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Seismicity and seismoactive faults of Cuba

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Abstract

The first catalogue of active regional faults of Cuba is presented. The seismotectonic map of Cuba is a base for studying the seismicity in this region. Of the 30 faults studied, only twelve are active. The main seismotectonic structure is the Bartlett-Cayman fault system, which borders the eastern and southeastern seismotectonic units in this region. Approximately 70% of Cuban seismicity is concentrated here. The Cauto-Nipe, Cochinos and Nortecubana faults border other seismotectonic units. The Nortecubana fault is the only one associated with a tsunami. All the faults are segmented. The faults described are related to the current tectonic stress regime of the Northern Caribbean. All the available information (maps, sections and profiles, photos, geological and neotectonic data on seismicity and focal mechanisms) is supported by a GIS.

Keywords: Crust types; fault; microplates; neotectonics; seismicity; seismic hazard; Cuba

Introduction

The relative motion between the North American and Caribbean plates controls the tectonic regime of the area at a regional scale (Cotilla, 1993) (Fig. 1). It has been argued that the eastward motion of the Caribbean plate relative to the North American plate occurs at a rate of 12–40 mm/yr (Dixon et al., 1998; Deng and Sykes, 1995; DeMets et al., 1990; Sykes et al., 1982). DeMets et al. (2000) estimate 18±3 mm/yr for southeastern Cuba. This eastward motion of the Caribbean plate produces a left-lateral strike-slip deformation along the Bartlett-Cayman (BC) fault zone (Calais et al., 1992; Renard et al., 1992; Mann et al., 1984a) and left-lateral slips along the Walton-Plantain Garden-Enriquillo fault zone (Pubellier et al., 2000; Burke et al., 1980). Four important local structures affect the tectonic regime in the area (Fig. 1): 1) the Mid-Cayman rise spreading center (Rosencratz and Mann, 1991; Rosencratz et al., 1988; Case and Holcombe, 1980; Caytrough, 1979); 2) the Cabo Cruz basin; 3) the Santiago deformed belt (Calais and Mercier de Lepinay, 1992; 1990); 4) the Maisi area (Cotilla et al., 199la; Pubellier et al., 1991). These structures account for more than 85% of the seismicity along this part of the plate boundary (Cotilla et al., 1991a).

Cuba is a megablock (or microplate) located in the southern part of the North American plate (Fig. 1) (Cotilla et al., 1991; Ladd et al., 1990; Lewis and Draper, 1990). The active plate boundary runs along the southeastern coast, where the main seismic activity follows the BC fault zone (Cotilla et al., 1997b; Calais et al., 1992; Mann and Burke, 1984). In this segment, faulting is mostly left-lateral strike-slip (Cotilla, 1998). The general pattern of seismicity in the Caribbean region is shown in Fig. 1. Large earthquakes occur along the plate boundary near Hispaniola, Jamaica and Puerto Rico (Fig. 2) (Pacheco and Sykes, 1992; Alvarez et al., 1990, 1985; McCann and Pennigton, 1990; Mann et al., 1984; Iniguez et al., 1975; Sykes and Ewing, 1965; Robson, 1964; Taber, 1922; Sherer, 1912), but since the 18th century no event has reached a magnitude of 7.0 (Fig. 3, *A*) (Cotilla, 1999; Cotilla and Udias, 1999). Low-magnitude seismicity (M_S < 4) occurs throughout the western region of the island and particularly around Santiago de Cuba (Fig. 3, *B*, *C*). The results in Cotilla et al. (1991a) suggest that Cuba is a seismotectonic province composed of four units (western, central-eastern, eastern and southeastern). Figure 4 shows the location of these units and their limits, three crust types (thick transitional, thin transitional and oceanic (Prol et al., 1993; Pusharovsky et al., 1987; Levchenko et al., 1976)) that compose the region, and some of the associated earthquakes. Figure 5 presents a simplified

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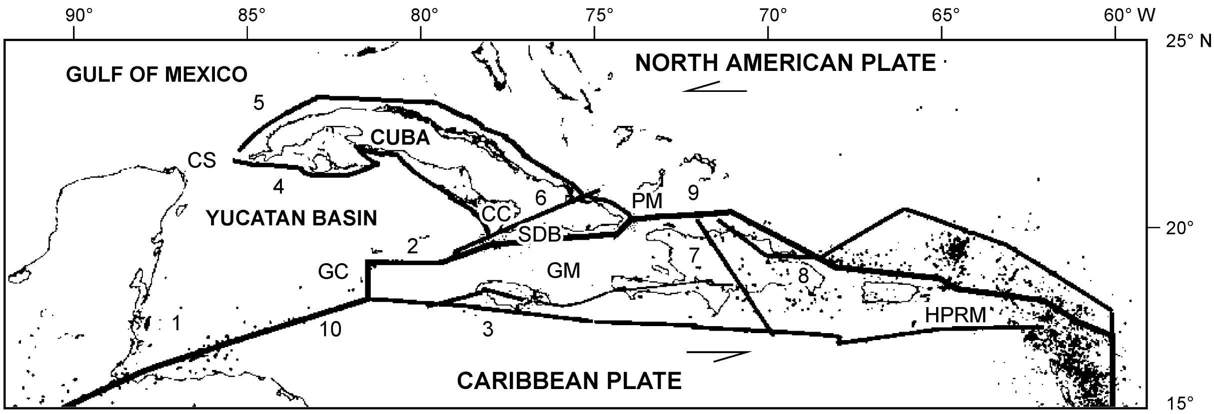

Fig. 1. Location of Cuba in the northern Caribbean with selected seismicity. Faults: 1 — Chixoi-Polochic-Motagua, 2 — Bartlett-Caiman, 3 — Walton-Plantain Garden-Enriquillo, 4 — Surcubana, 5 — Nortecubana, 6 — Cauto-Nipe, 7 — Bonao, 8 — Septentrional System, 9 — North Hispaniola, 10 — Swan. Microplates: Cuba, GM — Gonave, HPRM — Hispaniola-Puerto Rico. Sites: Mid-Cayman Spreading Center (GC), Cabo Cruz (CC), Punta de Maisi (PM), Santiago Deformed Belt (SDB).

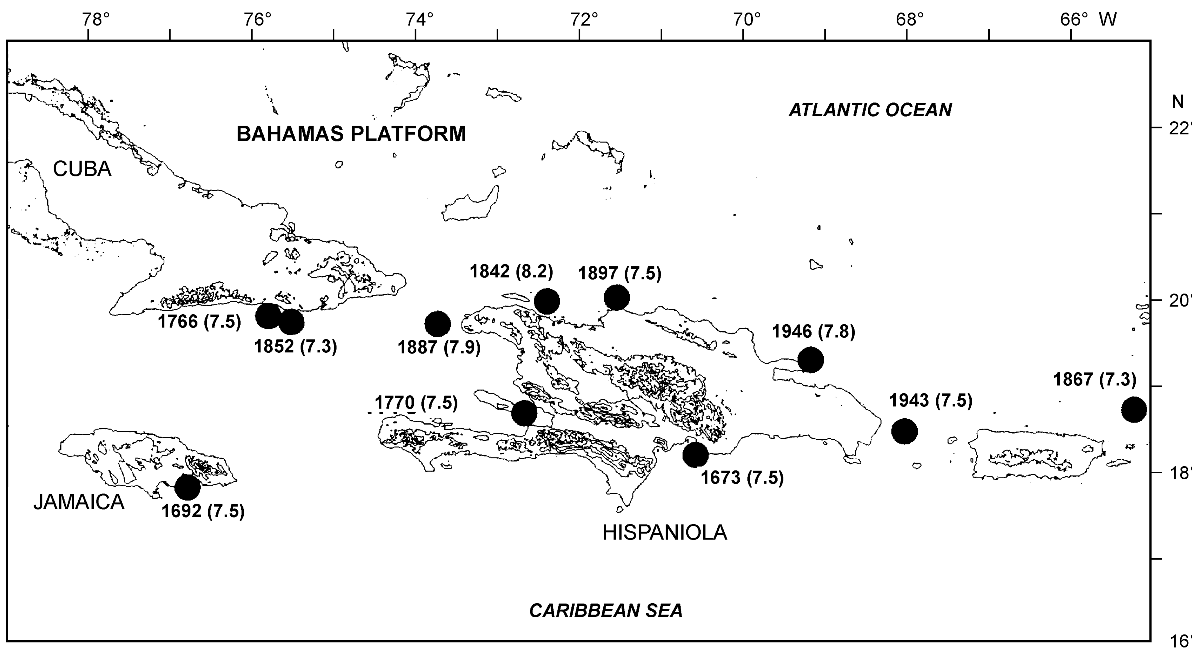

Fig. 2. Historical seismicity in Cuba and surrounding (from Alvarez et al., 1990). Parenthesized numerals are magnitudes.

seismotectonic map (SMp) of Cotilla et al. (199la), which is the basis for the present work.

Alvarez et al. (1985) identify two types of seismicity in Cuba, interplates (or plate edge) and intraplates. The first type is due to the direct interaction of the North American and Caribbean plates (Alvarez et al., 1990). Because of this interaction, the greatest number of seismic events, and those of greatest magnitude (M_S > 7.0), occur in the BC zone (Fig. 3, *B*) (Cotilla et al., 1998). The intraplate earthquakes take place in the rest of the island territory and the adjacent marine area out of the PBZ (Fig. 3, *C*) (Cotilla et al., 1998a). They are significantly less strong (M_S < 7.0) and less frequent than the previous type. Later, Cotilla et al (1997a) demonstrated the existence of an intermediate type of seismicity that corresponds to the eastern seismotectonic unit (USOR) (Fig. 4).

Perez and Azcuy (1992) found a good relationship (>80%) between the seismogenetic zones of the SMp and the linear elements of the geomagnetic field. Rodriguez (1996) employed the SMp for seismic hazard studies, with satisfactory results. Cotilla (1998) discussed the seismicity registered in the seismogenetic zones of Cuba. Cotilla (1998a) demonstrated some seismic data and focal mechanism solutions, from the international network (Perrot et al., 1997; United States Geological Survey, 1986; Mocquet, 1984; Dziewoski and Woodhouse, 1983; Harvard CMT 1977–1998; Kafka and Weiden, 1979; Molnar and Sykes, 1969; Sykes and Ewing, 1965), the validity and the scope of the SMp. Cotilla and Udias (1999) confirmed the differentiation of some of the seismotectonic zones and the regional differential influence in the seismic activity of Cuba. This last aspect was initially discussed by Cotilla (1998a) on the basis of microtectonic

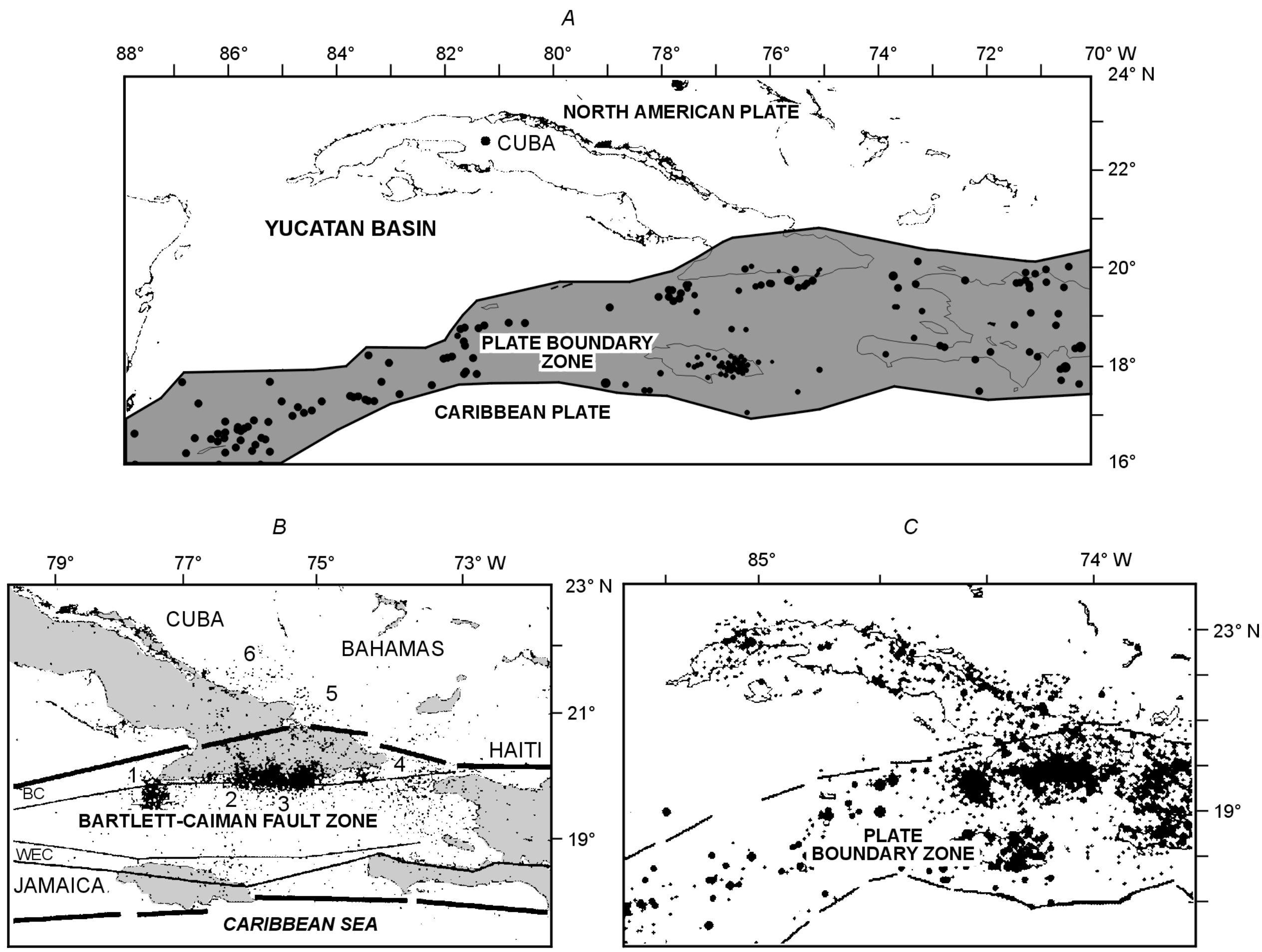

Fig. 3. Seismicity of Cuba and its surrounding. *A* — Seismicity of 1990–2004 ($M < 6.0$) determined with the international network (Plate Boundary Zone is in gray); *B* — Seismicity of 1979–1994 determined with the Eastern Cuban network ($n > 6$ and $M < 7.0$) (1 — Cabo Cruz, 2 — Sierra Maestra, 3 — Santiago de Cuba, 4 — Maisi, 5 — Nipe, 6 — Manati; Fault zones (BC — Bartlett-Caiman, WE — Walton-Plantain Garden-Enriquillo-Cul-de-Sac)]; *C* — Seismicity of 1977–1994 ($M < 7.0$) determined with the Cuban and international networks (Plate Boundary Zone is discontinuously outlined).

studies. The present work completes the fifth and final part of our research program which, as originally described in Cotilla (1993), sought to improve the SMp of Cuba and prepare a catalogue of active regional faults and its implementation in a GIS.

Faults, neotectonics and seismicity

Seismic hazard assessment is a difficult task for any country (Ballassanian et al., 1994). But it is a particularly more difficult task for countries facing severe social, political and economic problems, such as Cuba (Cotilla and Alvarez, 2001). Also, a fundamental problem in assessing earthquake hazard from an active fault zone is determining the extent of future rupture. Fault zones can be discontinuous, and the extent of rupture may be physically bounded by the fault zone discontinuities. Nevertheless, plate tectonics provides a framework in which seismic activity and seismic hazard can be explained as recurrent phenomenon associated with faults.

It is known that the fundamental criterion used to define a fault refers to movement in a break surface. Thus, Lay and Wallace (1995) identify as a fault any tectonic structure which has a fracture and a differential displacement of the adjacent materials throughout, parallel to the plane of fracture. Meanwhile, Reiter (1990) tempers the definition for the case of a seismic active fault (ASF). He argues for the existence of an ASF when there is evidence that, at some given time, at least one earthquake occurred. On the other hand, the authors of NUREG-1451 (1992) in their seismic hazard studies described three types of faults. Furthermore, they consider that a fault is active when it demonstrates a displacement in the Quaternary, directly associated seismicity, structural relationship with other faults subject to displacement, and a favorable direction with respect to the current tectonic stress field. Meanwhile, Trifonov and Machette (1993) consider that the active faults are those which offer evidence of this kind in the Holocene or Late Pleistocene.

On the basis of Hatter et al. (1993) a fault, fault zone or fault system are considered seismically active if one or several of the following criteria are satisfied: a) direct observation of faulting in connection with at least one earthquake; b) occur-

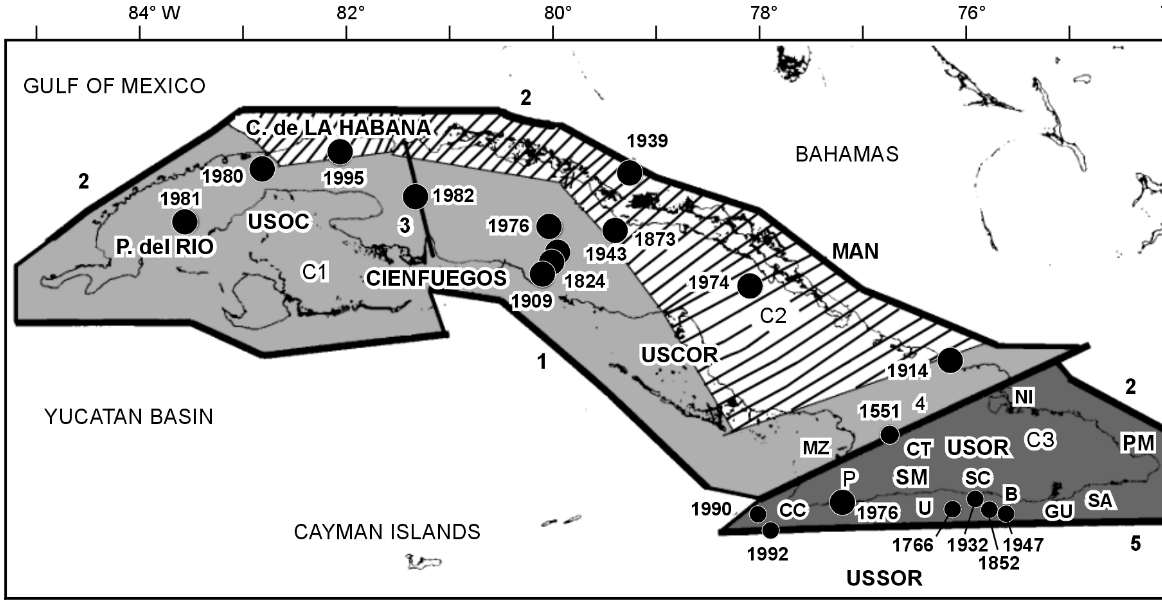

Fig. 4. Crust types and seismotectonic units of Cuba. Faults: 1 — Surcubana, 2 — Nortecubana, 3 — Cochinos, 4 — Cauto-Nipe, 5 — Bartlett-Caiman. Crust type: Cl — thin transitional, C2 — thick transitional, C3 — oceanic. Seismotectonic unit (SU): OC — western, COR — central-eastern, OR — eastern, SOR— southeastern. Black circles — selected epicentres (1824 — year). Localities: B — Baconao, CC — Cabo Cruz, CT — Cauto, GU — Guantanamo, MN — Manati, MZ — Manzanillo, NI — Nipe, P — Pilon, PM — Punta de Maisi, SA — San Antonio del Sur, SC — Santiago de Cuba, SM — Sierra Maestra, U — Uvero.

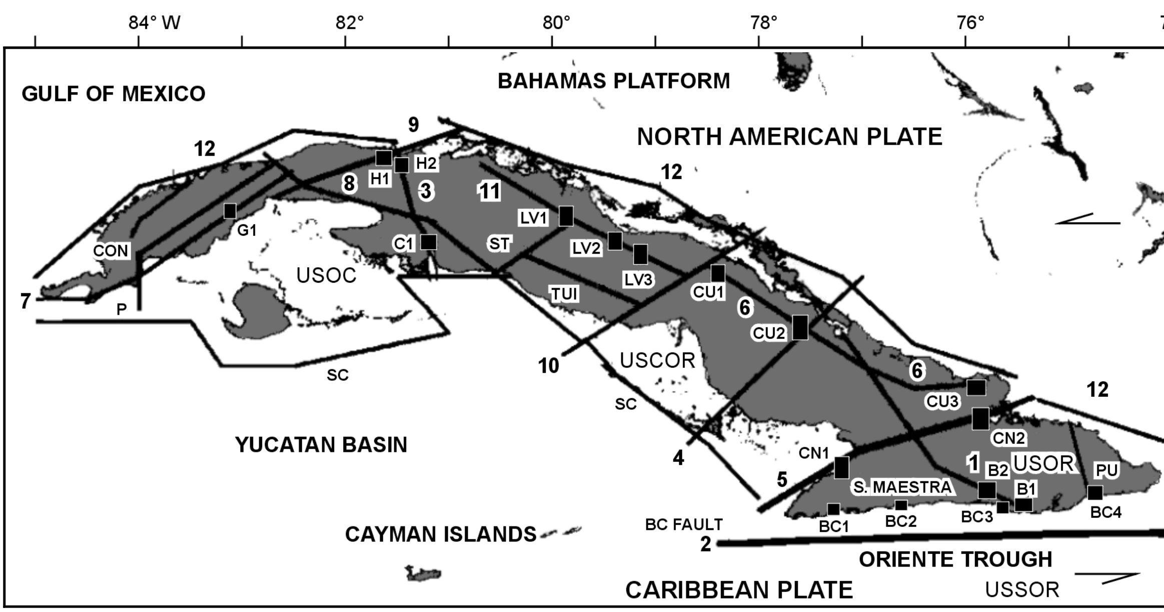

Fig. 5. Simplified seismotectonic map of Cuba (Cotilla et al. (1991a). Active faults: 1 — Baconao, 2 — Bartlett-Caiman, 3 — Cochinos, 4 — Camaguey, 5 — Cauto-Nipe, 6 — Cubitas, 7 — Guane, 8 — Habana-Cienfuegos, 9 — Hicacos, 10 — La Trocha, 11 — Las Villas, 12 — Nortecubana. Other faults: CON — Consolacion del Norte, P — Pinar, PU — Purial, SC — Surcubana, ST — Santa Clara, TUI — Tuinicii. See Tables 1 and 2. Black squares are sites for which microtectonic measurements are made (see Fig. 10).

rence of well-located earthquake or microearthquake activity close to a known fault. In addition, a well-constrained fault-plane solution with one nodal plane showing the same orientation and sense of displacement as the fault is required; c) close correspondence of orientation of nodal planes and senses of displacement of well-constrained fault-plane solutions to the type and orientation of young faults or fault zones observed in the epicentral region; d) mapping of hypocenters by high-precision location of individual events of local clusters of earthquakes displaying almost identical signal forms, controlled by well-constrained fault-plane solution (*s*).

Sykes (1978), however, observed that the intraplate seismicity areas are located throughout pre-existing tectonic weakness zones. Similar results where obtained by Johnston

(1989) and Johnston and Kanter (1990). Also, the Working Group on California Earthquake Probabilities (1995) concludes that the hidden (or blind) faults are potentially dangerous structures that future seismotectonic studies should concentrate on, especially when earthquakes are expected in the immediate future.

McKenzie and Parker (1967) argued that deformation is concentrated at plate margins whereas plate interiors are rigid and undeformable. Zoback (1992) showed that horizontal compressional stresses can be transmitted over great distances through the continental and oceanic lithospheres. Also, Van der Pluijm et al. (1997) assured that continental interiors registering plate tectonic activity and intraplate fault reactivation (and earthquake triggering) are mainly dependent on the orientation of (weak) fault zones relative to the plate margin, and that deformation of continental interiors can be represented by relatively simple rheologic models. Then, on the basis of these arguments we can explain the existence of compressional and transpressional intraplate structures in Cuba.

At present (modern stage) the territory of Cuba is split into two large superposed geological mosaics that correspond to different stages of its development: a folded substrate and a neo-autochthonous substrate (Iturralde, 1977). The folded substrate is composed of rocks and structures of oceanic and continental origin, which emerged and evolved with very complex tectonics of thrust mantles (in a much larger area) beyond the present-day territory (Bush and Sherbakova, 1986). The neo-autochthonous substrate possesses rocks and structures that have originated in the immediate surrounding of the modern archipelago, since Late Eocene, after the consolidation of the folded substrate. In the neo-autochthonous substrate, oscillatory vertical movements, of varying speeds and affecting areas of various sizes, make the megablock to rise. Thus, Cuba has been characterized as a structure in blocks (of the horst and graben types) with a trend of oscillatory vertical movements since the Late Eocene (Iturralde, 1977). With the emergence of this structure, in the tectonic context of the Caribbean-North America, the previous compressive geological plan of volcanic island arches (folded substrate) including its faults, was disturbed. Therefore, the new fractures possess characteristics (kinematic, dynamic and morphologic) of their own, quite different from the previous stages. Gonzalez et al. (2003) assured that there are several landforms in Cuba that show evidence of neotectonic activity. The neotectonic stage began with the activation of the Bartlett-Cayman trough and its pull-apart system when the processes of tectonic convergence of the Caribbean plate were moved successively and progressively toward the northeast (Mauffret and Jany, 1990; Ross and Scotese, 1988).

It is established that no universal geological criteria can be used for assessing maximum magnitude ($M_{\max}$) because earthquakes occur in different geologic environments and can be produced by different sets of conditions. Instead, Borissoff et al. (1976) synthesized the ideas of other Russian researchers on the basis of pattern recognition. They supported the use of geological data in the assessment of earthquake danger, arguing that seismicity is a continuation and consequence of lasting tectonic processes which are evidenced by various manifestations in rocks and structures. To study seismotectonics on Cuba, Cotilla et al. (1991a) relied upon the above-mentioned works, though with some critical reservations, as well as upon studies of Schwartz and Coopersmith (1984), Slemmons and Depolo (1986) and Cluff et al. (1972). Furthermore, the techniques of Spiridonov and Grigorova (1980) used in remote sensing were found to be very valuable. Thus, it was possible to delimit the general outline of the active faults and its seismic potentials.

The geological map (Linares et al., 1986) and the tectonic maps (Mossakovsky et al., 1989; Shein et al., 1985) of Cuba show a highly diverse cartography of faults (Cotilla et al., 1996). Also, active fault zones in Cuba present various interrelated natural hazards (Cotilla and Alvarez, 1999). The main characteristics of these faults were previously discussed by Cotilla et al. (1991a). However, many aspects of geometry, kinematics, and slip rates of these faults are still unclear. Consequently, their seismic hazard remains to be assessed (Cotilla et al., 1996).

Seismic hazard assessment based on a neotectonic approach relies on an understanding of the coseismic behavior of every active or potentially active fault in any region. It is well known that seismogenic faults only break along a segment of their entire length when a large earthquake occurs (Schwartz and Coppersmith, 1984). The fault segments have their own seismic history and should be bounded by barriers that avoid rupture propagation outside the segment (Machete et al., 1991). Regions like Cuba with a relatively low poor record of historical and instrumental seismicity require detailed neotectonic field work. This is quite important and necessary in order to establish the geometric discontinuities of faults because such barriers are likely to be the area of a future seismic event. In this sense, the interception, bifurcation and convergence of faults [called knots by Cotilla et al. (1991)] are sites of the greatest seismic interest (Turko and Knuepfer, 1991; Zhidkov et al., 1975).

Historical earthquake data indicate that over the past 500 years southeastern Cuba has been affected by at least 20 destructive earthquakes (Fig. 2) (Alvarez et al., 1990; 1985). The seismicity registered in the eastern and southeastern seismotectonic units in 1979–94 by the Cuban network (more than 6 stations) (Fig. 3, *B*) indicates that 93% of the earthquakes occur with $h < 40$ km (Cotilla, 1998c). Figure 1, from Moreno (2002), shows a very similar picture to the aforementioned period. Deep seismicity ($h = 70$ km) seems to be restricted only to the Sierra Maestra-Santiago de Cuba segment (Cotilla et al., 1997). In general, the seismicity along the plate boundary is shallow in the west but increases in depth eastward (Cotilla and Udias, 2000; Cotilla, 1998c). It is mainly concentrated along three sectors: Cabo Cruz, Sierra Maestra-Santiago de Cuba and Maisi (Fig. 3, *B*) (Cotilla et al., 1991). Also, the rate of seismicity appears to be different on either side of the Mid-Cayman Spreading Center, 62% and 38% until the Punta de Maisi, respectively. More exactly, the rate is 25% in Cabo Cruz, 9% between Pilon and Uvero, 55% between

Uvero and Baconao, and 11% between Baconao and San Antonio del Sur. So, on the basis of these data we conclude that the BC fault zone is seismically active and is located close to densely-populated centers (i.e., Santiago de Cuba and Guantanamo) (Fig. 4) (Cotilla and Udias, 1999a). There are some transverse neotectonic faults (i.e., Baconao and Cauto-Nipe) that constitute a set of active push-up and pull-apart basins (Cotilla et al., 1998; 1991a). All this demonstrates that its seismic hazard is definitely significant.

A characteristic feature of the seismicity in eastern Cuba is the occurrence of many earthquakes in clusters or swarms: 1) Cabo Cruz, 2) Sierra Maestra, 3) Santiago de Cuba, 4) Maisi, 5) Nipe and 6) Manati (Fig. 3, *B*) (Cotilla, 2003; 1993). Cotilla (1998) indicated that when an earthquake occurs at the intersection of faults with BC, the strike of the greater axes of the ellipses of the isoseists does not always coincide with the main structure, as it does with the secondary structure. In this way, a marked polarization of energy toward the interior of the eastern SU stands out. Examples are the following strong earthquakes: 1) 03.02.1932 and 20.08.1852 (in the strike of the fault Baconao); 2) 26.08.1990 and 25.05.1992 (in the strike of the Cauto-Nipe). Also, Cotilla (2003) suggested that most of the stress accumulated by the Caribbean-North American plate motion is released seismically along the northern Cuban continental margin during a relatively small number of strong earthquakes.

The Plate Boundary segment related to Cuba (Fig. 3, *A*) has two seismic fault zones, BC and Walton-Enriquillo-Plantain Garden, which mark the northern and southern limits, respectively, of the southeastern SU (Rubio et al., 1994) (Fig. 1). These fault zones are associated with very different focal mechanisms (Fig. 6) (Cotilla and Udias, 1999). Also, Cotilla et al. (1997b; 199la) argue that the strongest earthquakes occur at the northern edge of the southeastern SU (BC fault). Nevertheless, the continuing movement along both northern and southern boundaries of the southeastern SU has resulted in internal deformation with several NE-SW-oriented structures (Cotilla et al., 1991a). The earthquake activity in the interior part of the southeastern SU (Fig. 3, *C*) (Cotilla, 1998b; Cotilla and Alvarez, 1999) and geophysical results of the Caribbean (Calais and Mercier de Lepinay, 1990; Drully, 1994; Mann et al., 1995) are well correlated. Accordingly, Cotilla et al. (1998) discuss the characteristics of the main active fault systems of the eastern and southeastern seismotectonic units (Baconao, Cauto-Nipe and Nortecubana) and their relationships with recorded seismicity throughout the Cuban network. They hold an opinion that there are seven fault segments, six intersections (or knots), and six cells or seismic zones. Thus, the seismicity of the eastern SU can be explained by the existence of a number of small faults (Boniato, Purial and Nipe-Cristal-Baracoa) linked to the aforementioned regional structures (Cotilla and Alvarez, 1999).

The Sierra Maestra tectonic structure is essential for understanding the seismic activity of eastern Cuba (Fig. 5). The Sierra Maestra is an E-W trending mountain range. In particular, its southern margin has rocks of Cretaceous-Eocene age and deposits of Miocene-Quaternary age. These deposits unconformably overlie Cretaceous and Paleogene rocks. On the basis of Mayer (1986), the authors have proven that the southern edge of the Sierra Maestra is a typical example of the escarpments and mountain fronts related to the Bartlett-Cayman fault zone, and it has important lateral and transverse differences. Some small faults widely represented in the southern Sierra Maestra are normal, and reverse types with a mean E-W, ENE-WNW orientation affect Pleistocene marine terraces up to Quaternary sediments. Pleistocene marine terraces contain information about the recent uplift of the region. Near the Pilon and Baconao areas, these marine terraces have been described as forming a staircase profile, which goes up to 20 m above the actual sea level. Between these localities narrow marine terraces occur, 25–30 m high. Field data from 40 widespread sites in Miocene-Pliocene rocks also indicate the presence of different sets of subvertical joints. The size of the fractures is highly variable, ranging from decimeters to hectometers, the latter being recognizable in aerial photographs (Cotilla et al., 1991). The geometry of fractures allows us to define their character and put forth some evidence regarding paleostress. The Miocene paleostress rocks are affected generally by NNW-SSE striking joints distributed in one or two sets. According to the architecture of the joint system (Hancock, 1985), these joints can be interpreted as tensional, with one joint set or two orthogonal joint sets (in Pilon); hybrid, with two joint sets forming an angle 0–65° (in Mula and Uvero); or shear, characterized by two joint sets with an angle of about 55° (in Baconao).

Figure 6 shows evident differentiation of focal mechanisms in western Cabo Cruz and east of Punta de Maisi as compared with the segment between these localities. This, evidently, is a response to different geodynamic conditions in the same regional tectonic framework. This has been discussed previously by Cotilla and Udias (1999). As far as the present work is concerned, only the Cabo Cruz to Punta de Maisi segment is analyzed. The earthquake focal mechanisms along this major structure show that transtension and transpression occur at the same time and at relatively short distances. Thus, Cotilla (1993) and Cotilla et al. (199la) believe that the Cabo Cruz area is dominated by transtension and the Sierra Maestra-Santiago de Cuba sector by transpression. However, the stress field for the entire southeastern region of Cuba is suggested to be transpressional, which is in agreement with the dominant structural trend associated with the Sierra Maestra-Santiago de Cuba sectors (Cotilla, 1998; Cotilla and Franzke; 1994). Thus, the medium stress axes have a near-horizontal σ_1 (ENE-WNW oriented) and near-vertical σ_3, indicating a thrust faulting regime.

According to Cotilla et al. (1991a) the geometry and the distribution of the neoforms in the eastern SU (Fig. 4) as well as the morphology of the southeastern coast are quite different east and west of Baconao. Unlike the Sierra Maestra and its environment, there are no neotectonical contrasts, eastward, until the Punta de Maisi, as evidenced by a succession of hilly marine terraces, mostly missed fluvial terraces, and N-S deepening of rivers, with gradients of up to 37%. For example, the main river of the eastern zone, in San Antonio del Sur,

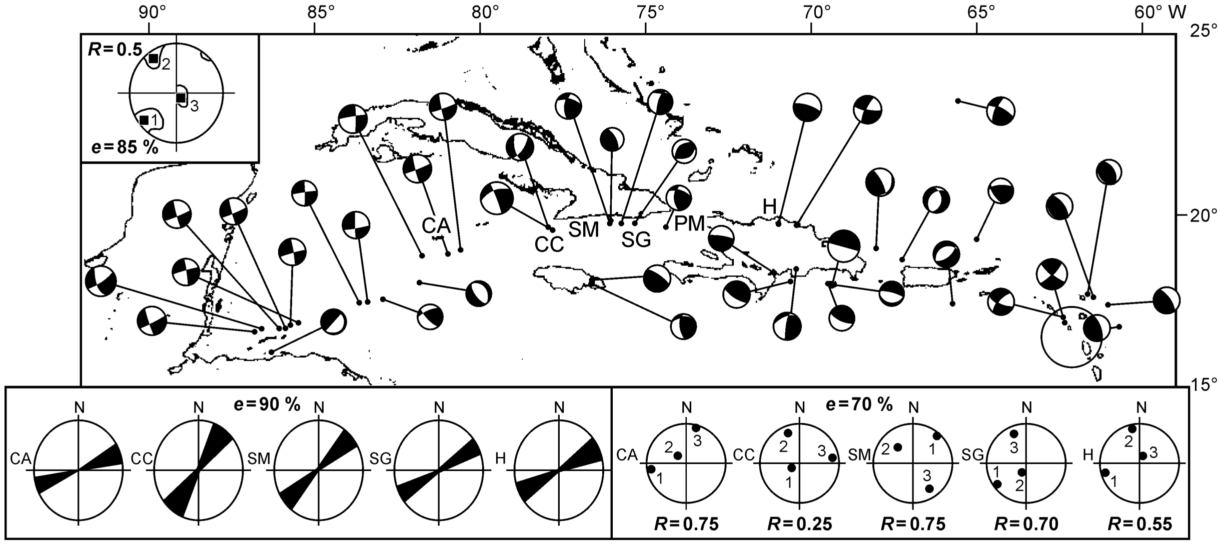

Fig. 6. Some focal mechanisms. In the left bottom there are rose diagrams with the Shmax according to the Zoback (1992) method, corresponding to the sectors: CA — Caiman, CC — Cabo Cruz, PM — Punta de Maisi, SM — Sierra Maestra, SC-G — Santiago de Cuba-Guantanamo, H — Haiti. In the right bottom there are solutions, of the previous sectors, according to the Rivera-Cisternas (1989) method for the principal stresses: 1 — σ_1 (vertical), 2 — σ_2 (maximum horizontal), 3 — σ_3 (minimum horizontal). Here: $R = (\sigma_2 - \sigma_1)/(\sigma_1 - \sigma_3)$ is the stress ratio. The solution given in the upper left side is obtained by the Rivera-Cisternas (1989) method for the southern Cuba region.

runs, in its last section, parallel to the coast and in a westerly direction. This differentiation is reflected also in the submarine relief (Cotilla et al., 1991). Those authors estimated values of 0.85 and 0.42 of the index form for the western and eastern parts, respectively. In addition, as Figures 3, *A*, *B* demonstrate: 1) the area of greatest seismicity is located in the sector of the Sierra Maestra, between Uvero and Baconao; 2) in San Antonio del Sur, east of Baconao, there is a swarm of earthquakes, though with a much lower energy level and density than in the previous area (Figs. 7, *A*, *B*). Therefore, it can be stated that in this region, a direct relationship exists between relief and seismicity. Calais and Mercier de Lepinay (1992; 1990) and Cotilla et al. (1991) previously came to similar conclusions.

With the help of the GIS implemented for PC (Cotilla and Cordoba, 2003) in order to outline, with greater reliability, the seismoactive layer of the BC fault, the distribution of earthquakes was studied with respect to depth and magnitude for the Pilon-Baconao segment (Fig. 8, *A*). Figure 8, *B* shows a model from active zones for the Chivirico-Baconao sector, which was an area with the largest epicentral density and most energy released. The predominance of seismic activity in the surrounding of Santiago of Cuba can be appreciated from these figures. The methodology used with the digital image processing was described by Cotilla and Cordoba (2004).

From Cotilla et al. (2003; 1991) and Gonzalez et al. (2003) data on two relative profiles for the Pilon-Baconao segment were prepared (Figs. 9, *A*, *B*). The figures make it feasible to prove the spatial coincidence of the greatest neotectonical contrasts in the surroundings of Santiago of Cuba.

The same, though less precise, approach was applied to the Habana-Matanzas region, in western Cuba (Fig. 4). On the basis of neotectonical, microtectonic and seismic data, Cotilla and Alvarez (2001) asserted the existence of eight cells or zones, seven intersections (or knots) and nine fault segments linked to five active faults (Cochinos, Guane, Hicacos, Habana-Cienfuegos and Nortecubana) (Fig. 8 in Cotilla and Alvarez, 2001).

In the World Stress Map (2003), the existence of compressive regime in the Nortecubana fault is inferred from focal mechanisms, as indicated for the northeastern area of Cuba, the eastern SU. Earlier, Cotilla (1993) had pointed out that: 1) the seismicity in this part of the fault is greater than in the western sector, 2) the neotectonic characteristics are also quite different: normal type in the western and reverse one in the eastern. All these phenomena can be interpreted as a result of the unequal stress transfer from the BC fault zone.

Catalogue of faults

We studied more than 30 faults, which according to Cotilla et al. (1996) are the most significant tectonic structures probably related to seismic activity in the Cuban territory and surroundings. However, after the field work only twelve of them were classified as active faults. Figure 5 shows the twelve faults that demonstrate contemporary activity in Cuba, according to the criteria of Hatter et al. (1993). Specifically, these faults meet the above criteria a) and b), while only two of them (Bartlett-Cayman and Nortecubana) satisfy the third criterion, that of focal mechanism. Also, all of the faults meet well-known criteria of geomorphologic type (Yeats et al., 1997). All are attributed to type 1 of the faults of NUREG-1451 (1992) and fulfill the conditions of Lay and Wallace (1995) and Reiter (1990) for active seismic structures. Hence, the Habana-Cienfuegos and Cauto-Nipe faults are

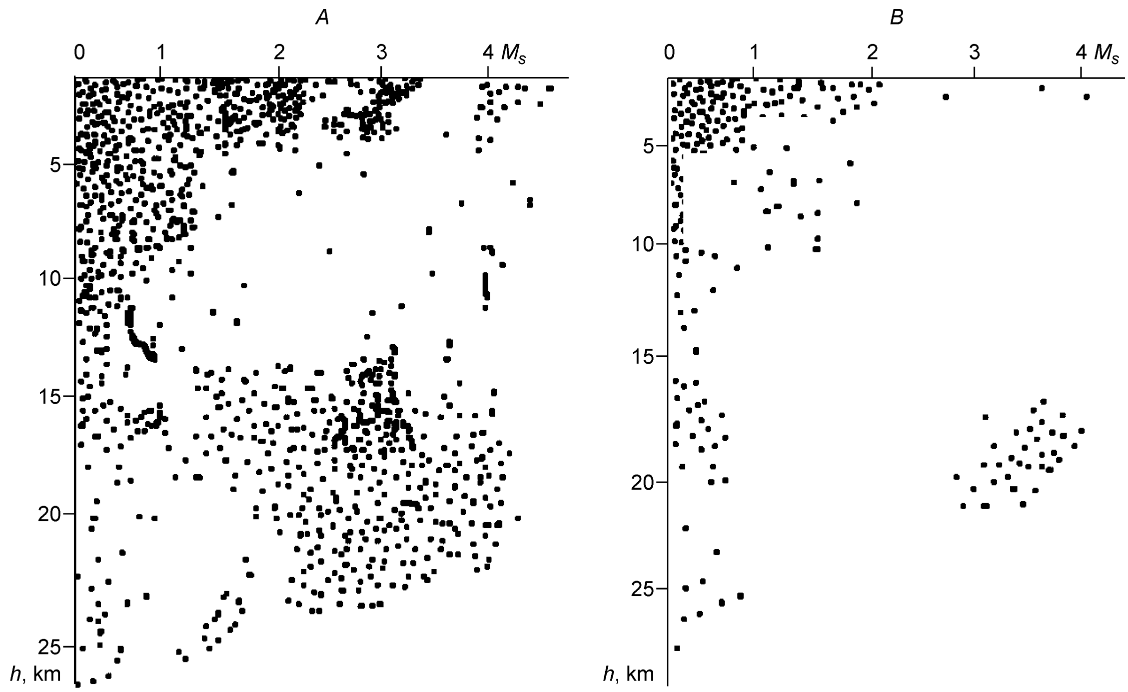

Fig. 7. Representation of the relation magnitude-depth (1979–1994) using Cuban catalogue. *A* — Pilon-Baconao segment; *B* — San Antonio del Sur-Maisi segment.

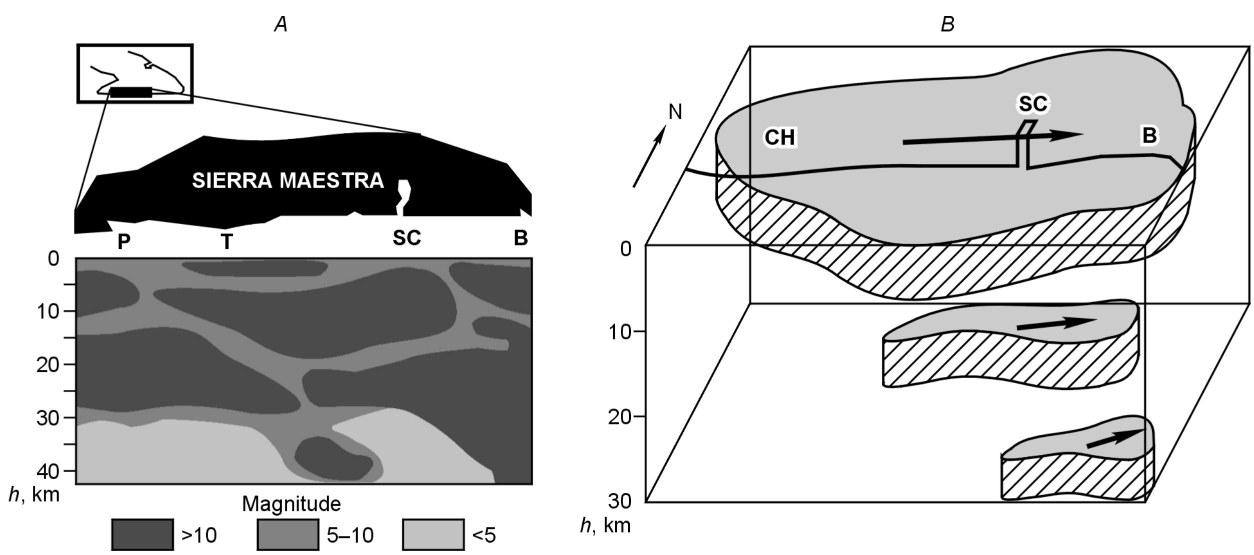

Fig. 8. *A* — Epicentral density to Sierra Maestra area. Second variant. *B* — Model of seismogenic layer around Sierra Maestra area. Localities: B — Baconao, CH — Chivirico, SC — Santiago de Cuba. Black arrow — largest deformation axis.

hidden structures, since they agree with the description of the Working Group on California Earthquake Probabilities (1995). Table 1 collects the data by which all of the structures are recognized in this work. This does not mean that the rest, seven, of the total of the seismogenetic structures defined in the SMp will not be active. It means that the data do not permit any definite determination in this regard. Some of these faults had been recognized, completely or partially, by other authors (Ad hoc Commission, 1991; Cotilla, 1998a; Cotilla et al., 1996). This should indicate that the recognition of those structures by other specialists does not mean the coincidence of criteria concerning their location and activity (Cotilla, 1999; 1999a; 1998a; Cotilla and Alvarez, 1999; Cotilla et al., 1996). Also, Cotilla (1993) stated that all these faults can be recognized in the gravimetric maps of Cuevas et al. (1991) and Sazchina (1969). A summary of the general characteristics of the faults appears in Table 2. Figure 10, obtained with a GIS, fundamentally on the basis of Bott's (1959) ideas, come from microtectonic study for the investigated faults, employing the Cotilla et al. (1991a) data. The fault planes used are generally striated, showing slickensides that enable kinematic interpretation. The displacement of subhorizontal bedding and the topographic scarps also help to interpret the direction of movements along the fault.

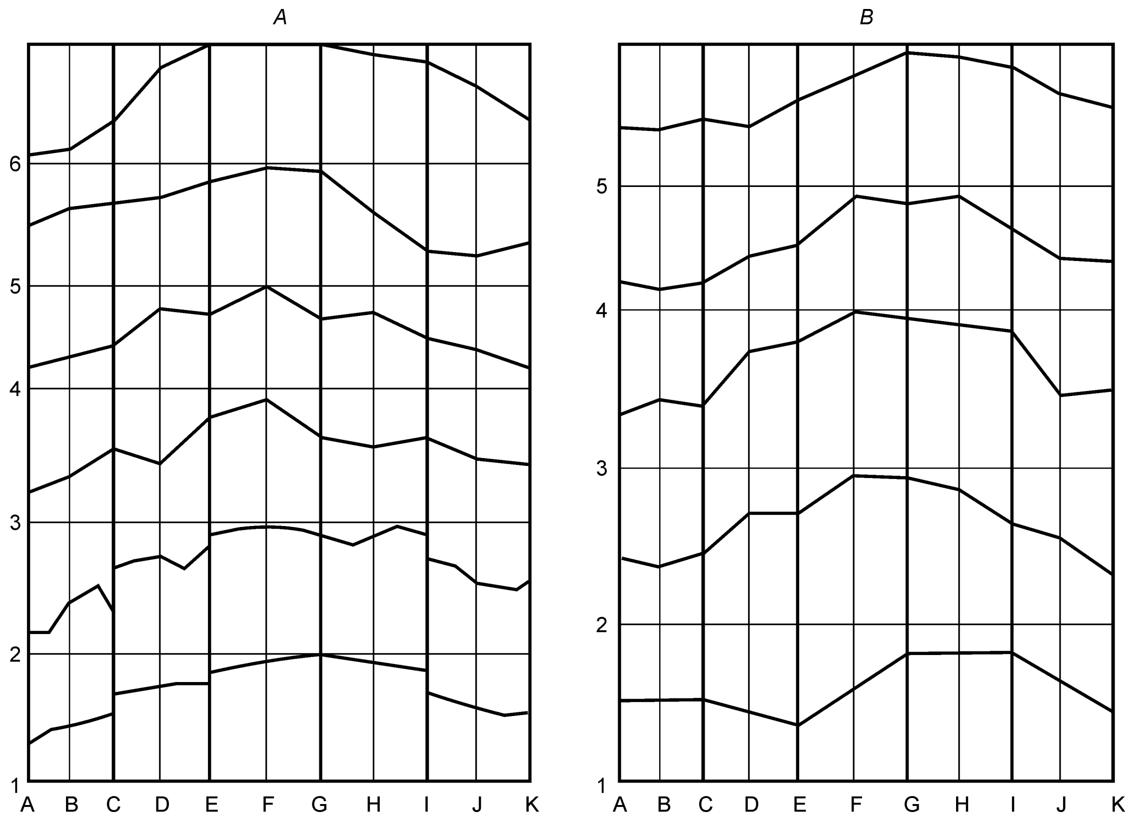

Fig. 9. Profiles to the Baconao-Pilon segment in the Sierra Maestra area. Localities: A — Pilon, B — Mota, C — Macio, D — La Plata, E — Turquino, F — El Uvero, G — Chivirico, H — Seco, I — Santiago de Cuba, J — Siboney, K — Baconao. A — Morphometry. 1 — hypsometry/bathymetry relation; 2 — relief gradient; 3 — fracture density; 4 — number of blocks; 5 — number of fluvial terraces; 6 — number of fluvial basins. B — Seismicity. 1 — $M_{\max}$; 2 — seismic activity; 3 — epicentral density; 4 — energy release; 5 — focal depth.

Baconao fault (B). An outline of this fault that combines normal type sectors, almost vertical, and inverse with left transcurrence. It is relatively deep and intercepts, in its northern extremes, the Nortecubana fault (in Manati) and to the south the Bartlett-Cayman fault (Baconao lagoon). It is bordered on the north by the Gran Piedra, a mountainous massif east of the Sierra Maestra. It has a NW-SE strike. In this sector of the fault, there are vast, continuous and abrupt escarpments and many distorted and broken fluvial terraces of the Quaternary and Pleistocene. The nearest segment to the Gran Piedra is associated with a homonymous river course. In the surroundings of the Cauto basin it is displaced by the Cauto-Nipe fault and configures two segments. The instrumental seismicity (Fig. 3, *B*) permits the outlines of three areas to be perfectly distinguished: 1) Sierra Maestra, 2) Cauto basin, and 3) Manati. Among the most significant earthquakes are: $I = 4$ MSK (23.10.1984, 01.09.1985, 07.01.1986, 16.04.1986 and 07.07.1987).

Bartlett-Cayman fault (BC). In our study, the fault extends from the spreading center to Punta de Maisi-Haiti. It is the Cuba's vastest and most complex structure. It is expressed in the submarine relief by a more than 7 km deep (Bartlett or Oriente) and in the emerged relief by an approximately 2 km high range, the Sierra Maestra. Therefore, the break is approximately 10 km. There is a steep but very irregular slope on the southern Cuban margin. The morphologic expression is a clear indicator of the existence of such a major fault. Seismic structures, recent fault scarps with associated colluvial wedges that deform the drainage network and the alignment of the southeastern coastline (Pilon-Baconao), indicate that this high-angle fault has been active at least since the Miocene. Cotilla et al. (199la) determined four deformation sectors along the southeastern coast of Cuba. They are: 1) N-S extension, conformed by karst-filled extensional veins and normal faults; 2) NE-SW to a nearly N-S compression; 3) NW-SE compression; 4) ENE-WSW to E-W compression. They correspond to the Riedel shears. They stated that two groups of fault regimes are dominant in the area: 1) left-lateral strike-slip; 2) reverse faulting. The first group corresponds to the transition area from Cabo Cruz basin to Santiago Deformed Belt occurring along this fault zone. Then, present-day structures vary along strike of the fault zone with dominant transtension in the west and transpression in the east. The fault planes follow the trend of the fault zone and dip 60–85° to the north. Type and orientation of the principal normal paleostress vary along the strike in accordance with observations of large-scale submarine structures at the southern Cuban continental margin (Cotilla et al., 1991). Neogene-Pleistocene limestones are deformed, faulted, fractured, and contain calcite and karst-filled extension gashes (Cotilla et al., 1991; 1991a). Figure 3, *B* shows the epicentral swarms of 1977–1994. Among the associated earthquakes are:

Table 1
Active faults

No	Name	Signature	Location	Recognized by	Localities
1	Baconao	B	Eastern zone	Ge, Gp, R, S	Baconao, El Cristo, Gran Piedra, Manati and San German
2	Bartlett-Caiman (Oriente)	BC	Southeastern edge	Ge, Gm, Gp, Gr, R, S	Southeast of island
3	Cochinos	C	Western zone	Ge, Gm, Gp, Gr, R, S, Sm	Bahia de Cochinos, Cardenas, Giron, Jovellanos, Pedro Betancourt, and Torriente-J. Grande
4	Camaguey	CA	Central-eastern zone	Ge, Gm, Gp, Gr, R, S	Camaguey, Minas, Senado and Vertientes
5	Cauto-Nipe	CN	Central-eastern zone	Ge, Gm, Gp, Gr, R, S, Sm	Bayamo, Manzanillo and Nipe
6	Cubitas	CU	Central-eastern zone	Ge, Gp, R, S	Esmeralda and S. de Cubitas
7	Guane	G	Western zone	Gp, R, S	Guane, Jaruco, Pinar del Rio and San Jose de las Lajas
8	Habana-Cienfuegos	HC	Central-western zone	Gp, R, S	C. de La Habana, Cienfuegos, San Jose de las Lajas and Torriente- J. Grande
9	Hicacos	H	Western zone	Ge, Gm, Gp, Gr, R, S	Batabano, Madruga, Matanzas and Varadero
10	La Trocha	LT	Central zone	Ge, Gm, Gp, Gr, R, S, Sm	Jatibonico, Majagua and Sancti Spitirus
11	Las Villas	LV	Central zone	Ge, Gm, Gp, Gr, R, S	Camajuani, Corralillo, Encrucijada, Guines, Marti, Quemado de Guines, Remedies, Sagua la Grande, and Yaguajay
12	Nortecubana (Septentrional)	NC	Northern edge	Gp, S	North of island

Note. Data: Ge — geology; Gm — geomagnetism; Gp — geomorphology; Gr — gravimetry; R — remote sensing; S — seismicity; Sm — seismic sounding; References: Cotilla (1999a; 1998a; 1993); Cotilla and Alvarez (2001; 1999); Cotilla et al. (1996; 1991; 1991a).

[I = 9 MSK: 11.06.1766 (M_s= 6.8) and 20.08.1852 (M_s = 7.3); I = 8 MSK: 11.02.1678, 11.07.1670, 13.11.1762, 18.09.1826, and 26.11.1852; I = 7 MSK: 08.1578, 1580, 11.02.1675, 1682, 1762, 11.02.1775, 01.11.1775, 07.07.1842, 20.01.1848, 28.01.1858, 19.09.1903, 22.06.1906, 25.12.1914 and 17.01.1930]. The focal mechanisms obtained by different authors like Alvarez et al. (1985), Harvard CMT, Dean and Drake (1978), Mocquet (1984), Molnar and Sykes (1969), Perrot et al. (1997) and Rubio (1985) correspond to the following earthquakes: 23.02.1887 [M_s = 7.5, (I = 9 MSK)], 20.02.1917 [M_s = 7.4], 03.02.1932 [M_s = 6.7, (I = 8 MSK)], 07.08.1947 [M_s = 6.7], 19.09.1957 [mb = 6.0], 20.04.1962, 25.07.1962, 23.02.1966 [mb = 4.9], 25.02.1969 [mb = 5.4], 11.10.1968 [mb = 4.3], 16.02.1969 [mb = 4.2], 16.03.1970 [mb = 4.7], 23.22.12.1970 [M_s = 4.7], 11.04.1972 [mb = 4.7], 20.05.1973 [M_s = 4.5], 19.02.1976 [M_s = 5.7], 23.02.1976 [mb = 4.6], 24.02.1976 [mb = 4.8], 17.10.1976 [mb = 4.6], 13.11.1978 [M_s = 5.1], 08.02.1980 [M_s = 4.2], 01.09.1985 [M_s = 5.1], 12.02.1989 [M_s = 5.2], 22.05.1990 [M_s = 5.2], 26.08.1990 [M_s = 5.9], 04.09.1990 [M_s = 5.2], 26.08.1991 [M_s = 5.2], 25.05.1992 [M_s = 6.9], 27.06.1992 [M_s = 5.3], and 27.06.1995 [M_s = 5.6].

Camaguey fault (CA). This fault transversely crosses, in a northeastern strike, the central-eastern SU from the south (Vertientes) until its intersection (Minas and Senado) with the Cubitas fault to the north. It is left transcurrent with an almost vertical plane. Though it is associated with a low level of seismic activity, both macroseismic and instrumental, in its outline there are meaningful epicentral concentrations. Among its seismic events are: 23.11.1949 (I = 4 MSK); I = 3 MSK (09.1955 and 12.1966), and noticeable without specification (1770, 12.04.1776, 28.04.1846, 10.1846, 07.03.1858, 10.11.1952, and 16.12.1954).

Cubitas fault (CU). An almost vertical normal fault with some sectors of inverse type. It is delimited to the south of the Sierra de Cubitas. There are some large scarps. Its age is Pliocene-Quaternary. The strike is WNW-ESE. It is related to the east and to the west with the Cauto-Nipe and Baconao, and La Trocha faults, respectively. It is an analogous structure to the Las Villas fault, though less active. Its limit is the northward extension of the Camaguey fault. The seismicity permits deduction of its surface outline. Among its associated earthquakes are: I = 5 MSK (16.03.1952 and 01.01.1953); I = 4 MSK (1964; 27.06.1972 and 08.10.1986); I = 3 MSK (1948 and 1960); 08.04.1974 (M_s = 3.7) and others noticeable, without specification (22.04.1837, 28.04.1864, 25.05.1941, 29.07.1943, 07.07.1952, 25.03.1954 and 1969).

Cochinos fault (C). A normal fault with a few inverse type sectors which demonstrates transcurrence to the left. It is covered by young sediments in a homonymous asymmetrical

Table 2
Main characteristics of the active faults

No.	Characteristics	B	BC	C	CA	CN	CU	G	H	HC	LT	LV	NC
1	Fault type	Normal and reverse type with left strike-slip	Left strike-slip	Normal and reverse type with left strike-slip	Left strike-slip	Left strike-slip	Normal and reverse type	Left strike-slip	Left strike-slip	Left strike-slip	Normal with left strike-slip	Normal and reverse type	Combined normal, reverse and vertical
2	Predominant strike	NW-SE	E-W	NNW-SSW	NE-SW	NE-SW	WNW-ESE	NW-SE	NW-SE	NE-SW	NW-SE, W-E	E-W, NW-SE	E-W, NW-SE
3	Length (km) / wide (km) / depth (km)	240/10/10	>1,000/200/20	200/30/20	180/30/10	150/20/20	190/20/10	280/10/30	230/20/20	310/10/10	200/30/10	250/30/10	
4	Expressed	land-sea	land-sea	land-sea	land	land.sea	land	land	land-sea	land-sea	land-sea	land	sea
5	Segments	2	3	2	1	2	2	3	3	4	1	2	6
6	Isoseists	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
7	Maximum magnitude (estimated/registered)	3.0/3.0	7.3/6.9	5.0/4.7	3.0/–	5.8/3.5	4.1/3.0	5.9/3.0	3.0/–	5.0/4.7	4.3/4.6	4.5/4.5	6.2/5.6
8	Instrumental seismicity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
9	Macroseismic events	5	>100	21	5	5	5	21	14	31	5	10	12
10	Historical seismicity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11	Focal mechanism	No	Yes	No	No	No	No	No	No	No	No	No	Yes
12	Injured	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	No	No	Yes
13	Seismotectonic unit	Eastern	E-SE	W-CE	CE	CE-E	CE	W	W	W-CE	CE	CE	Northern boundary of megablock
14	Neotectonic category	3–4	1	4	3	2–3	4	3	4	5	3	3	2
15	Seismotectonic category	3A, 4	1A, 1B	3A	3A	2A	2B, 3A	2A	3A	3A	3A	2A, 3B	2A, 2B
16	Intersections / knots	6/4	25/20	6/3	2/2	5/4	2/2	15/10	4/3	5/5	3/3	3/2	8/6
17	Limited by	Blocks	Megablocks	Macroblocks	Blocks	Macroblocks	Blocks	Macroblocks	Blocks	Blocks	Macroblocks	Blocks	Megablocks

Note. 1–3, 13, 15, 16 — Cotilla et al. (1991a); 4, 5, 14, 17 — Cotilla (1999), Cotilla et al (1991); 6–12 – Alvarez et al. (1985; 1990), Cotilla (2003; 1999a; 1998b; 1993), Cotilla and Alvarez (2001; 1999), Cotilla and Udias (2000), Cotilla et al. (1997; 1997a; 1991 a), Perrot et al. (1997), and Rubio (1985).

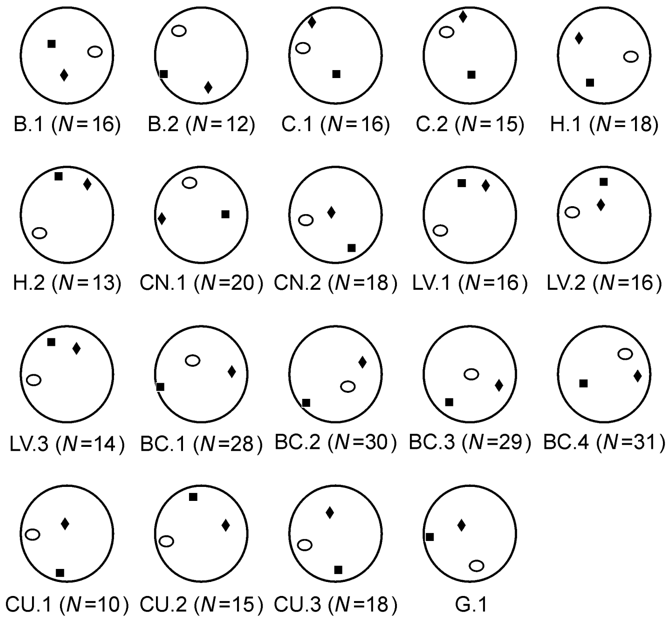

Fig. 10. Mean solutions of the microtectonic determinations under the ideas of Bott (1959) in Wulff stereonet, lower hemisphere. Black square — σ_1 (vertical); small black square — σ_2 (horizontal maximum); open circle — σ_3 (horizontal minimum). Where: $R' = 1/R$; e = 75%. It corresponds to Fig. 5. Localities: B.1—Baconao; B.2 — Santiago de Cuba; C.l — Cochinos; C.2 — Canimar; H.I and H2 — Matanzas; CN.1 — Manzanillo; CN.2 — Nipe; LV.1 — Sagua la Grande; LV.2 — Yaguajay; LV.3 — Florencia; BC.1 — Pilon; BC.2 — Punta Camaron Grande; BC.3 — Playa Aguadores; BC.4 — San Antonio del Sur; CU.1 — Cunagua; CU.2 — Camajan; CU.3 — Gibara; G.l — Galope sugar cane factory, San Cristobal.

basin of NNW-SSE strike. It is expressed very well to the south in the relief of the Bay of Pigs (Cochinos) and intercepts one of the two branches of the Surcubana fault system, where the Giron earthquake occurred in 1964. The extreme north of the fault is in the surroundings of Matanzas Bay (river outlet, located vertically at 10–20 m, in the Canimar River), an area where it crosses the Hicacos fault and the western branch of the Nortecubana fault system. It is assumed that it originated during the Oligocene. This fault breaks the northeastern regularity of the Cauto-Nipe and La Trocha structures, and justifies the inflection of the morphostructural plan of Cuba. The associated events are all of low intensity: 1903, 01.1927, 05.06.1928, 27.03.1964, and 1974. The most important earthquake detected occurred 16.12.1982 (M_S = 5.0) at the intersection with the Habana-Cienfuegos fault, in the locality of Torriente-Jaguey Grande.

Cauto-Nipe fault (CN). A fault system with transcurrence to the left, with a normal type of NE-SW strike, which is extended from the intersection with Bartlett-Cayman up to the Nortecubana. It is a structure linked to a pull-apart basin in the surroundings of the Cauto River. It delimits very well the morphostructural plan of the island on both sides and its outline is labeled by several epicenters. In the southwestern extreme (Cabo Cruz, intersection with the BC fault) and in the northeast (Nipe, intersection with the Nortecubana fault) there are some epicentral swarms (Fig. 3, *B*). The eastern network detected more than 100 events with M_S < 3.0 in 1979–1994. It is related to the following historical earthquakes: 1551 (I = 8 MSK); I = 7 MSK (10.1624 and 03.08.1926); I = 4 MSK (16.04.1987 and 25.04.1987); and noticeable without specification: 26.11.1856 and 28.01.1858.

Guane fault (G). Large and complex structure totally covered by young sediments in the Los Palacios basin. It is predominantly vertical with left transcurrence. It has a NE-SW strike. It is located to the south of the recognized Pinar fault, which has very nice relief expression but is inactive. It extends from the Cabo de San Antonio, where it intercepts with the Nortecubana and Surcubana fault systems, until the locality of Jaruco, La Habana. The associated epicenters are: I = 8 MSK (23.01.1880); I = 6 MSK (20.12.1937); I = 5 MSK (11.09.1957 and 11.06.1981); I = 4 MSK (23.09.1921, 1978 and 31.08.1886); I = 3 MSK (15.02.1939, 09.03.1976, 10.03.1976, 15.03.1976, 09.06.1981, 1982 and 09.1988); noticeable without classification (20.04.1939, 1958, 1964 and 1974). In the ruins of the Ingenio Galope (a sugar cane factory), near the locality of San Cristobal, destroyed by the earthquake of 1880, a stress tensor could be determined, from some seismic open cracks in a wall that is still standing (Fig. 11). The earthquake of the 09.03.1995 (M_S = 2.5) at the locality of San Jose de las Lajas, in La Habana, occurred at the intersection with the Habana-Cienfuegos fault.

Hicacos fault (H). Defined as a normal fault, transcurrent to the left, it is expressed throughout the Peninsula de Hicacos and is internal in the island territory by the eastern edge of Matanzas Bay, delimiting very well the Matanzas block. The predominant strike is NE-SW. Its morphology is different throughout its outline, in particular the southern sector (Guines-Batabano), where it is very weakly represented. In the northern extreme, it emphasizes the joint with the Nortecubana fault (in two branches) at the aforementioned inflection of the arch of the Cuba megablock. In spite of the absence of instrumental records (no seismic station in its surroundings) there are macroseismic epicenters [I = 5 MSK (05.03.1843, 1852, 28.05.1914 and 10.09.1854); I = 4 MSK (1812, 27.05.1914 and 27.04.1974); I = 3 MSK (1978); and noticeable without specification (1854 and 1880)].

Habana-Cienfuegos fault (HC). A left transcurrent fault. It is recognized to be a heterogeneous and large structure of NW-SE strike. Its northwestern and southeastern extremes are very well expressed in the relief of La Habana and Cienfuegos bays, respectively. Both extremes conform morphostructural knots with the Nortecubana and Surcubana systems. On the basis of the data of Le Roy (1998) and the earthquakes registered by the USGS (Cotilla and Alvarez, 2001), this fault is thought to extend toward the Gulf of Mexico. The associated earthquake epicenters are macroseismic and instrumental [16.12.1982 (M_S = 5.0); 09.03.1995 (M_S = 2.5); I = 5 MSK (21.02.1843, 04.10.1859, 25.03.1868 and 10.02.1970); I = 4 MSK (15.04.1907, 1941, 18.12.1942 and 11.09.1957); I = 3 MSK (12.1862), and noticeable without specification (1693, 1810, 1835, 08.03.1843, 1844, 1852, 1854 and 1880)]. This fault has demonstrated recent seismic activity at two knots

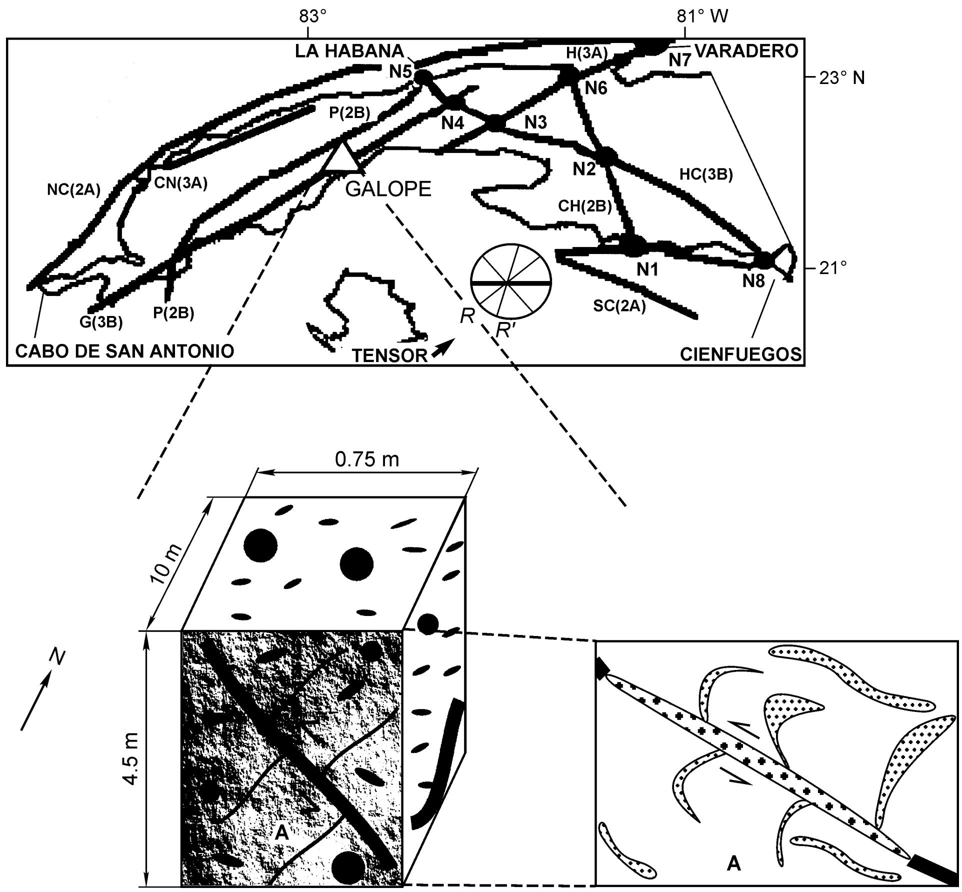

Fig. 11. Galope sugar cane factory destroyed by the 28th January 1880 earthquake (I — 8 MSK). It was located in the western seismotectonic unit. This seismic event was called San Cristobal, because the most heavy damages were produced in this locality.

(intersections) of faults: 1) 16.12.1982 with the Cochinos fault; 2) 09.03.1995 with the Guane fault (Cotilla, 1999a).

La Trocha fault (LT) constitutes a fault zone transcurrent to the left with a large angle. It extends from the mouth of the Zaza River, to the south, in a northeast strike to the Los Perros Bay on the northern part of the island, where it intersects the Nortecubana fault. Its age is Pliocene-Quaternary. It limits a basin of less than 1 km of sediment thickness. It is associated with the following earthquakes: 30.07.1943 (I = 5 MSK); I = 4 MSK(11.11.1970 and 26.07.1971).

Las Villas fault (LV). This fault maintains the prevailing strike of the island on the southern part of the Alturas del Norte de Las Villas, from the surroundings of the Sierra de Bibanasi to the Sierra de Jatibonico. It is a normal type fault with a large angle, with inverse type sectors. It is intercepted to the east by the La Trocha fault. Its outline has young eroded scarps. It is of Pliocene-Quaternary age. The associated seismic events are: 15.08.1939 (M_S = 5.6); 01.01.1953 (I = 5 MSK); I = 4 MSK (03.02.1952 and 25.05.1960), 22.01.1983 (I = 3 MSK); and noticeable without specification 04.01.1988.

Nortecubana fault (NC). This is a normal system of inverse, vertical, and en echelon faults that occur sideways to each other, in the form of arch along the entire continental slope of northern Cuba (Levchenko and Riabujin, 1971; Buznevy, 1968). The depth and the gradient of the slope vary considerably from east to west. The deepest and most abrupt parts are, in this order, the eastern (Punta de Maisi-Camaguey) and the western (Cabo de San Antonio-Hicacos), and the most representative with respect to transverse spectrum is the central part (east of the Peninsula de Hicacos until Camaguey). The situation is a contemporary differential geodynamic reaction to the different geological contents of the region (Cotilla et al., 1996). The system is linked at knots to the faults that cross the Cuban megablock: Habana-Cienfuegos, Hicacos, La Trocha and Cauto-Nipe. The most important morphostructural knot coincides to the east with the Bartlett-Cayman (with great density of epicenters). This knot is characterized by very significant historical and contemporary seismic activity (Cotilla et al., 1991; 199la). Analysis (Cotilla, 1993) for the period 1979–1991 demonstrated that 20% of the registered seismicity of the Cuban network corresponds to the northeastern segment of this fault, while only 5% is recorded in the northwestern segment. All the events were M_S < 4.0. Concerning the most meaningful data of the historical and contemporary seismicity, the following events can be cited: [12.08.1873, 03.02.1880, 28.02.1914 (M_S = 6.2); 15.08.1939 (M_S = 5.6); 24.07.1970, 13.05.1978, 05.01.1990 (mb = 4.5); 20.03.1992 (M_S= 4.0);

24.09.1992 (I = 5 MSK), and 28.12.1998 (mb = 5.4)]. This fault produced a tsunami (15.08.1939) (Rubio, 1985).

This group of twelve faults constitutes the main active structures with related seismicity, representing a moderate seismic hazard in Cuba. They affect, at least, the upper part of the crust. BC and NC are the most active faults and furthermore constitute the limits of the Cuban microplate. Another set of faults also exists [Boniato, Cienfuegos-Santa Clara, Consolacion del Norte, Guama, Purial, Surcubana (segment of Cienfuegos), and Tuinicu] which, though fulfilling the established conditions concerning activity, are not included in the catalogue because of their dimensions: they are not regional faults. But they were included in the SMp (Cotilla and Alvarez, 1999) and were employed for the seismic hazard estimates.

The epicenter determination for the faults located in the western, central and central-eastern seismotectonic units have limitations because of scarce or no permanent seismic stations (Cotilla, 1998c). However, the macroseismic data (affectations and isoseists) permit an acceptable fault-earthquake relationship to be assumed in all cases (Cotilla and Alvarez, 2001). On the other hand, it is possible from the deviations observed in the watersheds and in the rivers and basins (Cotilla et al., 2003) to establish the existence of the mentioned faults. In particular, the arrangement and the geometry of the river basins as well as the strike of the rivers in the north and south sides of the Sierra Maestra indicate the activity of the B and CN, and BC faults, respectively. The morphostructural analysis by Gonzalez et al. (2003), concerning configuration, strike and hypsometry of the relief facilitates the visualization of the neoforms and particularly that of the regional faults. Thus it is possible, from another perspective, to interpret their presence in the relief and to explain a hierarchy-activity relationship.

It is worthy of note that the Baconao and Habana-Cienfuegos faults, though in different seismotectonic units, maintain a similar NW-SE strike in the current morphostructural plan of the island. We consider that it favors the block composition and the transmission of the stress, with the consequent seismic energy release (Cotilla, 1993). These two faults have a similar geometry to the Bonao fault in Hispaniola (Cotilla et al., 1997). Also we consider that the strike, geometry, and activity of the C, G, HC and NC faults in the western SU can be explained by the presence of two large depressed oceanic structures, the Gulf of Mexico and the Hoya de Yucatan, opposed in the contemporary tectonic stress field, derivative of the influences of the Caribbean, Cocos and North America plates. Also, those corresponding to the B, C, CN, CU, LT, LV and NC faults, of the eastern and central eastern seismotectonic units, have been certified in the context of the lateral differential collision of the Caribbean plate with the southern part of the North American plate. In the North American plate there is a lateral west-east succession, of Continental Platform and oceanic crust type structures that responds to a stress in a different way.

As previously mentioned, Cotilla et al. (199la) assumed that now there is only one stress tensor for the Cuban megablock. This assumption was based on the delimited neotectonical structures and their deformations, and on the analysis of the focal earthquake mechanisms. Then, data from slickensides, striations, joints and tension gashes were collected at 1600 stations within Miocene-Quaternary formations to evaluate the kinematics and stress history of Cuba (Cotilla et al., 199la). They used a ZIPE computer program package (actually GeoforschungZentrum) for fault-slip analysis and determination of maximum (σ_1), medium (σ_2), and minimum (σ_3) paleostress axes. This was a preliminary numerical result on the tensor. The tensor was obtained by the inverse method, i.e., from the strikes of the fault population measured in the field. Therefore, it was proposed that there was a transcurrent

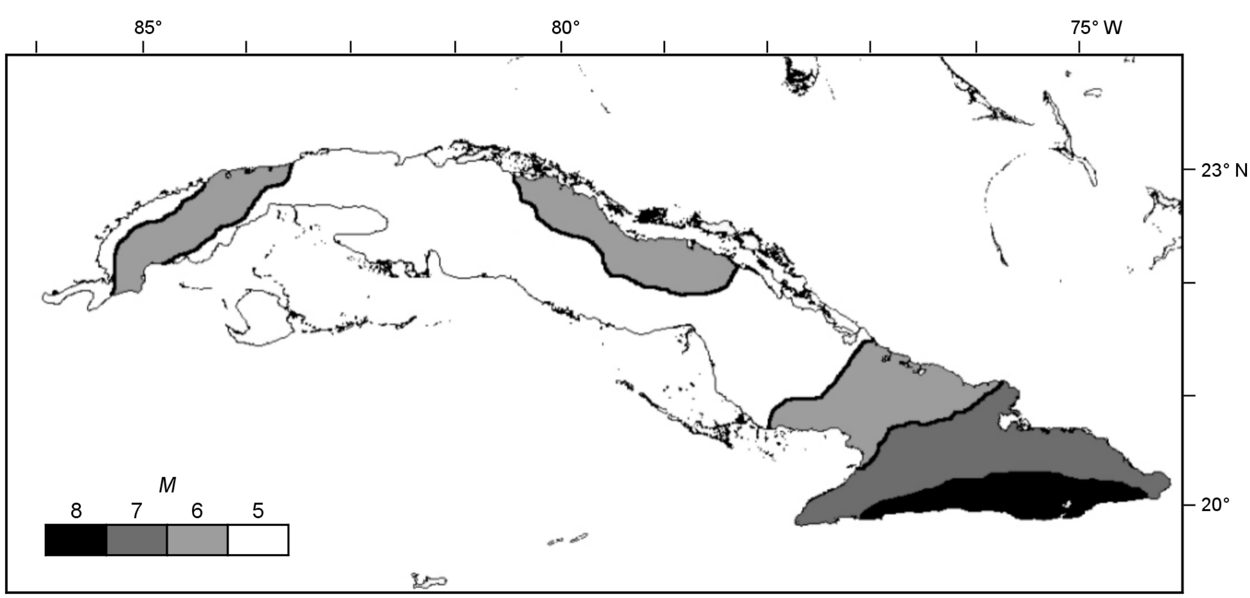

Fig. 12. Seismic hazard map of Cuba. Gray gradation corresponds to maximum seismic intensity, scale MSK, T = 100 years.

(strike-slip) predominance to the left with a reverse faulting component. Also, the main axis orientation is close to those obtained by fracture diagrams (Cotilla et al., 199la).

Using focal mechanism data we obtained the maximum horizontal compression stress ($\sigma_{h\,\max}$, 90% confidence) for five sectors (Cayman, Cabo Cruz, Sierra Maestra, Santiago de Cuba-Guantanamo and Haiti) following the ideas of Zoback (1992) (Fig. 6). Also, we applied the Rivera and Cisternas (1989) method to those sectors (Fig. 6). In order to determine the stress tensor in the entire region we used a total of 50 focal mechanisms (Fig. 6). The regional stress directions and the axial ratio that fit best with the available focal mechanism are determined by a grid search of stress ellipsoids under the assumption of uniform stress in the source region. These results confirm what was obtained previously.

The implemented GIS contain general and specific information. The general information includes: 1) a tectonic scheme of the Northern Caribbean; 2) a digital image of the Cuban relief, scale 1:100,000; 3) the river net (Cotilla et al., 2003); 4) a geological map at a scale of 1:250,000; 5) a morphostructural map at a scale of 1:250,000 (Gonzalez et al., 2003); 6) a neotectonical map at a scale of 1:1,000,000 (Cotilla et al., 1991a); 7) a map of main lineaments and associated structures, at a scale of 1:100,000 (Cotilla et al., 1991); 8) geomorphological profiles; 9) cities and villages of importance; 10) historical and macroseismic seismicity, XV–XIX centuries; 11) instrumental seismicity, 1964–2004; 12) focal mechanisms. The specific information includes the twelve seismoactive faults. To characterize each of them, there are: 1) cartography; 2) photos and schemes; 3) data on geometry, kinematics and microtectonics.

In the GIS it is feasible to execute a set of specific programs (Cotilla and Cordoba, 2004) to analyze: 1) the seismicity (seismic activity, epicenter density, earthquake profiles, mean and maximum magnitude, main epicenter alignments, etc.); 2) geomorphology (faults, fractures, alignments and rivers; hypsometry and slopes (middle and maximum)); 3) statistics, pattern recognition and digital images treatment and processing. A dictionary, a user handbook and the fundamental references were always available. This system is very user-friendly and has been employed, satisfactorily, for similar studies in the Iberian Peninsula (Cotilla et al., 2005).

Finally, with the help of the GIS three seismic hazard maps for periods of 100, 500 and 1000 years were obtained. Figure 12 shows the result for T = 100 years. After checking the estimates of $M_{\max}$ for the seismogenetic zones considered by Cotilla et al (199la) we conclude that they did not change. These appear in Table 2.

Conclusions

Cuba has its first catalogue of active regional faulting (Baconao, Bartlett-Cayman, Camaguey, Cauto-Nipe, Cochinos, Cubitas, Guane, Habana-Cienfuegos, Hicacos, La Trocha, Las Villas and Nortecubana). The major fault in the study area is the BC fault zone, which is located on the southeast side of the eastern SU. There, 85% of seismic energy of the Seismotectonic Province of Cuba is released. During the Quaternary, the BC is characterized by strike-slip movement rather than vertical uplift. All the information that includes photos, maps and profiles is implemented in a GIS for PC.

The seismotectonic complexity of the Cuba region is remarkable, due to the fact that the region corresponds to part of the contact between the plates of North America and Caribbean. In this sense, Cuba is differently affected by the NE-SW transpressive stress, resulting from the interaction of the Caribbean and North American plates. The stresses are reflected, mainly, in the epicentral group areas of the south-eastern and eastern seismotectonic units, where there are fault intersections that accommodate the regional displacement and permit its heterogeneities to be distinguished. Nevertheless, there are also some small and moderate intraplate events occurring throughout the country. The intraplate seismicity seems to be localized in the pre-existing zones of crustal weakness.

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References

Ad hoc Comision, 1991. Dictamen de la comision ad-hoc para la determination de las zonas sismogeneradoras de la region Oriental de Cuba y sus zonas adyacentes, in: Archive del Departamento de Sismologia, Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba [in Spanish].

Alvarez, L., Cotilla, M., Chuy, T., 1990, Informs final del tema 430.03: Sismicidad de Cuba, in: Archive del Departamento de Sismologia, Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba [in Spanish].

Alvarez, L., Rubio, M., Chuy, T., Cotilla, M., 1985. Informe final del tema de investigation 31001: Estudio de la Sismicidad de la region del Caribe y estimation preliminar de la peligrosidad sismica en Cuba, in: Archive del Departamento de Sismologia, Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba [in Spanish].

Balassanian, S.Yu., Karakhanian, A.S., Nazaretian, S.V., Arakelian, A.R., Melkumain, M.G., Manukian, A.V., 1994. Retrospective analysis of the Spitak earthquake. Proc.Intern. Conference at Yerevan-Sevan, Armenia, pp. 1–12.

Borissoff, B.A., Reisner, G.I., Sholpo, V.N., 1976. Tectonics and maximum magnitudes of earthquakes. Tectonophysics 33, 167–185.

Bott, M.H.P., 1959. The mechanics of oblique slip faulting. Geol. Mag. 96 (2), 109–117.

Burke, K., Grippi, J., Sengor, A.M., 1980. Neogene structures in Jamaica and the tectonic style of the northern Caribbean plate boundary zone. J. Geol. 88 (4), 375–386.

Bush V., Sherbakova B.E., 1986. New data on the tectonics of Cuba. Geotectonics 20 (3), 192–203.

Buznevy E.M., 1968. Informe sobre investigaciones sismicas marinas realizadas en los anos 1966–1967 en la plataforma insular de Cuba y en la region de aguas profundas adyacentes, por la expedition sovietica del barco "Vladimir Obruchev" y las conclusiones geologicas. Direction de Petroleo, Instituto Cientifico-Investigativo de Geologia y Geofisica Marina de la URSS y Ministerio de Mineria, Co*mb*ustibles y Metalurgia. Republica de Cuba [in Spanish].

Calais, E., Mercier De Lepinay, B., 1990. A natural model of active transpressional tectonics: The echelon structures of the Oriente deep, along the northern Caribbean transcurrent plate boundary. Rev. Inst. F. Pet. 45, 147–160.

Calais, E., Mercier De Lepinay, B., 1992. From transtension to transpression along the northern Caribbean plate. Tectonophysics 116, 329–350.

Calais, E., Bethoux, N., Mercier De Lepinay, B., 1992. From transcurrent faulting to frontal subduction: A seismotectonic study of the northern Caribbean plate boundary from Cuba to Puerto Rico. Tectonics 11 (1), 114–123.

Case, I.E., Holcombe, T.L., 1980. Tectonic map of Caribbean. U.S. Geol. Surv. Misc. Invest. Ser., Map 1-1100 (scale 1:2.500.000).

Caytrough (1979): Geological and geophysical investigations of the Mid-Cayman rise spreading center. Initial results and observations, in: Talwani, M., Harrison, C.G., and Hays, D.E., (Eds.), Deep drilling results in the Atlantic Ocean: Ocean crust. Maurice Ewing Ser., vol. 2, pp. 66–93.

Cluff, L.S., Hansen, M.R., Taylor, C.C., Charles, L., et al., 1972. Site evaluation in seismically active region an interdisciplinary team approach, in: Microzonation Conference, Seatle, Mash. Proc., Vol. 2, pp. 957–987.

Cotilla, M., 1993, Una caracterizacion sismotectonica de Cuba. PhD Thesis, Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba, 200 p. [in Spanish].

Cotilla, M., 1998a, Sismicidad y sismotectonica de Cuba. Revista Fisica de la Tierra 10, 53–86. (E. Buforn and A. Udias, Eds.). Servicios de Publicaciones de la Universidad Complutense de Madrid [in Spanish].

Cotilla, M., 1998b. Una revision de los estudios sismotectonicos en Cuba. Revista Estudios Geologicos 54 (3–4), 129–145 [in Spanish].

Cotilla, M., 1998c, Terremotos de Cuba. GEOS 18 (3), 180–188 [in Spanish].

Cotilla, M., 1998d, An overview on the seismicity of Cuba. Journal of Seismology 2, 323–335.

Cotilla, M., 2003. The Santiago de Cuba earthquake of 11 June 1766: Some new insights. Geofisica International 42 (4), 589–602.

Cotilla, M., Bankwitz, P., Alvarez, L., Franzke, H.J., Rubio, M., Pilarski, J., 1998. Cinematica neotectonica de Cuba Occidental. Revista de la Sociedad Geologica de Espana 11 (l–2), 33–42 [in Spanish].

Cotilla, M., Bankwitz, P., Franzke, H.J., Alvarez, L., Gonzalez, E., Diaz, J.L., Grunthal, G., Pilarski, J., Arteaga, F., 1991a. Mapa sismotectonico de Cuba, escala 1:1.000.000. Comunicaciones Cientificas sobre Geofisica y Astronomia, 23, 35 p. Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba [in Spanish].

Cotilla, M., Millan, G., Alvarez, L., Gonzalez, D., Pacheco, M., Arteaga, F., 1996. Esquema neotectogenico de Cuba. Informe cientifico-tecnico del Departamento de Geofisica del Interior, in: Archivo del Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba, 100 p. [in Spanish].

Cotilla, M., Rubio, M., Alvarez, L., 1997a, Sismicidad de tipo intermedio en Cuba. Revista Geologia Colombiana 22, 35–40 [in Spanish].

Cotilla, M., Rubio, M., Alvarez, L., Grunthal, G., 1997b. Potenciales sismicos del sector Centra-Occidental del arco de las Antillas May ores. Revista Geofisica 46, 129–150. Instituto Panamericano de Geografia e Historia [in Spanish].

Cotilla, M., Udias, A., 1999. La ciencia sismologica en Cuba II. Algunos terremotos historicos. Revista Historia de America 125, 4690. Instituto Panamericano de Geografia e Historia [in Spanish].

Cotilla, M., Udias, A., 2000. El terremoto del 11 de junio de 1766 en Santiago de Cuba. Revista Geofisica 52–53, 5–26. Instituto Panamericano de Geografia e Historia [in Spanish].

Cotilla, M.O., 1999a. Apuntes necesarios acerca de los acontecimientos sismologicos en Cuba. Anales de Geografia de la Universidad Complutense 19, 71–93 [in Spanish].

Cotilla, M.O., 1999b. El controvertido alineamiento Habana-Cienfuegos, Cuba. Estudios Geologicos 55 (l–2), 67–88 [in Spanish].

Cotilla, M.O., Alvarez, J.L., 1999. Mapa de zonas sismogeneradoras de Cuba. Geologia Colombiana 23, 97–106 [in Spanish].

Cotilla, M.O., Alvarez, J.L., 2001, Regularidades sismogeneticas de la unidad neotectonica occidental de Cuba. Revista Geologica de Chile 28 (l), 3–24 [in Spanish].

Cotilla, M.O., Cordoba, D., 2003. Caracterizacion morfotectonica de Galicia, Espana. Revista Geofisica 58, 5–56. Instituto Panamericano de Geografia e Historia [in Spanish].

Cotilla, M.O., Cordoba, D., 2004. Present geomorphological characteristics of Alboran islet and surroundings, Spain: a diagnosis. Geogr. Fis. Dinam. Quat. 27, 3–19.

Cotilla, M.O., Udias, A., 1999. Geodinamica del limite Caribe-Norteamerica. Revista de la Sociedad Geologica de Espana 12 (2), 175–186 [in Spanish].

Cotilla, M.O., Cordoba, D., Herraiz, M., 2005. Main morphotectonic characteristics of Asturias, Spain. Geofisica International 44 (1), 65–101.

Cotilla, M.O., Diaz, L., Gonzalez, D., Fundora, M., Pacheco, M., 1997. Estudio morfoestructural de La Espanola. Revista Mineria y Geologia XIV, 3, 73–88 [in Spanish].

Cotilla, M.O., Gonzalez, E.G., Canete, C.C., Diaz, J.L., Carral, R., 2003. La red fluvial de Cuba y su interpretacion morfoestructural. Revista Geografica 134, 47–74. Instituto Panamericano de Geografia e Historia [in Spanish].

Cotilla, M.O., Gonzalez, E.G., Franzke, H.J., Diaz, J.L., Arteaga, F., Alvarez, L., 1991. Mapa neotectonico de Cuba, escala 1:1.000.000. Comunicaciones Cientificas sobre Geofisica y Astronomia, 22, 37 p. Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba [in Spanish].

Cuevas, J.L., Pacheco, M., Polo, B., Hernandez, M.E., 1991. Mapa de anomalias gravimetricas en reduction de Bouguer total a 2,67 t/m de Cuba Oriental, a escala 1:500.000. Informe Cientifico-Tecnico del Departamento de Geofisica del Interior. Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba, 20 p. [in Spanish].

Dean, B.W., Drake, Ch.L., 1978. Focal mechanism solution and tectonic of the Middle America Arc. Jour. Geol 86, 11–128.

DeMets, C., Gorden, R.G., Arges, D.F., Stein, S., 1990. Current plate motions. Geophysics. J. Intern. 101, 425–438.

DeMets, C., Jansma, P., Mattioli, G.S., Dixon, T., Farina, P. ; Bilham, R. ; Calais, E., Mann, P., 2000. GPS geodetic constraints on Caribbean - North American plate motion. Geophys. Res. Lett. 27, 437–440.

Deng, J., Sykes, L.R., 1995. Determination of Euler pole for contemporary relative motion of the Caribbean and North American plates using slip vectors of intraplate earthquakes. Tectonics 14, 39–53.

Dixon, T.H., Farina, F., DeMets, C., Jansma, P., Mann, P., Calais, E., 1998. Relative motion between the Caribbean and North American plates and related boundary zone deformations from a decade of GPS observations. J. Geophys. Res. 103, 15,157–15,182.

Drully, T.W., 1994. The Caribbean sea floor, in: Caribbean Geology: an Introduction, pp. 41–63. VWI Publisher's Association Kingston.

Dziewonski, A.N., Woodhouse, J.H., 1983. An experiment in systematic study of global seismicity: Centroid-moment tensor solution for 201 moderate and large earthquakes of 1981. J. Geophys. Res. 88, 3247–3271.

Gonzalez, E.G., Cotilla, M.O., Canete, C.C., Diaz, J.L., Carral, R., Arteaga, F., 2003. Estudio morfoestructural de Cuba. Geogr. Fis. Dinam. Quat. 26 (1), 49–70 [in Spanish].

Hancock, P.L., 1985. Brittle microtectonics. Principles and practice. J. Struct. Geol. 7, 437–457.

Harvard Centroid Moment Tensor Project Catalogue 1977–1998 of focal mechanisms (13°/21° N; –65°/–72° W) (URL:http://www.seismology.harvard.edu/projects/ CMT).

Hatter, K.M., Michael, N., Richard, L.D., 1993. Guidelines for US database

and map for the maps of major active faults, Western Hemisphere, International Lithosphere Program (ILP), Project II-2. US Department of Interior, US Geological Survey, 45 p.

Iniguez, H.M., Acosta, R., Vizcaino, J.A., 1975. Relacion de sismos en Republica Dominicana, 1551-1975. Instituto Geografico, Universidad Autonoma de Santo Domingo. Republica Dominicana, 49 p. [in Spanish].

Iturralde, M., 1977. Los movimientos tectonicos de la etapa de desarrollo plataformico de Cuba. Informe cientifico-tecnico, 20, in: Archive del Instituto de Geologia y Paleontologia, Academia de Ciencias de Cuba [in Spanish].

Johnston, A.C., 1989. The seismicity of stable continental interiors, in: Gregersen, S., and Bashau, P.W., (Eds.), Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Resound, pp. 229–327.

Johnston, A.C., Kanter, L.R., 1990. Earthquakes in stable continental crust. Scientific American 10, 42–49.

Kafka, A.L., Weiden, T.J., 1979. The focal mechanisms and depths of small earthquakes as determined from Rayleigh wave radiation pattern. Bull. Seismol. Soc. Am. 69, 1379–1390.

Ladd, J., Holcombe, J.L., Westbrook, G.K., Edgar, N.J., 1990. Caribbean marine geology: active margins of the plate boundary, in: Dengo, G., and Case, J.E. (Eds.), The Geology of North America, Vol. H. The Caribbean Region (A decade of North American Geology). Boulder Colorado, Geological Society of America, pp. 261–290.

Lay, T., Wallace, T.C., 1995. Modern global seismology. International Geophysics Series, 58. Academic Press, San Diego, California.

Le Roy, S.D., 1998. Treating the Gulf of Mexico as a continental margin petroleum province. The Leading Edge, 209–212.

Levchenko, V.A., Riabujin, A.G., 1971. Block structure of the northern shelf of Cuba. Geotectonika, 5 [in Russian].

Levchenko, V.A., Gurevich, G.S., Zabichina, V.V., Kitias, N.A., Pafinova, S.I., 1976. Caracterizacion comparativa de la constitution geologica de Cuba y otros paises de la cuenca del Mar Caribe y el Golfo de Mexico con el objeto de evaluar las perspectivas petroliferas y gasiferas de Cuba y las acuatorias adyacentes. Informe Cientifico-Tecnico del Ministerio de la Industria Basica, 150 p. [in Spanish].

Lewis, J., Draper, G., 1990. Geology and tectonic evolution of the northern Caribbean region. The Geology of North America, Vol. H. The Caribbean Region. The Geol. Soc. of Am., chapter 4, pp. 77–140.

Linares, E., Dovbnia, A.V., Osadchiy, P.O., Judoley, C.M., Gil, S., Garcia; D., Zuazo, A., Furrazola, G., Brito, A., Evdokimov, Y.B., Markovskiy, B.A,; Trofimov, V.A., Vtulochkin, A.L., 1986. Mapa geologico de Cuba, escala 1:500.000. Centro de Investigaciones Geologicas, Ministerio de la Industria Basica de Cuba.

Machette, M; Personius, S., Nelson, A., Schwartz, D., Lund, D., 1991. The Wasatch fault zone, Utah: segmentation and history of the Holocene earthqaukes. J. Struct. Geol. 13 (2), 137–149.

Mann, P., Burke, K., 1984. Neotectonics of the Caribbean. Review of Geophysics and Space Physics 22 (4), 309–392.

Mann, P., Burke, K., Matumoto, T., 1984. Neotectonics of Hispaniola: Plate motion, sedimentation and seismicity at a restraining band. Earth Plan. Sci. Lett. 70, 311–324.

Mann, P., Schubert, C., Burke, K., 1984a. Review of Caribbean neotectonics, in: Dengo, G., and Case, I.E. (Eds.), The Caribbean Region. Bulder Colorado. Geological Society of America. The Geology of North America, Vol. H, pp. 307–338.

Mann, P., Taylor, F.W., Lawrence Edwards, R., Theh-Lung, Ku., 1995. Actively evolving microplate formation by oblique collision and sideways motion along strike-slip faults: An example from the northeastern Caribbean plate margin. Tectonophysics 246, 1–69.

Mauffret, A., Jany, I., 1990, Collision et tectonique d'expulsion le long de la frontiere Nord-Caraibe. Oceanol. Acta 10, 97–116 [in French].

Mayer, L., 1986. Tectonic geomorphology of escarpments and mountain fronts, in: Active Tectonics. National Academy Press, Washington, D.C., pp. 125–135.

McCann, W.R., Pennigton, W.D., 1990. Seismicity large earthquakes and the margin of the Caribbean plate. The Geology of North America, Vol. H. The Caribbean Region. The Geol. Soc. of Am., chapter 4, pp. 291–305.

McKenzie, D., Parker, R.L., 1967. The North Pacific: an example of tectonics on a sphere. Nature 216, 1276.

Mocquet, A., 1984. Vitesses de deplacement discontinue le long d'une zone limite de plaques: Caribes-Amerique du Nord. Master Thesis, University of Rennes, France, 53 p. [in French].

Molnar, P., Sykes, L.R., 1969. Tectonics of the Caribbean and Middle America regions from focal mechanism and seismicity. Geol. Soc. Amer. Bull, 80 (9), 1639–1684.

Moreno, B., 2002. The new Cuban seismograph network. Seismological Research Letters,

Mossakovsky, A., Pusharovski, Y., Nekrasov, G.E., Sokolov, S.R., Formell, F., Cabrera, R., Iturralde, M., Flores, R., Oro, J., Morales, A., Pantaleon, G., Perez, L., Pszozolkowski, A., et al., 1989. Mapa tectonico de Cuba, escala 1:500.000. Instituto de Geologia y Paleontologia, Academia de Ciencias de Cuba.

NUREG-1451, 1992. Staff technical position on investigations to identify fault displacements and seismic hazards at a geologic repository. McCornell, K.I., Blackford, M.E. and Ibrahim, A.K. US Nuclear Regulatory Commission Washington, D.C. 20555.

Pacheco, J.F., Sykes, L.R., 1992. Seismic moment catalog of large shallow earthquakes, 1900 to 1989. Bull. Seismol. Soc. Am. 82, 1306–1349.

Perez, E., Azcuy, E., 1992. Aplicacion de nuevas tecnologias para la interpretacion geomagnetica regional. Trabajo de diploma del Departamento de Geofisica, 85 p. Institute Superior Politecnico "J.A. Echeverria", La Habana, Cuba [in Spanish].

Perrot, J., Calais, E., Mercier De Lepinay, B., 1997. Tectonic and kinematic regime along the northern Caribbean plate boundary: new insigths from broadband modelling of the May 25, 1992, M_s = 6.9 Cabo Cruz, Cuba earthquake. Pure and Applied Geophysics 149, 475–487.

Prol, J., Ariaza, G., Otero, R., 1993. Sobre la confection de los mapas de profundidad del basamento y espesor de la corteza terrestre en el territorio cubano. Informe Cientifico-Tecnico de la Empresa Nacional de Geofisica, Ministerio de la Industria Basica de Cuba, 36 p. [in Spanish].

Pubellier, M., Mauffret, A., Leroy, S., Vila, J.M., Amilcar, H., 2000. Plate boundary readjustment in oblique convergence: Example of the Neogene of Hispaniola, Greater Antilles. Tectonics 19 (4), 630–648.

Pubellier, M., Vila, J.M., Boisson, D., 1991. North Caribbean neotectonic events: the Trans-Haitian fault system. Tertiary record of an oblique transcurrent shear zone uplifted in Hispaniola. Tectonophysics 144, 217–236.

Pusharovsky, Yu., Vtulochkin, M.A., Mossakovsky, A., 1987. Structures and types of the Earth's crust on Cuba. Dokl. Akad. Nauk SSSR 294, 178–182.

Reiter, L., 1990. Earthquake hazard analysis. Colombia University Press, New York, 254 p.

Renard,V., Mercier De Lepinay, B., Buffet, G., 1992. North Caribbean plate boundary: High resolution imagery of the Oriente fault across the Windward Passage and South of Tortuga Island: A model for strike-slip tectonics. EOS (Transactions American Geophysical Union, Vol. 73, 278 p.)

Rivera, L., Cisternas, A., 1989. Stress tensor and fault plane solutions for a population of earthquakes. Bull. Seism. Soc. Am. 80 (3), 600–614.

Robson, G.R., 1964. An earthquake catalogue for the eastern Caribbean. Bull. Seism. Soc. Am. 54 (2), 785–832.

Rodriguez, M., 1996. Estimaciones probabilisticas de la peligrosidad sismica en Cuba. Editorial MAPFRE, 80 p. Espana [in Spanish].

Rosencratz, E., Mann, P., 1991. Mapping of transform faults in the Cayman trough, Caribbean Sea. Geology 19, 690–693.

Rosencratz, E., Ross, M.I., Sclater, J.G., 1988. Age and spreading history of the Cayman trough as determined from depth, heat flow and magnetic anomalies. J. Geophys. Res. 93, 2141–2157.

Ross, M.I., Scotese, Ch., 1988. A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. Tectonophysics 15, 139–168.

Rubio, M., 1985. Seismicity of the Republic of Cuba and adjacent areas. PhD Thesis, Institute of Geophysics. Academy of Sciences Checoslovaquie, 160 p.

Rubio, M., Cotilla, M., Alvarez, L., 1994. Evidencias sobre la microplaca Gonave. Informe cientifico-tecnico, p. 20, in: Archive del Departamento de Sismologia, Instituto de Geofisica y Astronomia, Academia de Ciencias de Cuba [in Spanish].

Sazchina, N. (1969): Mapa gravimetrico de Cuba, escala 1:500.000. Publication del MMCM (Cuba) y MINGEO (U.R.S.S.), Moscu-La Habana, 51 p.

Schwartz, D.P., Coppersmith, K.J., 1984. Fault behaviour and characteristic earthquakes: examples from the Wasatch and San Andreas fault zones, in: Special section: Fault behaviour and the earthquake generation process. J. Geophys. Res. 819 (7), 5681–5698.

Shein, V.S., Klishov, K.A., Jain, V.E., Dikenshtein, G.E., Yparraguirre, J.L., Garcia, E., Rodriguez, R., 1985. Mapa tectonico de Cuba, escala 1:500.000. Centro de Investigaciones Geologicas, Ministerio de la Industria Basica de Cuba.

Sherer, J., 1912. Great earthquakes in the island of Haiti. Bull. Seism. Soc. Am. 2, 161–180.

Slemmons, D.B., Depolo, C.M., 1986. Evolution of active faulting and associated hazards, in: Active Tectonics, pp. 45–62. National Academy Press.

Spiridonov, N., Grigorova, E., 1980. On the interrelation between seismicity and fault structures identified by space image interpretation. Space Res. Bulgaria 3, 42–46.

Sykes, L.R., 1978. Intraplate seismicity reactivation of preexisting zones of weakness, alkaline magmatism and tectonic postdating continental fragmentation. Reviews of Geophysics and Space Physics, 16 (4).

Sykes, L.R., Ewing, M., 1965. The seismicity of the Caribbean region. J. Geophys. Res. 70 (20), 5,065–5.074.

Sykes, L.R., McCann, W.R., Kafka, A.C., 1982. Motion of the Caribbean plate during last 7 million years implications for earlier Cenozoic movements. J. Geophys. Res. 87, 10,656–10,676.

Taber, S., 1922, The great fault troughs of the Antilles. J. Geol. 30, 89–114.

Trifonov, G.V., Machette, N.M., 1993. The world map of major active faults project. Annali di Geofisica 36 (3–4), 225–236.

Turko, J., Knuefer, P., 1991. Late Quaternary fault segmentation from analysis of scarp morphology. Geology 19, 718–721.

United States Geological Survey, 1986. Catalog of first motion focal mechanisms 1984-1988. Open File Rep., 86-520 A.

Van Der Pluijm, B.A; Craddock, J.P. Graham, B.R., Harris, J.H., 1997. Paleostress in cratonic North America: Implications for deformation of continental interiors. Science 277, 794–796.

Working Group on California Earthquake Probabilities, 1995. Seismic hazards in southern California: Probable earthquakes, 1994–2024. Bull. Seism. Soc. Amer. 85, 379–439.

World-Stress Map, 2003. World Stress Map Project. Research Group of the Heidelberg Academy of Science and Humanities. (http://www:World-Stress Map.org).

Yeats, R.S., Sieh, K., Allen, C.R., 1997. The geology of earthquakes. Oxford University Press.

Zhidkov, M.P., Rotvain, I.M., Sadowskiy, A.M., 1975. Forecast of the more probable sites occurrence of strongest earthquakes, IV. Papers of Seismology 8, 53–70 [in Russian].

Zoback, M.L., 1992. First- and second-order patterns of stress in the lithosphere: The World Stress Map project. J. Geophys. Res. 97, 11,703–11,728.