Seismicity and seismoactive faults of Cuba

M.O. Cotilla Rodriguez a, *, H.J. Franzke b, D. Cordoba Barba a

a Universidad Complutense de Madrid, Facultad de Ciencias Físicas, Departamento de Física de la Tierra y Astrofísica I, Ciudad Universitaria, s/n, 28040 Madrid, Spain
b Institut für Geologie und Paleontologie, TU Clausthal, Leibnizstrasse 10, D38678 Clausthal-Zellerfeld, Germany

Received 20 January 2006; accepted 9 August 2006

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, Cochin os 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; Calais et al., 1991b; 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 Udías, 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
seismotectonic map (SMp) of Cotilla et al. (1991a), 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 (Ms > 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 (Ms < 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).

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. 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).
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...
earthquakes are expected in M5.509

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 \( M_{\text{max}} \) 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 (Mossakovskiy 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 Udisia, 2000; Cotilla, 1998c). It is mainly concentrated along three sectors: Cabo Cruz, Sierra Maestra-Santiago de Cuba and Maisí (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 Maisí, 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 Guantánamo) (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-Enriqueillo-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; 1999a) argue that the strongest earth- quakes 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; Drutty, 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 (Boniatio, 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 unformably 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 Plion 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 Plion); 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. (1991a) 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 $\sigma_1$ (ENE-WNW oriented) and near-vertical $\sigma_3$, 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,
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 surroundings 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...
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 microtechtonic 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. 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.
**Baconao fault (B).** An outline of this fault that combines normal type sectors, almost vertical, and inverse with left transcurrent. 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. (1991a) 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:
An almost vertical normal fault with a few inverse type sectors which demonstrates transference to the left. It is covered by young sediments in a homonymous asymmetrical

\[ I = 9 \text{ MSK}; 11.06.1766 (M_s = 6.8) \text{ and } 20.08.1852 (M_s = 7.3); \]
\[ I = 8 \text{ MSK}; 11.02.1678, 11.07.1670, 13.11.1762, 18.09.1826, \]
\[ 26.11.1852; I = 7 \text{ MSK}; 08.1578, 1580, 11.02.1675, 1682, \]
\[ 1762, 11.02.1775, 01.11.1775, 07.07.1842, 20.01.1848, \]
\[ 28.01.1858, 19.09.1903, 22.06.1906, 25.12.1914 \text{ and } 17.01.1930]. \]

### Table 2
Main characteristics of the active faults

<table>
<thead>
<tr>
<th>No.</th>
<th>Characteristics</th>
<th>B</th>
<th>BC</th>
<th>C</th>
<th>CA</th>
<th>CN</th>
<th>CU</th>
<th>G</th>
<th>H</th>
<th>HC</th>
<th>LT</th>
<th>LV</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fault type</td>
<td>Normal and reverse type with left strike-slip</td>
<td>Left strike-slip</td>
<td>Normal and reverse type with left strike-slip</td>
<td>Left strike-slip</td>
<td>Normal and reverse type</td>
<td>Left strike-slip</td>
<td>Left strike-slip</td>
<td>Left strike-slip</td>
<td>Normal with left strike-slip</td>
<td>Combined normal, reverse and vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Predominant strike</td>
<td>NW-SE</td>
<td>E-W</td>
<td>NNW-SSW</td>
<td>NE-SW</td>
<td>NE-SW</td>
<td>WNW-ESE</td>
<td>NW-SE</td>
<td>NW-SE</td>
<td>NE-SW</td>
<td>NW-SE, W-E</td>
<td>E-W, NW-SE</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Length (km) / width (km) / depth (km)</td>
<td>240/10/10</td>
<td>&gt;1,000/200/20</td>
<td>200/30/20</td>
<td>180/30/10</td>
<td>150/20/20</td>
<td>190/20/10</td>
<td>280/10/30</td>
<td>230/20/20</td>
<td>310/10/10</td>
<td>200/30/10</td>
<td>25/30/10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Segments</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>Isoseists</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Maximum magnitude (estimated/registered)</td>
<td>3.0/3.0</td>
<td>7.36/9</td>
<td>5.04/7</td>
<td>3.0/3.5</td>
<td>5.8/3.5</td>
<td>4.1/3.0</td>
<td>5.9/3.0</td>
<td>3.0/3.5</td>
<td>5.04/7</td>
<td>4.3/4.6</td>
<td>4.5/4.5</td>
<td>6.2/5.6</td>
</tr>
<tr>
<td>8</td>
<td>Instrumental seismicity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>Macroseismic events</td>
<td>5</td>
<td>&gt;100</td>
<td>21</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>21</td>
<td>14</td>
<td>31</td>
<td>5</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>Historical seismicity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>Focal mechanism</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>12</td>
<td>Injured</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
<td>Seismotectonic unit</td>
<td>Eastern</td>
<td>E-SE</td>
<td>W-CE</td>
<td>CE</td>
<td>CE-E</td>
<td>CE</td>
<td>W</td>
<td>W</td>
<td>W-CE</td>
<td>CE</td>
<td>CE</td>
<td>Northern boundary of megablock</td>
</tr>
<tr>
<td>14</td>
<td>Neotectonic category</td>
<td>3–4</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2–3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>Intersections / knots</td>
<td>64</td>
<td>25/20</td>
<td>6/3</td>
<td>2/2</td>
<td>5/4</td>
<td>2/2</td>
<td>15/10</td>
<td>4/3</td>
<td>5/5</td>
<td>3/3</td>
<td>3/2</td>
<td>8/6</td>
</tr>
<tr>
<td>17</td>
<td>Limited by</td>
<td>Blocks</td>
<td>Megablocks</td>
<td>Macroblocks</td>
<td>Blocks</td>
<td>Macroblocks</td>
<td>Blocks</td>
<td>Macroblocks</td>
<td>Blocks</td>
<td>Macroblocks</td>
<td>Blocks</td>
<td>Megablocks</td>
<td>Blocks</td>
</tr>
</tbody>
</table>

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 transcurrent. It has a NE-SW strike. It is located to the south of the recognized Pinar fault, which has very nice relic expression but is inactive. It extends from the Cabo de San Antonio, where it intersects 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 (05.18.1843, 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. 10. Mean solutions of the microtectonic determinations under the ideas of Bott (1959) in Wulff stereonet, lower hemisphere. Black square $= \sigma_1$ (vertical); small black square $= \sigma_2$ (horizontal maximum); open circle $= \sigma_3$ (horizontal minimum). Where: $R' = 1/R$; $e = 75\%$. It corresponds to Fig. 5. Localities: B.1 — Baconao; B.2 — Santiago de Cuba; C.1 — Cochinos; C.2 — Canimar; H.1 and H.2 — 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.1 — 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 knot with the Nortecubana and Surcubana systems. On the 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.
(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 (Ms = 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; Buznev, 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 Ms < 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 (Ms = 6.2); 15.08.1939 (Ms = 5.6); 24.07.1970, 13.05.1978, 05.01.1990 (mb = 4.5); 20.03.1992 (Ms= 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, Sercubana (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. (1991a) 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., 1991a). They used a ZIPE computer program package (actually GeoforschungZentrum) for fault-slip analysis and determination of maximum ($\sigma_1$), medium ($\sigma_2$), and minimum ($\sigma_3$) 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
(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., 1991a).

Using focal mechanism data we obtained the maximum horizontal compression stress ($\sigma_{H_{\text{max}}}$, 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; hypersymmetry 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 $M_{\text{max}}$ for the seismogenetic zones considered by Cotilla et al (1991a) 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 southeastern 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.

Acknowledgements. We are thankful to Armando Cisternas, Luis Rivera, Herve Philip and Miguel Herraiz for their valuable comments and to Barbara Fernandez and Joachim Pilarski and Monika Pilarski for their kind help and scientific support during the field work. The main author thanks Jose L. Alvarez, Jorge Diaz Comesanas, Enio Gonzalez, Guillermo Millan, Mario Rubio and Manuel Serrano for their support during the project. We thank the Laboratoire Geophysique, Tectonique et Sedimentologie in Montpellier and the Ecole et Observatoire des Sciences de la Terre, Ecole de Physique du Globe in Strasbourg for use of their installations and facilities. M. Cotilla thanks the Comunidad de Madrid (Postdoctoral Grant for 2001-2004) for partial financial support. Also, financial support came from the Ministerio de Educacion y Ciencia, Spain (REN 2003-08520-C02-02 and REN2002-12494-E).

Our thanks go to Dr. Yury Gatinsky, Chief Researcher of the Vemadsky State Geological Museum of the RAS, Moscow, and an unknown reviewer for greatly improving our original manuscript.

References


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).


