Final Report - Seismic Hazard in Latin America and the Caribbean
Seismic Hazard Maps for the Caribbean

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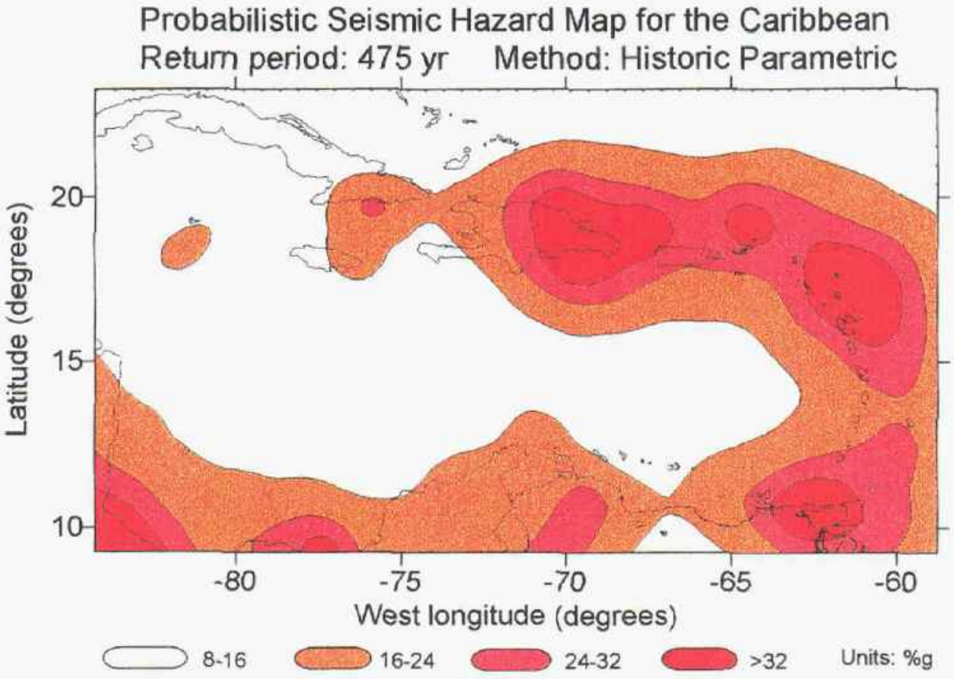

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Abstract

We present new seismic hazard maps for the Caribbean region. The data base on which the maps are based is a revised earthquake catalogue with uniform moment magnitudes covering the entire Latin American and Caribbean region. The method of assessment used is the Historic Parametric which we describe in detail in companion reports. The attenuation relationships used have been selected from a large number of existing relationships which we consider most appropriate for this region. The results expressed as the peak ground acceleration (PGA) with 90% probability of not being exceeded within any fifty-year period. On land areas within the Caribbean this quantity varies from less than 16% to more than 32% of gravity. The highest values apply to the eastern half of the island of Hispaniola, most of the Leeward Islands and Trinidad. The lowest values are found over the central Lesser Antilles and western Jamaica, but there is nowhere within this region where the level of seismic hazard can be considered to be negligible. More detailed maps are available on request.

Introduction

A widely-used way of expressing levels of seismic hazard at a given location in a numerical and probabilistic way is to state the level of some parameter of ground motion with a given probability of occurrence in a given period of time. The most commonly-used parameters of ground motion are quantities such as peak ground acceleration, peak ground velocity or intensity on the Modified Mercalli scale. The most widely-used method of assessing the level of hazard was introduced by Cornell (1968) and though the method has been refined extensively both by the original author and his colleagues and by numerous other authors the basic principles of the method and the assumptions underlying it remain the same. Methods of this general type are often referred to as Cornell-type methods or b-value methods.

In a previous study (Shepherd et al 1994B) we presented results obtained by this method for the Trinidad and Tobago region. In this paper we extend these results to the rest of the Caribbean region applying some modifications to the method of calculation suggested by comments on the earlier paper. Results presented for the Caribbean exclusive of the Commonwealth portion are less well constrained by local information. Therefore this study should not replace local, site specific evaluations of seismic hazard which have taken place within this larger region. This earlier study by Shepherd et al, 1994 was extended in scope by the undertaking of a recently completed thesis study (McQueen, 1997) which made an evaluation of three different methods of probabilistic seismic hazard determination. This research concluded that the Historic Parametric method (Shepherd, Tanner and Prockter, 1994B) seemed to best suit the situation in the Caribbean, although the other two methods (source zone or Cornel-type and the extreme value methods (Gumbel 1958, Makropoulos and Burton 1986)) produced reasonable results, they did not seem quite as robust to varying conditions for the computation. In this paper we present what we regard as the best model of seismic hazard obtained by McQueen (1997) with the Historic Parametric method.

The parameter which we use to describe seismic hazard in this paper is the peak ground acceleration with 90% probability of non-exceedance in any 50 yr period. This is exactly equivalent to the ground acceleration which has a return period of 474.56 yr and is chosen simply because it is a quantity familiar to most practitioners who apply the results of seismic hazard studies. We refer to this quantity as PGA or more simply as estimated seismic hazard.

Theory and assumptions

The theory of, and assumptions underlying, the source zone method of seismic hazard estimation, have been given frequently in the literature and are not repeated in detail here. The essential steps in the procedure are:

(i) Identification, from patterns of seismicity, surface geological studies and general seismotectonic theory, of active and potentially active seismic sources.

(ii) Estimation of the rate of activity of each source

(iii) Selection of appropriate attenuation relationships from which an appropriate measure of strong ground motion can be estimated as a function of earthquake magnitude, distance and focal depth.

We modify this procedure for the Historic Parametric method as follows:

(i) Choose a uniform catalogue of earthquakes likely to affect a given area.

(ii) Choose a site at which to compute hazard levels.

(iii) For every earthquake in the catalogue calculate the peak acceleration at that site expected from the attenuation relationship.

(iv) Tabulate return periods for exceedance of a range of values of acceleration.

(v) Fit a curve to the tabulated data.

(vi) Extrapolate the curve to estimate the ground acceleration which has a return period of 474.56 years at this site.

(vii) Repeat (ii) to (vi) on a regular mesh of sites covering the whole area.

(viii) Draw smooth contours through sites with equal values of ground acceleration

Previous Investigations

No previous study has attempted to apply this method to the entire Caribbean region but there have been several studies of restricted areas within the region. Gay (1977) and Pereira (1977) applied the basic Cornell method to the southeastern Caribbean and to Jamaica respectively and Taylor et al (1977) applied it to the whole eastern Caribbean region. Subsequently, Shepherd and Aspinall (1983) published a study of the Trinidad and Tobago region and most recently Aspinall et al (1994) have published a single-site study of St. Lucia.

The three earliest studies were severely restricted by imperfect knowledge of the seismicity of the region and by imprecise magnitude determinations. In the two later studies these deficiencies were corrected to some extent but several major problems remained. The first is a direct scientific problem. Most studies of this sort rely heavily on surface geological observations, that is direct measurements of the rates and timing of movements on recently-active faults, to identify potential seismogenic sources. In the islands of the Caribbean the utility of this approach is severely limited by the facts that most of the region is covered by water and that a high proportion of all earthquakes occur at significant focal depths. Although we have accounts (Shepherd et al 1994A) of over one hundred damaging earthquakes and locations of over 10,000 instrumentally-located earthquakes in this region since the early sixteenth century not one of these earthquakes has been unambiguously associated with a specific surface geological feature and there are no documented instances of visible surface fault breakage associated with earthquakes anywhere within the region.

Because of this, geological input into seismic hazard assessment in this region is often speculative and may in fact be positively misleading. Two important examples are the two largest islands of the Commonwealth Caribbean, Jamaica and Trinidad. The earliest studies of seismic hazard in Jamaica (Shepherd 1971, Pereira 1977) concentrated on supposed major offshore seismic sources. More precise instrumental observations since then (Figure 5) have shown that most earthquakes felt in Jamaica occur either within the island itself or very close to it. Burke et al (1980) identified a series of east-west trending left-lateral strike-slip faults in Jamaica on which the cumulative offset during the past 10 million years is about 40 km. Positive identification of these faults, or any one of them, as the sources of Jamaican seismicity would result in very high local concentrations of seismic hazard but, as yet, we have no evidence whatsoever to identify individual faults as earthquake sources.

In Trinidad the situation is even more complicated. Early studies (Robson 1965, Gay 1977, Tomblin 1978) suggested that a major right-lateral strike slip fault, a continuation of the El Pilar fault of eastern Venezuela, passes across the north of Trinidad passing through Port-of-Spain and the heavily-developed east-west corridor. If the Trinidad section of the El Pilar Fault is included as a seismogenic source then very high levels of seismic hazard are estimated for the most heavily populated part of Trinidad. If it is not included then the levels are much lower.

The evidence which suggests that the Trinidad section of the El Pilar Fault is active is entirely geological. One set of geological observations (Robertson and Burke 1985) suggests that this fault is currently active and constitutes part of the boundary between the South American and Atlantic tectonic plates. An alternative, equally-respectable set of observations (Speed 1985) suggests that contemporary seismic activity on the El Pilar fault terminates considerably to the west of Trinidad. Seismological evidence (Shepherd et al 1992, Russo et al 1993) suggests that the fault is not seismically active in Trinidad but resolution of the differences between geological interpretations will require many further years of detailed ground observations.

An alternative method of identifying seismogenic sources is to look at the overall pattern of global plate motions. To the present this approach has not proved to be particularly fruitful in the Caribbean. A large number of plate-tectonic interpretations of the Caribbean have been published over the past twenty-five years (e.g. Jordan 1975, Sykes et al 1982, Burke et al 1984, Stein et al 1988). Although all of these studies agree about the general configuration of the Caribbean plate there are major differences in detail. These differences amount to tens or hundreds of kilometres in plate-boundary position and factors of one to five in rates of movement. While these differences are small in terms of global tectonics they are crucial in terms of seismic hazard in islands whose dimensions are smaller than the uncertainties in plate-boundary position.

A final problem with full implementation of the Cornell method is less obvious. To produce a full contour map covering the entire Caribbean region at reasonable density - e.g. a grid of points at 0.1 intervals - requires approximately 50,000 individual site computations. In a recent exercise (Aspinall et al 1994) using the full Cornell method and state-of-the-art programmes on a fast SPARC workstation the time required for each individual site calculation was of order 20 - 30 minutes. Full implementation of the procedure for the entire Caribbean would therefore require about 20,000 to 25,000 hours (two to three years) of computer time.

Modifications to the method

The modification to the basic method which we have adopted is to take no account of geological speculations about the positions of seismogenic sources. The complete data base which we use for hazard estimation is the catalogue of recorded earthquakes. We proceed as described earlier in the introduction..

(i) Choose a uniform catalogue of earthquakes likely to affect a given area.

(ii) Choose a site at which to compute hazard levels.

(iii) For every earthquake in the catalogue calculate the peak acceleration at that site expected from the attenuation relationship.

(iv) Tabulate return periods for exceedance of a range of values of acceleration.

(v) Fit a curve to the tabulated data.

(vi) Extrapolate the curve to estimate the ground acceleration which has a return period of 474.56 years at this site.

(vii) Repeat (ii) to (vi) on a regular mesh of sites covering the whole area.

(viii) Draw smooth contours through sites with equal values of ground acceleration

This method has been applied previously but, as far as we are aware, only rarely. Veneziano, Cornell and O'Hara (1984) applied essentially the same method to a study of seismic hazard in California and the method is referred to by McGuire (1993) as the Historic Parametric method. Larsson and Matson (1987) applied a very similar method to a seismic hazard study of Nicaragua. The main uncertainty in the method is inherent in step (vi), extrapolation, above. If the period covered by the catalogue (step (i)) is long in comparison with the return periods of the earthquakes which are of interest then the method will give accurate estimates of the recurrence rates of different levels of ground acceleration. The further assumption that these rates will remain constant in the future is inherent in all applications of Cornell-type methods.

In our instance, and probably most others, the period of completeness of the catalogue is very much shorter than the return periods of the earthquakes of greatest interest so that the graph of acceleration against return period must be extrapolated over a considerable distance. For this study we have an earthquake catalogue (Shepherd et al 1994A) which is complete for earthquakes of magnitude greater than 4 for the period 1964-1993 - a period of 30 years. We can therefore establish return periods for ground accelerations with reasonable confidence, provided that those return periods do not exceed about 10 years. This must be extrapolated over 1 - 2 orders of magnitude in order to make estimates of the levels of ground accelerations with return periods of 475 years

Outline of the method

The method used is described in detail by Tanner and Shepherd (1997). The assumptions upon which the method is based are that:

- The ground motion law is of the general form

$$\ln A = c_1 + c_2 M + c_3 \ln(R + c_4) \tag{1}$$

- Source zones are infinitesimal elements of volume

- Within the i'th source zone the rate of earthquake occurrence is governed by Gutenberg-Richter law

$$\ln N_i = a_i - b_i M$$

Tanner and Shepherd (1997) then show that

$$\ln \mathrm{A} = \mathrm{a} \ln \mathrm{R} + \mathrm{b} \tag{2}$$

Where A is the PGA with return period R and a and b are constants which can be determined from the seismicity data alone. An alternative form of the relationship is the power-law representation suggested by Grases (1990)

$$\mathrm{A} = \alpha \mathrm{R}^{\beta} \tag{3}$$

The unmodified power-law relationship (3) is unbounded at the upper end. That is, it predicts that as $R \to \propto$ $A \to \propto$ .We consider that this result is physically unreasonable - it follows from the fact that the simple Gutenberg-Richter relationship allows all magnitudes up to $M = \infty$. In order to remove this feature we have used an extrapolation relationship of the form

$$\ln A = \ln(A_{\max}) - \alpha \exp(-\beta R \tag{4}$$

where α and β are new empirical constants determined from the data , and $A_{\max}$ is the maximum possible PGA at the site. This relationship is exactly equivalent to the power-law relationship when A is small compared with $A_{\max}$, but has the property

$$A \to A_{MAX} \quad \text{as } R \to \propto$$

This is equivalent to setting a maximum magnitude in the Gutenberg-Richter relationship.

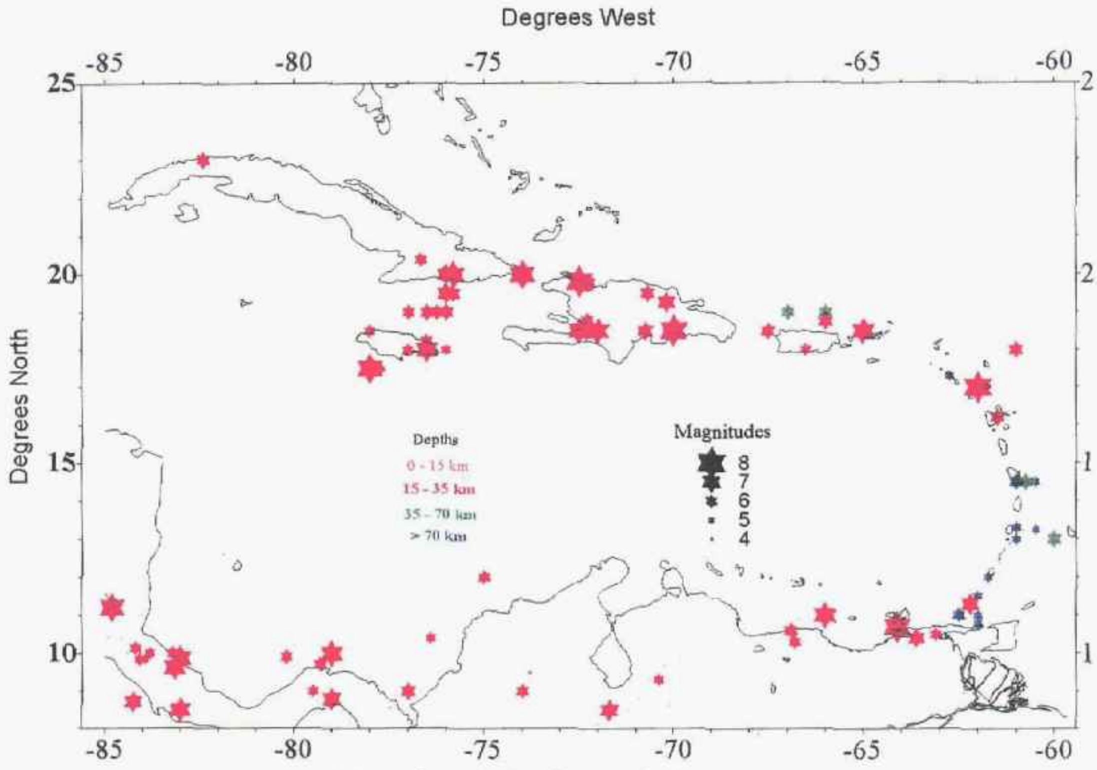
Seismicity of the Caribbean - the pre-instrumental period

The seismicity of the Caribbean up to the year 1900 has been described by Shepherd and Lynch (1992). The results are summarised in figure 1 which shows the earthquakes which were felt in the Caribbean at sufficient intensity to cause some damage during the period 1532 to 1900. Shepherd and Lynch (1992) show that, for the Caribbean region as a whole, the periods during which the data can be regarded as complete for different intensity levels on the Modified Mercalli scale of earthquake intensities are as shown in table 1.

Table 1: Periods of completeness. Earthquakes of different intensities.

Intensity	Period of completeness	Number (to 1900)
≥ MMV1	1820 - Present	73
≥MMVII	1800- Present	47
≥MMVIII	1750- Present	30

Figure 1



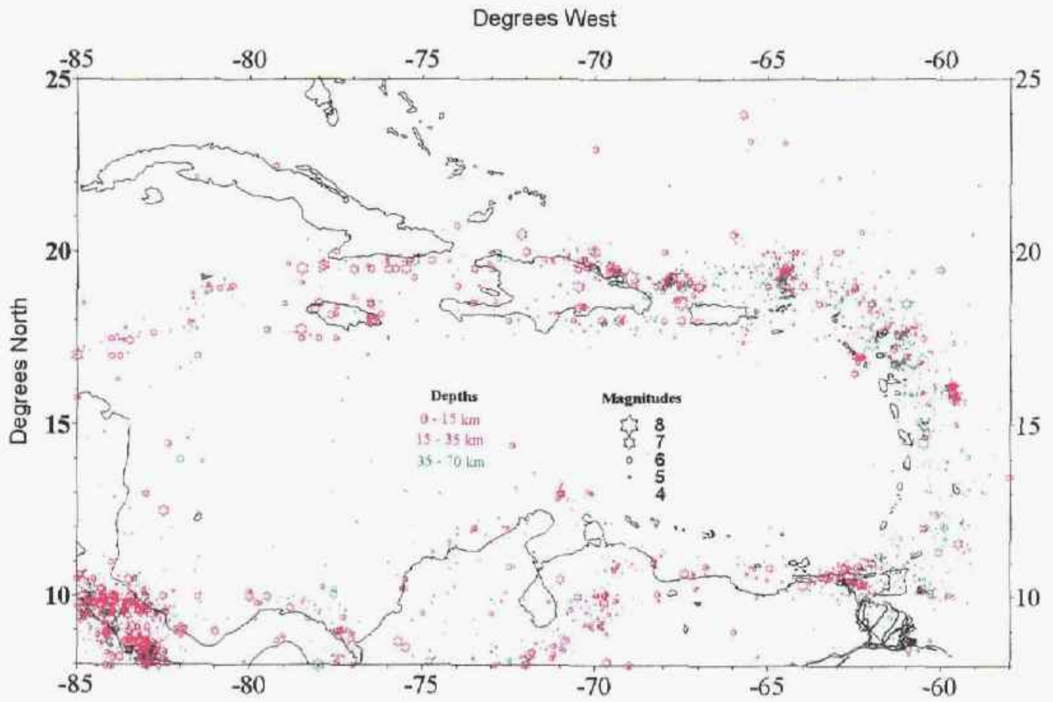
Historical Seismicity of the Caribbean

There are insufficient earthquakes of intensity MMIX or greater on which to base meaningful conclusions. These numbers provide some reference figures against which the quantitative assessments of seismic hazard presented in this paper can be cross-checked but the data are insufficiently detailed to provide a basis for quantitative assessment of the geographical variation of seismic hazard.

Seismicity of the Caribbean - the instrumental period

Seismicity of the Caribbean during the present century, which is based mainly on instrumental recordings, is described by Tanner and Shepherd (1997). The results are summarised in figures 2 and 3.

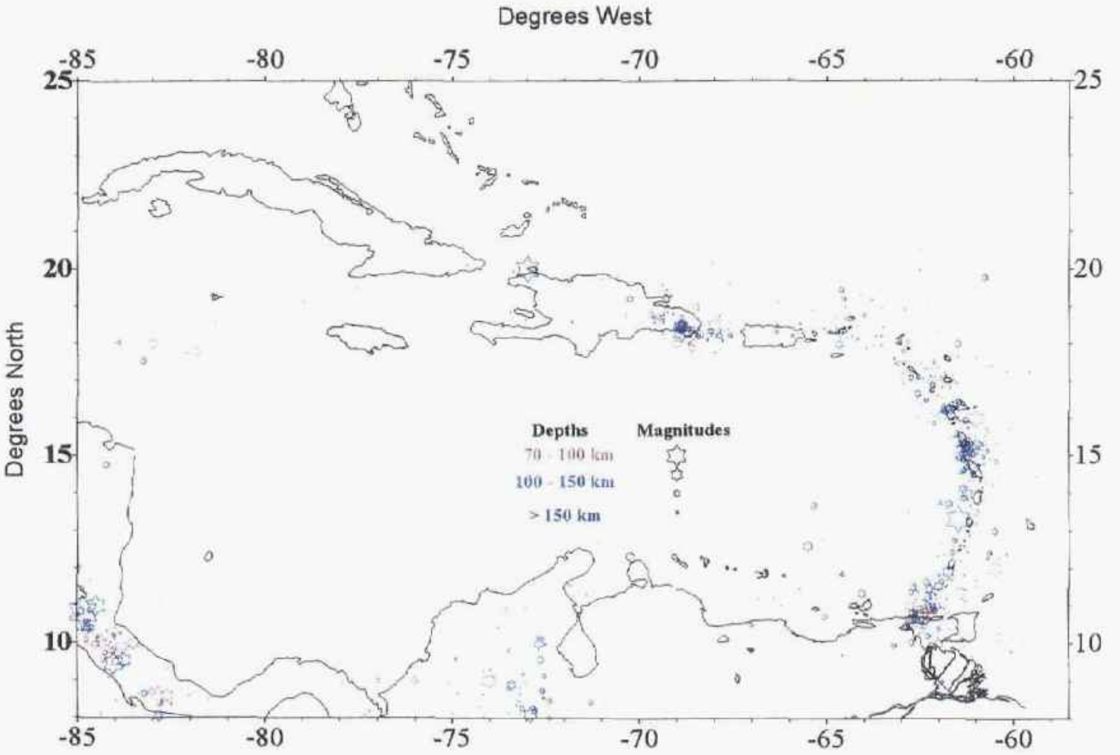
Figure 2



Caribbean Region. Shallow seismicity 1901-1994

The data represented by figures 2 and 3 have been analysed extensively by Shepherd et al (1994). The magnitudes represented are plotted on a uniform moment magnitude scale. Shepherd et al (1994) show that the data are most probably complete for the whole of the Caribbean region for all earthquakes of magnitude (M_ω) greater than or equal to about 4.0. Subsequent analyses have used the method described in the earlier part of this report and have been based on earthquakes of magnitude 4.5 and greater.

Figure 3



Caribbean Region. Intermediate to deep seismicity 1901-1994

Hazard Estimates

All calculations of seismic hazard given here have been computed using what we have termed the JB93 (Joyner and Boore 1993) attenuation relation for events with depths less than 15 km and the WC82 (Woodward-Clyde 1982) relation for all other events. The resulting hazard estimates are shown in figure 4. For this map the hazard levels have been computed on a grid of 0.25 degrees. This scale permits us to present a comparative map for the whole Caribbean region but provides little detail on the scale of individual islands. These more detailed maps can easily be prepared by the authors.

Figure 4

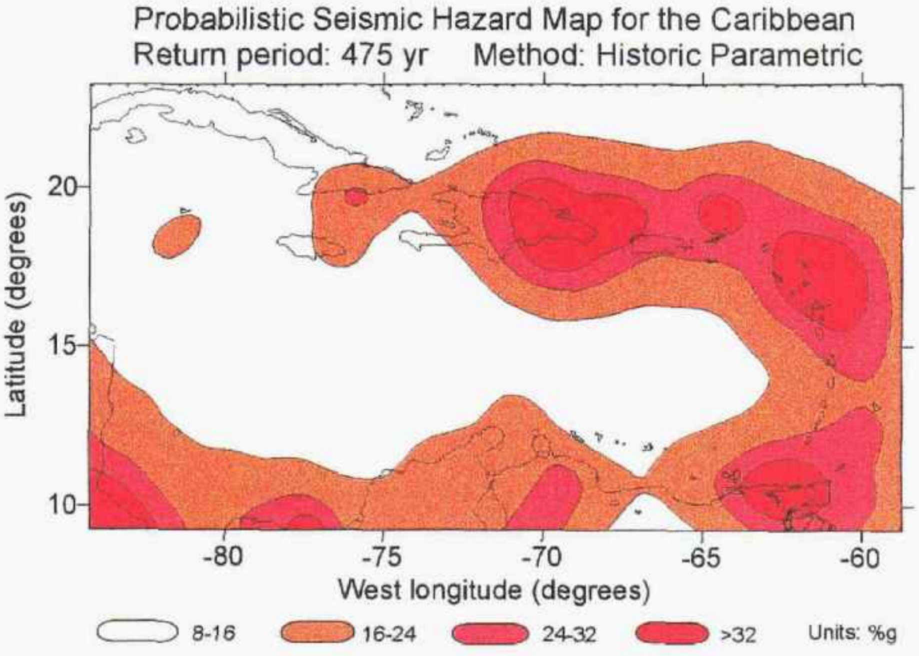
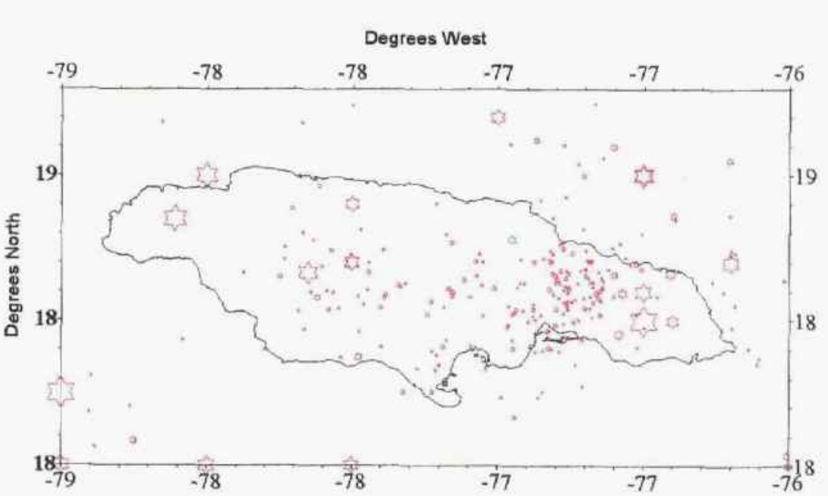
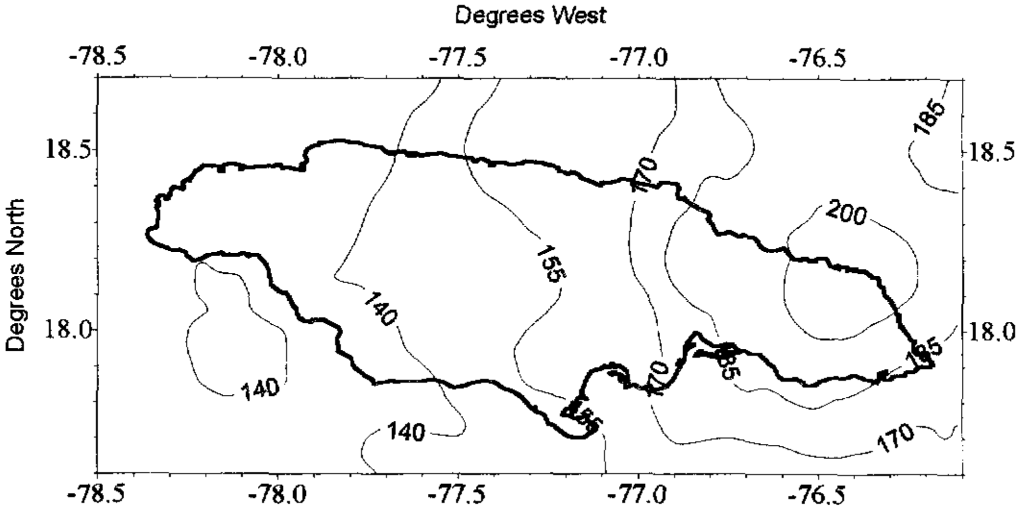


Figure 5



Seismicity of Jamaica 1900-1993

Figure 6



Seismic Hazard Map for Jamaica

One example of a more detailed grid, computed for the island of Jamaica, is shown in figures 5 and 6. Figure 5 shows the seismicity of Jamaica and its immediate surroundings. Figure 6 is the corresponding hazard map. PGA values for Jamaica have been gridded on a scale of 0.1 degrees. The detail of a map at this scale and grid spacing is much more revealing than that for a smaller-scaled map computed at a coarser grid interval.

In comparison with the results for the adjacent parts of the United States (Frankel et al 1996) computed by similar methods, our results show similar peak levels of hazard as in the western United States but a rather higher background level of hazard. The second feature results from the inclusion in our earthquake catalogue of a fairly large number of intermediate depth earthquakes which generally produce moderate levels of ground acceleration over wide areas.

Acknowledgements

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