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ORIGINAL ARTICLE

Revised seismic history of the El Pilar fault, Northeastern Venezuela, from the Cariaco 1997 earthquake and recent preliminary paleoseismic results

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Abstract In light of the July 9, 1997, Cariaco earthquake, it is clearly understood now that damage in the city of Cumaná – located in northeastern Venezuela and frequently destroyed by the largest earthquakes since the first recorded event in 1530 – is strongly enhanced by poor soil conditions that, in turn, are responsible for site amplification and widespread earthquake-induced effects. Therefore, most previous macroseismic studies of historical earthquakes must be revaluated because those localized high-intensity values at Cumaná surely led to the misestimation of past epicenters. Preliminary paleoseismic results, gathered at three exploratory trenches dug across the surface break of the Cariaco 1997 earthquake in 1998, allow us to associate the 1684 earthquake with this recently ruptured fault segment that extends between the towns of San Antonio del Golfo and Río Casanay (roughly between the two gulfs of Cariaco and Paria, state of Sucre). Other major results from the reassessment of the seismic history of this fault are: (a) the 1766 event seems to have generated in a different source to the El Pilar fault because the size of the felt area suggests that it is an intermediate-depth earthquake; (b) damage to Cumaná produced by the 1797 event suggests that this was a local earthquake, perhaps equivalent to the 1929 earthquake, which ruptured for some 30 km just east of Cumaná into the Gulf of Cariaco; and (c) seismogenic association of the 1530 and 1853 earthquakes still remains unclear but it is very likely that these ruptures occurred offshore, as suggested by the rather large tsunami waves that both events have generated, placing their hypocenters west of Cumaná in the Cariaco Trough. This reassessment also sheds light into the El Pilar fault segmentation and the behavior of its seismogenic barriers through time.

Keywords Historical seismicity · Paleoseismology · Recurrence · Segmentation · El Pilar fault · Caribbean

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1 Introduction

This paper intends to revise the past – historical and instrumental – seismicity of the larger events that occurred in eastern Venezuela that are – or were somehow – correlated to the El Pilar fault in the light of an integrated approach that combines historical, macroseismic, instrumental, and paleoseismic data, taking into account the bias introduced by the particular soil conditions of the Cumaná city subsoil. From this, a new time–space distribution of – both historical and instrumental – earthquakes larger than Ms 6 along the El Pilar fault is herein presented, which brings significant insights on the fault segmentation and on the behavior of the seismogenic barriers through time. The historical investigations carried out during this research rested on the original historical accounts – all in old Spanish – mostly gathered in Centeno-Graü (1940) and Gómez (1990), and more recently complemented by Grases et al. (1999). Instead, most of the published macroseismic maps are from Grases (1990), but several of them unfortunately are only available in technical or in-house reports.

2 Historical seismicity in eastern Venezuela

Northeastern Venezuela at present is the most seismically active area nationwide, as documented by the instrumental seismicity catalog of Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS) for the period 1910–2003 (refer to Fig. 4 in Audemard et al. 2005). In historical times, the seismic activity was not much different, as indicated by historical reports on damage in this region by earthquakes and tsunamis from the dawn of the Spanish conquest (Centeno-Graü 1940; Gómez 1990; Grases 1990; Grases et al. 1999). Such colonization started at the beginning of the sixteenth century with Nueva Toledo in 1515, today known as Cumaná—the oldest Spanish settlement on continental America. In fact, this city has been repeatedly destroyed to some extent during historical earthquakes, such as in 1530, 1629, 1684, 1766, 1797, and 1853, as well as during two events in the twentieth century (in 1929 and 1997).

All these events have been related by different authors to the El Pilar fault, which is considered to be the second major seismic source in eastern Venezuela after the southern end of the NW-dipping slab of the Lesser Antilles subduction zone that lies under Trinidad and partly under the Paria Gulf and Peninsula (Fig. 1). The El Pilar fault, along with the right-lateral strike-slip Boconó and San Sebastián faults, appears to accommodate a large fraction of the dextral transcurrent motion (Fig. 1; Molnar and Sykes 1969; Minster and Jordan 1978; Pérez and Aggarwal 1981; Stephan 1982; Aggarwal 1983; Schubert 1984; Soulas 1986; Beltrán and Giraldo 1989; Speed et al. 1991; Singer and Audemard 1997; Pérez et al. 2001; Weber et al. 2001; Audemard and Audemard 2002; Audemard et al. 2005; Audemard 2006; among many others) within the over 100-km-wide transpressional plate-boundary zone between the

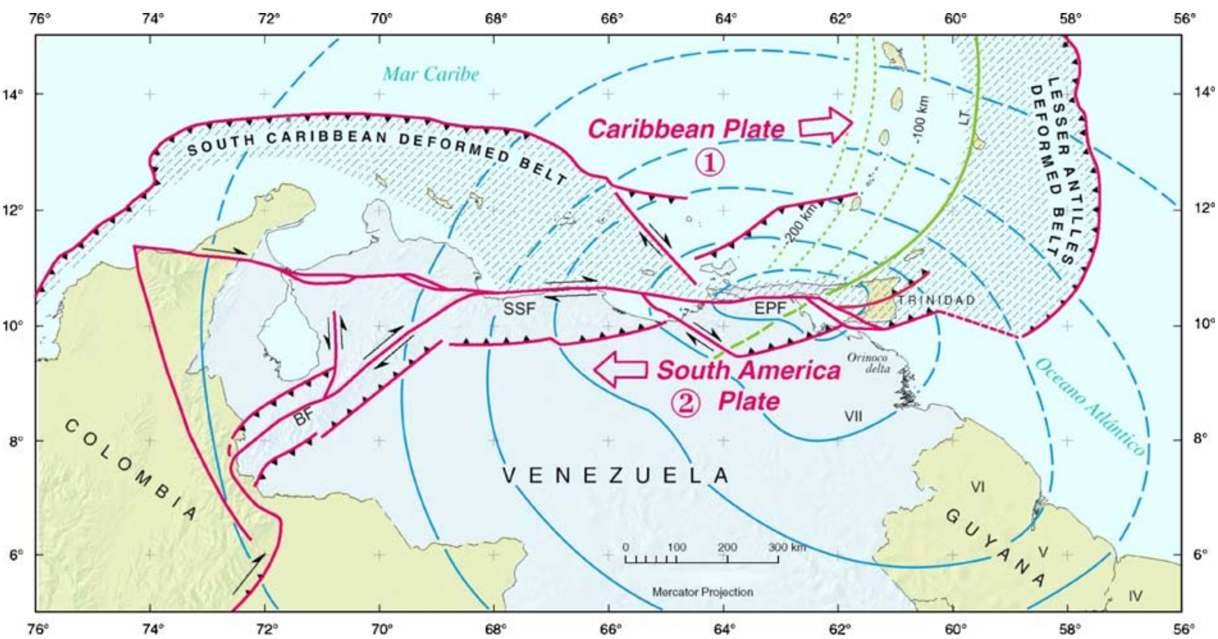

Fig. 1 Simplified geodynamic setting of the southern Caribbean region (after Audemard et al. 2000). The figure also shows the larger-intensity isoseismals for the 1766 earthquake (after Grases 1990). The general structure of the Lesser Antilles subduction slab is also depicted: Isodepth lines of that slab are from Gudmundsson and Sambridge (1998) and the lithospheric trace (*LT*) of the subduction plate boundary between the Caribbean and South America plates is from VanDecar et al. (2003). Abbreviations for the major strike-slip faults are as follows: *BF* Boconó fault, *SSF* San Sebastián fault, and *EPF* El Pilar fault

Caribbean and South America. It is worth mentioning that the active fault trace of the El Pilar fault to which this paper refers corresponds to the fault mapped by Beltrán et al. (1996). This mapping is more easily accessible from Audemard et al. (2000; Fig. 2). All the previously published seismogenic associations of historical destructive earthquakes in eastern Venezuela with the El Pilar fault, except for those of the twentieth century, do not rely on geological corroboration. Moreover, each of these events has been associated with a particular segment of the fault only based on intensity maps. These associations have not always satisfied all documented aspects of the events themselves, as discussed later in this paper.

3 Earthquake-related damage in Cumaná

The comparative analysis of damage from all these earthquakes shows a common factor. The city of Cumaná has always been severely affected, which results from geologic site conditions of a city sited on a thick sequence of Holocene alluvial/delta plain deposited by the Manzanares River (e.g., Beltrán and Rodríguez 1995; González et al. 2004). Damage is mostly due to the repeated occurrence of induced effects, such as liquefaction and lateral spread phenomena, during most known earthquakes (refer to Table 1). Besides this, large areas of the Cumaná subsurface are characterized by long predominant periods and high amplification ratios, as deduced from microtremor analyses (Nakamura method) performed by Abeki et al. (1998). This implies that sediment sequence in those areas of the Cumaná alluvial plain is poorly consolidated. Poor ground response to shaking has been increased because the development of this seashore city has required that most of the active saltflats and floodplains under mean sea level had to be artificially filled to reclaim land to the sea during the last 40 years, as directly witnessed by the author in the 1960s and 1970s. Reclaimed land areas such as this have been proven to behave unsatisfactorily during large earthquakes, as evidenced in the Marina Bay District in San Francisco;

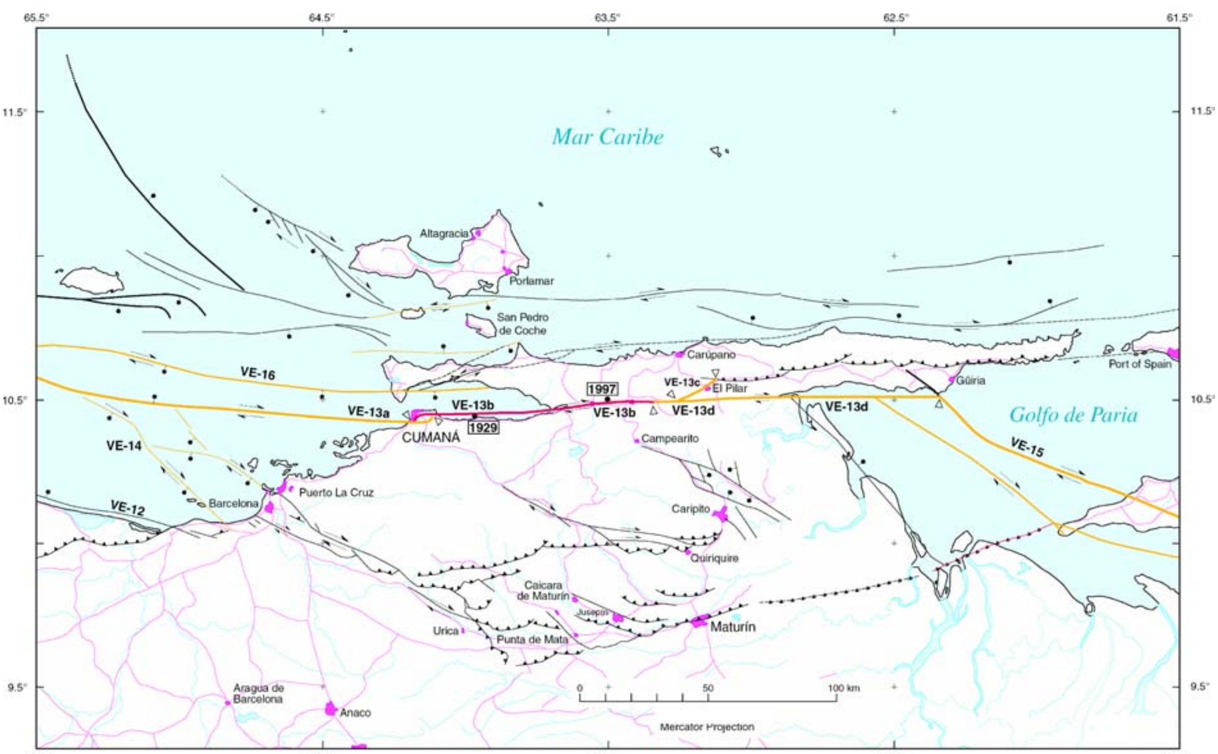

Fig. 2 Quaternary fault map of northeastern Venezuela (after Audemard et al. 2000). *VE-13* identifies the El Pilar fault and the suffixes (*a* through *d*) label the different individual fault portions or segments. Epicenters of the 1929 and 1997 earthquakes are shown as *solid circles*

Table 1 Major destructive earthquakes in eastern Venezuela for the period 1530–1997

Date	Local time	Location (maximum MM intensity)	Associated natural effects	Other relevant observations	Interpretations
September 1, 1530	1000	Nueva Toledo (X) (today known as Cumaná)	Tsunami waves at the Manzanares River mouth (north part of the old city) higher than treetops, which flooded inland as far as the ranges (Caigüire Hills?)	At the Manzanares delta, complete destruction of wooden fort built by Jácome Castellón	Tsunami waves on Cumaná's north coast, as high as 5–7 m, drowned many inhabitants
			Cracks in the lowlands and ranges of Cumaná, where dark-colored salty water sprang, with sulfur smell	Many Indian dwellings collapsed	Clear evidence of soil liquefaction associated with lateral spread
			Range at the south of Gulf of Cariaco was split into two	Many deaths, most of them drowned Seismic aftershocks	Possible hillslope slides
May 4, 1684	2000	Cumaná (VIII) Araya (VIII)	Ground cracks	Area also struck by hurricane	Soil liquefaction
			In Cumaná and Araya, venting of dark-colored sand and water, with sulfur smell	Severe damage in Cumaná to several houses, the fortresses of San Antonio de la Eminencia and Santa María de la Cabeza, and the Santo Domingo monastery. In Araya, damage to the fortress, church, and jail Aftershocks felt for more than 20 days	
October 21, 1766	0445	S.J. Oruña (IX) Guayria (IX) Monserrate (IX) Sabana Grande (IX) (all on Trinidad Island)	Flames were observed in the vicinity of the Gulf of Cariaco	Earthquake-felt area of more than 4×10^6 km^2 (the most extensive earthquake ever felt in Venezuelan history)	Based on the area where the seismic event was felt, hypocenter should be located in the Gulf of Paria and at an intermediate depth (60–200 km deep).
			Ground cracks near Monte Parauri (not found on maps), and along the Orinoco riverbanks	No tsunami reported	The absence of a tsunami suggests that sea bottom was not deformed (subduction event whose sea-bottom rupture, if any, should have been SE off Trinidad with polarity toward open sea)
			Uplift of the Guarapiche riverbed (at the junction with the San Juan river)	No casualties reported	
				Seismic aftershocks felt for over 14 months	
December 14, 1797	1830	Cumaná (IX)	Half and hour before earthquake, sulfur smell felt in the nearby hill to the San Francisco monastery (Cumaná)	Damage in Cumaná to the church and monastery of San Francisco, also to the new churches of la Pastora (8 deaths) and Santo Domingo	Soil liquefaction
			Flames were observed along the Manzanares River banks, at Marigüitar, and in the	Severe damage to the Carúpano's church of Santa Rosa	A foreshock happened the same day

Table 1 (continued)

Date	Local time	Location (maximum MM intensity)	Associated natural effects	Other relevant observations	Interpretations
			vicinities of Hospicio de Los Capuchinos (Cumaná)		
			A minor event reported the same day	Less than 12 deaths in Cumaná	Taking into account the distribution of soil liquefaction and that people felt the P wave (vertical motion) and heard the earthquake coming from the SE all suggests that this earthquake occurred slightly east of Cumaná
			People reported feeling vertical before horizontal motion	Aftershocks for several days	
July 16, 1853	1400	Cumaná (IX)	Sea flooded lowlands of the El Salado and Caigüire (in Cumaná) up to 200 yards inland (4–6-m-high tsunami)	Severe damage in Cumaná to the San Antonio de la Eminencia fortress, the churches of Santa Inés, del Carmen, de la Trinidad, and Altagracia, and a fortified house	High tsunami waves, widespread severe damage to houses, up to collapse. High numbers of casualties
			Several N–S-oriented ground cracks	More than one thousand deaths, most of them soldiers living in the castle	Soil liquefaction
			Water springs along seashore and Manzanares riverbanks	113 civil deaths	Lateral spread
			At El Dique, in Cumaná, a coconut-palm grove sunk (slid?)	Aftershocks for more than 15 days	Strong event and/or important vertical component
			Water springs in Cariaco	A 2.5-yard-deep water tank spilled all water out	
August 17, 1874	1030	El Pilar (VIII?)		At the town of El Pilar, severe damage to houses and church	Local seismic event (on either El Pilar or Tunapuy fault?)
				Felt in Margarita and Trinidad. Strongly felt in Guaraúnos and Tunapuy	
January 17, 1929	0730	Cumaná (IX)	4-km-long cracks in the sabanas of Caigüire-El Peñón (due east of Cumaná)	Damaged buildings in Cumaná: the church which was under construction, a spinster, La Industrial Manzanares, the jail, the Sucre museum, the Theater, the Hall of Justice and the fortress of San Antonio	First nationwide survey on a coseismic rupture
			Over 20 km in length along southern seashore of the Cariaco Gulf, riverbanks showed parallel cracks. Some rockslides also reported	Aftershocks felt for several days	Lateral spread and slope instability
			Venting of dark-colored	More than 200 casualties	Clear evidence of soil

Table 1 (continued)

Date	Local time	Location (maximum MM intensity)	Associated natural effects	Other relevant observations	Interpretations
			water with sulfide smell at the banks of the Manzanares River and sabanas of El Salado and Caigüire. Also at Tarabacoa and Pericantar (near Marigüitar)		liquefaction
			Landslides and rockslides on slopes of Cerro San Antonio	Foreshock was felt several months before the main event	
			3-m-high tsunami waves at the western part of Cumaná, near El Salado, and at the sabanas of Caigüire (north of Cumaná). In Chiguana, located at the far east end of the Cariaco Gulf, the sea receded several meters and came back without causing any damage		
October 4, 1957	0126	San Juan de las Galdonas (IX) - *Ms 6.7-*	Landslides and rockslides on the northern watershed of the Paria penin-sula, between Río Caribe and San Juan de Unare	Several wounded people in towns of the northern side of Paria peninsula	Offshore event to the north of Paria peninsula
				Severe damage to coastal towns to the east of Carúpano	
				The church of Santa Rosa de Lima in Carúpano had to be demolished	
June 12, 1974	1226	Casanay (VIII) - *Ms 6. 1; mb 5.7-*	Ground cracks between the towns of Galerón and La Pica; also in the vicinities of balneario Poza Azul, near Pantoño	Toll of 2 deaths and 14 wounded (in Casanay, 1 dead and 10 wounded)	Epicenter (10.563°N, 63.382°W) near the town of Río Casanay, in association with the El Pilar fault
			Cracks at the foot of the Guarapiche hill, within the property of Mr. Abundio Martínez (personal communication, 1998).	Several houses were damaged in Casanay (from 153 damaged houses, damage to 42 was severe), Río Casanay, and nearby towns; also in Cariaco. In Carúpano, some buildings had light structural damage, such as the General hospital, the Santa Catalina church, the City Market, fire station, Marines quarters, airport terminal, and some schools	
June 11, 1986	0948	El Pilar (VII) Guaraúnos (VII) Las Palomas (VII) - *mb 5.9-*	Several ground cracks and landslides were reported	In El Pilar town, about a 100 bahareque houses were damaged; structural damage of a church and an elevated	Epicenter (10.55°N, 62.93°W), between the towns of El Pilar and Yaguaraparo; possibly associated with the

Table 1 (continued)

Date	Local time	Location (maximum MM intensity)	Associated natural effects	Other relevant observations	Interpretations
				water tank were also reported. Structural damage in a cylindrical water tank and some reinforced adobe houses, in the town of Guaraúnos 3 deaths and 45 wounded 0.16 g was recorded at Casanay, with strong motion of 10 s duration	El Pilar fault

The table summarizes the most relevant observations with implications on the relocation of the ruptured portions of the El Pilar fault. This table integrates data from Arcia et al. (1974), FUNVISIS (1994), Gómez (1990), Grases (1979, 1990), and Malaver et al. (1988)

Kobe harbor facilities; and Izmit naval base, marina, and harbor areas during the Loma Prieta 1989, Hyogoken-Nanbu 1995, and Kocaeli 1999 earthquakes, respectively.

As to the historical information regarding earthquake and damage descriptions, it is also very likely that profusion of damage reports in Cumaná before the twentieth century (sixteenth through nineteenth centuries) may reflect the city's political and economic relevance because it was the province capital at that time (Rodríguez and Audemard 2003). In the same way, these authors stress that the unequal distribution of historical accounts over northeastern Venezuela was also enhanced by an uneven regional demographic density and/or by population isolation (neighboring settlements poorly linked with – or completely isolated from – the province capital), strongly conditioned by orographic factors that definitely hindered population spreading and settlement (read also Christianization) during colonial times. Northeastern Venezuela has a rough topography that still impedes its socioeconomic development at present. Equally important may be the unequal historic document preservation in the different churches of the region. The Cariaco 1997 earthquake finally discloses this hidden fragility of Cumaná to earthquakes. In fact, the Cumaná seashore underwent several landslides triggered by this event located 70 km to the east, whereas many small seashore towns and villages along the southern Cariaco Gulf suffered relatively much less, though they were closer to the epicenter (refer to González et al. 2004). An additional argument supporting this hypothesis is that instrumentally recorded events in eastern Venezuela in the last 25 years, which were also macroseismically evaluated (damage report by localities), indirectly revealed the unfavorable site response to shaking in Cumaná through their isoseismal maps: Cumaná exhibits a higher degree of damage compared to neighboring towns attested by the pull of higher-intensity isoseismals towards Cumaná. For instance, the intensity map in MMI scale for the El Pilar 1986 earthquake (Malaver et al. 1988; Fig. 3) illustrates this effect. Bearing this in mind, the isoseismal map for the Cariaco 1997 earthquake was drawn discarding local effects (González et al. 2004), as clearly stated by FUNVISIS (1997, p 27), to more accurately reflect the seismic attenuation with distance and regional earthquake intensities.

4 Reassessment of major historical earthquakes

From the above discussion, it is obvious that geologic site characteristics have magnified damage in Cumaná during the most recent events. It seems reasonable to believe that this has also happened during earlier historical earthquakes. This – jointly with the historical social importance of the city of Cumaná – may have induced epicenters of historical events to shift towards Cumaná, and even to be ascribed to the city itself or nearby, such as for the 1853 earthquake (Fig. 3). Consequently, I believe that macroseismic epicenter determinations for those historic events are

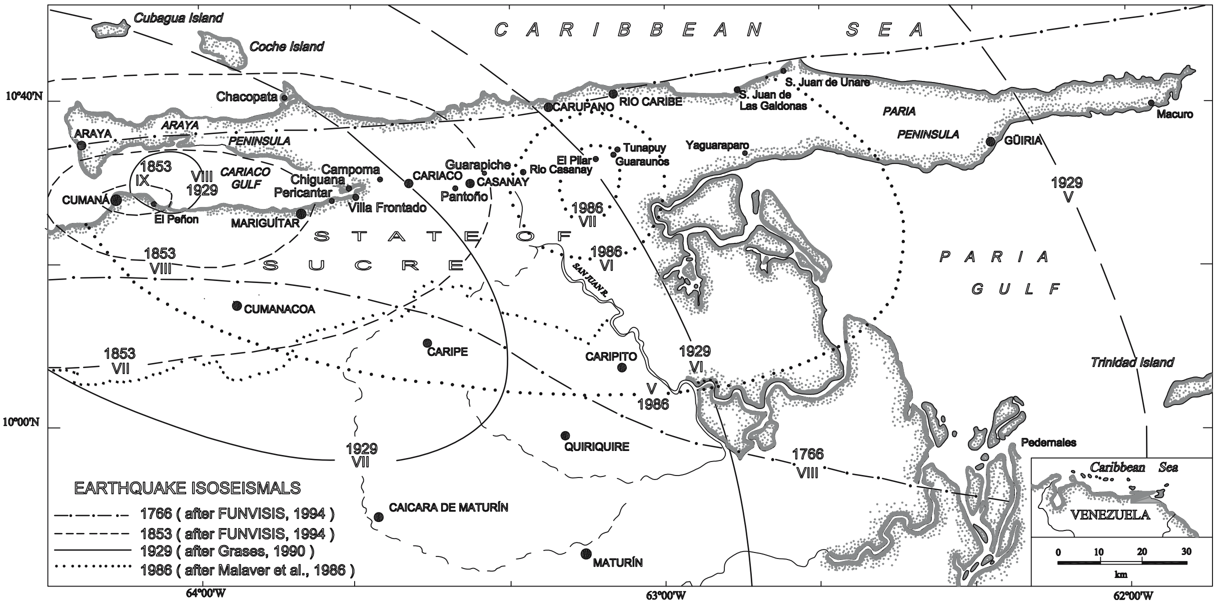

Fig. 3 Intensity maps in the meizoseismal area of a few earthquakes that occurred in eastern Venezuela, showing how damage in Cumaná during individual earthquakes controls the shape of isoseismals, even for the intermediate-depth 1766 earthquake, whose epicenter is in the Paria Gulf near the western coast of Trinidad (*right edge* of the figure). Intensity maps of the 1766 and 1853 earthquakes are after FUNVISIS (1994), 1929 after Grases (1990), and 1986 after Malaver et al. (1988)

in need of revaluation and should take into account the magnification effect in Cumaná introduced by: (1) site effects (soil shaking amplification because of soft soils in the lowland areas and topographic effect for buildings – such as the Spanish fortress San Antonio de la Eminencia – built on top of the Caigüire hills), (2) seismically induced effects in young unconsolidated saturated alluvial sediments (soil-liquefaction and lateral spreading), and (3) the sociopolitical significance of Cumaná throughout its history – as the capital of the Nueva Andalucia province – in a region of uneven population distribution. Figure 3 shows intensity maps for the meizoseismal area of several earthquakes (two earlier historical events and two moderate ones of the twentieth century), where this effect is clearly evident. Besides, reassessment of some historical destructive earthquakes in northeastern Venezuela, except for those of the twentieth century, is needed because of other facts available in historic documents, which have been summarized in Table 1. Instead, the epicenters of the Cumaná 1929 (Paige 1930) and Cariaco 1997 (Audemard 1997, 1999, 2006; Baumbach et al. 2004) earthquakes are well located because of association with reported surface rupturing.

Cumaná has had liquefaction effects from all large earthquakes but the 1766 event, though this is the largest earthquake felt in northeastern Venezuela, and probably nationwide, based on the size of the felt area. The occurrence of this process allows inferring that the intensity in Cumaná during all those earthquakes was at least MM VII and earthquakes were of enough duration (Audemard and De Santis 1991), without giving hints on either the epicentral distance, the location of the earthquake epicenter, or even the earthquake magnitude. Therefore, to assess these key parameters, other indicators or actual observations are needed, as we shall see below for each of the major events recorded in this region that could be or have been attributed to the El Pilar fault.

4.1 September 1, 1530, earthquake

This event – the first reported earthquake of our seismic history that occurred 15 years after the foundation of Cumaná – only damaged Nueva Toledo (prior name of Cumaná) from written reports. Those accounts are scarce in number and poor in damage descriptions because of the prevailing conditions: (a) the settlement was recently founded and lacked any urban structure; (b) on-site document preservation was highly unlikely; and (c) there were few literate people and the population was scarce over the region, and was probably unevenly distributed and isolated as well. Nevertheless, the existing Indian settlement of huts was practically washed away by tsunami waves and most casualties were due to drowning. This description differs from later ones of tsunami waves during other earthquakes as to size and effects on population and constructed environment, with the exception of the 1853 earthquake. Most of the later events produced rather small waves along the Cumaná seashore, no higher than a couple of meters and similar to those of the Cumaná 1929 and Cariaco 1997 earthquakes. This allows the discrimination of its potential source area and it requires that such type of earthquakes had to happen offshore to generate waves as high as treetops (refer to Table 1 for more details). This only leaves a potential source area: the El Pilar fault west of Cumaná along its portion within the deep marine fault-bounded Cariaco Trough (fault VE-13a in Fig. 2). Its maximum intensity (X in Cumaná) is highly conditioned by settlement distribution.

4.2 May 4, 1684, earthquake

This event affected Cumaná and Araya, located on each side of the Cariaco Gulf outlet. However, its macroseismic epicenter could not be determined from known historical accounts. The location of its epicenter will be established in this report based on paleoseismic investigations that were carried out in 1998 across the surface rupture of the Cariaco 1997 earthquake (reported on Fig. 2). This is discussed later in Section 5.

4.3 October 21, 1766, earthquake

This earthquake is very likely the largest event ever felt in eastern Venezuela (Grases 1990). This event has been ascribed to the El Pilar fault by many authors because they neglected key macroseismic information (Suárez and Nábelek 1990; Pérez et al. 1997; Pérez 1998a,b). Among such relevant facts are: (a) this earthquake did not generate liquefaction at Cumaná though intensity there has been estimated at MMI VIII (Figs. 1 and 3); (b) there is no report of tsunami waves or casualties, though it strongly shook Trinidad (intensity IX) and the eastern state of Sucre (Table 1); and (c) its felt area is as large as 4,000,000 km^2, extending almost throughout Venezuela and neighboring regions. Consequently, a preliminary estimate of its magnitude is in the order of Ms 7.5. Consequently, I agree with the epicenter location proposed by Grases (1979), within the Paria Gulf, but not with the depth. I believe this event happened at intermediate depth, in association with the southern end of the Lesser Antilles subduction slab (underneath the Paria Peninsula or Gulf), due to the size of the felt area and the scarce occurrence of reported surface effects, as proposed by Lugo and Giraldo (1989) and also later published by Grases (1990). Further supporting evidence to this interpretation is brought by the close similarities between the intensity map of the September 20, 1968, earthquake and that of the 1766 event; both reported by Grases (1990). Besides being isoseismals for both events elongated in the NW–SE direction, isoseismal spacing shows the same general behavior: they tend to get tighter to the NW, whereas its spacing increases towards the SE. The 1968 event is a 108-km-deep, Ms 7.0 event. Consequently, the 1766 earthquake is not ascribable to the El Pilar fault due to its focal depth.

4.4 December 14, 1797, earthquake

Fiedler (1961, in Grases 1990) located this event at 10.6°N and 64.1°W, coinciding rather well with the macroseismic epicenter location derived from historical accounts proposed here. There are two key observations that locate this event epicenter close to the east of Cumaná (refer to Table 1): (a) noise was heard coming from the SE of Cumaná and (b) locals reported feeling the up-an-down motion related to P waves, which was immediately followed by the S wave shaking (there was a small difference between S and P first arrival times). Besides this, this earthquake is one of those showing the largest intensity in Cumaná (MMI IX), and there is evidence of liquefaction at Marigüitar. Therefore, its epicenter in the southern Cariaco Gulf seems well supported.

4.5 July 16, 1853, earthquake

This earthquake is cataloged as destructive in Cumaná (Fig. 3). Similar to the 1530 event, it generated a tsunami wave that flooded the lowland areas of Caigüire (eastern Cumaná) and El Salado (western Cumaná, near the Manzanares River mouth). Historical accounts reported water spill from elevated tanks, implying that earthquake shaking was strong indeed and/or it produced a strong vertical acceleration. Due to similarities between the 1530 and 1853 earthquakes, it is proposed that both events occurred offshore west of Cumaná, and were generated by the rupturing of the submarine El Pilar fault segment bounding the Cariaco Trough to the south (VE-13a in Fig. 2). If this interpretation happens to be correct, a very rough and preliminary estimate of the return period along this underwater segment would be of the order of 300–320 years. Earthquake magnitudes are unknown, but they are very likely over Ms 7. In that sense, their magnitude can be estimated from the length of the longest axis of the VIII isoseismal line. Depending on the macroseismic interpretation used for the calculation, that of FUNVISIS (1994) or Grases (1990), its magnitude is in the range between 7.1 and 7.3, based on a lengths of 65 or 90 km along the major axis, respectively. However, the application of tsunami inversion techniques should provide a more accurate magnitude estimate for any of these two events, taking into consideration the particular local conditions: (a) earthquakes take place on a right-lateral strike-slip fault, (b) water volume is pushed eastward and then upwards because the El Pilar fault bounds a deep – over 1,000 m – marine close anoxic trough on its south side, and (c) the eastern end of this WNW–ESE elongated trough – probably a pull-apart basin (Schubert 1984) – is right next to the western seashore of Cumaná.

4.6 August 17, 1874 earthquake

This strong earthquake damaged the towns of El Pilar, Carúpano, and Río Caribe and was felt equally strongly in Guaraúnos and Tunapuy. Its macroseismic epicenter is not well constrained, but it could be attributed, by analogy with the El Pilar 1986 earthquake – to be discussed later in this paper – to about the same section of the El Pilar fault, though it could be slightly west of the 1986 epicenter.

4.7 Cumaná January 17, 1929, earthquake

This earthquake – in the overlap between the historical and instrumental records – is probably the best-ever studied earthquake in this region prior to the Cariaco 1997 event. The presence of surface rupture described by Paige (1930) in the marshy lowlands of Punta Baja – east of Cumaná – undoubtedly constrains the location of this event along the El Pilar fault east of the Caigüire hills restraining stepover. Its magnitude – originally overestimated at Ms 6.9 – was reassessed by Mocquet et al. (1996), who calculated its magnitude in Ms 6.3, resulting from a fault rupture of some 30 km in length. Because only 4 km of the rupture was onshore, between the northern foothill of the Caigüire hills and Punta Baja (or Delgada) from west to east (Paige 1930), the remainder of the rupture should be offshore on the Cariaco Gulf shelf, extending as far east as San Antonio del Golfo (just west of Pericantar), as suggested by macroseismic data and felt aftershocks (Mocquet et al. 1996). The Cariaco 1997 earthquake rupture is just east of that of the 1929 event (Audemard 1997, 1999, 2006; FUNVISIS 1997; FUNVISIS et al. 1997; Romero et al. 1998). This 1929 event seemed to have ruptured the same segment as that which was ruptured during 1797. Consequently, a very rough 130-year-long return period can be preliminarily deduced between the two similar Ms 6.3 events.

4.8 October 4, 1957, earthquake

This strong earthquake essentially produced damage along the northern Paria coast, between Río Caribe and San Juan de Unare, east of Carúpano (Table 1). Its epicenter determination (10.86°N, 62.77°W; Ms 6.7) by Russo et al. (1992) matches well with the reported macroseismic observations, locating it offshore near the northern coast of the Paria Peninsula. This is a shallow event (6 to 10 km deep), within the upper seismogenic crust. From the proposed focal mechanism solution by Russo et al. (1992), this earthquake occurred along a NE–SW-trending thrust fault. Consequently, this shock is not ascribable to the El Pilar fault.

4.9 Casanay June 12, 1974, earthquake

This Casanay Ms 6.1 earthquake essentially damaged the central state of Sucre, between Casanay and Río Casanay and other neighboring villages (Table 1). Cracks and fractures in association with this event were poorly described and located, though their rough location allows their correlation with the El Pilar fault section between Aguas Calientes and Guarapiche (both villages are a few kilometers west and east of the 1997 epicenter, respectively; Fig. 2). A possible aftershock occurred on October 29, 1974. Some minor structural damage was also reported in buildings of Carúpano (Table 1 and Arcia et al. 1974), but the most-damaged town was Casanay. Additional information about this event has been reported by Guarapiche locals recently (Table 1) and was also collected through paleoseismic assessment, the results of which are still under evaluation at present.

4.10 El Pilar June 11, 1986, earthquake

This shock produced damage in El Pilar, Guaraúnos, Las Palomas, and La Loma; all within isoseismal VII in Fig. 3. Its hypocenter does not seem to be well constrained (focal depth of 69 km; Malaver et al. 1988), though its epicenter seems to be along the El Pilar fault, between the towns of El Pilar and Yaguaraparo. It is very likely that this earthquake happened on this fault near El Pilar. However, this earthquake could be also ascribed to the subduction slab under eastern Venezuela and Trinidad, based on its depth, but it should be located farther east, after the fault geometry proposed by Pérez and Aggarwal (1981) for the southern termination of the subduction. This inconsistency might be attributed to the poor coverage of the seismic network at that time. If such a problem is unrelated to data quality and quantity, a reassessment of this earthquake location could help discriminating between the two candidate seismic sources because present geographic coordinates and depth seem incompatible. It is worth mentioning that, intercalated in time and space between the Casanay 1974 and El Pilar 1986 Ms 6+ earthquakes, another smaller event happened on June 23, 1981 (maximum intensity: V). These three shocks added together seem to have broken the entire segment labeled VE-13c (Fig. 2).

5 New paleoseismic data

From difficulties encountered when studying the seismicity of this particular region, through both the instrumentally recorded seismicity of the twentieth century and the critical evaluation of historical accounts for prior destructive earthquakes of the sixteenth through nineteenth centuries, it has been necessary to widen the seismicity time window to the geologic recent by means of complementary classical geologic studies named as paleoseismology. One of the most common practices is to expose, by means of man-made trenches, Holocene (even up to late Pleistocene) sedimentary perturbations recording surface warping, ground subsidence or uplift, fault surface rupturing, and even indirect ground deformations, due to slip along a given active fault, aiming at quantifying and dating individual deformations. When applied to outcropping faults on onshore settings, this technique has certain limitations because it relies on the occurrence of surface faulting, which does not always occur. For instance, most intermediate-magnitude (5.0–6.9) earthquakes do not usually exhibit surface rupture, except for those on normal faults and rarely along wrench faults. Blind faulting, regardless of earthquake magnitude, can also become a difficult target for paleoseismic studies because these faults, although active, may not necessarily have any surface expression. However, this technique has proved to be very useful and powerful on onshore wrenching settings like in Venezuela (for more details on Venezuela's experience, refer to Audemard 2003, 2005).

After the Cariaco 1997 earthquake, FUNVISIS undertook the assessment of the Holocene seismic history of the recently ruptured segment by excavating three 20-m-long, 4-m-wide, and 3-m-deep trenches located at Las Manoas, Carrizal de la Cruz, and Guarapiche, which were spread over a distance of 15 km along the rupture between Cariaco and Río Casanay (for relative location, refer to Figs. 2 and 3). In this paper, there is no intention of discussing all gathered results from these trenches that covered a 7,000-year time window, but some relevant observations will be discussed to support my arguments:

1. Besides the structural features related to the 1997 rupture, in trench walls, shallow open cracks containing buried plastic bag pieces were observed, suggesting the occurrence of a very recent event prior to the 1997 one along this segment. Therefore, an event in the last 40 years ("plastic era") took place, which was confirmed by the ^{14}C age of the underlying organic-rich soil. The only possible candidate in this time span is the Casanay 1974 earthquake, which seems to be the prior event on this segment that displayed

surface cracking, though it was poorly located at that time because the Casanay rupture might have been imperceptible due to the heavy tropical vegetation of the area. However, it was actually spotted by Mr. Abundio Martínez within his property at Guarapiche along the northern foothills of the Guarapiche Hill, as referred by himself to the author in 1998. Consequently, the investigation of the Guarapiche trench in Martinez's land had a double objective that was accomplished: (a) to confirm the position of the 1974 rupture in his backyard at the foot of the Guarapiche hill and (b) to evaluate the fault at depth, as well as its seismic history. Therefore, the Casanay 1974 earthquake appears to be the product of a maximum rupture length along the El Pilar fault of some 10–15 km (distance between the villages of Aguas Calientes and Guarapiche).

(2) The three trenches equally exposed a prior event to 1974. This event was coincidently radiocarbon-dated at 270±60 years BP (years before 1950 A.D.) in all three trenches. The age of this event perfectly correlates to one of the less constrained historic earthquakes of our entire seismic history in eastern Venezuela – the May 4, 1684, earthquake – with a surface rupture in an area that was probably unpopulated at that time. Additionally, a rupture similar in style and age was also observed in a complementary man-made cut at a house backyard in Terranova (Fig. 4a,b), between Villa Frontado and Cariaco, thus extending the probable 1684 surface rupture to over 25 km. This event appears to be the predecessor to the 1997 earthquake on this particular section of the El Pilar fault.

(3) No evidence of the 1530, 1766, or 1853 earthquakes were reported in the trenches and consequently along this segment of the El Pilar fault.

6 Discussion and conclusions

Widening the time window of seismicity through gathering data from different sources (instrumental and historical seismicity and paleoseismicity) certainly gives a more accurate insight on the seismic history of a given fault and its seismic hazard assessment (maximum credible earthquake vs return period). It also helps to determine any eventual (time–space) migration of the seismic activity along an active fault. In fact, the combination of observations resting on historic documents with new relevant data collected at three trenches dug across the recent rupture of the Cariaco 1997 earthquake has led to the revaluation of the historic earthquakes of the region in this paper and to the construction of a time–space distribution for Ms 6+ earthquakes along several seismogenic segments of the El Pilar fault, between the Cariaco Trough and the Paria Gulf, from west to east (Fig. 5). This time–space distribution of earthquakes has to be envisaged as a proposal that may undergo future changes or refinements, depending on the evaluation of unknown

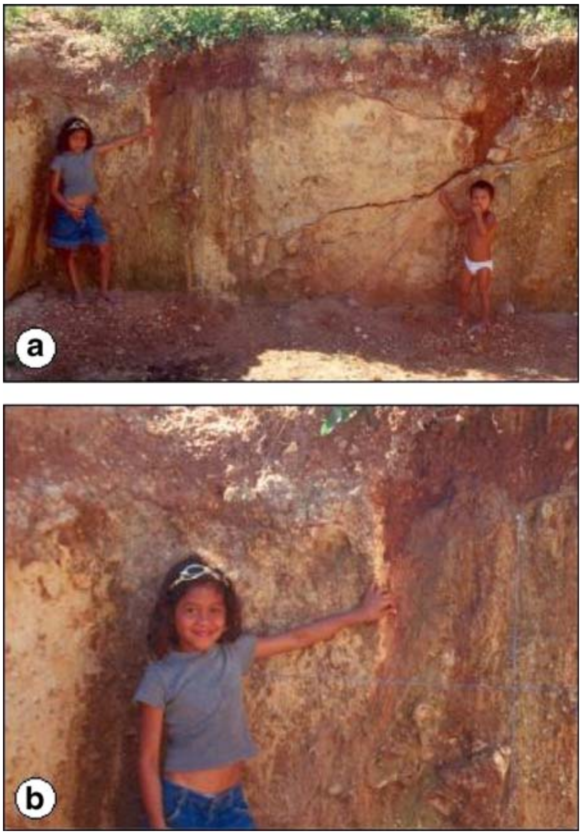

Fig. 4 Backyard outcrop near a house at Terranova exhibits earthquake-related open cracks filled by organic soils (locality spotted by Luis Acosta). **a** General view to the south of the east–west-oriented man-made outcrop displaying two subparallel soil-filled wedges; **b** *the girl's hand* indicates the sampling site of deposits that correlate with the 1684 event, within the easternmost wedge

existing historical data or new acquisition of further paleoseismic information, either onshore or offshore.

In the past, the lack of combination of these different sources of seismic information (or evaluation of any of them) has led to incorrect interpretations, such as those of Pérez (1998a,b), when: (a) deducing return periods for the El Pilar fault based on a seismic history that includes the 1766 earthquake, which did not actually occur on that fault, as previously suggested by Lugo and Giraldo (1989) and Grases (1990), and (b) determining migration of seismic activity along the El Pilar fault towards the west from the 1986 epicenter to the 1997 one. In fact, the 1997 event fills the gap between the 1929 and 1974 earthquakes, located west and east of the latest event, respectively (Fig. 5). Actually, the 1997 event even fully overlaps the 1974 rupture. If any migration might be proposed, it would appear that the larger (≈Ms 7.0 or larger) events migrate from west to east.

As to the El Pilar fault segmentation proposed by Beltrán et al. (1996), it would seem from this revision of seismic history that the Caigüire pop-up (inside present-day Cumaná urban area) does act as a persistent geometric barrier to rupture propagation between segments “A” (west of Cumaná; VE-13a in Fig. 2) and “B” (Cumaná-Casanay/Guarapiche; VE-13b in Fig. 2), whereas the Casanay/Guarapiche restraining bend seems to be a leaking barrier between segments “B” and “D” (VE-13b and VE-13d in Fig. 2), as evidenced by the Cariaco 1997 surface rupture (Fig. 2). Instead, the Cariaco 1997 earthquake seems to have nucleated on the barrier or very near to it (Audemard 1999, 2006). Moreover, segment B seems not to be filled by a single major earthquake

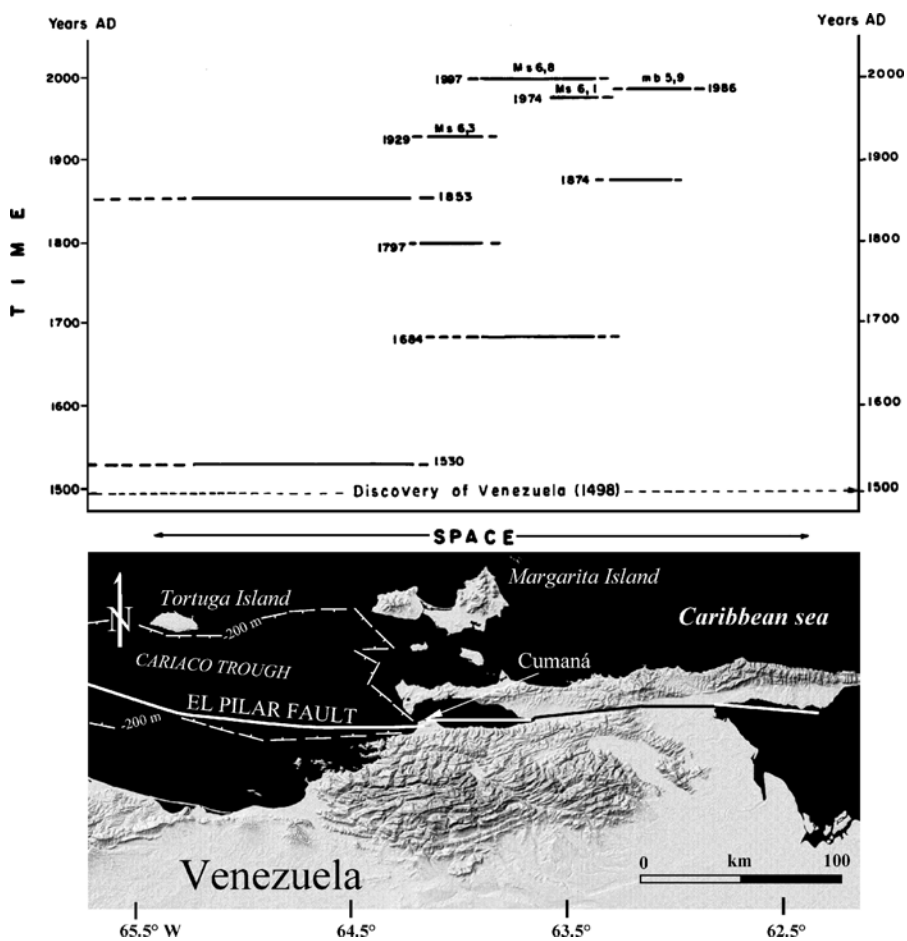

Fig. 5 Time–space distribution of the seismic activity along the El Pilar fault, in eastern Venezuela, for the period 1498–1997 (between the third Columbus trip and the Cariaco earthquake). Notice that proposed rupture lengths in the *upper diagram* geographically match with the active trace of the El Pilar fault shown in *lower map*, which is reported on digital shaded-relief map from Garrity et al. (2004). It also includes the 200-m isobath of the Cariaco Trough

because it is generally accompanied by Ms 6+ earthquakes towards the tips of the fault segment.

In the particular case of the city of Cumaná, which has been repeatedly damaged by several earthquakes since its foundation, 1530, 1629, 1684, 1766, 1797, 1853, 1929, and the recent Cariaco 1997 earthquake, the latest event has revealed that most damage to this city during earthquakes is related to site effects (refer to González et al. 2004). Consequently, earlier macroseismic intensity evaluation in eastern Venezuela must be carefully revised to prevent misplacement of these earthquake epicenters, as discussed in this paper.

The present reassessment of the seismic history along the El Pilar fault has several main contributions: (1) The 1530 and 1853 earthquakes, which generated rather large tsunami waves and were not expressed in any of the three trenches, should be ascribed to the underwater segment of the El Pilar fault, located west of Cumaná and south-bounding the Cariaco Trough. No magnitude has been calculated for these two earthquakes but it could be estimated by means of numerical modeling that relates tsunami-wave height to amount of sea-bottom slip, which in turn is a function of the earthquake magnitude itself. Their magnitudes are tentatively estimated at Ms 7.1–7.3 and their return period seems to be tentatively in the order of 300–320 years for this westernmost segment of the El Pilar fault. (2) The 1684 earthquake seems to have occurred along the same portion as the Cariaco 1997 event (segment VE-13b in Fig. 2, after Audemard et al. 2000), whose coseismic surface faulting was mapped onshore for over 36 km between Muelle de Cariaco and Río Casanay (Audemard 1999, 2006), and its rupture may have a total length of surface rupturing of about 50–55 km between San Antonio del Golfo and Río Casanay, as suggested by very shallow aftershock distribution (Baumbach et al. 2004). (3) Damage in Cumaná during the 1797 earthquake suggests that it may be equivalent to the 1929 event, whose rupture was just east of Cumaná, from Punta Baja (NNW of El Peñón) to San Antonio del Golfo over a distance of 30 km. (4) Correlation of the Casanay June 12, 1974, earthquake to the El Pilar portion extending between Aguas Calientes and Guarapiche was made from local accounts and trenching results. (5) The 1766 event has to be associated with an intermediate-depth (60–200-km-deep) source, such as the southern termination of the Lesser Antilles subduction slab, due to size of the felt area and other macroseismic observations. (6) The segment of the El Pilar fault extending between Cumaná and Guarapiche seems to be characterized by the occurrence of events of magnitude above 6 on both ends preceding and/or following earthquakes of magnitudes of about 7. Near Cumaná, Ms 6+ earthquakes very roughly recur in the order of 130 years, whereas the filling ~Ms 7 earthquakes show return periods of 300–320 years. (7) There is no clear behavior pattern between contiguous or successive fault segments, but activity on one clearly acts on the adjacent segment by increasing stress and generating earthquakes after a certain and variable lag time.

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