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Study of the Earthquake of the January 23, 1880, in San Cristóbal, Cuba and the Guane Fault[1]

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Abstract—All available data on the January 23, 1880, earthquake near San Cristobal, Western Cuba, are compiled and presented here. The earthquake reached a maximum intensity of eight degrees (MSK) and caused three fatalities. It was accompanied by 65 aftershocks and was felt as far away as the Florida Keys. Twentieth century specialists has associated this event, in its day the strongest recorded (Ms = 6.2) in the region, with the Pinar fault. The Pinar fault is well expressed topographically as the boundary between the Guaniguanico Range in the north and an alluvial plain to the south. Most of the major damage caused by the earthquake was located on the alluvial plain, which in consequence has been considered the epicenter area. In the study presented here, the data compiled from the first reports of Father Benito Vines Martorell, S.J., and Pedro Salteraín y Legarra, indicate that the seismic structure was located in the alluvial plain, and that it was the Guane fault, and not the Pinar fault, that was responsible for the earthquake. The Guane fault, found below the alluvial sediments, extends NE-SW for over 110 km. Its eastern extreme, near San José de las Lajas (La Habana), is linked to another active fault which represents a seismoactive knot responsible for the earthquake of March 9, 1995 (I = 5 degrees, MSK). Seismic events of the Western Cuban region are related to the transpressive interaction of the North American and Caribbean Plates, damped by oceanic structures.

Keywords: Active fault, active tectonics, Cuba, earthquake, San Cristóbal, seismotectonics.

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1. INTRODUCTION

The presence of a geological fault, for example, a rupture of earth's crust, is of interest not only from a scientific point of view, but also from the point of view of economics and society in general. When these interests converge, specialists typically undertake, among other things, exploration, mining investigations, and research on seismic risk. A prior classification of the faults greatly enables the work of specialists. Two aspects that historically have been taken into consideration are morphology and the expression in the relief. At times, the level of seismic activity of the structures does not permit the recording of both of these aspects. One characteristic observed about the faults is the presence of earthquakes. Thus, it can be possible to link faults well—expressed in the relief with earthquakes that have occurred in a territory, even though their epicenters are relatively far from the faults. Molnar [1988] stated that the systems of faults are the common mechanisms of the accommodation of the motion of the plates in the continental lithosphere. Nur et al. [1993] maintain that quasi—stable areas represent the zones of intersections of faults; in other words, the crust deformations are widely distributed.

During the two last decades (1970–1990), Cuban and European geologists and geophysicists have engaged in an ongoing debate over the existence of the Guane fault (GF) [Cotilla et al., 1991a; Shein et al., 1985a]. Butticaz [1946a] mapped the fault in the southern part of the Pinar del Río province (Fig. 1). However, more recently, seismologists could not correlate the seismic movements registered along the trace mapped by Butticaz [1946b] as showed Cotilla and Álvarez [2001]. The seismicity of the Western Cuba region is analyzed in this work and in particular that associated with the GF. A determination of the existence of the GF is the object of this work. Any such discussion must begin with the work of the two nineteenth century specialists, Father Benito Viñes Martorell, S.J., and Pedro Salteraín y Legarra, who first described the fault and located the strong earthquake of the January 23, 1880, earthquake in San Cristóbal (SC), in Pinar del Río province.

2. GENERAL GEODYNAMICS CONSIDERATIONS

North American plate (NAP) has had a long and complex evolution and at present experiences a differentiated seismic activity. Its largest energetic release is localized along the Pacific Ocean coastline, where the strongest and frequent earthquakes have occurred [Sykes and Seeber, 1985]. There are earthquakes associated to the Bartlett–Cayman (BC) fault at the

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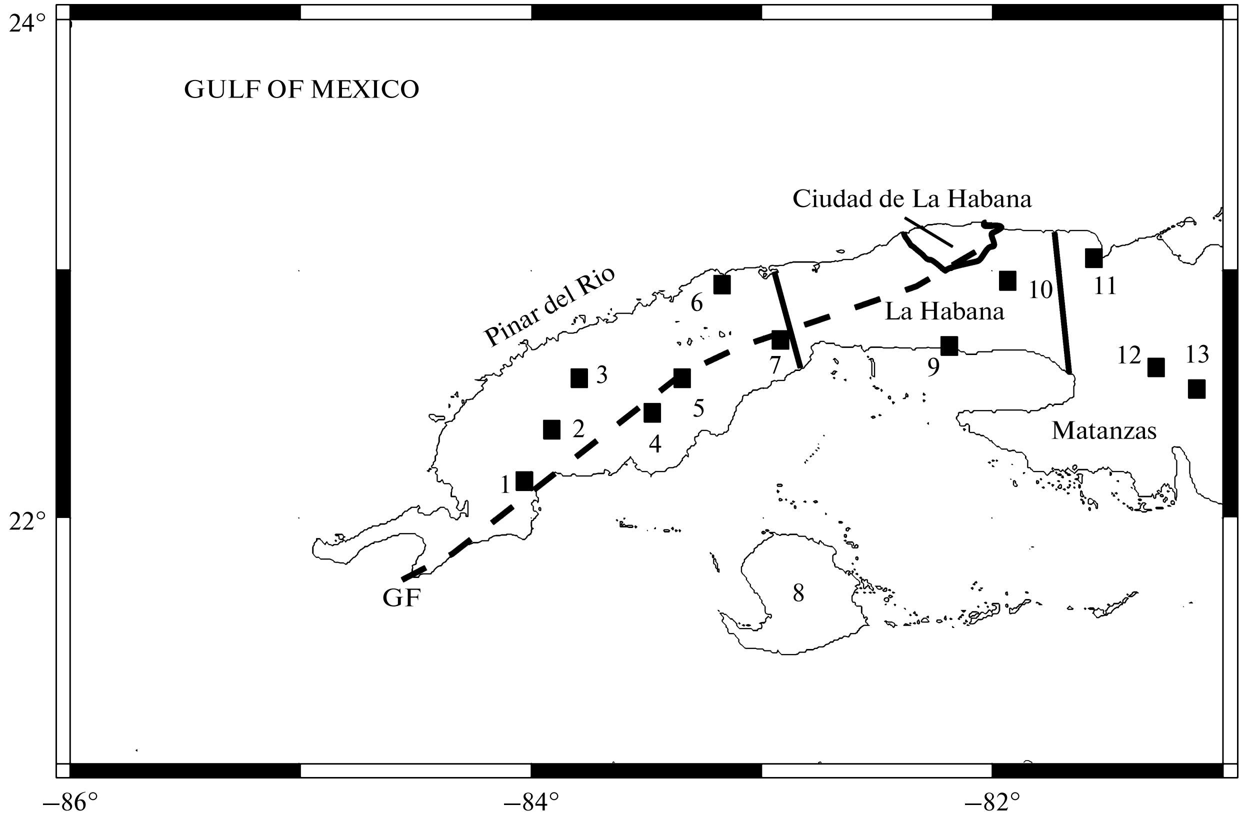

Fig. 1. Scheme of the Pinar del Río province and its surrounding. In it appears: (1) four administrative provinces of the Western Cuba (Pinar del Río, Ciudad de La Habana, La Habana, and Matanzas) with their boundaries; (2) the Guane fault (GF) in discontinue trace; (3) the localities with black squares (1 = Guane, 2 = Pinar del Río, 3 = Viñales, 4 = Consolación del Sur, 5 = Los Palacios, 6 = Bahía Honda, 7 = San Cristóbal, 8 = Isla de la Juventud, 9 = Batabanó, 10 = San José de las Lajas, 11 = Matanzas, 12 = Torriente, 13 = Jagúey Grande).

southern boundary [Mann et al., 1995; Rosencratz and Mann, 1991; Rosencratz et al., 1988]. The eastern boundary is related to the rift zone of the Atlantic Ocean and smaller transforming faults [Sykes and Ewing, 1965]. Opposite to what would be expected, the plate's interior zone suffers strong earthquakes [Johnston and Kanter, 1990] of magnitudes similar to the ones along the Pacific coast, although they are less frequent; these earthquakes are related to readjustments or reactivation of the crust faults [Johnston, 1989]. The NAP possesses a very diverse mosaic of geological structures: region of very ancient rocks (pre Cambrian) that constitute the basement, and which in consequence are very much strengthened, with a relief that is not very energetic; a younger region of consolidated rocks, surrounding the older one, constituted by the mountainous mass that stand out in the Pacific and Atlantic areas; and a third region that is related with a system of heights and plains articulated in depth and pulled apart in the superficial present—day layout, characterized by large thicknesses of sediments, that widely acts as a transitional zone toward the big morphologic contrasts of the south (Gulf of Mexico and Bahamas Platform) [Johnston and Kanter, 1990]. The Cuban megablock is inserted in this southern border (Cuban microplate), which includes the North Cuban fault, the Eastern Yucatan alignment, and the BC fault system [Ushakov et al., 1979] (Fig. 2). This result is supported by the Bouguer's map of [Prol et al., 1993].

Neotectonics and Geodynamics of Cuba

The Caribbean plate (CP) performs as a discontinuity between the North American and South American plates [Mann and Burke, 1984] (Fig. 2). It experiences a general relative displacement to the east of 2—4 cm/year; in the Cuban sector displacement is 2 cm/year and in Jamaica 1—2 cm/year [DeMets et al., 1990; Deng and Sykes, 1995; Jordan, 1976; Mann and Burke, 1984; Mann et al., 1995; Molnar and Sykes, 1969]. At its western boundary, the Cocos and Nazca plates, belonging to the Pacific plates system, are subducted under the CP. At the eastern boundary, the subduction of the NAP is not so well—defined [Westbrook et al., 1973]. The northern boundary is a system of transforming faults with left—strike displacement and with subduction components to the north of Hispaniola [Mann et al., 1995] and Puerto Rico—Virgin Islands [Mann and Burke, 1984; McCann, 2000; McCann and Pennington, 1990]. On

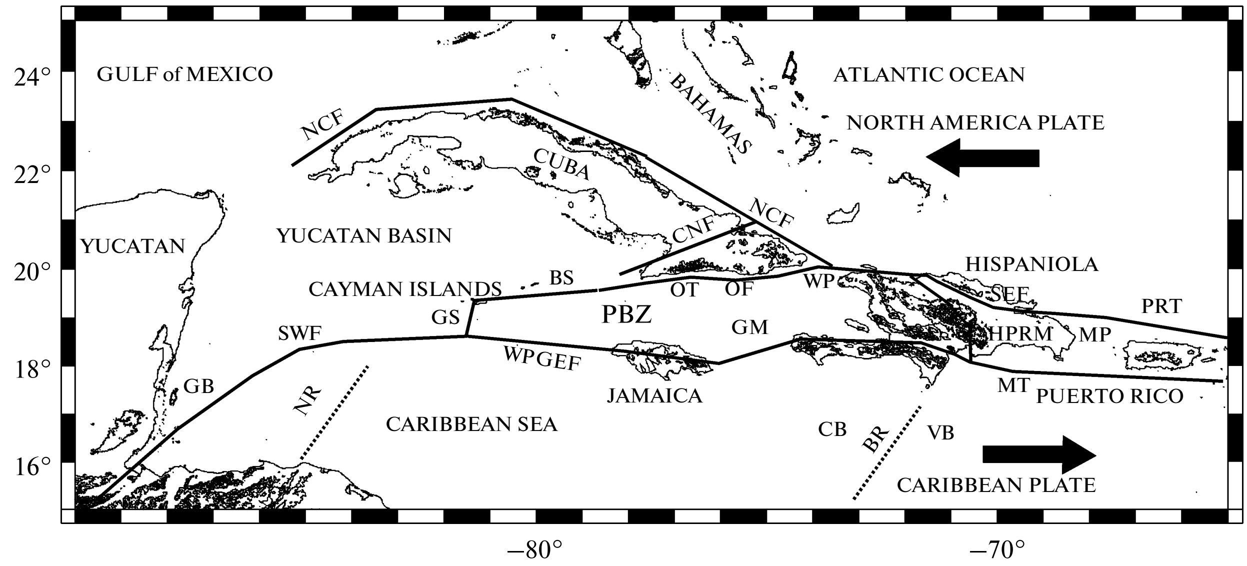

Fig. 2. Tectonic scheme of the Caribbean. Heavy black arrows show the sense of the plate movements. With points trace appear the ridges (BR = Beata, NR = Nicaragua). Other structures are: (1) the main faults (BC = Bartlett-Caimán, CNF = Cauto-Nipe, NCF = Nortecubana, OF = Oriente, SEF = Septentrional, SWF = Swan, WPGEF = Walton–Plantain Garden–Enriquillo); (2) passages (MP = Mona, WP = Windward); (3) islands (Cuba, Hispaniola, Jamaica, Puerto Rico); (4) basins (CB = Colombia, GB = Guatemala, VB = Venezuela); (5) microplates (GM = Gonave, HPRM = Hispaniola–Puerto Rico); (6) troughs (MT = Muertos, OT = Oriente, PRT = Puerto Rico); (7) PBZ = Plátes boundary zone.

the northern boundary there is the Mid Cayman rise, 110 km in width [Holcombe et al., 1973; Rosencratz and Mann, 1991; Ross and Scotese, 1988]. The southern boundary is a complex fault system with left—strike displacement and subduction of the South American and Nazca plates under CP [Burke et al., 1984; Mann and Burke, 1984; Wooters, 1986].

Cuba is located between the zones of active displacements of the CP and NAP and presents vertical moderated movements that do not exceed 1 cm/year [Álvarez et al., 1990; Hernández, 1987; Hernández et al., 1988]. Díaz et al. [1990] determined the blocks' geometry and disposition for a sector of Western Cuba (Cabo de San Antonio—Cochinos), noticing that an increment of the uplifts from west to east, as well as an inclination to north of the entire region. González et al. [2003] consider that these geodetic evaluations are not complete enough to establish the real values of the recent crustal movements of the Cuban structures. These authors argue that the fixed geodetic points not only are insufficient in quantity, but rather have a heterogeneous distribution in addition to a lack of the necessary adjusting control with the net of marigraphs. However, these same authors consider that it is feasible to use them to evaluate tendencies of movements. With considerations in mind, Cotilla et al. [1991a] maintain that Cuba is a megablock of differential ascent in the south of the NAP border that maintains a narrow space and a temporary and energetic relation with the CP through the southeastern zone (Fig. 2).

Various hypotheses attempt to explain the geological development of the Cuban megablock, for example those found in [Hernández, 1987; Iturralde, 1992]. The objective of the present work is neotectonic; we will mainly discuss the geological history from the Oligocene. We agree with Iturralde [1992] that development was of the neoplatform type (intermediate status between platform and arch of volcanic islands). At the whole territory exists as a set of four large blocks with oscillatory differential motions vertical in relation to the dynamics of plates [González et al., 2003]. This structure has been checked against different methods: (1) geophysical [Cuevas, 1994; 1991; Pardo, 1993; Prol et al., 1993; Sherbakova et al., 1977; 1975], (2) geological [Álvarez, 1992; Millán and Somin, 1981], (3) morphostructural [González et al., 2003] and (4) geomorphological and geodesic [Díaz et al., 1990; Hernández et al., 1989].

Cuban megablock (Fig. 3) is composed of a Cretaceous tectonic belt over which there is an extensional deformation with a set of NE-SW strike—slip faults and associated basins (without magmatic activity) containing clastic and carbonated sediments. This deformation is correlated to the transpressive motion of the CP and began during the Upper Eocene and continues to the present time [Iturralde, 1992]. Three principal stages in the evolution of these basins have been found, each with a complete cycle of transgression-regression where uplifting took over. It is considered that the neo - autochthonous stage began with the activation of the BC trough and its pull—apart, when the processes of convergent tectonics progressively changed eastward [Ross and Scotese, 1988].

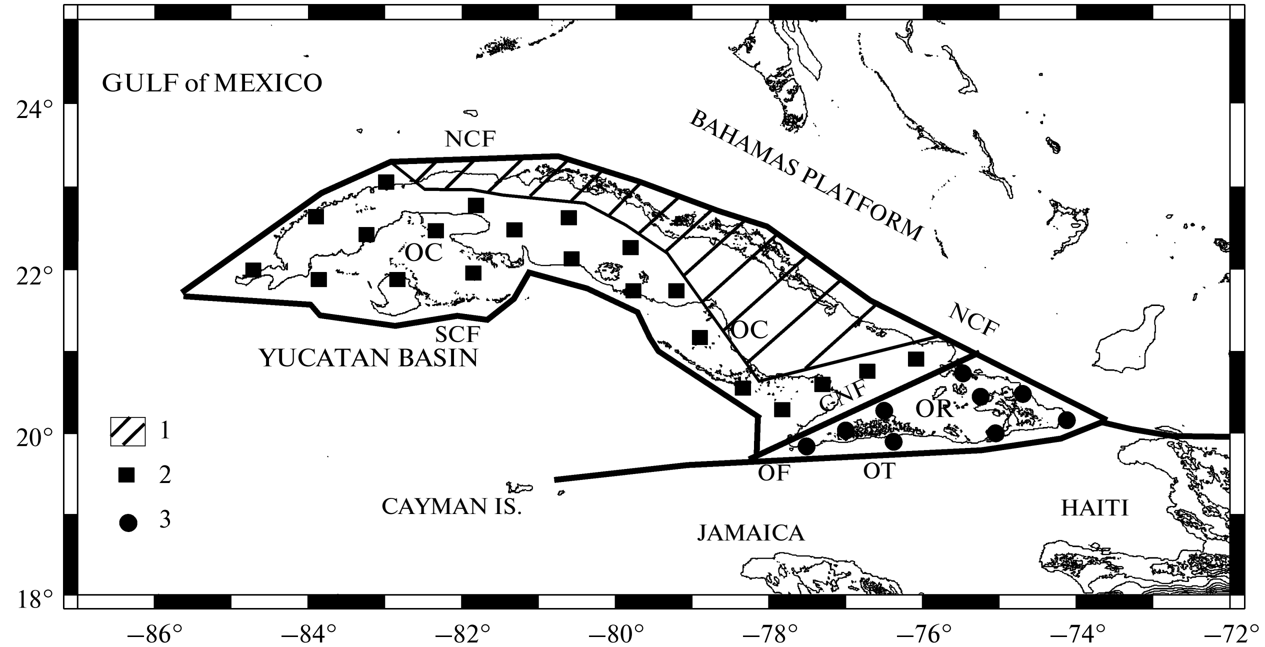

Fig. 3. F Cuban megablock. Heavy black lines are faults (CNF = Cauto-Nipe, NCF = Nortecubana, OF = Oriente, SCF = Surcubana). Appear: (1) Neotectonic Units (OC = Western, OR = Eastern); (2) crust type (1 = post-orogenic complex, 2 = orogenic complex, 3 = volcanic arc complex).

The deep structure of the Western Neotectonic Unit (WNU) has been studied by means of seismic profiles [Sherbakova et al., 1977; 1975], gravimetrics [Díaz Duque et al., 989], magnetics and electrics [Álvarez and Kolesova, 1983]. Prol et al. [1993] argue for the existence of three types of crust in Cuba: oceanic, transitional thick, and transitional thin (Fig. 3), the latter two of which correspond geographically with those of the WNU; Cotilla et al. [1991b] assert that automatic and analogic processing of photos and imageries and the consequent interpretation conform this finding. Nevertheless, the results of other specialists [Cuevas, 1994; Shein et al., 1985a; Shebakova et al., 1977; 1975] do not agree with the proposal of Prol et al. [1993] and hold that the crust structure is of fairly regular, good thickness or thinness.

Cotilla et al. [2003] and González et al. [2003] found a morphostructural differentiation to the south of Pinar del Río province compared to the north and eastern parts, this ends at the provinces of Ciudad de La Habana and La Habana. These morphostructures, quasi longitudinal, belong to the larger area and a lesser relief category than those delimited in the Guaniguanico Range (GR). The slopes in the morphostructures of the plain increased toward east and west, from the SC locality. A modification exists, very easily seen in the classification by size of particles, in the sediments in profiles N-S. Those profiles differ slightly to the south of the Sierra de los Órganos (SOr) and the Sierra del Rosario (SR). They are for always flooded areas like coastal marshes. The southernmost morphostructures demonstrate a tendency toward sinking. Cotilla and Álvarez [2001] have suggested there are some neotectonic characteristics in SC's surrounding, as shown by a sedimentary basin (Los Palacios). Then, for the SOr and from west to east there is inflection (Fig. 4a): (1) in the Camarones River to the south of the Sierra de Contadores; (2) to the southwest the San Juan and Martínez Rivers empty into Cortés Bay; (3) of 10 km in the Feo River between San Juan and Martínez and Pinar del Río; (4) in the Guamá River (tributary of the Feo River) in the south of Pinar del Río (Santa María); (5) to the southwest of the La Majagua River (to the east of Pinar del Río), tributary of the Hondo River between Consolación del Sur and Pinar del Río; (6) in the Santa Clara and Herradura Rivers between Consolación del Norte and Paso Real de San Diego. These authors stand out than the inflections of the rivers are minor south of the SR than the correspondents of SOr. Examples (Fig. 4a): (1) Los Palacios River (in Los Palacios); (2) Santo Domingo River (between Los Palacios and Taco-Taco); (3) San Cristóbal River (Sugar Cane Factory "José Martí").

3. THE GUANE AND PINAR FAULTS

A large number of faults have been detected in both the Pinar del Río province, for example, the Pinar fault (PF) (Academias de Ciencias de Cuba y de Polonia, 1978), and La Habana provinces [Academia de Ciencias de Cuba, 1981] (Fig. 5). These provinces are in the westernmost part of the Cuban territory (Fig. 1). The PF was considered the most important in the region. Also, this fault is recognized in Linares et al. [1986]; Mossakovsky et al. [1989]. However, the GF was not

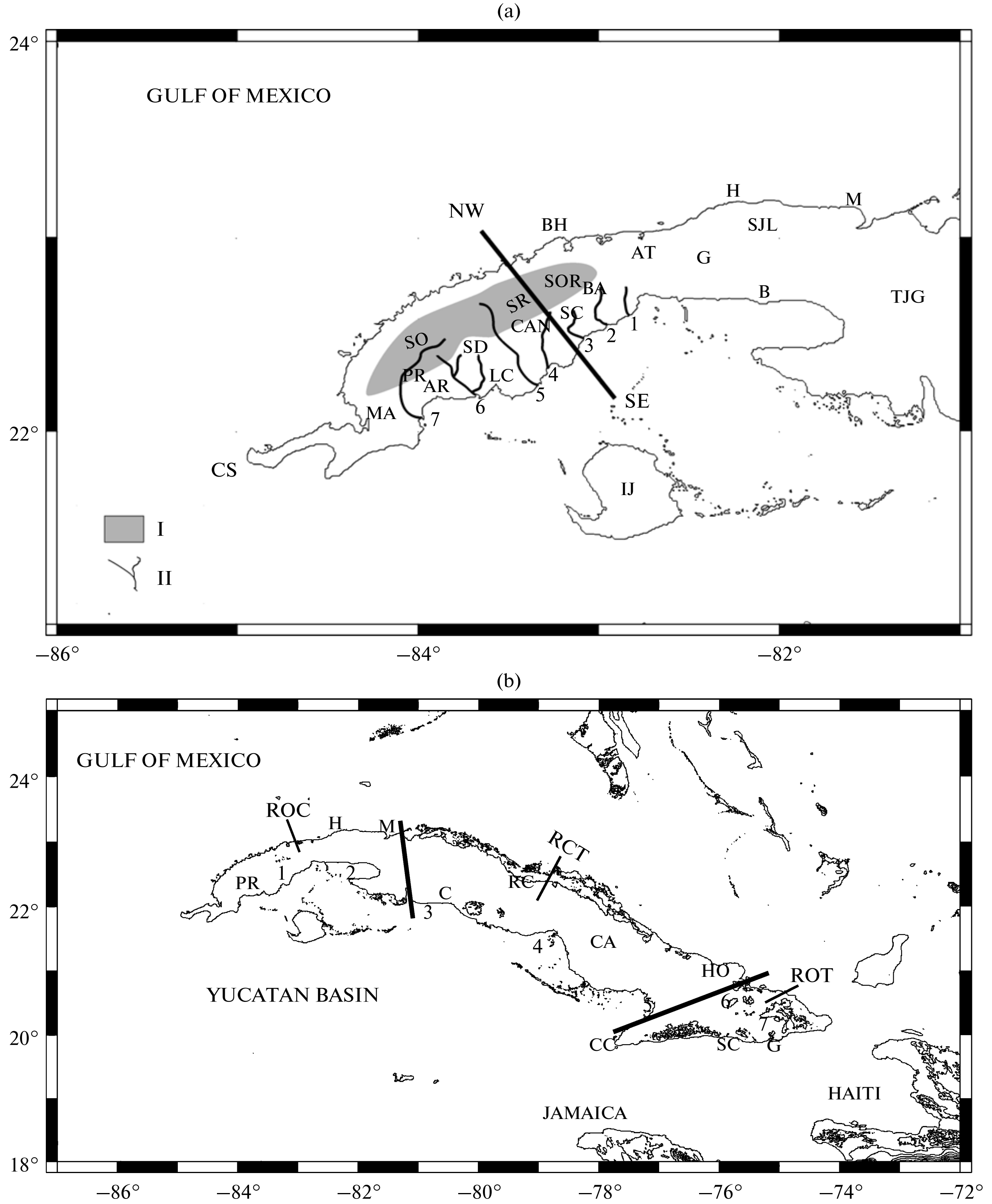

Fig. 4. (a) Scheme of Western Cuba. In it is represented (I = Montañas de Guaniguanico (SO = Sierra de los órganos, SR = Sierra del Rosario), II = rivers (1 = Bayate, 2 = San Cristóbal, 3 = Bacunagua, 4 = San Diego, 5 = Hondo, 6 = Feo-Agabama, 7 = Cuyaguateje)). Other aspects included: (1) localities (AR = Alonso de Rojas, AT = Artemisa, B = Batabanó, BA = Bayate, BH = Bahía Honda, CAN = Candelaria, CS = Cabo de San Antonio, G = Guanajay, IJ = Isla de la Juventud, LC = La Coloma, M = Matanzas, MA = Mantua, PR = Pinar del Río, SC = San Cristóbal, SD = San Diego de los Baños, SJL = San José de las Lajas, SOR = Soroa, TJG = Torriente-Jagúey Grande); (2) the profile trace (SE-NW). (b) Cuban regions. In it appears: (1) basins (1 = Los Palacios, 2 = La Broa, 3 = Cienfuegos-Cochinos, 4 = Ana María, 5 = Cauto, 6 = Nipe, 7 = Guantánamo); (2) localities (C = Cienfuegos, CA = Camagúey, CC = Cabo Cruz, G = Guantánamo, H = La Habana, HO = Holguín, M = Matanzas, PR = Pinar del Río, RC = Remedios-Caibarién, SC = Santiago de Cuba); (3) heavy black lines are the boundary of Cuban regions (ROC = Western, RCT = Central, ROT = Eastern).

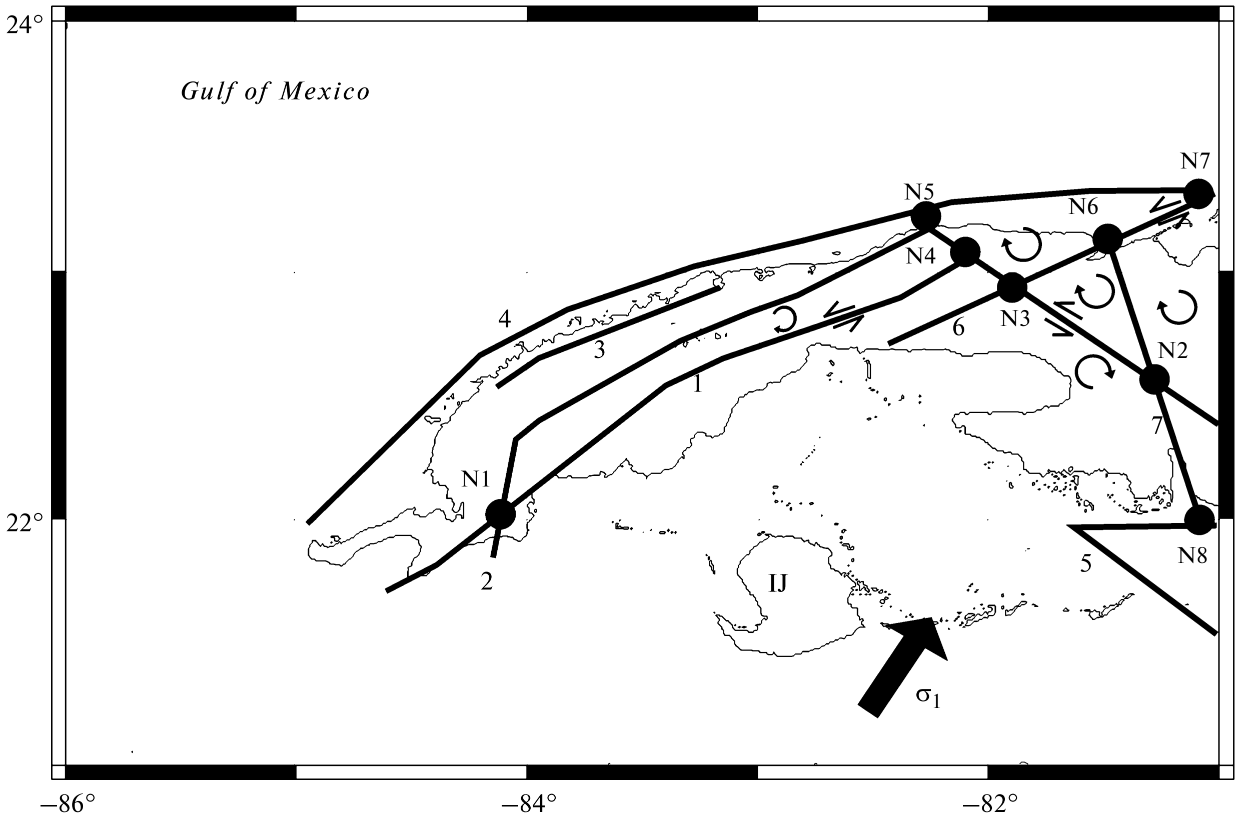

Fig. 5. Celds and stress tensor of Western Cuba [modified of Cotilla and Álvarez, 2001]. Heavy black lines are faults (1 = Guane, 2 = Pinar, 3 = Consolación del Norte, 4 = Nortecubana, 5 = Surcubana, 6 = Hicacos, 7 = Cochinos); black circles = knot of faults (N1), heavy black arrow = main stress (*1*), curve black arrow = sense of movement and with code of the locality IJ = Isla de la Juventud.

even mapped in those works. The PF is quite well—expressed in the Pinar del Río province's relief and separates the northern mountain territories (SR and SOr) of the alluvial plain from the south (Figs. 1, 4a). This fault is recognized and described in all the works of type: (1) remote sensing [Pérez et al., 1985; Portela et al., 1981; Trifonov et al., 1981]; (2) neotectonics [Iturralde, 1992; Shein et al., 1975]; (3) geomorphology [Díaz et al., 1990]; (4) geophysics [Prol et al., 1993]; (5) seismotectonic [Chuy et al., 1988b; 1984; González and Chuy, 1983; Orbera, 1983; Orbera et al., 1990]; (6) seismic [González et al., 1995]. However, Buticaz [1946a; 1946b] aimed at subordinating PF to a tectonic structure covered up more south (at the alluvial plain), conforming a system of step—shaped deep faults. This idea was developed later by Álvarez [1992; 1989; 1981] who catalogued it as a system of slowly evolving, deep, active faults thus similar to the main ones in Western Cuba. In the tectonic map of Shein et al. [1985a], known as the map of the oilers, it was mapped to the GF, although in a schematic way. The decision borrowed from the geophysical interpretations, but they were not accepted by the vast majority of the Cuban geologists. The fault is located under ample thicknesses of sediments of the plain in southern Pinar del Río and assumes it to be the axe of the basin of the San Diego de los Baños–Los Palacios (Fig. 4b). It has 110 km of longitude (NE-SW strike) and is classified as a deep structure that cuts the crust. Cotilla [1993] considered it a seismogenetic zone. Cotilla and Álvarez [2001] discussed both faults.

According to Cortada et al. [1996] the Los Palacios basin (80 km in length, 7–35 km in width, and SW-NE strike) (Fig. 6) is constituted in its base by ophiolitic rocks of the volcanic arch, belonging to the Zaza tectonic terrene, covered by an enlarged layer of sediments (6 km) of the Upper Cretacic—Recent. López [1993] distinguished in that basin three floors: (1) (a) Aptian–Huronian: Volcanogenic and volcanogenic sedimentary rocks; (b) Coniacian–Santonian: Clays and calcareous sandstones with intercalations of limestones and rarely flints; (2) Campanian–Lower Eocene: Clay—conglomerate—sandy deposit; (3) Eocene—Quaternary: Terrigenic—carbonate rocks.

4. SEISMICITY

The Caribbean region from the seismologic point of view is locked—up by heterogeneous bands, where the activity is concentrated and where the plate inter-

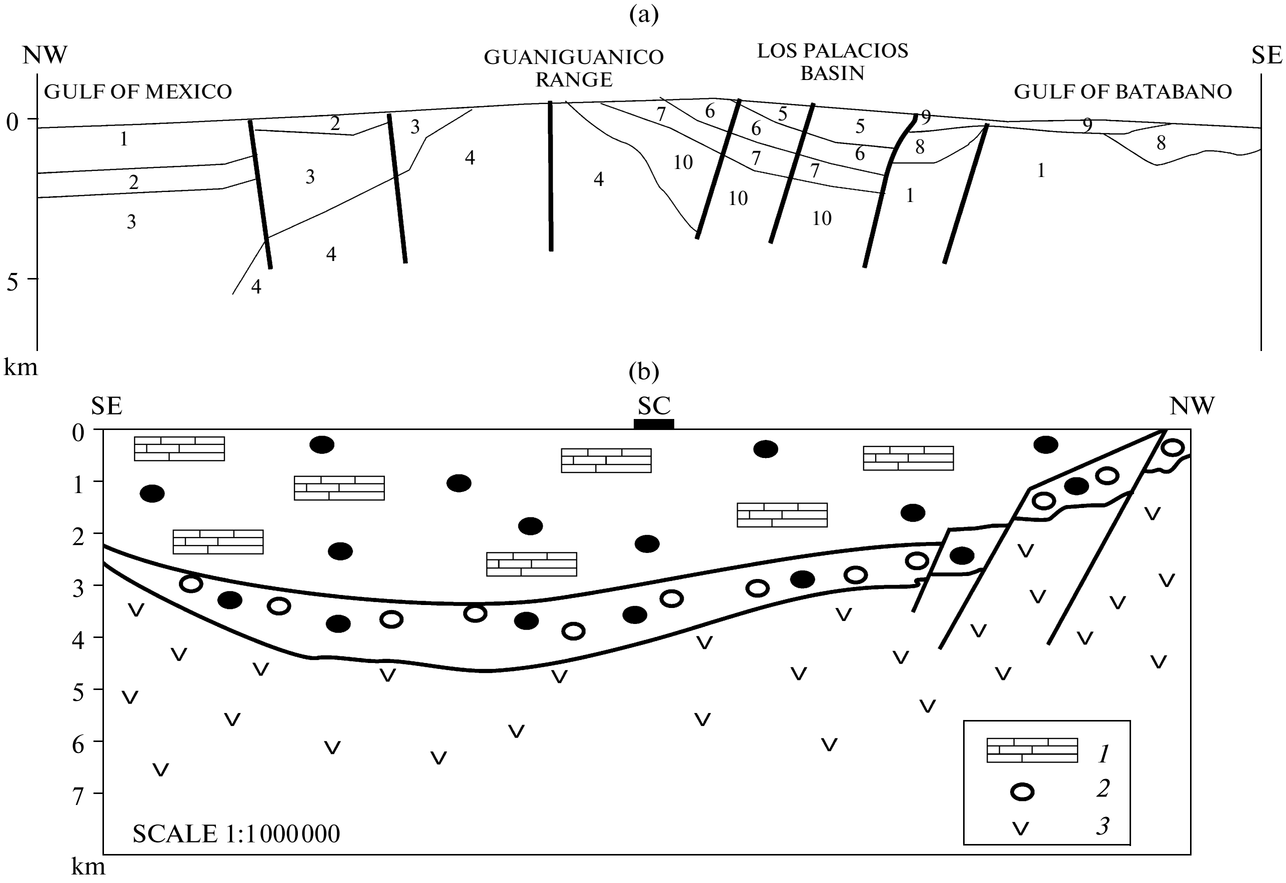

Fig. 6. (a) NW-SE profile of the Pinar del Río region (correspondence with the Fig. 4A). (1 = 1 = K_1^{al}–K_1^t, 2 = $K_1^{v\text{-}al}$, 3 = J_3^t–K_1^{ne}, 4 = J_{1-2}, 5 = N_1^{1-2}, 6 = P_2^2, 7 = P_2^{1-2}, 8 = P_2^1, 9 = N_2^{1-2}, 10 = $K_2^{cn\text{-}s}$. (b) Scheme of San Diego de los Baños basin. In it is indicated the locality of SC San Cristóbal and the crust type (1 = continental thin, 2 = continental thick, 3 = oceanic).

actions are manifested [Mann and Burke, 1984; Sykes and Ewing, 1965; Sykes et al., 1982] (Fig. 2).

The level of seismic activity (frequency of occurrence and magnitude) decreases substantially from those plate boundary zones toward the maritime interior. The thickness of the crust in general is not thick [Bowin, 1968] which favors the occurrence of cortical earthquakes. Nevertheless, in the Pacific and Atlantic subduction zones, and on Hispaniola and Puerto Rico the thickness generates deep events [Álvarez et al., 1990]. This is due to the different geodynamic conditions the plates are subjected. The strongest earthquakes, in Greater Antilles according to different sources, are recorded in Table 1. For Cuba, the strongest earthquakes since 1528 for the WNU are shown in Table 2 [Álvarez et al., 1990; Chuy et al., 1988a; González et al., 1994].

The influence of subjectivity in the seismotectonic results does not limit itself to the interpretative stage, since in the initial data a strong subjectivity is evident [Gitis et al., 1992]. This is the case with the macroseismic information used to explain much of the seismicity in a study of the effects attenuation of the earthquakes at greater distances from the epicenter [Álvarez et al., 1990]. An example of this is case of the macroseismic research of Chuy et al. [1984] and Chuy et al. [1988a] that, just months after being concluded were modified significantly for at least four earthquakes by Orbera et al. [1990] regards: (1) the perceptibility points; (2) the isoseismal reliability; (3) the isoseismal figures [Cotilla, 1999]. These issues cause one of the most frequent sources of error in the process of acquisition and the processing of the information to manufacture isoseismal maps of historic earthquakes [Álvarez et al., 1990]. In this specific case, and without scientific arguments, the seismic hazard of a territory was significantly reduced [Cotilla, 1993].

The Cuban macroseismic catalogs possess a variable quality from one event to the next. Even though some earthquakes have been studied enough to elaborate isoseismal maps, with the resulting increase in reliability in placing the epicenter, the majority have scarce data, preventing a single association with another seismogenetic zone [Cotilla et al., 1991a]. What is known about the seismicity is very incomplete,

Table 1. Strongest earthquakes of the Greater Antilles [Cotilla, 1993]

Date			Coordinates		Magnitude
D	M	Y	N	W	Ms
07	06	1692	(17.8)	(–76.8)	(7.5)
04	06	1770	(18.6)	(–72.6)	(7.9)
07	05	1842	(19.8)	(–72.2)	(8.2)
23	09	1887	(19.4)	(–73.4)	(7.9)
29	12	1897	(20.1)	(–71.2)	7.5
11	10	1918	18.5	–67.5	7.5
29	07	1943	19.25	–67.5	7.75
04	08	1946	19.5	–69.5	8.1

Note: The numbers in parentheses indicate determinations as from macroseismic data.

but it becomes more detailed as one moves from west to east. Reliability is also variable, from a small number of events whose epicenters are known with good precision to a large number with great uncertainty [Cotilla, 1993]. Quantitative reliable evaluations are lacking for national historic—macroseismic source material, both for the initial data (intensity felt by locality) as well as its later interpretations (epicenter, depth, magnitude, isoseismals layout, etc.) [Cotilla, 1999; Cotilla and Álvarez, 2001]. Also, the sources of the initial data are various (press, chronicles, ancient witnesses' memories of the earthquake, immediate interviews post—earthquakes, etc.) and not everything is equally reliable [Cotilla, 1999]. However, these catalogs do not make an analysis of the data quality [Cotilla, 1993]. For all these reasons, an earthquake catalog was prepared for the westernmost part of Cuba (Pinar del Río and La Habana provinces) from 18 sources [Castellanos García, 1933; Chuy et al., 1994; 1988a, 1980; Cruz, 1958; Fuchs, 1882; González and Chuy, 1983; Mallet, 1906; Martínez-Fortún y Follo, 1948; Montelieu, 1968; Morales y Pedroso, 1931; Perrey, 1843; Pichardo, 1854; , 1857; 1855; 1855a; Salteraín y Legarra, 1884; Sieberg, 1932; Somohano, 1969; Tomblin and Robson, 1977] (Table 3). The catalog contains 56 earthquakes from the 1678–1981 periods (303 years) and, in Table 3a, a summary by locality. Some characteristics of the catalog are in Tables 4 and 5. This material coincides with Álvarez et al. (1999) in 94%.

5. THE SAN CRISTOBAL EARTHQUAKE

During the early morning of the January 22–23, 1880, a part of the Western Cuba region was strongly shaken once by an earthquake that according to Chuy et al. [1988] had maximum intensity of VIII (MSK scale) (Table 6). This seismic event is still the strongest to hit the Western, Central and Eastern-Central regions (Fig. 4b). All the inhabitants perceived the earthquake since it was noticeable in the provinces of Pinar del Río, La Habana and Matanzas, and in localities such as Cienfuegos (~300 km east).

Before this event, the Cuban authorities and population had considered the Eastern region, and in particular Santiago de Cuba, the only one that could suffer the consequences of the earthquakes ($I = 9$ degrees, MSK), like the one on June 11, 1766 and August 20, 1852. They were shocked by the strong seismic events in the western part of the country. In this way, logical fears and not a few speculations sprung up on the ori-

Table 2. Strongest earthquakes of the Western Neotectonic Unit [Cotilla, 1993]

Date			Intensity (MSK)	Magnitude	Locality
D	M	Y			
23	01	1880	8	(6.0)	San Cristóbal
11	06	1981	5	3.7	Alonso de Rojas–La Coloma
16	12	1982	6	5.0	Torriente–Jagüey Grande
05	01	1824	6	(4.3)	Trinidad
12	08	1873	6	(4.5)	Remedios
24	01	1909	6	(4.3)	Trinidad
15	08	1939	7	(5.6)	Remedios–Caibarién
30	07	1943	6	(4.6)	Trinidad
08	04	1974	6	(3.7)	Esmeralda
24	10	1976	6	4.1	La Felicidad (Manicaragua)

Note: The numbers in parentheses indicate determinations as from macroseismic data.

Table 3. New catalog of earthquakes for the most Western part of Cuba from 18 source

Date	Locality	Catalog																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Σ
1678	Habana			X																1
1693	Habana	X	X		X	X	X	X	X	X	X	X	X							11
13.11.1762	S. de las Vegas	X	X				X	X		X	X	X	X	X						9
07.07.1777	Güines	X	X	X	X	X	X					X	X		X	X				10
21.06.1791	La Habana		X	X			X	X				X	X							6
1810	La Habana		X	X		X	X					X	X							6
1835	La Habana		X	X	X	X		X	X			X		X						8
08.03.1843	La Habana	X											X	X						3
21.03.1843	La Habana	X											X	X						3
1846	La Habana		X				X					X	X			X				5
1852	La Habana		X			X		X				X	X							5
1854	La Habana		X			X		X	X			X	X							6
04.10.1859	La Habana												X							1
–.12.1862	La Habana		X				X					X	X							4
25.03.1868	La Habana											X								1
–.03.1873	La Habana		X									X								2
–.12.1878	Bahía Honda		X																	1
–.12.1879	Candelaria		X									X					X			3
21.12.1879	San Cristóbal		X					X					X				X			4
23.01.1880	San Cristóbal		X	X								X						X	X	5
31.08.1886	Ceiba del Agua		X	X				X				X	X							5
16.09.1899	San Cristóbal												X							1
06.05.1905	San Cristóbal		X				X	X									X			4
12.10.1905	Jaruco		X				X					X	X							4
06.05.1906	San Cristóbal		X				X						X				X			4
08.05.1906	San Cristóbal		X				X						X				X			4
19.02.1907	La Habana		X				X					X	X							4
15.04.1907	La Habana												X							1
27.05.1914	Batabanó		X				X					X	X							4
28.05.1914	Batabanó												X							1

Table 3. (Contd.)

Date	Locality	Catalog																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	S
23.09.1921	Caimito de Guayabal		X				X					X	X							4
17.04.1937	San Cristóbal		X					X					X				X			4
20.12.1937	San Cristóbal		X					X					X				X			4
21.12.1937	San Cristóbal		X				X						X				X			4
15.02.1939	Consolación del Sur		X					X					X				X			4
20.04.1939	Consolación del Sur							X					X				X			3
–.–.1940	Hermanos Bacón												X							1
–.–.1941	La Habana												X							1
18.12.1942	La Habana						X					X	X							3
16.06.1953	Tapaste		X				X					X	X							4
11.09.1957	La Habana				X			X				X	X							4
–.–.1958	Hermanos Bacón												X							1
–.12.1958	San Cristóbal		X										X				X			3
–.–.1959	Hermanos Bacón												X							1
04.06.1962	San Cristóbal												X				X			2
–.–.1964	Punta Cartas												X							1
24.06.1964	San Cristóbal		X					X												2
16.10.1970	Bahía Honda											X								1
09.03.1976	Central“J.Marti”		X										X				X			3
10.03.1976	Central“J.Marti”		X										X				X			3
15.03.1976	Central“J.Marti”		X										X				X			3
18.10.1980	Viñales												X							1
24.10.1980	Viñales												X							1
25.10.1980	Viñales												X							1
09.06.1981	San Juan y Martínez												X							1
11.06.1981	Alonso de Rojas												X							1
	S	5	33	7	4	6	17	15	3	2	2	23	46	4	1	2	15	1	1	187

Note: Catalog (1 = [1857; 1855a; 1855b]); 2 = Chuy and González [1980]; 3 = Somohano [1969]; 4 = C. Cruz [1958]; 5 = Hernández; 6 = Martínez–Fortún y Follo [1948]; 7 = Montelieu [1968]; 8 = Morales y Pedroso [1931]; 9 = Tomblin and Robson [1977]; 10 = Mallet [1906]; 11 = Chuy et al. [1983]; 12= Chuy et al. [1988]; 13 = Perrey [1842]; 14 = Pichardo [1854]; 15 = Castellanos [1933]; 16 = González and Chuy [1983]; 17 = Fuchs [1880]; 18 = Sieberg [1932]).

gin of the earthquake and the possible repetitions in the future. A scientific commission was named, composed of Father Benito Viñes Martorell, S.J. and Pedro Salteraín y Legarra, two prestigious local figures. The former was designated leader of the investigation. They were to inspect the affected localities and present a final report. It was to contain all data and scientific opinions available and make safety proposals [Viñes and Salteráin, 1880]. Other specialists also provided information on the earthquake [Fuchs, 1882; Rockwood, 1880]. The national and foreign press reported the event (Table 7). At later dates, various authors have made reference to this earthquake [Edo Llopis, 1888; Graces, 1990; Morales y Pedroso, 1931; Rousseau and Díaz, 1888; Taber, 1922] but whiout mention any relation to a fault.

Álvarez et al. [1999; 1993] and Chuy [1999] have the same principal data on the earthquake (January 23, 1880, 04 h 39 m, 22.70°N–83.00°W, h = 25 km, $M = 6.0$). Using Álvarez et al. [1999] we correlated 19 earthquakes to the GF (Table 8). On this basis, Tables 9 and 10 have been prepared. The epicentral and perceptibility areas appear with aftershocks. 89% of the aftershocks are in an area of 100 km^2 approximately, with a predominantly latitudinal main axis. The perceptibility area is around 40 000 km^2. Chuy and González (1980) assigned to the main shock an intensity of 8 degrees (MSK) and the first isoseismals map had the main axis in the PF. The isoseismals of Chuy (1989) and Chuy et al. [1988a] for this earthquake were, as stated previously, very modified by Orbera et al. [1990], who is so doing significantly reduced the perceptibility data in Ciudad de La Habana, although they maintained the seismogenetic element PF.

The Tables 11, 12 and 13 show aftershocks, magnitudes and estimated depths, respectively. 85% of earthquakes are to a 15 km depth, and 90% are magnitude 4.0. In Table 14, the evaluations of this earthquake from two catalogs appear (made for two different nuclear power plants projects) for a set of localities. With respect to these evaluations and their posterior and successive modifications, we indicate: (1) the data of Chuy et al. [1988] does not enable the modification of the seismic intensity; (2) in Fig. 4 (map of seismic intensity for recurrence period of 100 years) of Chuy et al. [1994], Ciudad de La Habana and the Center of Nuclear Research (CNR) appear framed in a very small area with $I < 5$ degrees (MSK). Furthermore, almost the entire Pinar del Río—La Habana—Matanzas region is within an area of 5 degrees (MSK). In this way, and with such considerations ($I < 5$ degrees MSK), it is feasible to construct a CNR, without using scientific special investigations, as recommended by the International Organization of Atomic Energy [Cotilla, 1999; 1998; Cotilla and Álvarez, 2001]. However, there is an evident contradiction reflected in the Orbera et al. [1990] data: the 1880 earthquake had an intensity of 6 degrees in Ciudad de La Habana. This means one of two things, or both: (1) mistake; (2) distortion.

Table 3a. Summary of earthquakes in the new catalog (Table 3)

Locality	Events	Locality	Events
Alonso de Rojas	1	Hermanos Bacón	3
Batabanó	2	Jaruco	1
Bahía Honda	2	La Habana	19
Candelaria	1	Punta Cartas	1
Caimito del Guayabal	1	San Cristóbal	12
Ceiba del Agua	1	San Juan y Martínez	1
Consolación del Sur	2	Santiago de las Vegas	1
Sugar Cane Factory “J.Martí”	3	Tapaste	1
Güines	1	Viñales	1

Table 4. Seismic intensity in the new catalog (Table 3)

Intensity (MSK)	8	7	6	5	4	3	¿?	Σ
Events	1	–	1	7	15	23	9	56

Table 5. Some data of the new catalog (Table 3)

Whiout information of	Events
Month	11
Day	16
Month and day	11

Vines and Salterain Data

The scientific work of Vines and Salterain [1880] demonstrates the genius of the thought and actions of these specialists. For the first time for Cuba, data from first—hand field work is accompanied by serious evaluation, highlighted by a magnificent synthesis and careful wording. Their research points out the affected sites and the economic ruin of the region, and includes some engineer-geological observations. It was the first scientific essay in the Caribbean utilizing the theory of focal region proposed five years before by E. Suess as indicated Cotilla [1993]. The authors tied, for the first time, responsibility for this seism to a structure belonging to the south plain of the Pinar del Río. Some paragraphs from their article demonstrate this theory, pointing out the aspects of concern.

Page 5: “*...After examining the ruins of Candelaria and having examined the composition of the land there, we moved on to Balestena, a house located at the foot of some hills on the property called Rangel of Sr. Sauvalle. Thanks to its solid construction and to the fact that the tremors were felt with much less intensity in the hills than*

Table 6. Some macroseismic evaluations of the San Cristóbal earthquake by Chuy et al. [1988]

Catalog

Locality/Intensity (MSK)	Description
San Cristóbal/8	A lot of installations and destroyed walls, thick split at some houses. The pigeonhole and the base of the tank of the “Calórica” resentful; destroyed Puente Pedroso. Once the stirrups of Arroyo Grande’s Bridge in spite of its solidity and volume was damaged. The Army house collapsed. The cracks at the land opened of to 100 m of length and 8 cm of opening, the ones that they gushed forth water, root pieces and fine and thick sands. It produced immense panic in the population; a lot of wounded persons and a dead person. Ground oscillations from NE-SW; subterranean loud noises. It cracked walls and roofs and knocked over the Church’s porch. Once the government house as well as Humara’s and Don Pascual’s house was destroyed. Very damaged the telegraphic and destroyed station the Town Hall. Very damaged all the houses of masonry for landslides of roofs and walls. Heavy booksellers' fall. The Court and the Clerkship were in ruins, as well as the complete locality. It stirred wooden posts and joists at the wooden houses. It displaced furniture and iron boxes; besides it broke tablewares.
Candelaria/8	The Church was knocked down completely. Houses of loud construction knocked down and another one with large cracks and flaws. It produced a lot of damages at the buildings; a strong wooden house getting destroyed collapsed. It produced panic in the population. All the houses of masonry got ruinous or destroyed and altogether uninhabitable for large cracks in the walls and fall of roofs. Furniture out of order. It stirred wooden posts and joists at the wooden houses. It knocked down shelves. The pictures fell down and it broke tablewares.
Ingenio San Juan Bautista/8	Factory’s house collapsed causing three dead persons, being left this in ruins. The towers of the house of machine and the boilerhouse fell down. The fall of windows and walls are indicated at the house of purging.
Ingenio Galope/8	Factory’s house collapsed almost totally. The walls that remained standing show enormous cracks. They felt loud subterranean noises.
Finca de Don Manuel Vega/8	(Near the San Cristóbal river.) It produced cracks of to 370 m in length and 11–15 cm in width and others of 15–20 m in length and more than 5 cm in width; water with sands went out of these cracks. The new springs sprang forth.
Paso Bordales/8	(In Mayarí road for the San Cristóbal river.) The bridge fell down.
Hacienda Los Pinos/7–8	It muddied the water of the rivers, which seemed to boil. The walls of the houses cracked; in the house (heavy building) the false ceilings and tiles fell down. The banana plantations oscillated. The shakes were strong. Loud subterranean noises.
Ingenio San Juan de Argudin/7–8	(In Guanajay.) The factory’s boilers fell down.
Finca Balestena/7–8	(In Rangel.) Loud subterranean noise. It produced panic. The walls of the houses cracked, vertical and horizontally largely.
Manantiales/7	A large rock came off from a mountain.
Soroa/7	They yielded the shakes less intense than in San Cristóbal and Candelaria.
Chirigota/7	Destroyed the walls and cracked other buildings. Loud senses subterranean noises.
Río Hondo/7	Two houses collapsed. The underground water levels climbed on dry wells and a lagoon.
Mangas/7	Panic and strong motions of the rooftops, landslides in walls; breakings in the tablewares; cracks at the road and sewers.
Bayate/7	The group of houses suffered very much.
Los Palacios/7?	The force of the shakes was minor than in San Cristóbal.
Taco-Taco/7	The river’s waters became blurred.

Table 7. Information about the 1880 earthquake in the press

No.	Press	Country
1	Diario de La Marina	Cuba
2	Diario de Cienfuegos	Cuba
3	Diario de Matanazas	Cuba
4	La Voz de Cuba	Cuba
5	La Discusión, La Habana	Cuba
6	New York Herald	United States of America

in the plain, the house suffered very little damage, although enough to be able to appreciate the direction of the oscillation... The second observation is that we became more and more convinced that the center of the oscillation or focus of greatest intensity of the tremors would not be found in those fearful hill, but rather away from them... "[The term hill refers to the mountainous areas (today SR and SOr) (Fig. 4a). Otherwise, it is obvious that these specialists place the search of the epicentral area on the southern plain.]

Page 5: "*... This final idea grew stronger within us on the occasion of new tremors felt on the night of the 29th to the 30th. Indeed: these tremors, which were felt with much force even at points located farther south toward the coastline, we did not feel at all in Balestena, in spite of being awak at the time."* [The area of location of the aftershocks is marked off (still strong) to the southern plain.]

Page 5: *...Luckily the area shaken by the tremors which on the night of the 22nd to the 23rd reached at least noticeable intensity from farther away than Mantua to the west, to Matanzas in the east, and to Cayo Hueso to the north remained apparently circumscribed to the area from the southern coast to the hills, San Diego de los Baños and Artemisa by the other, with the notable particularity that in both cases they had the same axis of greatest intensity of the phenomenon..."* [They indicate very well the aftershock area and it spatial orientation (SW–NE).]

Page 10: "*...From there we continued our journey to Candelaria and then on the next day to the Galope farm, in Bayate... In our opinion three fatal circumstances contributed to its total destruction; that the farm was situated in the zone of greatest intensity of the phenomenon, the ground's lack of stability, and the verified diagonal oscillation with respect to the stones' arrangement in the constructions, which meant that all the walls were broken apart and destroyed, some falling, some breaking to bits, these leaning, those twisting... The farm's tower was split as if cut and beveled at an angle of NE 1/4 E, and as for the two towers of the outlying constructions, one fell to the NE 1/4 E and the other to the SW 1/4 W... The under-*

Table 8. Other earthquakes related with the Guane fault according with Álvarez et al. [1999]

		Coordinates			
Date	Time	N	W	h (km)	Magnitude
13.11.1762	–	(22.98)	(–82.7)	(10)	(3.1)
31.08.1886	22:20:00	(22.94)	(–80.1)	(15)	(3.8)
1905	–	(22.75)	(–83.0)	(20)	(3.5)
12.10.1905	–	(23.05)	(–82.01)	(10)	(3.1)
23.09.1921	–	(22.91)	(–82.64)	(10)	(3.1)
15.02.1939	16:45:00	(22.60)	(–83.30)	(15)	(2.7)
20.04.1939	–	(22.50)	(–83.52)	–	–
1958	–	22.71	–83.06	15	3.3
1964	–	21.94	–78.43	10	3.1
1974	–	22.70	–81.20	18	3.4
09.03.1976	16:05:00	22.65	–83.01	15	2.7
10.03.1976	15:40:00	22.65	–83.01	15	2.7
15.03.1976	18:50:00	22.65	–83.01	15	2.7
1978	–	22.24	–83.58	10	3.1
09.06.1981	23:03:00	22.28	–83.84	15	3.0
11.06.1981	18:35:00	22.20	–83.48	10	3.7
1982	–	22.66	–83.96	20	3.5
05.09.1988	04:49:52	22.68	–82.95	–	1.04
09.03.1995	18:29:13	22.90	–82.21	3	2.1

Note: The numbers in parentheses indicate determinations as from macroseismic data.

Table 9. The largest perceptibility zone of the San Cristóbal arthquake according with Álvarez et al. [1999]

	Coordinates	
Eastern zone	22.8°N	–80.8° W
Western zone	22.1° N	–83.2° W

Table 10. Epicentral area according with Álvarez et al. [1999]

Coordinates		Events
22.78° N, –83.30° W	22.78° N, –82.80° W	40
22.60° N, –83.30° W	22.60° N, –82.80° W	–

ground terrain shook ceaselessly to the SW,... From the same man we learned that on the Nuestra Señora de Lourdes horse farm, of Mr. Antonio Garcia, known before as the Larrazabal farm, all the stone buildings had been destroyed. Our desire to see and examine those ruins, heightened as we grew closer and closer to the south coast.... The main walls of the buildings of the old Larrazabal farm are oriented from NE 1/4 E to SW 1/4 W in approximately the same direction in which the oscillation was verified to have occurred, which resulted in the walls being perpendicular to the oscillation; some fell, others broke apart and out of plumb." [They recognized the epicentral area and the sense of propagation of the seismic waves. There are some engineering-geological assessments of the ground. This fits with the sketch of the GF and not the PF.]

Page 13: "*...The late hour meant we had to hurry to arrive before nightfall to the Flora property to which we had been most cordially invited by the President of the provincial government, Mr. José Rivero... This property, situated between Candelaria and Manantiales, and not far from the slopes of the hillsides, had suffered very little from the tremors. In the house, we saw small cracks, and the tower of the house was intact.*" [This points out that: (1) the main shock and the aftershocks are not in the PF scarp that is exposed in the relief of the GR; (2) the epicenters are located on the southern plain, in the surroundings of SC—Candelaria area; (3) the epicenters can correlate a geological structure covered up by sediments (GF); (4) the fractures and cracks have a prevailing NE strike; (5) noises, perceived by the inhabitants and the Commission's two specialists, come from the SW.]

Other Data and Notes on the Earthquake of 1880

Taber [1922] stated that... *"In contrast with the Sierra Maestra region the north and central parts of Cuba have been virtually free from seismic disturbance. A severe earthquake followed by aftershocks originated in the Sierra los Organos of western Cuba in 1880, but, before that this time and since, earthquakes have been almost unknown in that section"*... [Taber also mentions the seismic difference between the Western and Eastern Cuban regions, and in particular the quasi stability of the former. This observation had been formulated before by Salteraín y Legarra [1884]. Taber points out that a strong earthquake happened in Western Cuba with a lot of aftershocks.]

On January 23, 1880, a strong earthquake took place in the surroundings of San Cristóbal de los Pinos's (today SC) (Fig. 1), founded in the year 1743. The earthquake affected a wide area: Isla de Pinos (today Isla de la Juventud) in the south, Cienfuegos in the southeast, and Key West (La Florida) in the north [Álvarez et al., 1999; Fuchs, 1882; Rockwood, 1880; Viñes and Salterain, 1880]. Taber [1922] maintains that there were many victims and that the epicenter was south of the SOr, in SC-Candelaria, and that it had an intensity of 8–9 degrees (Rossi-Forel). The observations of Wooters (1986) are: (1) precise in that the epicenter was in the Southern Plain, between SC and Candelaria and in assigning it an intensity evaluation of 8–9 degrees (Rossi-Forel), that corresponds to 8 degrees (MSK); (2) imprecise regarding the number of dead (they were only 3) and when indicating that the epicenter was south of the SOr (Western zone of the GR), when in reality it is south of the SR (Eastern zone of the GR).

Table 11. Aftershocks of the San Cristóbal earthquakes according with Álvarez et al. [1999]

	Day/Events									
Month										Σ
01	23/6	24/5	25/2	26/6	27/5	28/1	29/1	30/5	31/3	34
02	01/1	02/1	09/2	23/1	24/1	25/1				7
03	15/1									1
04	01/1									1
05	20/1									1
06	05/1									1
										65

Table 12. Magnitudes determinated to the San Cristóbal earthquake and its aftershocks according with Álvarez et al. [1999]

Magnitude	–	2.7	2.8	3.0	3.3	3.5	3.6	4.0	4.3	4.5	4.6	6.0	Σ
Events	6	6	1	5	12	1	3	7	1	1	1	1	45

6. SEISMOTECTONIC STUDIES OF WESTERN CUBA

There are several seismotectonic works for the Western Cuba region (Fig. 4, Table 15), but three stand out. Two present seismogenetic maps [Orbera, 1983; Orbera et al., 1990]. However, the only shared element in these two works is the region of study and the absence of the GF; in other words, all the seismotectonic structures changed. Cotilla [1999; 1998; 1993] exhaustively discussed these modifications. The third material is the seismotectonic map (SM) of Cotilla et al. [1991] that definitely included the GF. Cotilla et al [1991] consider that it extends from southwest of the South Alluvial Plain of Pinar del Río up to La Habana provinces. There, it is blocked with the Habana-Cienfuegos fault (HCF), on the same map, and conforms an active knot (N4) (Fig. 5). With respect to existence and the HCF's activity, there has also been much controversy [Cotilla, 1999]. Specifically, at that crossing area, San José de las Lajas, an earthquake took place (March 9, 1995, $I = 5$ degrees, MSK) [González et al., 1995]. This locality is to the southwest of the aforementioned construction, in the sub-epigraph of the San Cristobal earthquake, CNR.

The work of Cotilla et al. [1991b] was based on remote sensing and the statistical treatment of the seismic information, with the application of the concept of alignment. This last term was rejected by the majority of the Cuban specialists [Cotilla, 1993]. In order to illustrate the subject, some explanation is necessary. The term "alignment" was coined for science by Hobs [1904]. Later, Hobs [1912] stated that a lot of alignments can be active seismotectonic lines, and for this reason much attention must be paid to the length of their lines and their shape, due to the clear danger of earthquakes. Hobs held that the most significant lines of relief can reveal elements of bedrock and crust architecture that are hidden and which have not been determined with traditional investigative methods. Brock [1972] defined it as a topographical or geological element, and that this linear condition is too precise to be a random occurrence and has no relation with its internal structure. Other specialists like: [Anisimova et al., 2007; Assinovskaya et al., 1994; Bankwitz et al., 2003; Spiridonov and Grigorova, 1980] demonstrate the benefit of this methodology in another regions. Cotilla et al. [199a] showed, for the first time, for Cuba, with help of remote sensing and field investigations that the active faults are segmented. This also was rejected, without scientific arguments, by the majority of the Cuban specialists [Cotilla, 1993]. Earlier Clark [1973] and Machette et al. [1991] showed with field studies that faults are geological discontinuous elements constituted by discrete segments. Bonilla [1979] indicated that, in the section of a fault, its geometry is too complex to remain homogeneous for its full length. Pérez and Azcuy [1992] confirm the remote sensing results, since more than 85% of their alignments determined with the magnetic and gravimetric processing coincide with the results of Cotilla et al. [1991]. Between those alignments is the GF. Later, the SM was validated by other investigations González [1996] and with other earthquakes by Cotilla [1998].

Table 13. Depth of the aftershocks of the San Cristóbal earthquake according with Álvarez et al. [1999]

Depth (km)	15	20	–	Σ
Events	38	1	6	45

On the other hand, Van der Plujin et al. [1997] stated that the tectonic efforts of the plate margins transmit inside the plates, even to distances of 2000 km. Also, they said that the status of forces at the interior continental zone seems to be relatively independent of the immediate surroundings, as well as of the previous tectonic style. That is, there is a predominance of transmission of information from the borders toward the interior of the plate, and, in consequence, force is dependent on distance and the magnitude of the transmitted effort. The reactivation of the faults and the presence of earthquakes are first dependent of the orientation of the zone of tectonic weakness to the force exercised and transmitted to the interior continental.

Cotilla et al. [1991a] considered that the interactions of the CP and NAP reflected in the differential seismic activity of the Cuban territory. This was one of their arguments for the differentiation of the Cuban Seismotectonic Provinces into three units, Southeastern, Eastern and Western. The first is in the contact zone of the mentioned plates through the Oriente fault, where the strongest and most frequent earthquakes take place. The other two units, much farther away from the zone of plate contact, and with a sharper angle of different influence, demonstrate an interior seismicity of weak and moderate plates, with periods of repetition greater than 100 years.

7. DISCUSSION

The epicentral area of SC's earthquake of January 23, 1880 ($I = 8$ degrees, MSK), is in the WNU of the Cuban megablock in the NAP's southern border and was defined as an interior plate territory. We have estimated the affected area at 40 000 km^2 on the basis of

Table 14. Seismic intensity of the San Cristóbal earthquake from two different sources

		Intensity (MSK)	
No.	Locality	Chuy et al. [1988]	Orbera et al. [1990]
1	Ingenio Almagro	8	7
2	Ingenio San Gabriel	8	7.5
3	Ingenio Dos Hermanos	8	7.5
4	Ingenio Ramos	7–8	7
5	Finca Balesterra	7–8	7
6	Chirigotas	7	8
7	Río Hondo	7	8
8	Bayate	7	8
9	Mangas	7	7–8
10	Plantación de Café Buena Vista	7	7–8
11	La Habana	6	6
12	Guanabacoa	6	¿?
13	Regla	6	¿?
14	Guanajay	5–6	6
15	Matanzas	5–6	5–6
16	Santa Cruz de los Pinos	5	7–8
17	Jaruco	5	5
18	Key West	4	3.5
19	Cárdenas	4	4
20	Cienfuegos	3	3.5
21	Puente Arroyo Grande	–	8
22	Puente Pedroso	–	8
23	Río San Cristóbal	–	8
24	Ingenio Rufino	–	7–8

the points of perceptibility. This value is superior to the appraisal (34000 km^2) made for December 16, 1982 ($Ms = 5.0$, $h = 30$ km, $I = 6$ degrees MSK in Torriente-Jagüey Grande (TJG)).

From a maximum intensity of 8 degrees (MSK) at SC and using the Sponheuer (1960) relation ($Ms = 0.66I_0 + 1.7\log h - 1.4$), assuming a depth of 20 km [Cotilla, 1993; Sherbakova et al., 1977; 1975], we obtain a magnitude of 6.3. Another expression that relates magnitude and intensity is $Ms = 1 + 2/3I_0$. This relation gives a magnitude value of 6.1. We considered the average value of those data (6.2). This result is reciprocated very well by the estimations of the areas of perceptibility of both earthquakes SC and TJG.

Table 16 shows the data foundation of the villages in the western Cuba region in which the 1880 seism was noticeable. On that basis, it is logical to reason that if in that Western Cuba region an event with these characteristics had not occurred previously then the structure responsible for the earthquake has a very long recurrence period. This agrees with the calculation (128 years) from the date of occurrence of the seism up to the present-day itself and concords with what was expected for an interior plate region. This means that Western Cuba is at the end of a seismic cycle.

The first seismic station on Cuba was located at Soroa (ESOR) (Fig. 4A). This obeyed the twentieth century Cuban and European specialists' theory that the PF was responsible for the SC earthquake. To date, a report of noticeable seism has not existed, at least not traceable to that fault. Over the PF and its uplifts there is a collection of industrial mining works (quarries) where explosives are systematically used for controlled blasting. Also, some artificial water reservoirs exist [Cotilla, 1993; Cotilla and Álvarez, 2001]. However, the ESOR only records blasting over the PF and not its own earth tremors [Cotilla, 1999; 1993]. Table 17 presents, for 13 localities in the surroundings of the SC, 34 earthquakes (1879–1982) associated with the GF, according to six groups of authors and which includes some events recorded by the ESOR, information which will be quite imprecise in regards to the coordinates, by not for the azimuth.

The fact that a hidden fault which does not manifest itself in the relief, like the GF, can be discarded in investigations of seismic hazard is not new [Johnston, 1989; Makarov and Schukin, 1976]. This can be justified, for the case of Cuba, by the presence, in the surroundings of the region, of another structure with very good expression in the relief, the PF. This same situation also occurred with the HCF, associated to the earthquake of TJG, $M = 5.0$, $I = 7$ degrees, MSK, which neither appeared on any map at all [Cotilla, 1993]. Other elements to consider are the quantity of earthquakes and the maximum magnitude yielded at the region. On the basis of the catalog of Álvarez et al. [1999], there are in the GF: (1) over 32 events at Pinar del Río's sector and 24 in La Habana; (2) the maximum magnitude in SC is 6.0 and in TJG 5.0.

The information of Viñes and Salteraín [1880] on SW of subterranean noise suggests that there is a sideways movement of the ground. This is supported by observations of the fluvial deviations and the characteristics of the morphostructures commented on for alluvial plain of the south of the Pinar del Río and by the intensity of the vertical motions. We have mapped

Table 15. Seismotectonic studies in the Western Cuba region [Cotilla and Álvarez, 2001]

Year	1980	1983	1988	1990	1991
Author(s)	Orbera	González and Chuy	Chuy et al.	Orbera et al.	Cotilla et al.

Table 16. Date of foundation of the cities in Western Cuba [Cotilla et al., 1991]

City	Year	
Original denomination / Actual denomination	Foundation	First seismic data
Villa de San Cristóbal de La Habana / Ciudad de La Habana	1514	1693
Matanzas / Matanzas	1693	1812
San Cristóbal de los Pinos / Pinar del Río	1743	–
Cienfuegos / Cienfuegos	1819 (1745*)	1849
Güines / Güines	?	1777

Note: * The fortress that puts away the entrance of the bay was edified in that date.

Table 17. Seismic activity on the Gaune fault and its surroundings from some Cuban catalogs [Cotilla and Álvarez, 2001]

Locality	Date		Locality	Date	
Candelaria	1879.12.–		La Isabel	1974	
San Cristóbal	1879.12.21	1937.12.20	Central "José Martí"	1976.03.09	
	1880.01.23	1937.12.21		1976.03.10	
	1905.05.06	1958.12.-		1976.03.15	
	1906.05.06	1962.06.04		1988.09.–	
	1937.04.17	1964.06.24			
Ceiba del Agua	1886.08.31		Punta de Cartas	1964	
Caimito del Guayabal	1921.09.23		La Coloma	1978	
Consolación del Sur	1939.02.15		Alonso de Rojas	1981.06.11	
			Las Martinas	1982	
San Juan y Martínez	1976.03.09	1976.03.15	Hermanos Barcón	1940	1959
	1976.03.10	1988.09.–		1958	

Note: CHG80 = Chuy and González [1980]; CHet83 = Chuy et al. [1983]; CHet88 = Chuy et al. [1988]; Get94 = González et al. [1994]; O90 = Orbera et al. [1990].

all epicenters of earthquakes that appear in the catalog of Álvarez et al.[1999] located at the coordinates of the perceptibility and epicentral areas of the 1880 earthquake (Fig. 7). They maintain an alignment SW-NE, practically through the middle south of the Pinar del Río—La Habana territory. Cotilla et al. (2005) applied, with good results, in Asturias the method of Tosi et al. [1994] in order to delimit, on the basis of a catalog of earthquakes, the seismoalignments. Therefore, with the catalog of Álvarez et al. [1999], we applied that methodology and, in Fig. 8, seven linear seism-elements are identified. Of these, number 1 agrees with a sector of the GF, precisely in SC.

It is known that the fundamental characteristic to define a fault is the motion and the presence of a surface of rupture. Lay and Wallace [1995] consider that a fault is any structure that presents a fracture and has a differential displacement with respect to adjacent materials located along the plane of a fracture. Reiter [1990] gives a definition of seismically active fault (SAF). He argues that its existence is due to the occurrence of at least one earthquake. NUREG-1451 [1992] presents three characteristics for active faults: (1) that they demonstrate displacements in the Quaternary; (2) that they have correlated seismicity; (3) that they possess a structural relationship with other faults in which relative displacement and a favorable orientation to observable fields of tectonic forces are identifiable. Machette et al. [1991] and Trifonov et al. [1993] considered that active faults are those with activity in the Holocene and the Upper Pleistocene. All these aspects suggest that the GF is an active structure. According to Hatter et al. [1993] one considers that a fault, a zone of faults, or system of faults is considered active if one or both of the following elements is true: (1) direct observation of the connection of the faulting with at least one earthquake; (2) occurrence and a good space location of the earthquakes or microearthquakes close to a known fault. Both are true of the GF.

Sykes [1978] noticed that the intraplate seismicity is localized, principally, at pre-existing zones of tectonic weakness. Similar results appear in [Johnston, 1989; Johnston and Kanter, 1990]. Working Group on California Earthquake Probabilities (1995) concluded that hidden faults are potentially dangerous structures

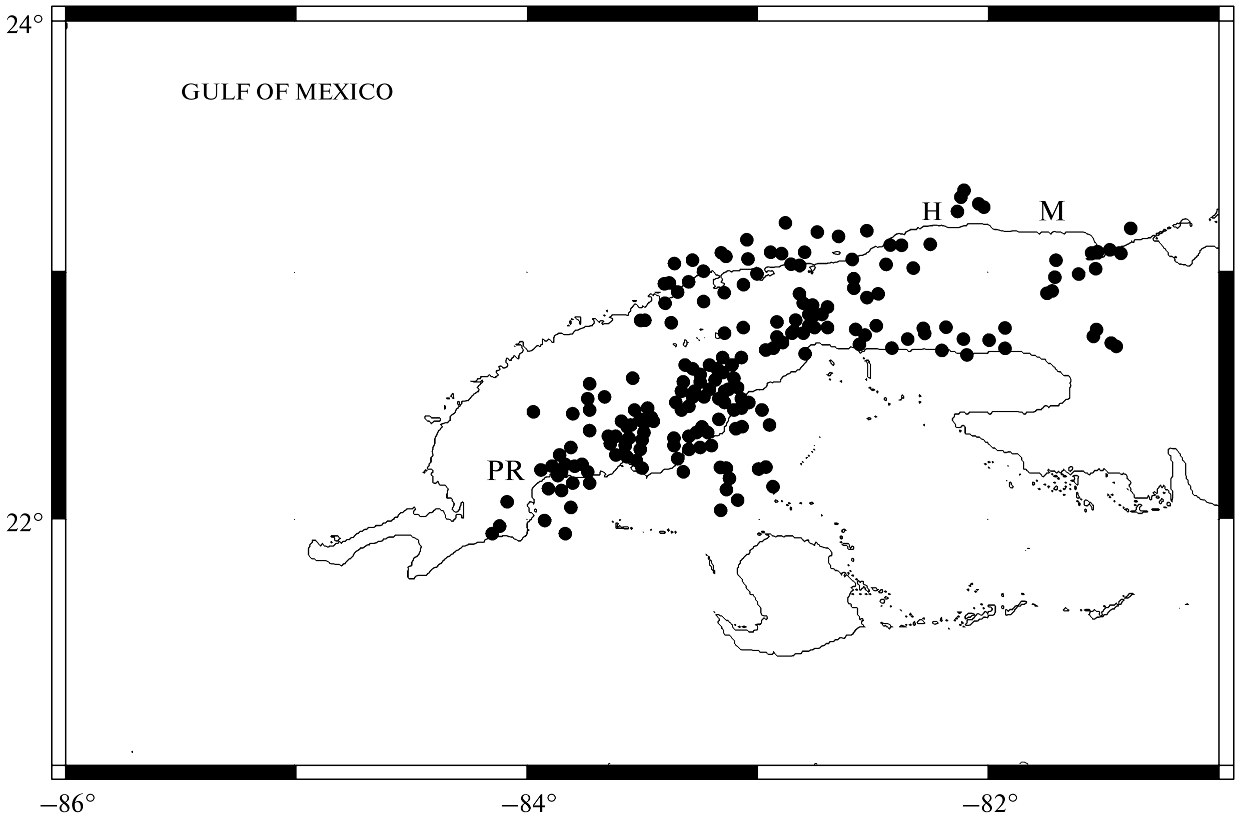

Fig. 7. Earthquakes in the surroundings of Guane fault [according with Álvarez et al., 1999]. The black circles are epicenters ($M < 2.0$) and the code of the localities (H = La Habana, M = Matanzas, PR = Pinar del Río).

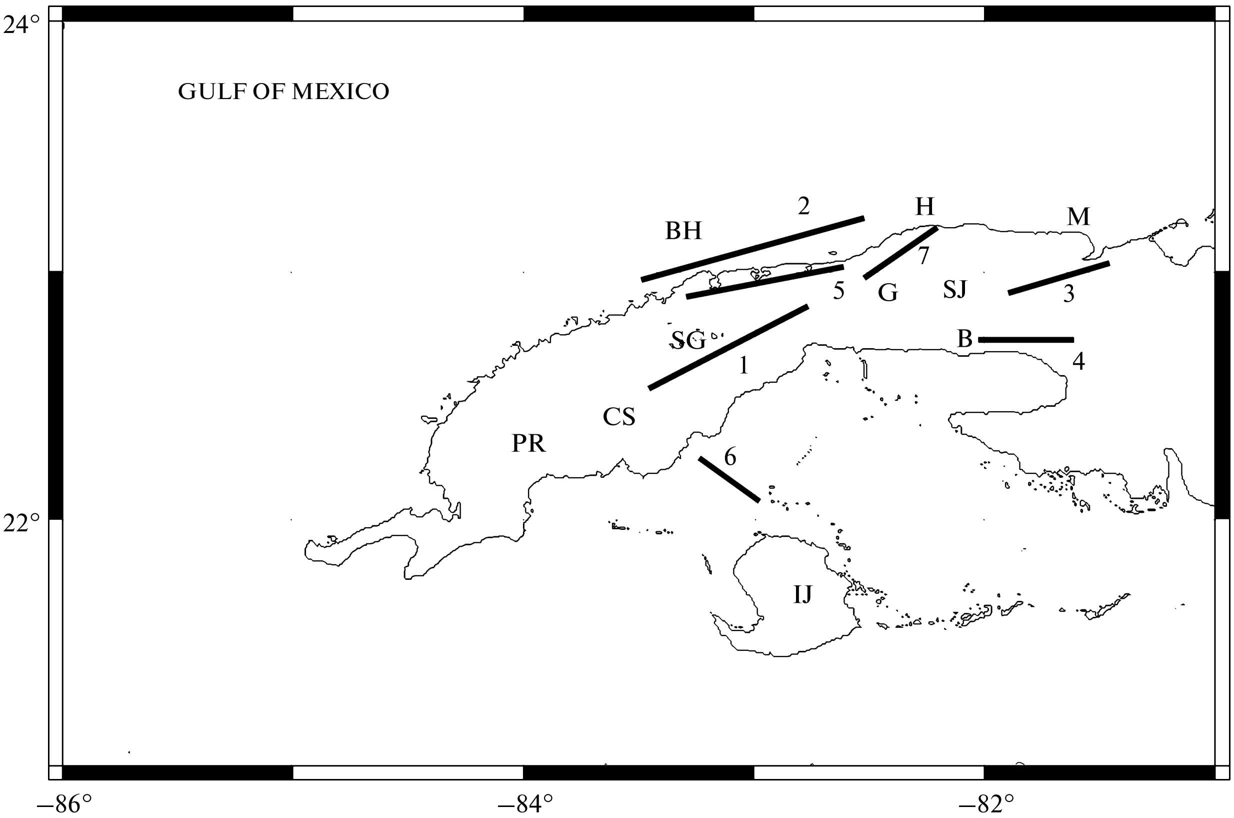

Fig. 8. Fig. 8. Seismoaligneaments. Heavy black lines are seismoaligneaments (1); the localities (B = Batabanó, BH = Bahía Honda, G = Guanajay, H = La Habana, IJ = Isla de la Juventud, M = Matanzas, P = Pinar del Río, CS = San Cristóbal).

and that seismotectonic studies should concentrate on them, especially when earthquakes are possible in the near future. This is the case with the GF. In addition, McKenzie and Parker (1967) argued that deformation is concentrated on the plate margins while the interior of the plates is rigid and non-deformable. Zoback [1992] showed that a horizontal compression can transmit over large distances through the lithosphere (continental and oceanic). Also, Van der Plujin et al. [1997] maintained that continental interiors are records of activity of those zones and the reactivation of the faults, with its paleoseismicity. All these elements are dependent on the strike of the zones of tectonic weakness for existing forces. With these arguments it is possible to explain for Cuba the presence of the compressive and extensive structures of interior plate types. In that way, Cotilla et al. [2007] found, in a preliminary way, a stress tensor for the Western region by examining kinematic indexes and the damages (cracks) in the wall of the Galope Sugar Factory (destroyed by the 1880 earthquake) that supports the idea of transpressive action toward the NE of the CP on the NAP (Fig. 5). Cotilla (1999) considers that the SC earthquake (Pinar del Río) and the earthquakes of TJG (Matanzas) and San Jose de las Lajas (La Habana) can be explained by the compression from the south produced by the CP to the NAP. That compression is very different from that located in southeastern Cuba, since this ends in direct interaction, while at the western region it is transmitted with a wider angle and through an oceanic structure, like the Yucatan Basin.

It can be appreciated in Fig. 2 how the plate boundary (represented by the Swan fault) is nearer to the SC than to San José de las Lajas and TJG. Therefore, the influence is greater at the first zone and logically the magnitude of the earthquakes should be greater. But also the disposition and geometric figures of the morphostructures are different in Pinar del José (longitudinal) and are approximately parallel to the zone of Swan faults, while correspondents to La Habana and Matanzas are transverse and square morphostructures. Also, the GF is longer in length and only has two segments, while the HCF possesses four segments. In this way, the maximum possible magnitude of the earthquakes decreases and, interestingly, they turn out to be bigger in Pinar del Río.

8. CONCLUSIONS

The data and results of Vines and Salteraín [1880] on the earthquake of the January 23, 1880, in SC, Pinar del Río province, Cuba, are of great importance. We found that: (1) The event caused only 3 fatalities; (2) the maximum seismic intensity was 8 degrees (MSK) in SC; (3) the estimated magnitude reached the value 6.2; (4) the area of perceptibility was of 40000 km ^{2}; (5) there were 65 aftershocks; (6) the depth did not exceed 20 km; (7) the GF: (a) was responsible of the earthquake; (b) is an interior plate structure with a long period of recurrence of strong earthquakes (128 years passed before there was another seismic event); (c) is correlated with 34 earthquakes in the 1879–1981 period; (d) is transversally relates with another active fault in the environs of San José de las Lajas, forming a seismoactive knot, responsible for March 9, 1995 earthquake; (8) the PF is not the seismogenetic element of the January 28, 1880 earthquake. The PF is considered subordinate to the GF.

We maintain that the mechanisms of plate interior readjustments through faults are the responsible for the earthquakes on January 23, 1880 (SC, Pinar del Río), December 16, 1982 (TJG, Matanzas), and March 9, 1995 (San José de las Lajas, La Habana), in the Western Cuba region. These earthquakes are explained by the transpression process of the CP on the NAP at the zone of Swan faults, and the consequent stress transmission toward the Cuban megablock.

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