3). Mole tracks occasionally developed at R shear overlaps (Fig. 5). No visible vertical slip component was observed across these features, except for across few open cracks or T fractures, or mole tracks.

The structural style of the 1997 earthquake ground fractures was best displayed at the western end of the Las Manosas Hill, where the El Pilar fault cut across the national road 9 – south of the eastern entrance of Cariaco – and in the northern asphalted yard of the Agropecuaria Las Manosas warehouse (Fig. 3). Here, the surface rupture was comprised of an echelon R shears, with individual crack length up to 15 m. Occasionally, R shears and mole tracks (Fig. 5) were accompanied by tension (T) cracks or sigmoidal tension gashes (Fig. 6). All fracture orientations are collectively and individually consistent with dextral simple shear (Fig. 3). In some cases, R shears terminated in open T cracks (Fig. 3). The rupture only exhibited small en echelon conic folds between relaying R cracks at the Las Manosas grounds (Fig. 7). The spatial configuration of all those brittle and ductile features described in the Agropecuaria Las Manosas backyard support the dextral slip motion of the El Pilar fault.

Nonetheless, the fault rupture style has been locally modified by superimposed processes, such as those



Fig. 5. Ground view of surface faulting at Las Manosas hardware store, where dextral R shears are connected by mounds at restraining stepovers. All these features were nicely developed and well preserved in paved lateral yard. For location, refer to Fig. 3.



Fig. 6. En echelon sigmoidal tension gashes along eastern rupture about 1 km west of Las Toscanas. Compare size of features to that of western rupture (with Fig. 5).

inferred from our observations at La Piragua pool. This property, heavily damaged by the Cariaco earthquake, is located over 1 km north of the town of Aguas Calientes, which is sitting astride the national road 10. A well-developed en echelon T crack system, exhibiting vertical throws of the order of half a meter, crossed the coconut groves and the swimming pool in 110°N direction

(Audemard, 1999a). This deformation was magnified by local lateral spreading, making it impossible to establish a reliable natural or cultural marker for estimating the coseismic slip. It is likely that the maximum coseismic slip happened here (slightly west of Pantoño) but it could not be measured. However, several factors described by Audemard (1999a), such as: a shallow (about 0.5 m deep) water table, sandy sediments as proved by coconut growth, a very surficial small creek feeding the pool, occurrence of rotational motion in cross-section of slabs detached between tension cracks, and curved traces of the cracks suggest that most of the observed deformation is due to north-directed ground spreading although surface inclination is very gentle to the north (less than 2°).

#### 4.3. Slip distribution along western surface break

Measure of coseismic slip, and postseismic slip as well, along surface break of the Cariaco 1997 earthquake was possible due to the presence of offset or bent cultural markers such as: roads, sidewalks, gutters, canals, house walls, pipelines, among others. Coseismic slip measurements at different localities are reported along western rupture on Fig. 1, and are graphically summarized in Fig. 8. Some of the aforementioned features persisted through time, thus permitting repeated measurements. Three measuring campaigns were performed by Audemard (1999a; Fig. 8): The first one was immediately after the main event in mid-July 1997; the second and third campaigns took place in December



Fig. 7. Ground view of en echelon conic folds at restraining stepovers between adjacent R shears in lateral yard of Las Manos hardware store, next to flower buckets in Fig. 3.

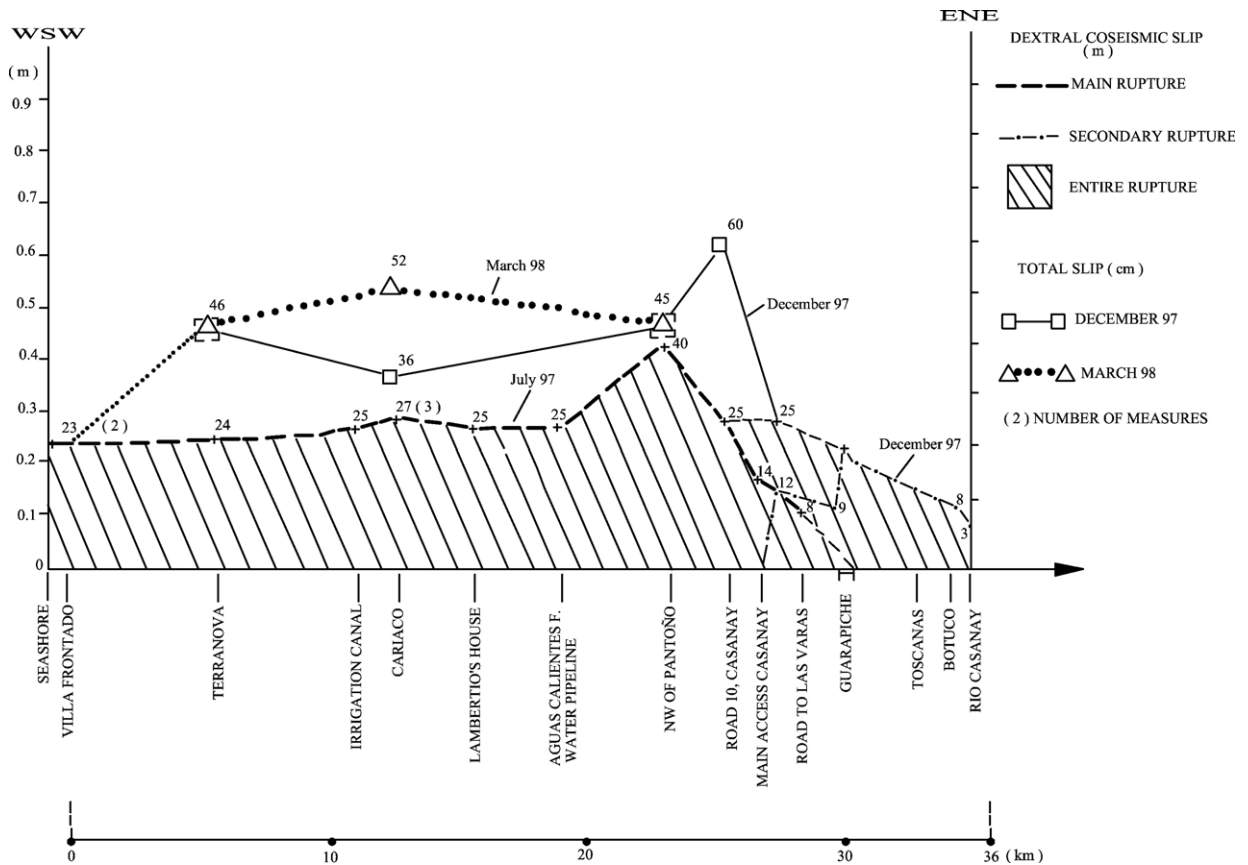


Fig. 8. Slip distribution along surface rupture related to the Cariaco 1997 earthquake. The western rupture very frequently exhibited a mean coseismic slip of about 25 cm, except for near Pantoño. Total slip doubles coseismic slip 6 months later, implying that important after-slip took place along this western rupture.

1997 and March 1998, respectively. Some markers – those that prevailed unrepaired longer – were measured for several more years.

Most of the rupture (between Villa Frontado–Carrizal de La Cruz) showed a rather constant, purely dextral coseismic slip of about 25 cm (Figs. 1 and 8), reached its maximum value of 40 cm slightly northwest of Pantoño (3 km west of Casanay; Figs. 1, 8 and 9) and tapered off abruptly to the east (Audemard, 1999a). Audemard (1999a) also reported that coseismic slip near the western tip at the seashore of Villa Frontado exhibited 23 cm of dextral slip (Figs. 1 and 8). The maximum coseismic displacement was reported on a NNE-oriented rural road, at about 1.5 km north of intersection with national road 10 (located nearby southern entrance of the Pantoño village; Audemard, 1999a). Surface faulting here crossed the asphalt road next to a concrete drain through which a small creek pours. The 40 cm coseismic right-lateral offset of July 97 increased to 45 cm in December 97 and thereafter stabilized (Audemard, 1999a; Fig. 9). This maximum

reported coseismic displacement near Pantoño is not located half way between both on-land rupture tips. This is even more evident if the total Cariaco 1997 rupture length considers that part of the break must lie underwater in the Cariaco Gulf, west of Villa Frontado (Muelle de Cariaco), regardless of adding the total length of the eastern rupture in the order of 10 km at the eastern tip of the western break. Several localities showed a similar pattern of sporadic slip increase to that reported in Pantoño. For instance, the 3–4 m wide rupture zone at Agropecuaria Las Manojas, which crossed the chainlink fence of the shop through the main gate (Fig. 3), exhibited 27 cm of coseismic dextral slip in the first week after the main event. The cumulative amount of slip progressively increased to 36 cm in December 97 and 52 cm in March 98 (Audemard, 1999a,b; Fig. 8). This value remained unchanged when remeasured in January 99.

At some places along the western surface rupture, after-slip was as large as or larger than coseismic slip (Fig. 8). This was observed at three sites at least, from



Fig. 9. Maximum coseismic slip of 40 cm observed on a rural road, adjacent to a concrete drain that deflects and concentrates all slip along a single plane. This locality is west of Pantoño and about 1 km north of national road 10 (refer to Fig. 1 for location).

west to east (Fig. 1; Audemard, 1999a): (a) at Agropecuaria Las Manos warehouse, south of Cariaco; (b) in the downtown area of Terranova; and (c) across a north–south stretch of the national road 10 (Casanay–Carúpano road), west of Casanay. In Terranova, the easternmost north–south-oriented street was damaged just few tens of meters north of the town church. At this location, dextral coseismic slip of sidewalk was 24 cm, but such offset increased to 46 cm in December of the same year (compare Fig. 10A and B). At the third locality and between both paved accesses to Casanay from the west, the pavement was cut across by two en echelon R shears, offsetting it dextrally in 8 and 17 cm, totalling 25 cm in July 97 (Fig. 10C). This site was revisited in December 1997 and dextral offset had increased to 60 cm (compare Fig. 10C and D); which remained unchanged by January 99.

No visible vertical displacement was detected along the western break except across either compressive features at restraining stepovers between R shears or local tensional features (e.g., open cracks, T fractures) that drove sinking of small fault-bounded slabs (Audemard, 1999a).

#### 4.4. Direction of rupture propagation along western surface break

Inhabitants of a house next to road heading north from west of Pantoño (next to where maximum coseismic slip was reported), who were watching TV outdoors in the backyard at the time of the main shock, indicated to Audemard (1999a) that surface cracking

progressed from east to west. This is the only account of this type it was made by several people but at a single place. However, Dr. Mocquet (in FUNVISIS, 1997) also reported westward rupture progression, from a house sitting next to fault crossing across national road 10, located due west of Casanay. He mentioned that the house owner accounted progression of rupture to the west. This locality is about 2.3 km east of the easternmost account reported by Funvisis (1997) and Audemard (1999a). Consequently, several eye-witnesses testified watching westward progression of ground rupturing from the western outskirts of the village of Casanay, which has significant implications for the location of the Cariaco 1997 earthquake epicenter and its nucleation.

## 5. Eastern rupture

### 5.1. Extent and location of eastern rupture

The second section of the surface rupture associated to the Cariaco 1997 earthquake is discontinuous, comprised of several, few kilometer long, discrete rupture portions (Audemard, 1999a). This eastern break exhibited an overall geometry that resembled a boomerang with northward convexity (Figs. 1 and 2). In addition, this eastern rupture was located north of the western one (showing left stepover), from which it bifurcated to the ENE within the town of Casanay (Fig. 2). The overall length of this rupture was of the order of 10 km, extending eastward from the town of Casanay to Río Casanay (Audemard, 1999a; Fig. 1). Pérez (1998a,



Fig. 10. Comparison of dextral slip between in the first week after the Cariaco 1997 earthquake and 5 months later (December 97), at Terranova (A and B) and at national road 10 west of Casanay (C and D). Total slip at both sites (B and D) roughly doubles the initial coseismic slip (A and C);

b) reported offset of 0.5 cm as far east as El Pilar (16 km farther east than any of the features described in this paper); features that could not be found or verified during this study.

### 5.2. Structural style of eastern surface rupture

The geometry of the eastern surface break was more complex than that of the western rupture. While the western rupture showed several-km-long, rather straight portions, the eastern rupture was composed of much shorter segments exhibiting an overall convex-to-the-

north shape. Besides, most of the overlaps on the secondary rupture were transpressive whereas the only one on the western rupture was transtensive. The eastern surface rupture could be subdivided into three portions (Audemard, 1999a). The western portion of the eastern break, extending eastward from within Casanay to the Guarapiche Hill pop-up (at the western entrance of the village of Guarapiche), was composed of several, approximately hundred-meter-long, rather straight, discrete cracks. These small ruptures were arranged en echelon and showed left-lateral stepovers, with compressive features (Fig. 11). This pattern was observed

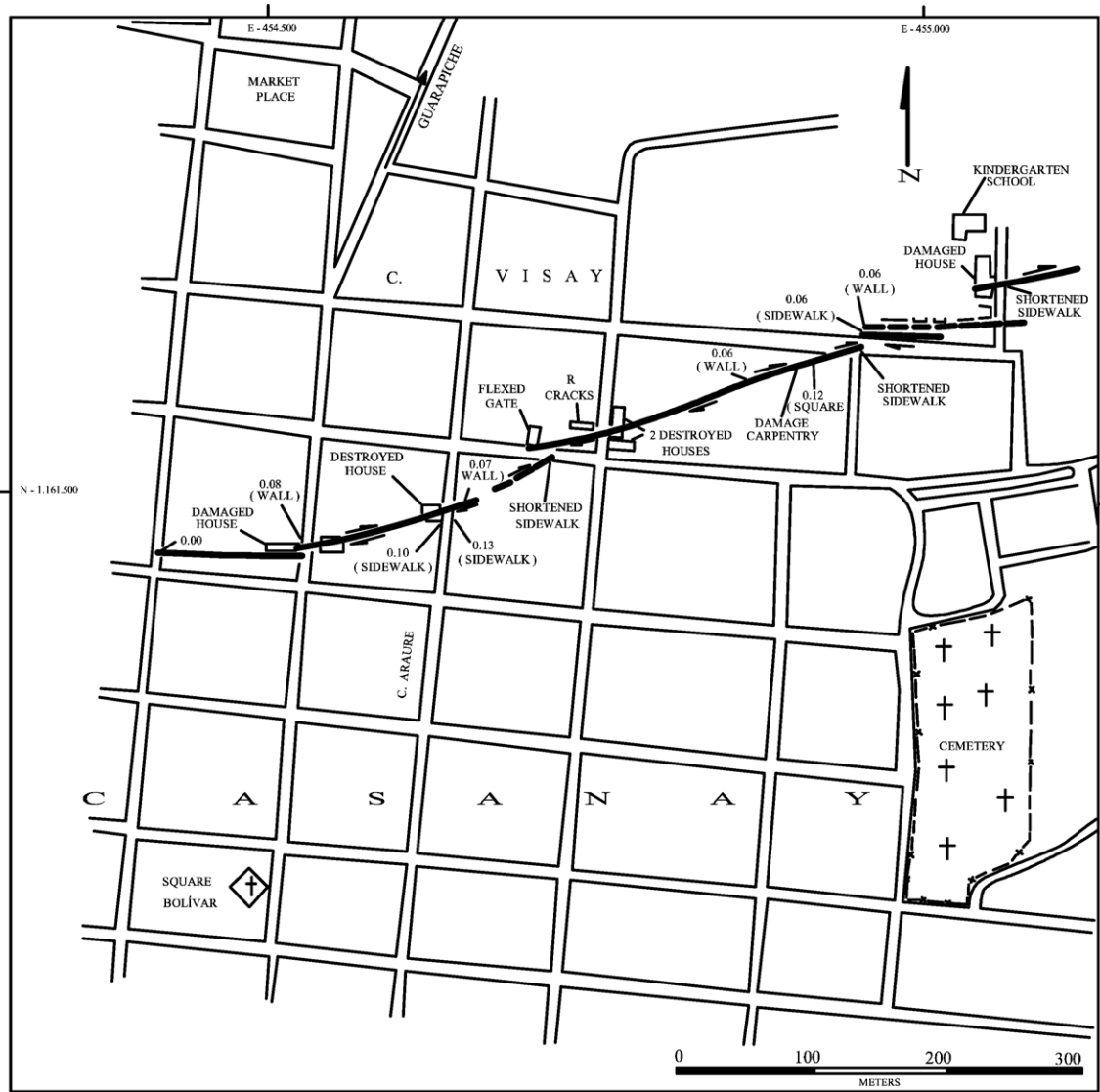


Fig. 11. Eastern rupture in Casanay. Many deformed cultural features allow mapping the en echelon R shear pattern displayed by the eastern rupture that branches off the western one within the downtown area. Relative location of this map is given in Fig. 2.

along most of the eastern rupture, except for between Las Toscanas and Río Casanay. To illustrate features at restraining stepovers, the best evidence is the Guarapiche Hill that structurally matches a pop-up (Fig. 2). Between both tips of this hill, the ground breaks appeared diametrically opposed at the foot of hillslopes: on the north at the eastern end while on the south at the western one (Fig. 2). The middle portion of this secondary break showed a convex-to-the-north arcuate shape, best expressed within the village of Guarapiche (Figs. 2 and 12). Within this settlement, the fault ground breaks were easily mapped due to the number of offset cultural markers (Fig. 12). This was also the case in

Casanay (Fig. 11). The most frequent cultural features affected were: sidewalks, gutters, fences, walls, gates and floor concrete slabs. The offsets were clearly observable although coseismic right-lateral offsets did not exceed 13 cm in Casanay (Fig. 11) nor 20 cm in Guarapiche (Fig. 12). Finally, the eastern most portion of this eastern rupture, between Las Toscanas and Río Casanay, exhibited right lateral stepovers between shears that were a few hundred meters long.

The eastern rupture displayed the same en echelon R shear pattern as the western rupture (Fig. 6), but structural features (R shears, open cracks, etc.) were smaller in size (either in length, width or opening) than

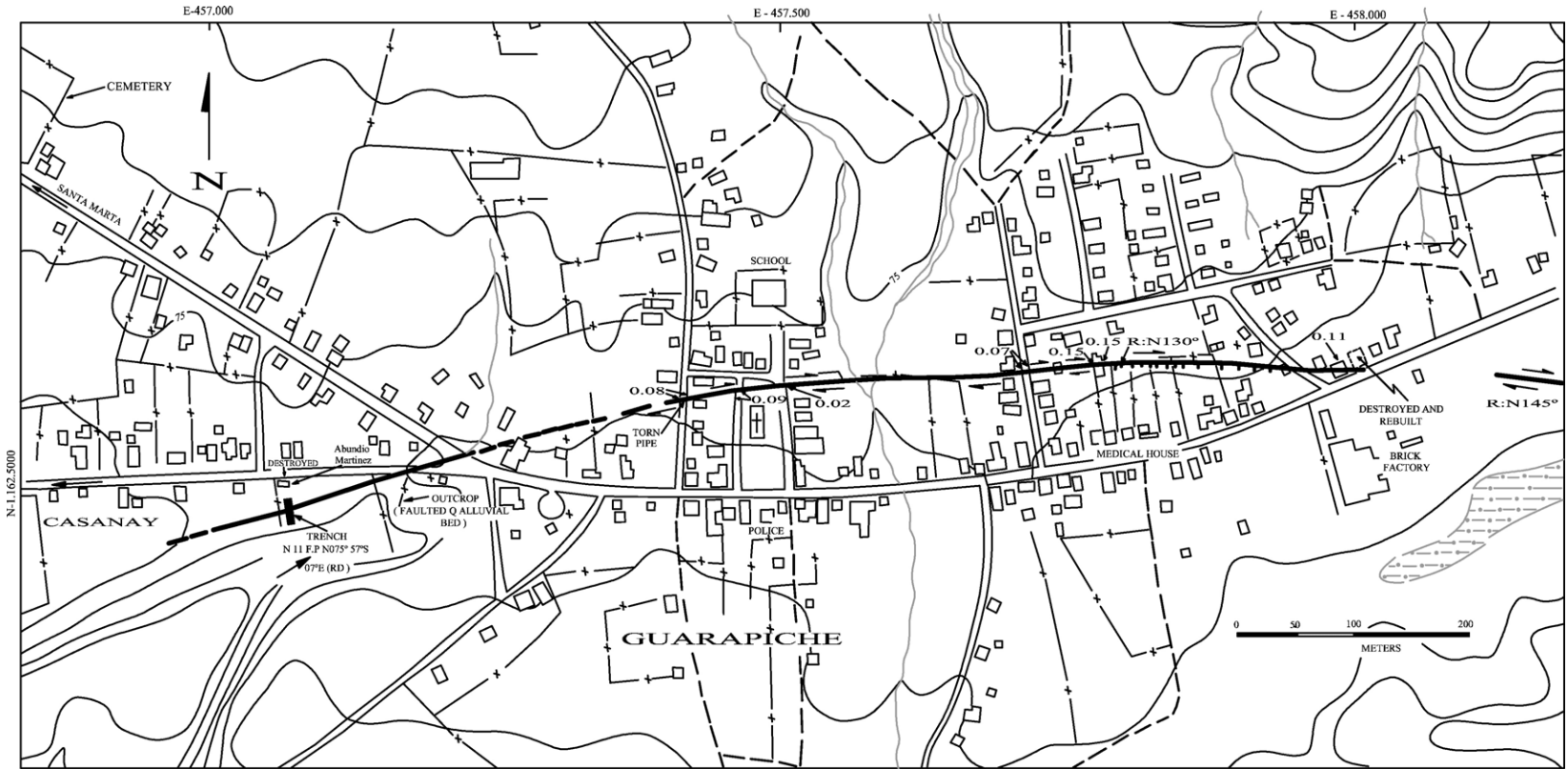


Fig. 12. Eastern rupture across Guarapiche, where maximum coseismic slip of 20 cm was measured. Notice smooth long-radius bend of rupture trace when crossing the urban area.

along the western one (Audemard, 1999a). This is in relation with the amount of coseismic slip, to be discussed next.

### 5.3. Slip distribution along eastern rupture

Distribution of coseismic slip along the eastern surface break went from zero at both ends – Casanay on the west and the cemetery of Río Casanay on the east – to a maximum value in the middle of 20 cm, at Guarapiche (Audemard, 1999a; Figs. 1 and 12). As for the western rupture, no vertical throws were detectable with the naked eye, with rare exceptions. For instance, in Mr. Abundio Martínez' property, where a trench was excavated in 1998, striations could be observed on the fault plane that slipped during the Cariaco 1997 earthquake. A 7°E striation pitch was measured on a fault plane whose attitude is 075°N 57°S (Audemard, 1999a; Fig. 13). This striation pitch implies that slip had a significant right-lateral component, which was accompanied by very minor north thrusting. This subordinate vertical component supports the vertical growth of the Guarapiche Hill.

Configuration of the 1997 rupture traces spotted at both ends of the Guarapiche Hill, combined with the



Fig. 13. Striations on surface of fault plane, on the eastern rupture, where bounding the Guarapiche Hill at its northeastern end, within Martínez' property (measuring point indicated by solid box, named trench, in Fig. 12). Although being located at a transpressive feature, striations (pitch of 7°E) indicate a dominant right-lateral component accompanied by very minor north-thrusting component, which is in agreement with the lack of vertical motion along the surface rupture during the Cariaco 1997 earthquake.

striation observed on fault plane in trench, definitely attest to the pop-up character of left-lateral steps within the right-lateral El Pilar fault zone (Fig. 2).

## 6. Discussion and interpretation

Consistency and persistency of the small scale structures along the entire length of the surface break, comprising a narrow (less than 5 m wide) system of en echelon Riedel (R) shears (e.g., Fig. 3), attest that the rupture is a single feature, despite the structural complexity the trace may occasionally display. The set of geological and structural observations gathered along the surface rupture of the Cariaco 1997 earthquake is conclusive evidence that the overall sense of motion on the El Pilar fault is right-lateral with no visible vertical component. Likewise, it can be stated that trace complexity of the surface rupture between Casanay and Río Casanay fully reflects the structural complexity of the El Pilar fault active trace(s), previously described by FUNVISIS (1994) and Beltrán et al. (1996), where the fault shows several subparallel or braided strands.

The total rupture length mapped as 37 km long does not correspond to the total length of surface break because the surface mapping started at the Villa Frontado seashore, where 23 cm of coseismic slip were measured. This value is the mean coseismic slip value for a large portion of the western rupture (for 20 km between Muelle de Cariaco and Carrizal de La Cruz; Fig. 8). Therefore, it is very reasonable that part of the ground rupture is underwater, west of Muelle de Cariaco and in the Cariaco Gulf shelf. Audemard (1999a) proposed that the surface rupture should extend at least some 15 km farther west, as far as San Antonio del Golfo, which would account for the considerable damage observed in both Chiguana and San Antonio del Golfo. This interpretation seems to be confirmed by the spatial distribution of the very shallow (<3–4 km deep) aftershocks of the Cariaco 1997 earthquake reported by several authors (Romero et al., 1998; Baumbach et al., 2004). The eastward extension of the surface faulting again coincides well with the epicenter distribution of the very shallow aftershocks at this rupture end. No very shallow aftershocks east of 63.25°W are reported by Baumbach et al. (2004) in their Fig. 11. Instead, aftershocks east of 63.25°W get progressively deeper, thus defining the shape of the eastern tip of the damage zone at depth, but precluding the occurrence of surface faulting at the town of El Pilar as claimed by Pérez (1998a,b). Therefore, total length of the coseismic surface faulting is 55–60 km at most (including the underwater portion), but total fault plane breakage at

depth could be as long as 80 km, as claimed by Pérez (1998a), and at least 60 km according to Baumbach et al. (2004). Taking into account the Cariaco 1997 earthquake depth of 10 km, this event has a total area of fault plane rupture on the order of 550–800 km<sup>2</sup>. The lower bound relies on the likely minimum total area of rupture, imposed by length of total surface faulting (55 km long) and depth of the main shock (10 km deep); whereas the upper bound is based on the fact that the deepest (about 10 km deep) aftershocks extend over some 80 km in length, between Marigüitar and El Pilar (Romero et al., 1998; Baumbach et al., 2004). This size of rupture area is in good agreement with other Ms 6.8 earthquakes, based on the empirical relationship proposed by Utsu and Seki (1954) and applied by Funvisis for Seismic Hazard Assessments in Venezuela (Audemard and Singer, 1996). The discussion above suggests that surface faulting does not necessarily coincide with the total length of the rupture area at depth that generates the main shock, as defined by the entire aftershock distribution during the healing process. For simplification, a rupture area is generally modeled as a simple geometric shape (e.g.: a rectangle), but it would be more realistic if a rupture area could be modeled as an ellipse or as the actual shape defined by aftershocks.

Observed slip distributions at the surface through time (Fig. 8) are as follows. Except for the rupture trace portion displaying the maximum coseismic slip (slightly west of Pantoño), the surface rupture exhibits a coseismic slip with a modal value of about 25 cm, which is fairly uniform along the western rupture. East of Pantoño, this value is similar if slips on both overlapping rupture portions are added. Moreover, this mean value is comparable to the total 20 cm “far-field” slip derived by Drewes et al. (2000; in Baumbach et al., 2004) from repeated GPS measurements performed across the El Pilar fault before and after the Cariaco earthquake (1996 and September 1997, respectively). The location along the rupture trace of the maximum coseismic slip matches rather well with the main shock epicenter of July 09, 1997, that is a few kilometers NW of Pantoño (compare Figs. 1 and 8). Coseismic slip very quickly attenuates to the east of the maximum slip at Pantoño. This contrasts with how constant it is to the west, implying that rupture propagation was strongly asymmetric as propagation was bidirectional. In this regard, locals near Pantoño, where maximum dextral coseismic slip was observed, described clearly and very precisely how ground cracks progressed from east to west, implying that earthquake nucleation should have occurred a few kilometers east of its present epicenter location (Audemard, 1999a). The observed maximum

coseismic slip is about half of what empirical relationships (Audemard and Singer, 1996) predict (0.8 to 1.0 m) for a Ms 6.8 earthquake on a strike–slip fault. Such an amount of slip (in the order of  $1.10 \pm 0.15$  m) across the El Pilar fault has been derived by Pérez et al. (2001) from repeated GPS measurements carried out in May 1994 and 1999, implying a large amount of after-slip. The meaning of the open cracks at Terranova, whose opening is of this order, remains unclear, but it may be related to some kind of mass instability since they stand on a trench on top of a small hill. After-slip in the epicentral region is significant, with a value similar in magnitude to that of the coseismic slip. In addition, total (coseismic + after) slip is shifted to the east (nearing Casanay) with respect to the maximum coseismic slip (slightly west of Pantoño).

The restraining bend of Casanay–Guarapiche on the El Pilar fault, whose most outstanding expression is the Guarapiche Hill pop-up, may be held responsible for both the epicentral location of the Cariaco 1997 Ms 6.8 earthquake and its highly asymmetric bidirectionality (Audemard, 1999a). In addition, the structural pattern of the 1997 surface faulting between Casanay and Guarapiche reveals this compressive behaviour (Fig. 2). This double bend with long oblique portion along the El Pilar fault, which opposes against the dextral slip of the fault, is an ideal place for stress build-up and for acting as a geometric barrier to fault propagation (Audemard and Singer, 1996). This place with increasing stress build-up may become the locus of a later large earthquake, as proposed by Crone and Haller (1991). Additional arguments in favor of this geometric barrier as the locus of the 1997 event are supported by studies of the Cariaco 1997 aftershock sequence. Baumbach et al. (2004) indicate that Casanay itself is located in an aftershock gap, which suggests that rupture nucleated there, and epicenter should actually be east of its present determination. This would also be in agreement with Pantoño-surrounds locals’ accounts of rupturing progressing westward, reported by Audemard (1999a). The western and eastern ruptures happened on different fault planes that are dipping in opposite direction, as revealed by the depth distribution of the aftershock sequence. Baumbach et al. (2004) determined that the westernmost portion of the rupture exhibits a steep north dip, the central portion is almost vertical and the eastern portion (corresponding exactly to the eastern rupture herein described) dips steeply south. Therefore, the rupture plane looks like a huge propeller, the hub being where coseismic slip was largest (Pantoño–Casanay). This subsurface shape corresponds with a sharp change of structural style along the El Pilar fault at surface, which

may not facilitate rupture propagation. That is to say, earthquake nucleation happened at or near the restraining bend and rupture quickly propagated westward, allowing only a small part of it to progress east, beyond the bend (Audemard, 1999a). The westward progression of the rupture process was confirmed by the results of the finite-fault waveform inversion applied by Mendoza (2000) to the broadband teleseismic P waves recorded for the Cariaco 1997 earthquake.

Furthermore, the seismological data recorded by the RESICA – temporary Cariaco 1997 Seismological Network – group brings new insight on the deep structure of the fault. Both the main shock and aftershocks along the western rupture section are located north of the fault trace, defining a fault plane that dips between 60°N and 75°N (Romero et al., 1998), which is in good agreement with focal mechanism solutions proposed by Berkeley (79°N; UCB moment tensor solution), Harvard (62°N; CMT solution), GFZ Potsdam (nearing 80°N; Maternovskaya and Nettles' CMT solution) and ERI (78°N; AutoCMT solution). Audemard and Romero (in Audemard et al., 2005) have determined an additional focal mechanism for this main event by using only local p-wave polarities recorded by the Venezuelan permanent seismological network (RESVAC), obtaining a nodal plane whose strike is east–west and dips 75°N (Fig. 1). An important issue needs to be highlighted as to these focal mechanism solutions: the north dip of one of the nodal planes forces all these solutions to seem to have a subordinate normal component to the dominant strike–slip motion. In fact, this is completely an artifact for this event because the surface rupture did not exhibit any vertical component at all, as indicated by many authors (FUNVISIS et al., 1997; Pérez, 1998a; Audemard, 1999a; among others). Therefore, if proposed focal mechanisms for this event are to comply with the actual steep-to-the-north fault dip, the normal component in the solutions is simply apparent and does not actually exist. It is usually assumed that wrench faults are almost vertical, which is not the case for the El Pilar fault. This issue needs further study because implications and later interpretations of such solutions may become very misleading. Nonetheless, deep structure of the El Pilar fault, determined from both the location of the main shock hypocenter and the spatial distribution of its hundreds of located aftershocks along the 1997 earthquake rupture, reveals its high degree of structural inheritance: this young active tectonic feature reactivates dextral wrenching along an old high-dip angle thrust fault of the previous subduction and collision stages.

From the seismic history viewpoint, this Cariaco 1997 event seems to belong to a seismic sequence because it re-broke the contiguous segment to the east of that broken by the January 17, 1929 earthquake. At that time, the El Pilar fault ruptured between the Caigüire Hills (south of Cumaná) and San Antonio del Golfo, some 30 km east of Cumaná (Mocquet et al., 1996). Only 4 km close to the western tip of the rupture were expressed onshore, east of Cumaná and northeast of the Caigüire Hills (Paige, 1930). The rest of the rupture was underwater in the Cariaco Gulf. The 1929 and 1997 ruptures together seem to complete the total length of a rather continuous and linear section of the El Pilar fault, extending between two large restraining geometric barriers (restraining stepover of the Caigüire Hills and the transpressive double bend of Casanay–Guarapiche; Audemard, 1999b). During the Cariaco 1997 earthquake, the Guarapiche restraining bend functioned as a leaky boundary or barrier (as defined by Crone and Haller, 1991), because it failed to fully stop rupture propagation to the east. The linearity of the El Pilar fault trace between Cumaná and Casanay allowed to postulate it as a persistent seismogenic segment (FUNVISIS, 1994; Beltrán et al., 1996). However, the seismic activity of this 20th century (1929 and 1997 events) and the actual behavior of the Casanay–Guarapiche double bend during the 1997 event proved otherwise, at least during this current seismic cycle.

## 7. Conclusions

The Cariaco 1997 earthquake had surface rupturing along a major portion of the onshore section of the dextral El Pilar fault, west of El Pilar. A very conspicuous and continuous 075°N-striking surface break was mapped eastward from Villa Frontado to Las Varas (slightly east of Casanay) for some 30 km. This western rupture portion was rather straight. It exhibited only a 400-m-wide releasing stepover as major geometric complexity, located slightly west of Terranova, where large (up to 88 cm wide) open cracks formed by local transtension. The entire western rupture was generally <3- to 4-m-wide and is basically expressed by an echelon, 90°N to 100°N trending right-lateral R shears, sometimes connected by mounds at restraining overlaps and occasionally associated with tension gashes. Most of the rupture between Villa Frontado and Carrizal de La Cruz exhibited a rather constant, purely-dextral coseismic slip of about 25 cm. Coseismic slip reached its maximum value of 40 cm slightly northwest of Pantoño (3 km west of Casanay); then it abruptly decreased eastward to 25 cm – just west

of Casanay (by 6 months later, slip here had increased to 60 cm), to 14 cm – within Casanay, and to 8 cm – between Casanay and Las Varas; all in about 5 km along the fault trace. This fault rupture extends offshore west of Villa Frontado for some 15 km, up to San Antonio del Golfo; as confirmed by the very shallow aftershock distribution.

Within Casanay, another ground rupture (eastern rupture) branched off northeastward, extending east up to Río Casanay, for some 10 km. This discontinuous rupture shows an overall convex-to-the-north boomerang shape. Its maximum measured coseismic slip is 20 cm at Guarapiche (close to the middle of this eastern rupture). Its coseismic slip died out at both ends, located at Casanay on the west and Río Casanay on the east.

Structures observed at various scales confirm the pure right-lateral character of the El Pilar fault, although aftershock activity clearly defined the steep north dip of the fault plane along the main continuous rupture. The overall geometry of the surface rupture matched well with the general fault trace previously mapped by Metz (1968) and FUNVISIS (1994), which is characterized by a large restraining double bend between Casanay and Guarapiche. From many locals' accounts, the rupture seemed to have propagated basically from Pantoño to the west (highly asymmetric bidirectionality), which could account for the quick attenuation of coseismic slip from Pantoño to the east. This all suggests that earthquake nucleation happened at or near the Casanay–Guarapiche restraining double bend. Rupture quickly propagated westward, and only a small part of it progressed east beyond the bend. The repeat of this seismic behavior would account for the linearity of the fault trace west of Casanay, as well as its complexity east of the restraining bend where the El Pilar fault comprises several subparallel active strands. Moreover, the large fraction of released after-slip is mainly due to the presence of such restraining bend, which seems to have partly locked slip during rupture.

Based on both the relative location of the main shock hypocenter and the space distribution of its hundreds of located aftershocks along the 1997 earthquake rupture, the deep structure of the current right-lateral strike-slip El Pilar fault reveals its high degree of structural inheritance: it reutilizes old high-dip angle thrust faults of the previous subduction and collision stages of the southern Caribbean geodynamic evolution.

The linear portion of the El Pilar fault bounded by two large so-called geometric barriers located at Cumaná on the west and Casanay–Guarapiche on the east, had been postulated as a seismogenic segment based only on geometric criteria. Two facts have proved

otherwise. The total length of this proposed segment has been broken by the combination of the Cariaco 1997 earthquake with the Cumaná 1929 earthquake. In addition, the Cariaco 1997 has leaked through the Casanay–Guarapiche double bend, at least during this current seismic cycle.

## Acknowledgements

Above all, I would like to acknowledge the neighbours of the struck region, for whom the rupture was known as “la raja” (the tear) because this field reconnaissance would not have been possible without their invaluable help. Our thanks also go to the Venezuelan Oil Industry that provided us with one of their hired choppers for 2 consecutive days to carry out a preliminary airborne reconnaissance. My appreciation also is for the Seismological Center of Universidad de Oriente and the Public Works Direction of the state of Sucre, particularly to Jermis Garcia from the latter institution for driving us around during the emergency. In Funvisis, I am grateful to the following colleagues who shared part of the fieldwork: Luis Acosta, Feliciano De Santis, Rogelio González and Michael Schmitz; for long and live discussions, to: André Singer, Gloria Romero, José Antonio Rodríguez and Herbert Rendón. I want to thank as well all those who enriched this paper by exchanging impressions during several author's lectures given at: the USGS – Golden, during the Cariaco 1997 Special Session at the 1999 AGU Spring Meeting and at different French institutions or universities (BRGM – Orleans, ISTEEM – Montpellier II, Geosciences Azur – Nice, IGP – Paris VI, LGCA/CISM – Savoie and Seismology Laboratory – Strasbourg). Drafting is Marina Peña's effort for which I am most grateful. Last but far from least, this contribution has been greatly improved from comments and suggestions from six reviewers: Jordan Muller of Stanford University, Robert Speed(†) of Northwestern University, Dr Thybo – Editor of *Tectonophysics*, Dr John Weber of Grand Valley State University and two other colleagues who preferred to remain anonymous.

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