Journal of Earthquake Engineering, 12:173–196, 2008

ISSN: 1363-2469 print / 1559-808X online
DOI: 10.1080/13632460701512902

Seismic Hazard Map for Cuba and Adjacent Areas Using the Spatially Smoothed Seismicity Approach

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The seismic hazard assessment for Cuba and the surrounding regions has been performed according to the spatially smoothed seismicity approach. The major motivation for using this methodology is to avoid drawing seismic sources in a region where the seismogenic structures are not well known. We have defined two different seismicity models and three zonation models, based on the evidence of seismotectonic heterogeneity of the broader Cuban region, and two attenuation models for rock and three for soil. The resulting hazard estimates have been treated with a logic tree approach. The highest hazard was obtained around Santiago de Cuba with a PGA larger than 0.28 g on rock and 0.40 g on soil, for a 475-year return period. When the epistemic uncertainties of the different models considered are taken into account, these ground motion values exceed 0.40 g on rock and 0.60 g on soil. A comparison between these new hazard estimates and those computed according to the standard approach of the seismotectonic probabilism indicates the areas where the spatial distribution of the seismicity supports the seismogenic zonation and the areas where a disagreement exists.

Keywords Probabilistic Seismic Hazard; Smoothed Seismicity; PGA Attenuation Relations; Cuba

1. Introduction

Since 1985, several seismotectonic studies have been performed for Cuba in view of a revision of its national building code. Seismic hazard maps for Cuba and neighboring areas, in terms of peak ground acceleration (PGA) for an average soil, and for macroseismic intensity, were computed by Garcia *et al*. [2003] according to the standard methodology of the seismotectonic probabilism (see Muir-Wood, 1993, for details about the generations of hazard maps), a methodology that was adopted also by the Global Seismic Hazard Assessment Program [GSHAP; Giardini, 1999]. These maps were based on the Cornell [1968] approach: a seismogenic zonation, with characterization of the seismicity inside each seismogenic zone (SZ) was, thus, requested. As different seismotectonic models were proposed for Cuba [Orbera *et al*., 1989; Iturralde-Vinent, 1994; Cotilla and Alvarez, 2001], which were rarely well constrained in the whole region by seismicity data, the delineation of the SZs becomes problematic. Furthermore, the definition of their seismicity rates, and the assessment of their maximum magnitude (M_{max}), presented some uncertainties due to the scarcity of seismicity data and, consequently, required some subjective choices as well.

Received 17 January 2006; accepted 13 June 2007.
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For recent, strong earthquakes that hit the United States where low ground motion was expected in the national seismic hazard maps, the robustness of the seismotectonic knowledge became less trustworthy, especially for what concerns intraplate regions. Consequently, an alternative approach used in probabilistic seismic hazard assessment (PSHA) was proposed by Frankel [1995]. In that approach, no delineation of seismic sources is needed, although SZs and active faults can be considered in the hazard computation. Seismic hazard is computed directly from seismicity spatially smoothed in different ways. The Frankel [1995] treatment of seismicity improves the concept of seismic activity already proposed by Riznichenko [1959]. The main difference with the Frankel [1995] approach is in the use of a distribution function for seismicity, instead of its simple averaging [Zakharova, 1986]. A similar approach, the Historical Parametric Method by Veneziano *et al*. [1984], was used for the seismic hazard map of the Caribbean [Shepherd *et al*., 1997] and was considered for the GSHAP hazard map of America [Shedlock, 1999; Shedlock and Tanner, 1999].

Since the northern part of the Cuban region lies in an intraplate region and is characterized by a moderate seismicity, the association of earthquakes to faults is problematic and, consequently, the definition of the SZs is based, in some cases, on subjective decisions. In this situation, hazard estimates based mainly on seismicity data can be a valid complement to the standard seismotectonic approach [Cornell, 1968]. In fact, although the definition of SZs is positive because it focuses on understanding the regional tectonics, this exercise could be misleading when not supported by data. Consequently, a mixture of the two approaches would probably be the best solution: a seismotectonic approach for the more seismic areas and only seismicity elsewhere [see, e.g., Frankel *et al*. 2002].

The goal of the present work is to produce a seismic hazard map for Cuba based on the Frankel [1995] approach, using only seismicity, and, close to what has already been done for southern California [Cao *et al*., 1996] and Alaska [Wesson *et al*., 1999], compare the results with those already obtained from seismotectonic probabilism [Garcia *et al*., 2003]. In this study, the main tectonic province in the western Caribbean region, the plate boundary zone, is taken properly into account. From this comparison, we aim at pinpointing the areas where seismicity data alone do not support the available seismogenic zonation, and at marking the possible corrections for that zonation in future hazard assessments.

2. Seismotectonic Framework

The region of the present study, the islands of Cuba, Jamaica, and Hispaniola (see Fig. 1a), is located on the boundary of the North American and the Caribbean plates, where an approximately sinistral transcurrent movement takes place.

The Caribbean–North American plate boundary zone comprises the fault zones of Polochic-Motagua and the Swan Islands, as well as the Mid-Cayman Spreading Center (CSC). Eastwards, the plate boundary splays into two branches: the northern one consists of the upper extremity of the CSC, the Oriental Fault Zone (OFZ), the Septentrional Fault Zone (SFZ), 19° Fault Zone (19°FZ) [Speed and Larue, 1991], Puerto Rico Trench (PRT), and Lesser Antilles Trench (LAT); the southern branch begins at the lower end of the CSC and comprises, from west to east, the Walton Fault Zone (WFZ), Enriquillo Fault Zone (EFZ), Plantain Garden Fault Zone (PGFZ), Los Muertos Trough (LMT), and Anegada Fault Zone (AFZ). The two branches meet together to the east, in the Lesser Antilles subduction zone. The eastward motion of the Caribbean plate produces left-lateral deformation [Moreno *et al*., 2002] along the EFZ, WFZ, and OFZ.

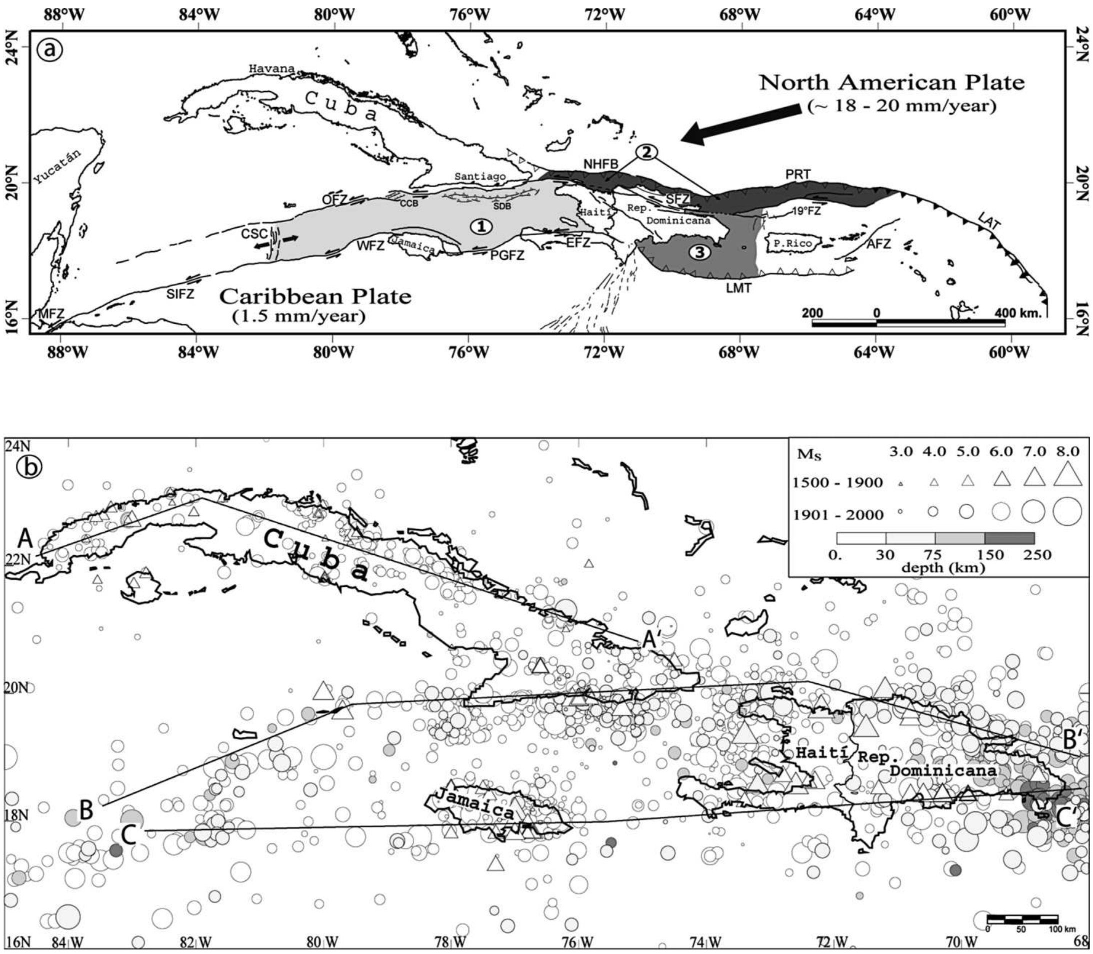

FIGURE 1 Seismotectonic framework of the Cuban region: (a) main tectonic features of the plate boundary zone which are indicated using the following abbreviations: MFZ Motagua Fault Zone, SIFZ Swan Islands Fault Zone, CSC Cayman Spreading Centre, WFZ Walton Fault Zone, OFZ Oriente Fault Zone, NHFB Northern Hispaniola Fold Belt, PRT Puerto Rico Trench, LAT lesser Antilles Trench, 19°FZ 19 degree Fault Zone, PGFZ Plantain Garden Fault Zone, EFZ Enriquillo Fault Zone, SFZ Septentrional Fault Zone, LMT Los Muertos Trough, AFZ Anegada Fault Zone, CCB Cabo Cruz Basin, SDB Santiago Deformed Belt. 1 Gonave Microplate, 2 Septentrional Microplate, 3 Hispaniola Microplate [Mann *et al*., 2002]; (b) epicentres of the earthquakes [Alvarez *et al*., 1999, updated catalog, see text for the description] with $M_S \geq 3.0$: the actual M_S is shown, while its reduced value M_{Se} was used for the computation of the activity rate. AA′, BB′, CC′ indicate the profile traces shown in Fig. 3.

The north-eastern Caribbean plate is characterized by complex tectonics, with several subduction zones. Different authors have suggested the existence of several microplates in the eastern Caribbean. For example, Rosencrantz and Mann [1991] identified as the Gonave Microplate the region delimited by the OFZ, WFZ, and EFZ-PGFZ.

The seismicity in the vicinity of Cuba (Fig. 1b) clearly indicates the capability of the boundary between the North American and Caribbean plates to produce large events: from the CSC, which generates normal faulting earthquakes, to the OFZ and SFZ, where very large transpressive and strike-slip earthquakes occur. The southern edge of the plate boundary zone, south of the OFZ, is defined by the left-lateral strike-slip WFZ, where some large events have been reported near the city of Kingston.

Cuban seismicity, which is documented by a catalog covering more than five centuries, can be divided into two types [Alvarez *et al*., 1991]: intraplate and interplate. Interplate seismicity affects the south-eastern region, where the earthquakes occur mainly in the OFZ. Seismicity in southern Cuba is located along the coast and mainly offshore. The strongest concentration of seismicity can be seen around Santiago de Cuba, where the largest Cuban earthquakes were felt (1766 and 1852, both with maximum intensity I_{max} = IX Medvedev – Sponheuer – Karnik, MSK). The intraplate seismicity affects the rest of the country, with events that occur in the vicinity of some tectonic structures. During the documented period, only one earthquake causing strong damage (the 1880 San Cristobal-Candelaria earthquake, $M_S = 6.0$ and I_{max} = VIII MSK) occurred in the Pinar del Rio region (north-western Cuba).

In recent times, small to moderate magnitude earthquakes were located by the Cuban seismographic network in the eastern part of the island, and some events occurred in the westernmost part, such as those of April 1974 (I_{max} = VI MSK; $M_s = 3.7$) and December 1982 (I_{max} = VI MSK; $M_s = 4.9$).

3. The Spatially Smoothed Seismicity Approach for PSHA

The concept of seismic activity was introduced by Riznichenko [1959] as being the number of earthquakes in a given energy interval in a time and space unit, and was used for the first quantitative estimations of seismic hazard, called seismic shakeability [Riznichenko *et al*., 1969].

Frankel [1995] retrieved the concept of seismic activity by computing seismic hazard directly through the *a*-values of the Gutenberg-Richter distribution derived from different magnitude thresholds. With the addition of the hazard produced by the known seismogenic sources, the seismic hazard maps of the United States were computed [Frankel *et al*., 1996, 2002]. This method, called the spatially smoothed seismicity approach [Frankel, 1995], refers to the Cornell [1968] approach and assumes that future large earthquakes will occur in areas that have experienced small to large earthquakes in the past. The main input data for the application of the Frankel [1995] approach are the earthquake catalog, identify the completeness periods for the different magnitude classes, attenuation relations, and correlation distance, used to smooth the seismicity. Furthermore, seismogenic sources, like SZs and active faults, can be introduced with their own seismicity as well. The software for hazard computation is freely downloadable at http://eqhazmaps.usgs.gov/html/hazsoft.html in form of Fortran and C routines. For the present research, all the Fortran routines have been grouped together eliminating the C routine and introducing attenuation relations suitable for the study region. In recent years, this approach was used to compute the seismic hazard maps of Slovenia [Lapajne *et al*., 1997, 2003], Alaska [Wesson *et al*., 1999], Hawaii [Klein *et al*., 2001], Puerto Rico and the U.S. Virgin Islands [Mueller *et al*., 2003], and some parts of Italy [Akinci *et al*., 2004].

4. PSHA of Cuba

For the computations, we used a December 2000 updated version of the parametric earthquake catalog of Cuba and neighboring areas [Alvarez *et al*., 1999], which covers the region from 67–86° W and from 16–24° N. It contains data reported by international agencies and those recorded by the Cuban seismographic network. The catalog covers a time period of about 500 years (1502–2000).

Four data sources were used to assess the source parameters (date, origin time, epicentral coordinates, depth, magnitude, and macroseismic data) reported in the Alvarez *et al*. [1999] catalog:

- macroseismic data, taken from several compilations, partially published and partially available in the archives of the Cuban National Centre for Seismological Research (e.g., Chuy and Alvarez, 1988; Chuy, 1999);
- instrumental data from international agencies, mainly from the International Seismological Centre [ISS, 1918–1963; ISC, 1964–2000] and the U. S. Department of Commerce [USCGS, 1968–1970; NOAA, 1970–1973; USGS, 1973–1988], integrated with computer compilations available from the 1970's on in the World Data Centres and, more recently, through the web;
- instrumental data from Cuban and Jamaican stations [UWI, 1969–1980; Wiggins-Grandison, 2001; Moreno *et al*., 2002];
- hypocentral relocations and magnitude revaluation, published by Sykes and Ewing [1965] and Russo and Villaseñor [1995] for the Hispaniola region.

A description of most of the global and local sources can be found in Alvarez *et al*. [1983] and Garcia *et al*. [2003].

Macroseismic data are available for all earthquakes of the catalog: they represent an important piece of information not only for the historical period (pre-1900), but also for the 20th century due to the poor deployment of the seismographic stations, especially in western Cuba and Hispaniola. Alvarez and Chuy [1985] showed that the isoseismals of earthquakes in the Greater Antilles can be fitted by a model of concentric ellipses whose attenuation with distance is given by a von Kovesligethy [1907] type formula. A simultaneous determination of hypocentral coordinates and magnitude was done [Alvarez and Chuy, 1985] in all cases of macroseismically documented earthquakes through a trial and error procedure. The quality of these locations depends, obviously, on the number and location of the intensity points. The magnitude estimation was calibrated on M_S values.

The part of the catalog based on data from international seismological agencies reports the same source parameters as the macroseismic part and does not suffer temporal non homogeneities due to wars or other local phenomena. Up until 1953, magnitudes were taken mainly from the Gutenberg-Richter [1954] catalog and were almost equal to M_S [Geller and Kanamori, 1977; Abe, 1981]. For the period 1954–1965, the main source of magnitudes was the Rothé [1969] catalog, where the reported magnitude is M_S. Moreover, magnitude values were taken from station bulletins, published papers, and earthquake compilations [Alvarez *et al*., 1983]; all these magnitudes were corrected when more reliable estimates existed. Preference was given to the ISS hypocenter locations, unless new computer relocations were available.

An important part of the catalog is given by the local network data. In the Cuban bulletins of the previous decades (1965–1978), the earthquake size was mainly presented in terms of energy class K_r [Rautian, 1964], The relationship $M_S = 0.48\,K_r - 1.5$ was established by Alvarez *et al*. [1990]. Since 1979, the magnitude, reported in the bulletins, was calibrated on M_S and computed from the duration D of the signals of all the recording stations with the relationship [Alvarez *et al*., 1990]:

$$M_S = 3.2 \log D - 4.5.$$

Only when it was not possible to determine the duration D, was magnitude computed through the energetic class K_r.

The data collection cannot be considered homogeneous over the whole study area because of the presence of the sea and the different kinds of data included in the catalog.

Nevertheless, the macroseismic data of the large quakes are satisfactory for the events that occurred in Cuba, Jamaica, and Hispaniola. The quality of the macroseismic locations is quite variable, ranging from good, when a detailed isoseismal map exists, to very approximate, when only one macroseismic intensity is available. The data of the seismographic networks are better in eastern Cuba and Jamaica than in the rest of the Cuban territory and in Hispaniola. For these network data, the quality criteria for the source parameters are approximately given by the number of recording stations. The same criteria hold also for the data of the international agencies, but magnitudes were, in general, determined by only a few stations.

The most common hypothesis in PSHA is that the earthquake occurrences form a Poisson process, i.e., a process stationary in time, of independent and non-multiple events. Aftershocks were, then, removed from the catalogue according to the Gardner and Knopoff [1974] technique with parameters calibrated for Cuba [Garcia *et al*., 2003]. From the complete catalogue counting 16,525 earthquakes, a data set of 10,376 independent events with magnitude M_S determination was obtained. A total of 2,041 earthquakes with magnitude greater than, or equal to 3.0 were judged suitable for the seismic hazard assessment.

4.1. The Logic Tree

The major motivation for using the smoothed seismicity methodology directly is to avoid the subjective judgment involved when drawing SZs in a region where is problematic to associate seismicity with tectonic features. Nevertheless, the application of the smoothed seismicity methodology also involves some decisions affected by their own uncertainties. These uncertainties can be considered epistemic uncertainties [McGuire, 1977; McGuire and Shedlock, 1981; Toro *et al*., 1997] and then can be treated with the logic tree approach. The different uncertainties determine the branches of the logic tree, whose nodes are described in the following.

The first node (N1 in Fig. 2) takes into consideration different seismicity models. Two seismicity models have been taken into account: they refer to different threshold

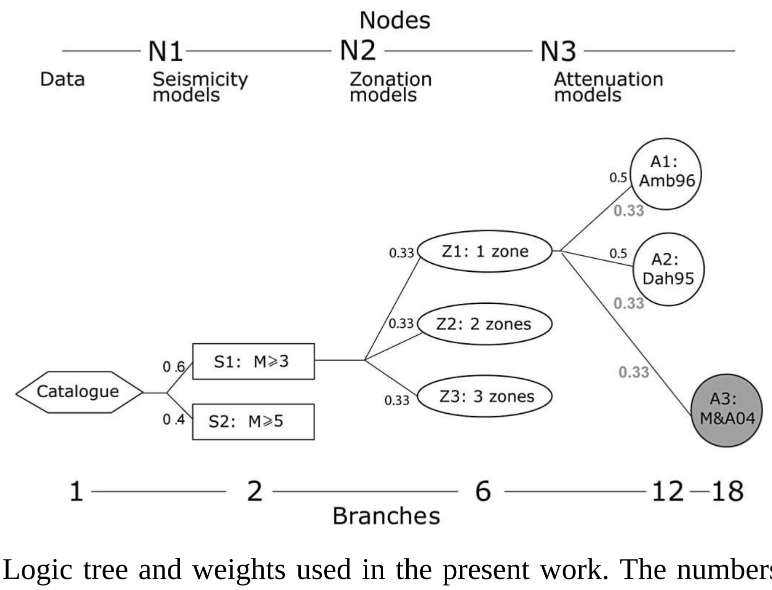

FIGURE 2 Logic tree and weights used in the present work. The numbers indicate the weights, the grey numbers refer to the soil hazard assessment, where model A3 was also used.

magnitudes (S1 to $M_S \geq 3$ and S2 to $M_S \geq 5$) for the computation of the activity rates. The two models require the different completeness periods for each magnitude class that exceeds the threshold value ($M_S \geq 3$ and $M_S \geq 5$, respectively; see Table 1). An additional model considered by Frankel *et al*. [2000] refers to magnitude 4.0, and is discarded here because the amount of data for medium to low magnitude events in our catalog does not produce any remarkable differences with respect to the hazard estimates obtained by the S1 model. Large earthquakes (about magnitude 7 and above) have occurred in the Cuban region (*e.g.*, M_S 7.2 in 1562, M_S 7.3 in 1852, M_S 8.1 in 1946, and M_S 6.9 in 1992), but no evidence of characteristic earthquake behavior has yet been found. Consequently, the additional seismicity model of Frankel [1995], which considers the characteristic earthquakes, is not elaborated here.

The second node (N2 in Fig. 2) refers to the zonation models. More precisely, the different models define the regions where the *b*-value and M_{max} are considered constant. We define three different zonations, on the basis of the regional seismotectonic features.

The third node (N3 in Fig. 2) considers the attenuation models. In the absence of PGA attenuation relationships specifically valid for the Cuban region, we decided to consider the ones for Central America and Puerto Rico [Dahle *et al*., 1995; Motazedian and Atkinson, 2005] and the most popular one for Europe [Ambraseys *et al*., 1996] that are available.

The logic tree used here (Fig. 2) is then constituted by two seismicity models, three seismicity parametrizations, and two and three attenuation relations for rock and soil, respectively.

4.2. Seismicity Models

As said before, two seismicity models were considered here (see Node N1 in Fig. 2): these seismicity models consist of the threshold magnitude used in the elaboration, and the suitable correlation distance for the magnitude range. Model S1 refers to a threshold magnitude M_S of 3.0, while Model S2 to a threshold value of 5.0. Many tests were carried out in order to determine an empirical value for the correlation distance *c*, for each seismicity model. Values of 10, 25, 30, 40, 50, and 100 km were tried for *c* and, by comparing the relative activity rate maps, we found that a *c*-value of 30 km can be well applied to the seismicity models S1, while a value of 40 km is more suitable for the seismicity model S2. A very fragmented pattern related to small clusters of earthquakes was found using a *c*-value smaller than 25 km.

The use of two seismicity models is motivated by the fact that some features of each seismicity model are not reflected in the other. To demonstrate this, we considered three profiles in the study region (see their location in Fig. 1b) representing, respectively, the intraplate region (profile AA'), the northern (profile BB'), and the southern (profile CC') plate boundaries. The activity rate 10^a for the two seismicity models (Fig. 3) was computed and compared for each of the three profiles. Hence, there are areas where a high rate related to model S1 is coupled to almost no seismicity computed with model S2 (e.g., the highest peak in Fig. 3a which is located in central Cuba). Conversely, regions in Jamaica and Hispaniola that show high activity according to model S2, show a very low one according to model S1 (see the two major peaks in Fig. 3c which correspond to Jamaica and southern Hispaniola). Although the activity rate is computed taking into account the proper completeness period of each magnitude class, these discrepancies could be, at least partly, explained by the presence of the Cuban seismographic network, which also records small events on the Cuban territory (in areas without strong quakes) but not elsewhere.

TABLE 1 Completeness periods and seismicity parameters for the different zonation models

Models	Zones	Completeness period (years before 2000)						b-value	b-value	
		$M_S = 3$	$M_S = 4$	$M_S = 5$	$M_S = 6$	$M_S = 7$	$M_S = 8$	$M_S \geq 3$	$M_S \geq 5$	M_{max}
Z1	W Caribbean	20	35	100	250	350	500	0.74	0.69	8.5
Z2	intraplate	40	60	150	500	–	–	0.90	0.84	6.5
Z2	interplate	20	40	150	250	400	500	0.73	0.64	8.5
Z3	intraplate	40	60	150	500	–	–	0.90	0.84	6.5
Z3	N plate boundary zone	20	40	100	200	350	500	0.76	0.60	8.5
Z3	S plate boundary zone	20	35	125	250	350	500	0.70	0.70	8.0

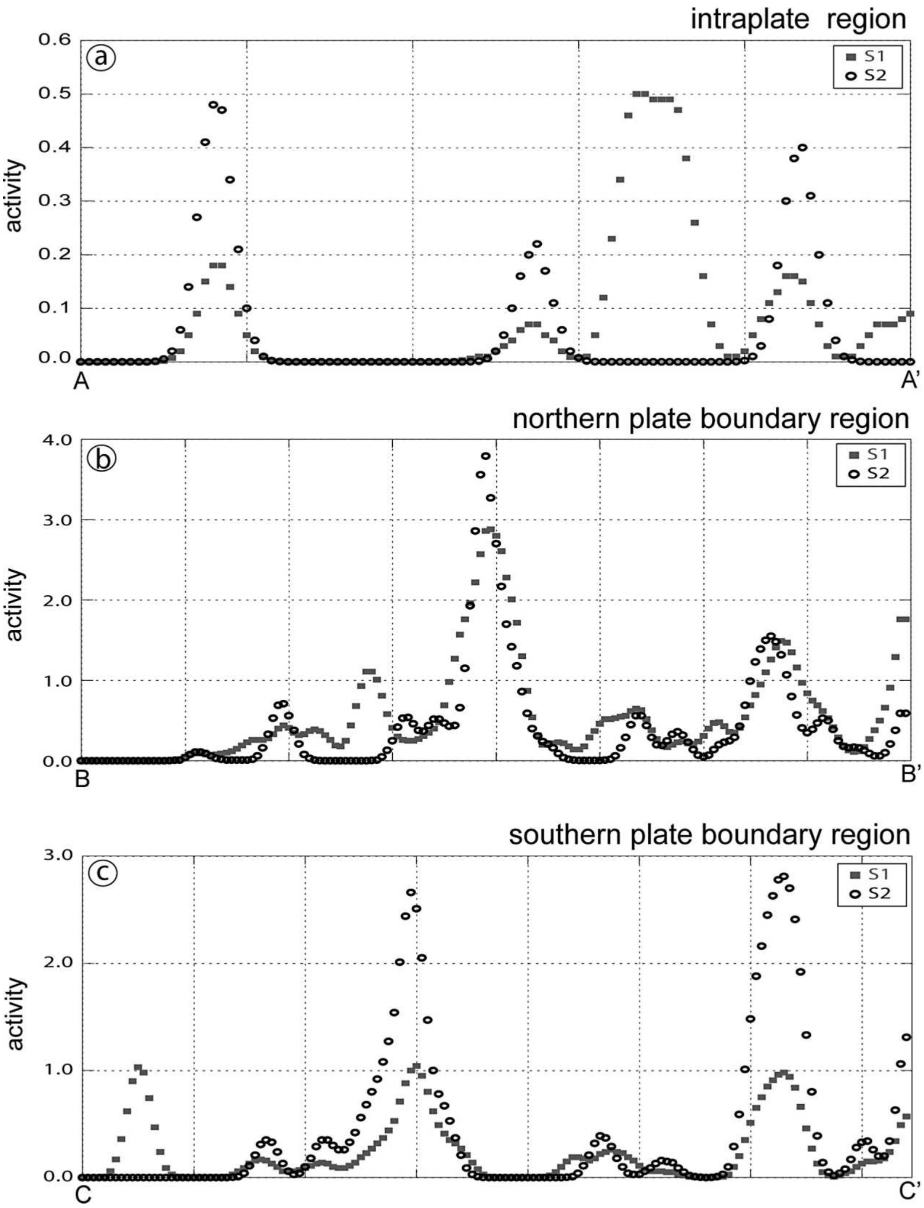

FIGURE 3 Smoothed 10^a values derived from models S1 (solid squares) and S2 (empty circles): (a) intraplate zone: (b) northern plate boundary zone; and (c) southern plate boundary zone.

4.3. Zonation Models

The Frankel [1995] method calls for the identification of areas in the investigated region where the seismicity parameters (*b*-value and M_{max}) are uniform. This identification was often motivated by the need to apply different attenuation relations [e.g., Frankel *et al*., 1996 for the U.S.; Akinci *et al*., 2004 for Italy]. This is not the case for the study region, where the use of specific attenuation relations is not required. In fact, the almost total absence of intermediate and deep earthquakes west of 70° W implies that there is no subducted slab in this region, which exists to the east [Dolan and Bowman, 2004]. We have characterized the Cuban region on the basis of different types of seismicity and identified some seismotectonically homogeneous sectors, where the seismicity parameters

(b-value and M_{max}) are constant (Fig. 4). We have avoided the introduction of SZs (e.g., Hawaii [Klein *et al*., 2001]) as well because our intention is to compare the results of the spatially smoothed seismicity approach with those obtained considering SZs [Garcia *et al*., 2003].

The catalog completeness for each magnitude class and each zone (see Table 1) was obtained by means of plots of the cumulative number of events vs. time [Stepp, 1972]. The related b-values (see Table 1) were obtained by fitting, separately for the seismicity models S1 and S2, the cumulative number of earthquakes in each magnitude class to the Gutenberg–Richter relation by the maximum likelihood method [Weichert, 1980]. The maximum magnitude for each zone (see Table 1) was assigned by increasing the maximum observed magnitude by 0.5 with respect to the central values of the magnitude classes when referred to a return period shorter than the earthquake catalog length ["one step beyond" technique: Slejko *et al*., 1998].

Zonation model Z1 (Fig. 4a) considers a unique, homogeneous zone (Caribbean) over the entire study area. The maximum observed magnitude refers to the M_S 8.2, 1946 Hispaniola earthquake, and the b-values of 0.74 and 0.69 were calculated, respectively, for models S1 and S2 (Fig. 5a).

In zonation model Z2 (Fig. 4b), the study region was divided into two parts, taking into account the two different global tectonic environments that exist in the area. The northern intraplate region is related to a moderate to low seismicity, the M_S 6.2, 1914 Gibara earthquake represents the maximum observed event and the calculated b-value is 0.90 for model S1 and 0.84 for model S2 (Fig. 5b). In this region, the earthquakes occur along tectonic faults with long periods of quiescence. In the southern interplate region, the earthquakes occur mainly on the plate boundary (northern and southern limits of the Gonave microplate), the M_S 8.2, 1946 Hispaniola earthquake is the maximum observed event and the calculated b-value is 0.73 for model S1 and 0.64 for model S2 (Fig. 5c).

The interplate region was divided into the northern and southern zones in zonation model Z3 (Fig. 4c), to emphasize the role of the two active branches along the plate boundary zone. The M_S 8.2, 1946 Hispaniola earthquake is the extreme event in the northern plate boundary area and the computed b-values are 0.76 and 0.60 for models S1 and S2, respectively (Fig. 5d). The M_S 7.8, 1692 Port Royal, Jamaica earthquake represents the major event in the southern plate boundary area and the computed b-value is 0.70 for both models S1 and S2 (Fig. 5e).

A 50 km-wide overlapping area was used to smooth the transition from one zone to another in models Z2 and Z3.

4.4. Attenuation Models

The strong-motion relationship used in seismic hazard assessment has a great influence on the hazard results. General relations valid over very large regions can be found in literature and used when local relations are not available. This is the case of the Cuban region, where no strong-motion data were available before 1998, when the first accelerometers were installed, and, consequently, PGA attenuation relations have not been calibrated yet. Very recently, an attenuation relation for Puerto Rico was proposed by Motazedian and Atkinson [2005]. This relation was calibrated for a soft-rock-site condition on waveforms stochastically simulated for earthquakes of moment magnitude from 3–8 and fault distances (known also as Joyner and Boore, 1981, distances) from 2–500 km. The stochastic model ground-motion relations were validated using data from about 300 earthquakes in Puerto Rico.

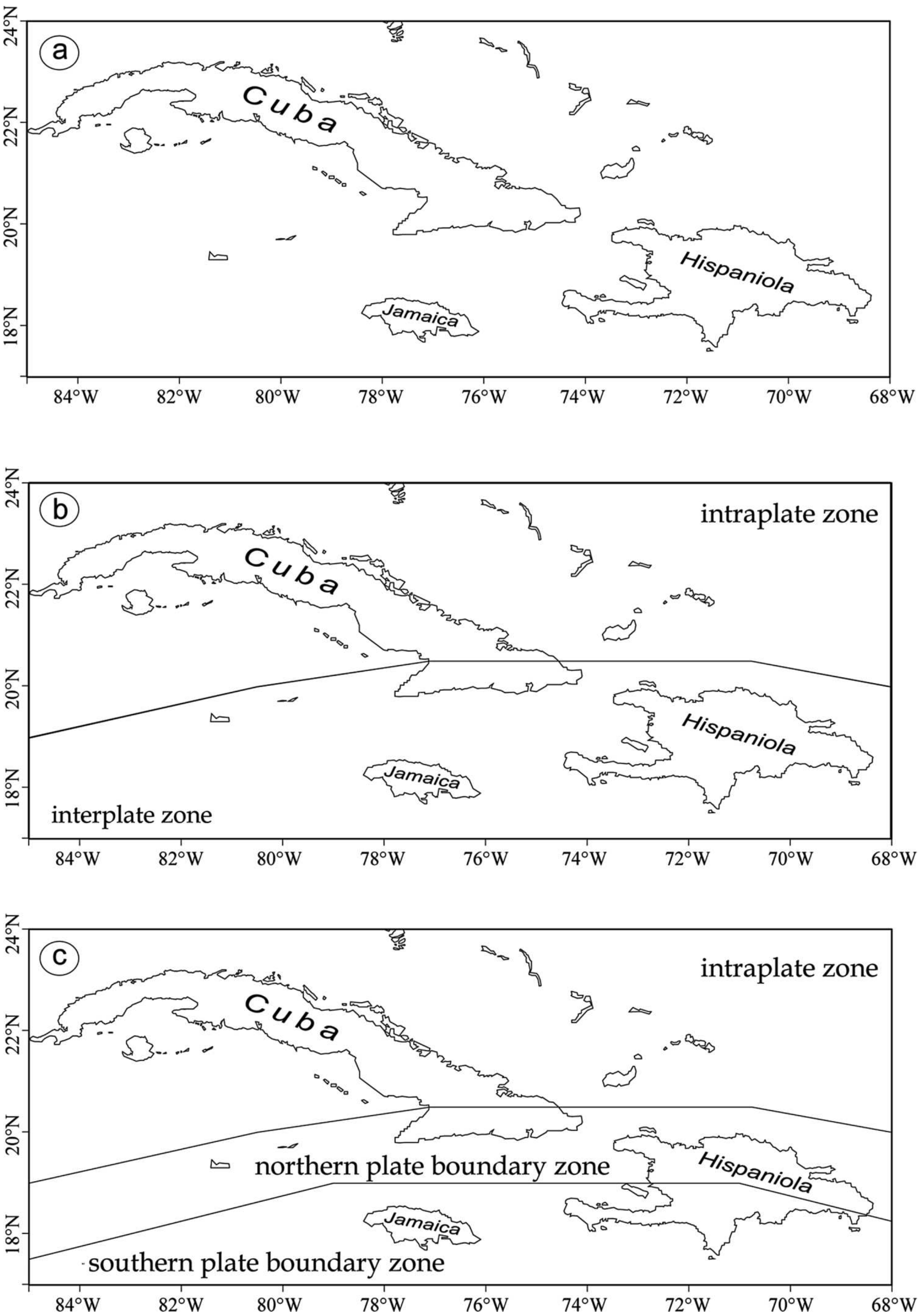

FIGURE 4 Zonation models. The *b*-value and M_{max} are considered homogeneous in each sector for the same seismicity model: (a) zonation model Z1 considers the whole region as homogeneous; (b) zonation model Z2 separates the southern interplate region from the less seismic northern intraplate region; (c) zonation model Z3 separates the northern plate boundary region from the southern plate boundary one.

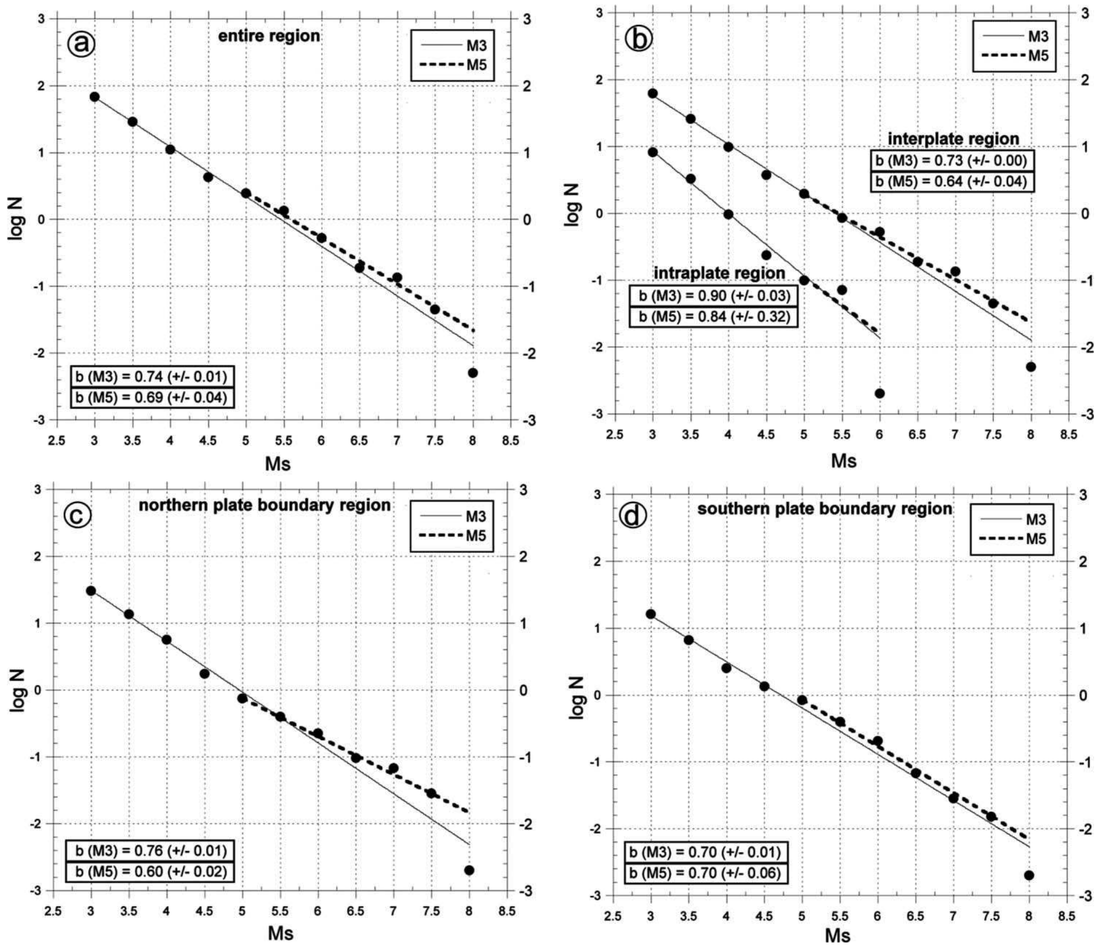

FIGURE 5 *b*-values considered in the different zonation models for seismicity models S1 (solid line) and S2 (dashed line): (a) zonation model Z1, (b) intraplate and interplate regions of zonation model Z2 (c) northern plate boundary region of zonation model Z3; (d) southern plate boundary region of zonation model Z3.

For the present study, we selected three attenuation models. The first model, A1, is the Ambraseys *et al*. [1996] relation, which was calibrated for rock, stiff soil, and soft soil on the basis of strong motion recordings of European earthquakes. The second model, A2, is the Dahle *et al*. [1995] one, which was calibrated for rock and soil on the basis of strong motion recordings of earthquakes in Central America. The Dahle *et al*. [1995] relation seems adequate for our needs as the records from subduction zones are a marginal part of the data set used for its calibration. The third model, A3, is the previously described Motazedian and Atkinson [2005] relation.

The Ambraseys *et al.* [1996] attenuation relation is defined for epicentral distances for earthquakes with magnitude M_S smaller than 6, and fault distances for the larger events. The Motazedian and Atkinson [2005] relation is defined for moment magnitude M_W and for fault distances. The Dahle *et al*. [1995] relation was defined for magnitude M_W and epicentral distances. Since we considered the fault finiteness in the present elaboration, a proper conversion for distance was introduced for the correct application of the Dahle *et al*. [1995] attenuation relation. More precisely, since the strong-motion data set used by Dahle *et al*. [1995] is not available, an average correction for fault vs. epicentral distance was estimated. Considering that this correction was estimated [Gruppo di Lavoro, 2004] for the Ambraseys *et al*. [1996] relation, and the proper correction can be easily obtained for another PGA attenuation relation (the Sabetta and Pugliese [1987] relation was calibrated for both distances), the average correction between these two was considered in the present study. The M_S estimates of the Alvarez *et al*. [1999] catalog were converted into M_W, when necessary, using the Ekstrom and Dziewonski [1988] relation.

All the selected relations [Dahle *et al*., 1995; Ambraseys *et al*., 1996; Motazedian and Atkinson, 2005] are defined for shallow earthquakes. Some events in the study area, mainly in the Hispaniola region, have a deep focus: 419 events with $M_S \geq 3.0$ have a depth between 30 and 230 km. In the available literature, the relations for deep events are not suitable for hazard computation [Bommer *et al*., 1996] or refer to subduction zones [Youngs *et al*., 1997; Atkinson and Boore, 2003]. In our case, subduction could take place only in a marginal sector of the study area. Consequently, depth has been taken into account in our computation by converting the real M_S value of the events that are deeper than 30 km into an equivalent magnitude (M_{Se}) of a shallow quake. In order to do this, the Bommer *et al*. [1996] PGA attenuation relation for El Salvador and Nicaragua

$$\ln \mathrm{PGA} = -1.47 + 0.608\, M_s - 1.181 \ln R + 0.0089\, h$$

was used because it explicitly contains the h term representing the depth in addition to the R term related to the hypocentral distance. The Bommer *et al*. [1996] relation is defined for M_S between 3.7 and 7.0 and for h between 62 and 260 km. In the present application, the Bommer *et al*. [1996] relation has been arbitrarily extrapolated to events with a depth of 30 km; maximum depth of the data set considered in the Ambraseys *et al*. [1996] relation. By equalizing the ground motion (ln PGA) generated by the actual earthquake (M_S and h) to that of the equivalent one (M_{Se}, $h_e = 30$), the correction $\Delta M_S = M_S - M_{Se} = 0.01464\,(h - 30)$, that depends only on h, has been found. This correction was computed for three average depth levels (h = 50, 100, 175 km) that represent well the deep events in our catalog:

$\Delta M_S = 0.3$ for 30 km $\leq$ h < 75 km (377 earthquakes);
$\Delta M_S = 1.0$ for 75 km $\leq$ h < 150 km (208 earthquakes);
$\Delta M_S = 2.1$ for h $\geq$ 150 km (27 earthquakes).

More precisely, the rock versions of the Dahle *et al*. [1995] and Ambraseys *et al*. [1996] relations were used for the rock seismic hazard assessment; the stiff soil version of the Ambraseys *et al*. [1996], the soil version of the Dahle *et al*. [1995], and the Motazedian and Atkinson [2005] relations were used for the soil hazard computation.

4.5. Results

Following the methodology previously described, 12 hazard maps were computed for rock and 18 for soil, considering 2 seismicity models, 3 zonation models, and 2 and 3 PGA attenuation models for rock and soil, respectively (Figs. 6–8). The hazard estimates refer

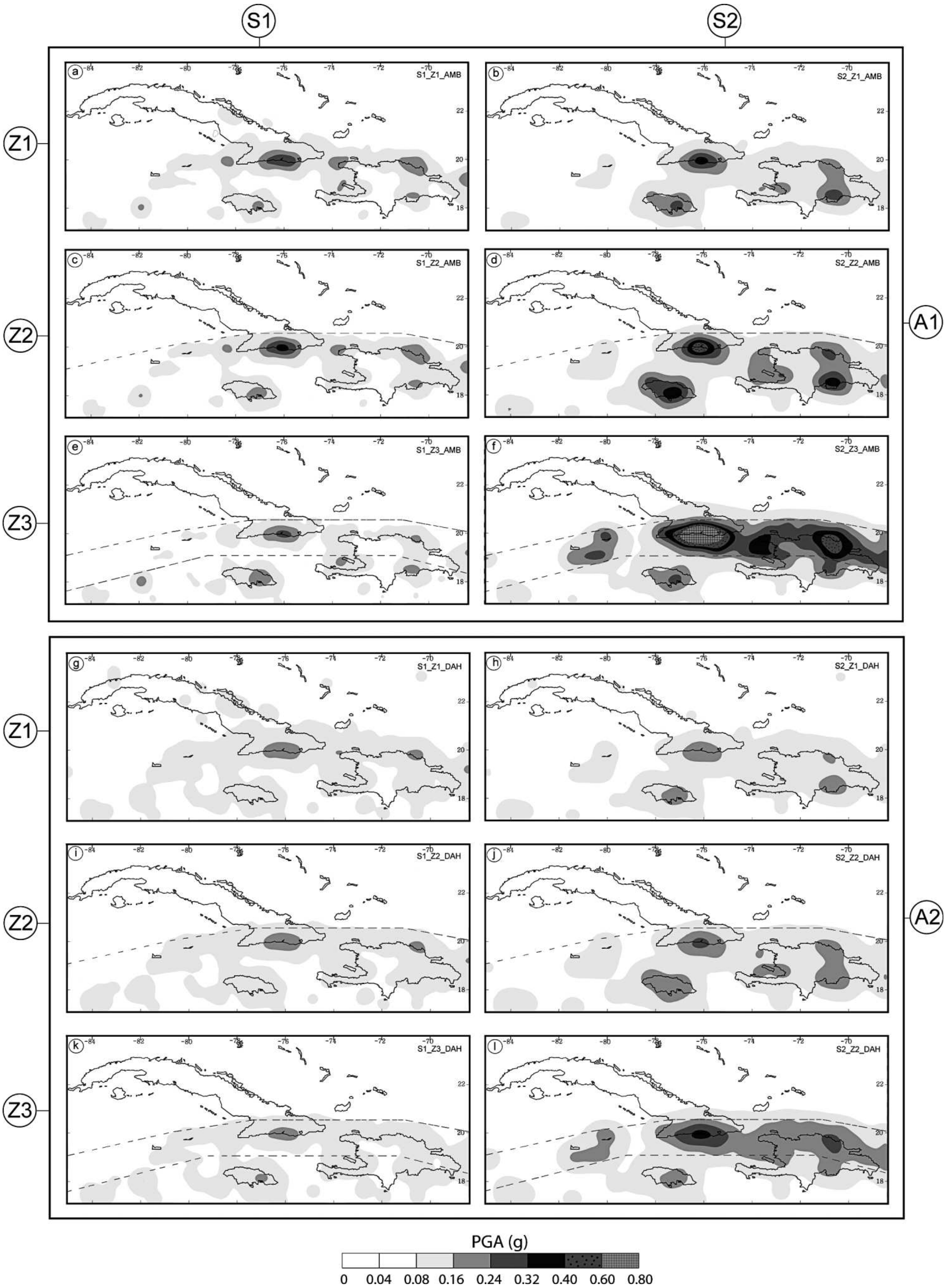

FIGURE 6 PGA on rock with a 475-year return period with standard deviation of the attenuation relation: (a) models S1, Z1, A1; (b) S2, Z1, A1; (c) S1, Z2, A1; (d) S2, Z2, A1; (e) S1, Z3, A1; (f) S2, Z3, A1; (g) S1, Z2, A2; (h) S2, Z1, A2; (i) S1, Z2, A2; (j) S2, Z2, A2; (k) S1, Z3, A2; (l) S2, Z3, A2.

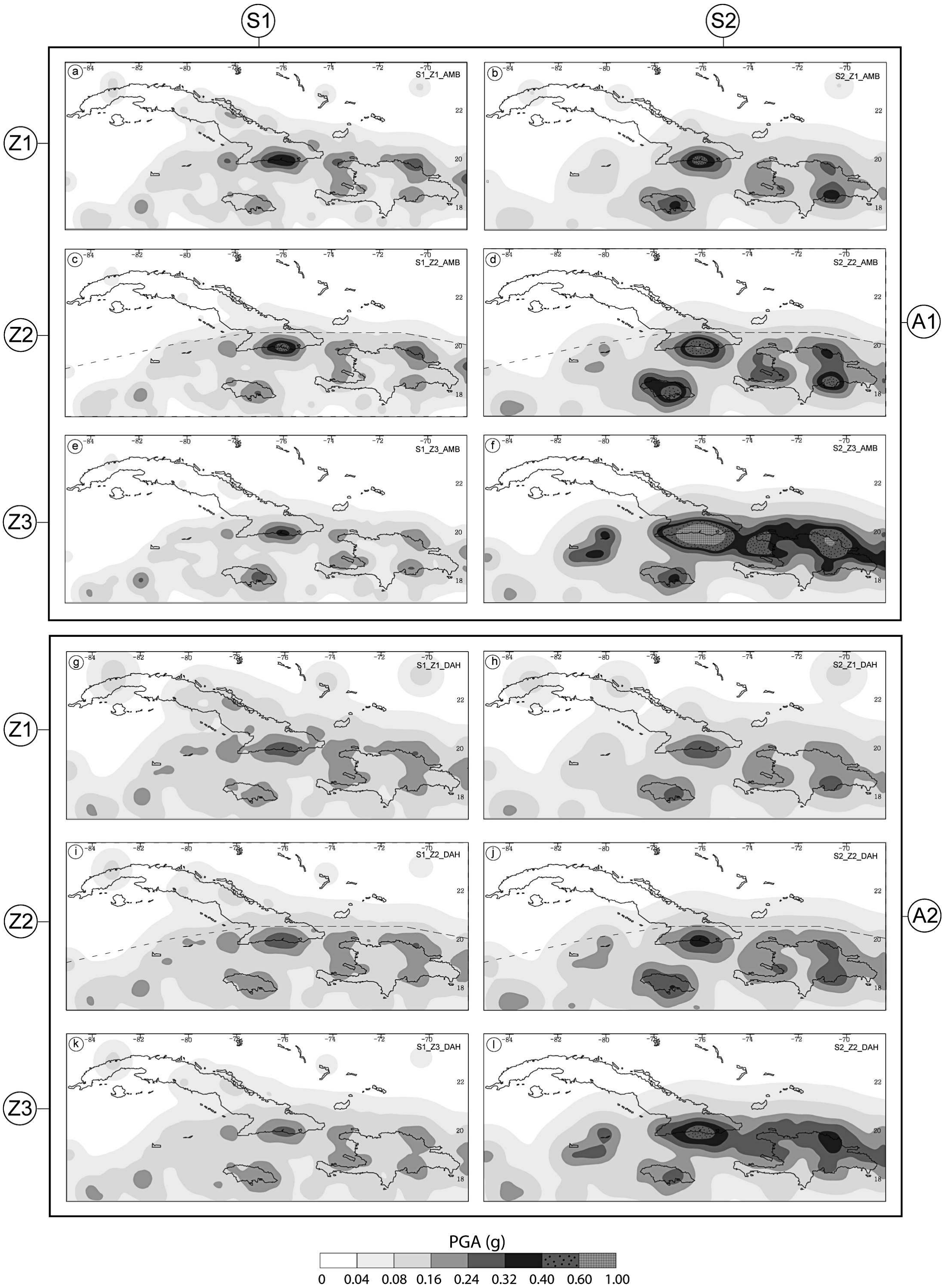

FIGURE 7 PGA on soil with a 475-year return period with standard deviation of the attenuation relation: (a) models S1, Z1, A1; (b) S2, Z1, A1; (c) S1, Z2, A1; (d) S2, Z2, A1; (e) S1, Z3, A1; (f) S2, Z3, A1; (g) S1, Z2, A2; (h) S2, Z1, A2; (i) S1, Z2, A2; (j) S2, Z2, A2; (k) S1, Z3, A2; (l) S2, Z3, A2; (m) S1, Z2, A3; (n) S2, Z1, A3; (o) S1, Z2, A3; (p) S2, Z2, A3; (q) S1, Z3, A3; (r) S2, Z3, A3.

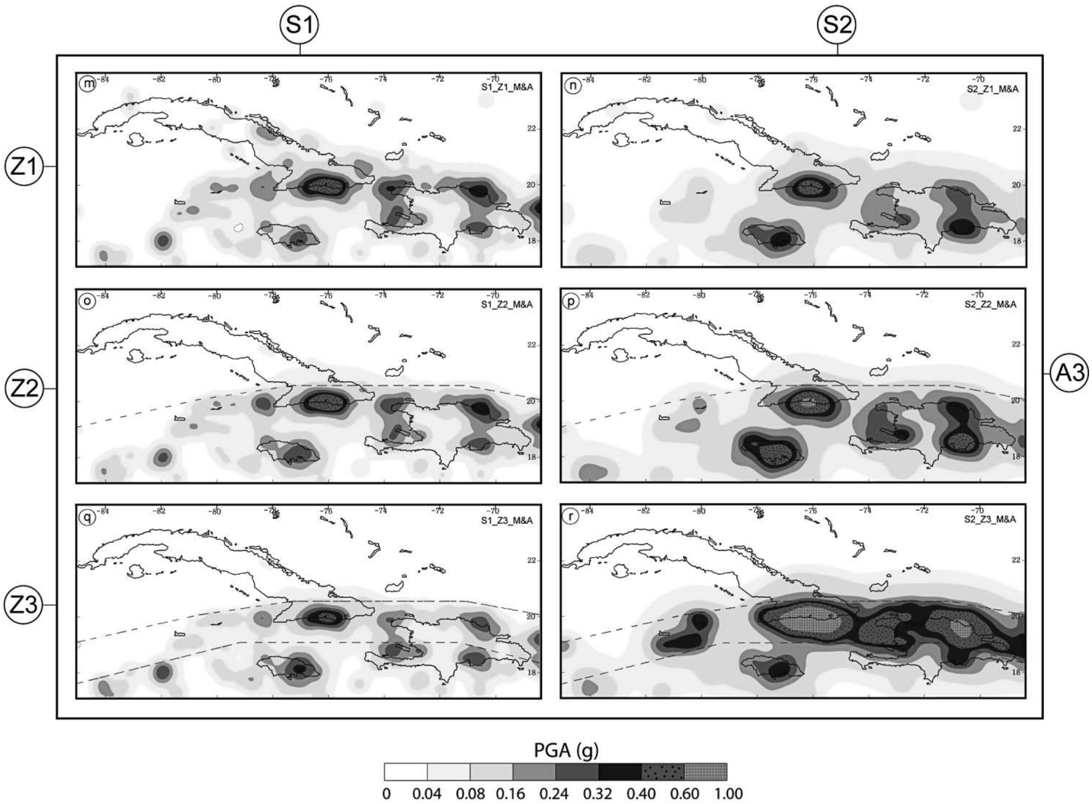

FIGURE 7 (*Continued*).

to a 475-year return period, which corresponds to the 90% non exceedance probability in 50 years. The data scatter around the attenuation models represents the aleatory variability and is quantified by the standard deviation of the attenuation relations: it is taken into account in the hazard computation.

The study area (17° N and 68°W to 24° N and 85° W) was divided into an 0.1° spacing grid (about 10 km in latitude and longitude) for the hazard computation.

The general features of the maps for rock (Fig. 6) are obviously similar and show the highest hazard located in correspondence to the plate boundary zone. More precisely, the main seismic spot can be seen on the southern coast of Cuba, around Santiago. Other areas with an expected high PGA can be seen in Jamaica and along the northern and southern coasts of Hispaniola. In the maps computed with seismicity model S1 (left column in Fig. 6), the hazard is represented by several spots, while in those with model S2 (right column in Fig. 6) by large areas. Furthermore, model S2 emphasizes the most seismic areas while model S1 also indicates some hazardous areas in the low-seismicity region (north-western Cuba). The influence of the zonation models is limited in seismicity model S1 while it strongly determines the ground motion level along the plate boundary in seismicity model S2. The PGA is larger in the most seismic areas (see Santiago) with the attenuation model A1 [Ambraseys *et al.*, 1996] while it is larger in the less seismic areas (compare, e.g., north-western Cuba in Figs. 6a and 6g) with the attenuation model A2 [Dahle *et al.*, 1995]. The largest PGA values (exceeding 0.40 g) are obtained with seismicity model S2, zonation Z3, and attenuation model A1, along most of the southern Cuban coast (Fig. 6f).

As expected, the general features of the maps for soil acceleration (Fig. 7) do not differ much from those of the rock maps (Fig. 6) and the estimated ground motion is larger. The results obtained with attenuation models A1 [Ambraseys *et al.*, 1996] and A3

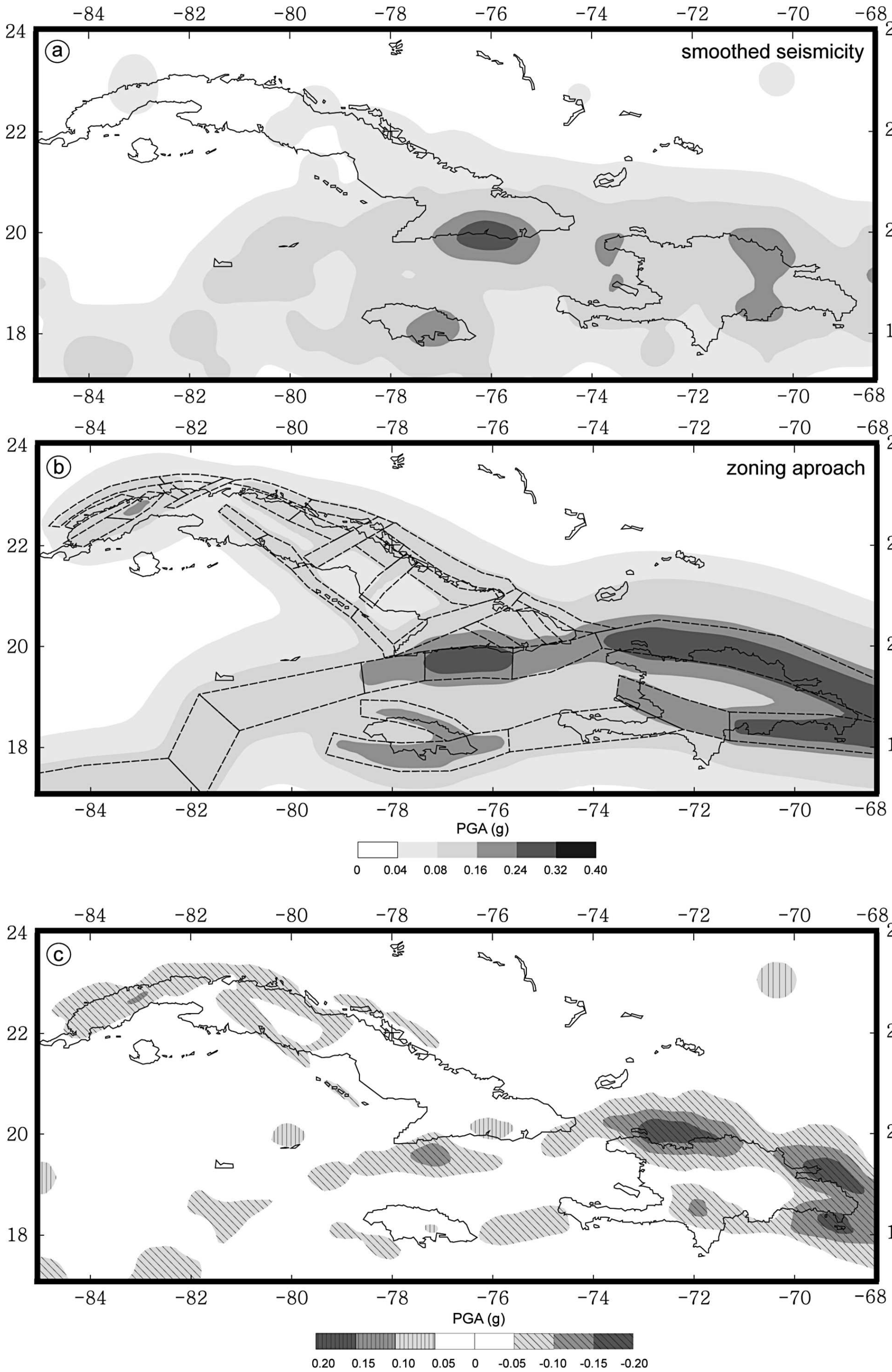

FIGURE 8 Comparison between the median PGA on rock with a 475-year return period, with the standard deviation of the attenuation relations used [Dahle *et al*., 1995; Ambraseys *et al*., 1996]: (a) computed by aggregating the results of the logic tree for the spatially smoothed seismicity approach (Fig. 2); (b) computed by the Cornell [1968] approach, the SZs used in the computation are drawn as boxes; (c) difference between the PGA estimates with the smoothed seismicity and Cornell [1968] approaches.

[Motazedian and Atkinson, 2005] are very similar: model A3 gives higher ground motion in the very near field and attenuates slightly faster than model A1 (compare Figs. 7e and 7q). Consequently, the highest-ground motion (PGA exceeding 0.60 g along most of the plate boundary from Cuba to Hispaniola) are obtained with seismicity model S2, zonation model Z3, and attenuation model A3 (Fig. 7r).

The final aggregate maps (Figs. 8a and 9a) were obtained by weighting the results from the two seismicity models, three zonation models, and two and three attenuation models, for rock and soil, respectively, according to the scheme shown in Fig. 2. All the different models were weighted evenly with the exception of the seismicity models, where a slight preference was given to model S1 (earthquakes with M_S 3 and over) because the major part of our main study area (Cuba) belongs to an intraplate region, where large earthquakes rarely appear in the catalog and, consequently, it is more problematic to define the actual hazard there using only the few large events. The map in Fig. 8a shows the median value of the PGA with a 475-year return period for rock. It highlights the features already seen in the maps of the individual results (Fig. 6) with the highest hazard along the plate boundary, especially along the southern Cuban coast, where PGA values exceeding 0.24 g are expected. The map in Fig. 9a displays the ground motion calculated for soil: similar features to those of the previous map can be clearly seen but with expected PGA values higher than 0.40 g around Santiago.

To quantify the epistemic uncertainty related to the hazard estimates, one standard deviation was added to the median PGA obtained by the weighted mean of the probabilities obtained from the different branches of the logic tree. The maps obtained (Fig. 10) are, obviously, very similar to those with the median PGA values (Figs. 8a and 9a) with a general increase in the ground motion. More precisely, the highest PGA values (exceeding 0.40 g on rock and 0.60 g on soil) can be seen along the southern coast of Cuba. Two spots with a PGA on soil exceeding 0.60 g can be seen in northern and eastern Hispaniola (Fig. 10b). Jamaica is involved in a slightly lower ground motion with a PGA exceeding 0.24 g on rock and 0.40 g on soil.

5. Comparison between the Hazard Maps Obtained with the Zone Approach and the Spatially Smoothed Seismicity Method

In a recent paper [Garcia *et al.*, 2003], the PSHA for Cuba and the surrounding region was computed for an average soil following the standard Cornell [1968] approach. A detailed seismogenic zonation with 36 SZs was used in that work. The results of the same approach are presented here for rock, considering the Ambraseys *et al.* [1996] and Dahle *et al.* [1995] attenuation relations (Fig. 8b), and for soil, using the Ambraseys *et al.* [1996], Dahle *et al.* [1995], and Motazedian and Atkinson [2005] attenuation relations (Fig. 9b). The wide differences in results obtained using the zoning and the spatially smoothed seismicity approaches should indicate either that the definition of a SZ has artificially concentrated the seismicity there or that an additional SZ is suggested.

Figures 8 and 9 display the median value of the PGA with a 475-year return period, with the standard deviation of the attenuation relations, and clearly show the different pattern of the maps obtained using the two different approaches. The ones from the spatially smoothed seismicity approach (Figs. 8a and 9a) are more detailed, while the ones from the zoning approach (Figs. 8b and 9b) average the hazard over the SZs considered. Thus, with the spatially smoothed seismicity approach (Fig. 8a), a PGA on rock higher than 0.24 g is expected around Santiago, whereas the same southern Cuban coast and the northern and southern coasts of Hispaniola are hazardous (PGA values larger than 0.24 g) with the zoning approach (Fig. 8b). The soil maps show similar features with values exceeding 0.40 g

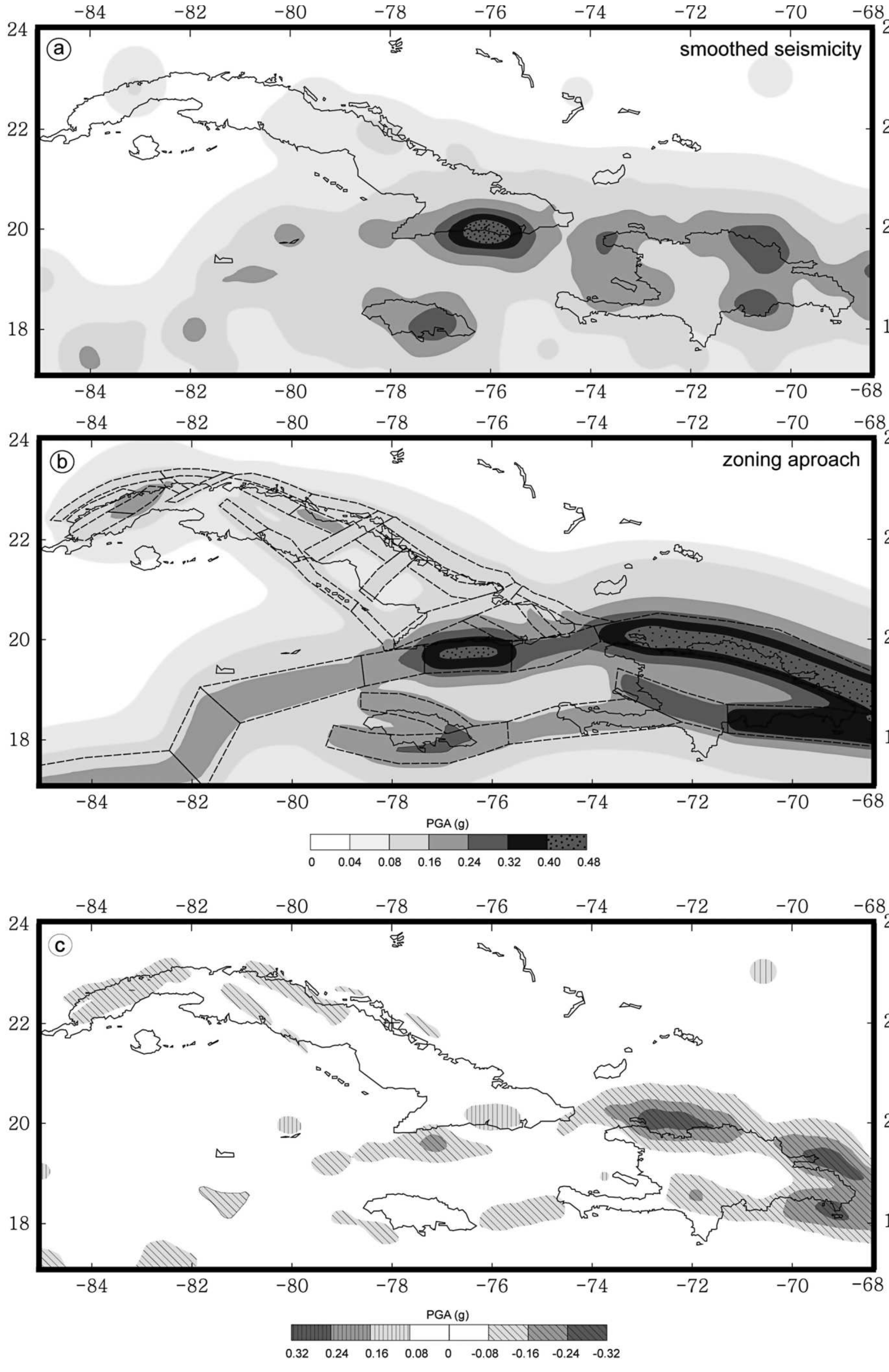

FIGURE 9 Comparison between the median PGA on soil with a 475-year return period, with the standard deviation of the attenuation relation used [Dahle *et al*., 1995; Ambraseys *et al*., 1996; Motazedian and Atkinson, 2005]: (a) computed by aggregating the result of the logic tree for the spatially smoothed seismicity approach (Fig. 2); (b) computed by the Cornell [1968] approach, the SZs used in the computation are drawn as boxes; (c) difference between the PGA estimates with the smoothed seismicity and Cornell [1968] approaches.

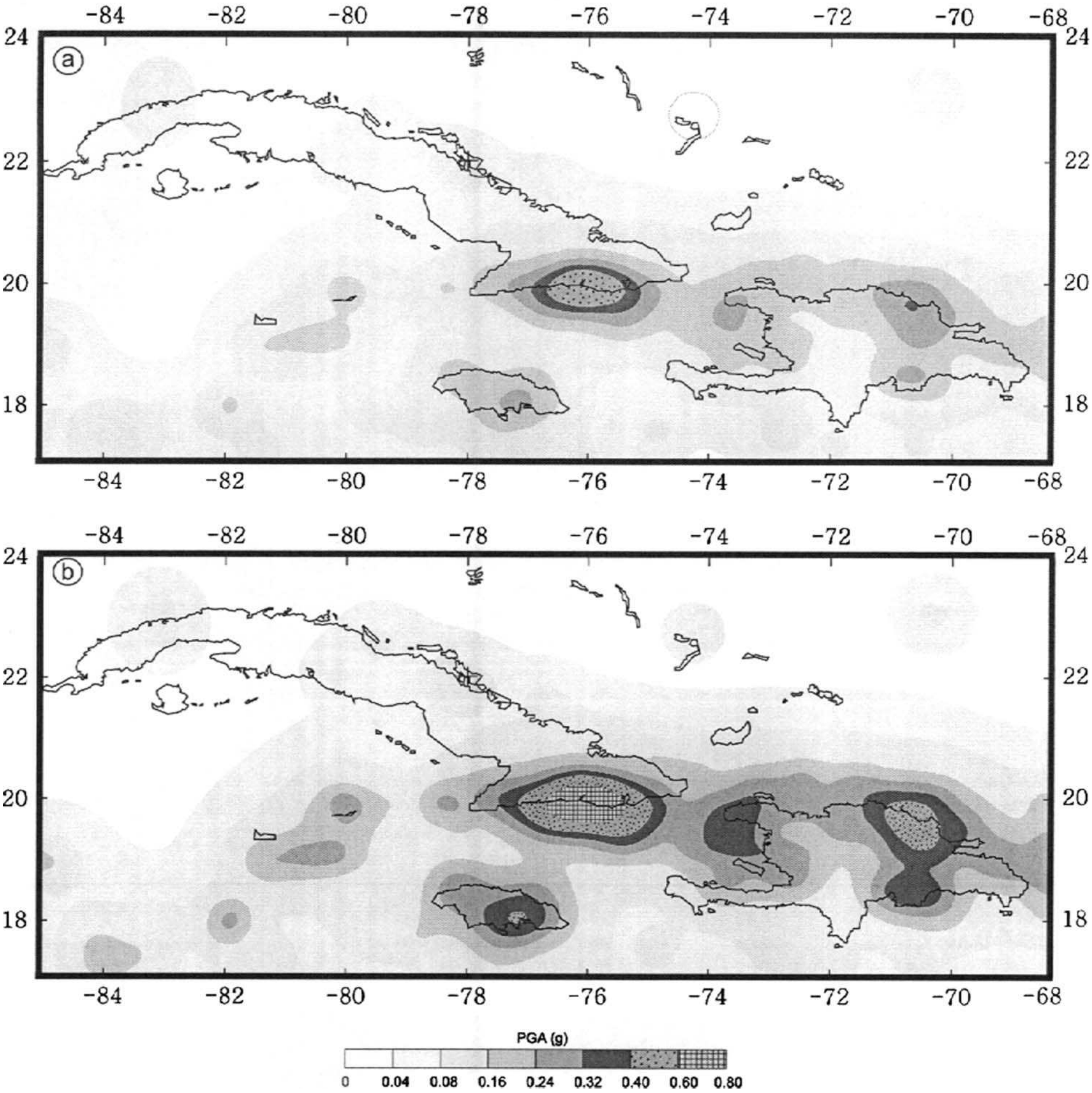

FIGURE 10 PGA with a 475-year return period with the standard deviation of the aleatory variabilities (attenuation relations) and one standard deviation of the epistemic uncertainties: (a) on rock; (b) on soil.

around Santiago, when considering the spatially smoothed seismicity approach (Fig. 9a), and the same values are obtained along a large part of the southern Cuban coast and along all the northern Hispaniola coast, when considering the zoning approach (Fig. 9b).

Figures 8c and 9c show the difference between the results given by the two approaches (estimates with the spatially smoothed seismicity approach minus those with the zoning approach) for rock and soil, respectively. As Cao *et al.* [1996] similarly pointed out for southern California and Wesson *et al.* [1999] for Alaska, the difference in our case is also rather limited. In fact, this difference rarely exceeds, in absolute value, 0.16 g and this occurs along the northern and southeastern coasts of Hispaniola, where the estimates from the zoning approach are larger than those from the spatially smoothed seismicity approach. Around Santiago, the estimates with the spatially smoothed seismicity approach exceed those of the zoning approach by less than 0.10 g. In addition, the zoning approach emphasizes the hazard in northwestern Cuba. For the Cuban coast the explanation is easy: the concentration of reported seismicity around Santiago de Cuba is distributed over a wider SZ in the zoning approach (Figs. 8b and 9b). In the case of Hispaniola, the definition of the SZs external, but close, to the studied region (east of longitude 68° W and, consequently, not shown in Figs. 8 and 9) play an important role because they contribute to the hazard computation. The SZ along the northern Hispaniola coast was also defined eastwards, outside the area shown in the maps of this work. Several earthquakes occurred there and those events are averaged over the whole SZ, thus increasing the hazard inside the SZ itself. This SZ, moreover, was not subdivided into several sectors as the seismicity would suggest.

6. Conclusions

The spatially smoothed seismicity approach [Frankel, 1995] has been applied for seismic hazard assessment of the Cuban region. Two seismicity models, three zonation models, where the seismicity parameters *b*-value and M_{max} are computed, and attenuation relations (two for rock sites and three for soil sites) have been considered to smooth and quantify the epistemic uncertainties. The final hazard maps (Figs. 8a and 9a) point out the high hazard of the southern Cuban coast, and especially in the Santiago area, with PGA values exceeding 0.24 g on rock and 0.40 g on soil. These ground-motion values exceed 0.40 g on rock and 0.60 g on soil when the epistemic uncertainties of the different models used are taken into account (Fig. 10).

A secondary aspect of this study is obtained when we compared the seismic hazard estimates obtained through seismotectonic probabilism. The compared analysis highlights the areas where the seismicity alone and the seismotectonic interpretation are in agreement and the areas where they are not. From this analysis, the possible mislocation of the events around Santiago de Cuba is evident, as well as the influence of the geometry used to model the seismogenesis of the northern and southern coasts of Hispaniola. Furthermore, the hazard in northwestern Cuba is emphasized by the zoning approach. As a general conclusion, the contrasted two approaches suggests that the plate boundary zone needs a better segmentation, especially along the Hispaniola coast and an improvement of the seismicity data collection would be welcome for a better knowledge of the seismicity in northwestern Cuba.

Acknowledgments

This research was developed with financial contributions of the “ICTP Programme for Training and Research in Italian Laboratories” of the International Centre for Theoretical Physics, Miramare, Trieste, Italy. Many thanks are due to Hilmar Bungum, NORSAR Kjeller Norway, for useful suggestions about attenuation relations suitable for Central America, and to three anonymous reviewers, who improved our text with their useful remarks.

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