Earthquake Hazard in the Eastern Caribbean

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Abstract

Gumbel's types I and III asymptotic distribution of extremes have been used to estimate seismic hazard in the eastern Caribbean region (8-20 °N, 58-66 °W) in terms of magnitude, acceleration and velocity using instrumental earthquake data for the period 1906 - 1992. The magnitude, acceleration and velocity hazards for 18 eastern Caribbean towns, together with iso-acceleration and iso-velocity maps for maximum amplitudes with 90% probability of non-exceedance in 50 years, are presented for the region. Gumbel's third type asymptotic distribution of extremes fits the observed magnitude extremes relatively well while for acceleration and velocity, the Gumbel I distribution provides a better representation.

The application of Gumbel III to the whole eastern Caribbean region yielded an upper bound magnitude $\omega = 7.97 \pm 0.14$, which agrees quite well with the largest instrumentally recorded earthquake magnitude of M_s 7.5. The return period for earthquakes of magnitude M_s 6.5, which is the minimum magnitude considered to be completely reported for the region for the 87 year period, is about 6.1 years. Upper bound magnitude values for most of the towns are generally very large, exhibit considerable variation and are associated with large uncertainties. Spatial variations in acceleration and velocity hazard, which are generally similar, exist and areas of high hazard (acceleration greater than about 200 cm/s^2) include northeastern Venezuela, the region from St. Lucia to Barbuda, and between Tobago and Barbados.

However, different attenuation relationships predict considerably different values for acceleration and velocity hazard, thus emphasizing the importance of region-specific strong ground motion data in the reliable evaluation of seismic hazard.

Introduction

Seismic hazard assessment usually aims at determining the probability that a ground motion parameter at a site due to various-sized earthquakes will exceed a certain value within a given time period. The most common current approach in seismic hazard assessment utilizes the 'Total Probability Theorem' (McGuire, 1976, 1978) which represents both the 'point-source models' (e.g. Cornell, 1968; Milne and Davenport, 1969; Esteva, 1970) and the 'fault-rupture model' (Der Kiureghian and Ang, 1977). The present preponderant use of the probabilistic as opposed to the deterministic approach in seismic hazard assessment is thought to be due to the former's provision for greater logic and consistency by allowing for the maximum utilization of a broad spectrum of data (geologic, geophysical, seismologic and historic) in a coherent manner (Erdik et al., 1985).

Studies of the seismicity of the eastern Caribbean on both local and regional scales (e.g. Sykes and Ewing, 1965, Molnar and Sykes, 1969; Bonneton and Scheidegger, 1981; Dorel, 1981; Stein et al., 1982; Girardin and Gaulon, 1983; Shepherd and Aspinall, 1983; Wadge and Shepherd, 1984; Russo et al., 1993) reveal that the area is fairly seismically active and that most of this activity is mainly due to plate boundary zone interactions. However, previous works on quantitative seismic hazard assessments in the eastern Caribbean are few. Taylor et al. (1979) evaluated seismic hazard in the Lesser Antilles and Trinidad and Tobago expressed as peak horizontal ground acceleration with 90% probability of non-exceedance in a

50-year period using the Cornell (1968) approach. More localized studies using a similar approach include those of Shepherd and Aspinall (1983) for the Trinidad and Tobago area and Aspinall et al. (1994) for the Roseau Dam site in St. Lucia.

Similarly to other parts of the world, the quality and quantity of earthquake data available for earthquake hazard estimation in the eastern Caribbean has increased with time because of the increase in the number and quality of available seismograph stations. The calculation of seismic hazard in terms of such parameters as expected magnitude, acceleration or velocity depends on the data time span considered. Short time spans, which are insufficient to establish stable estimates of hazard, and significant revisions in earthquake parameters, generally result in ensuing hazard maps differing for different observation periods.

In this study, data from a catalogue compiled for the eastern Caribbean (8 °N - 23 °N, 56 °W - 68 °W) is used to evaluate seismic hazard in terms of magnitude, acceleration and velocity using Gumbel's (1966) first and third asymptotic distribution of extremes. This approach addresses the problem of seismic hazard assessment in the eastern Caribbean through the statistical manipulation of the past instrumental data with no consideration for seismic source zoning. The results are presented mainly in the form of contour maps of maximum hazard parameter with 90% probability of non-exceedance in 50 years. Estimation of these hazard parameters should provide a basis for both informed decisions as regards structural design and planning criteria and also allow comparison of seismic hazard distributions expressed in different models. Seismic hazard for the most important towns in the area (Figure 1) is also examined in more detail.

Earthquake Data

Sources for origin times and hypocentral parameters

Historical seismicity records provide an important contribution to our understanding of the seismic behaviour of a region. Modern techniques of quantitative seismic hazard assessment necessitate the use of instrumental data that is as accurate, homogeneous and complete as possible. However, significant improvements in both the quality and quantity of seismological stations worldwide have generally occurred with time, especially since the 1960s, making it impossible to prepare an earthquake catalogue that is complete and accurate for the period under consideration, 1906 - 1992.

The most important initial compilation of a catalogue of global instrumental seismicity data was made by Gutenberg and Richter (1954). For various areas of the eastern Caribbean, attempts at compiling catalogues for historical and/or instrumental earthquake data have been made (e.g. Robson, 1964; Shepherd and Aspinall, 1983; Feuillard, 1984; Shepherd and Rogers, 1985; Shepherd et al., 1994a).

The data used in this study are from an earthquake catalogue prepared for the area bounded by latitudes 8 °N and 23 °N and longitudes 56 °W and 68 °W. The catalogue, which contains estimates of origin time, epicentral coordinates, focal depth and magnitude, mainly relies on a systematic procedure of selecting and combining earthquake parameters from several agencies rather than on a re-determination of these parameters. In general, hypocentres for pre-1964 earthquakes are extracted from the International Seismological Summary (ISS), the bulletins of the Bureau Central International de Seismologie (BCIS) and the Seismic Research Unit (SRU), and the catalogues of Gutenberg and Richter (1954), Sykes and Ewing (1965) and Rothé (1969). Recalculated hypocentral parameters of some of the larger pre-1964 events provided by Russo et al. (1992) were used in preference to all others. For the period 1964 to 1992, the source parameters calculated by the International Seismological Centre (ISC) are generally preferred. Events considered to be foreshocks or aftershocks were generally not included.

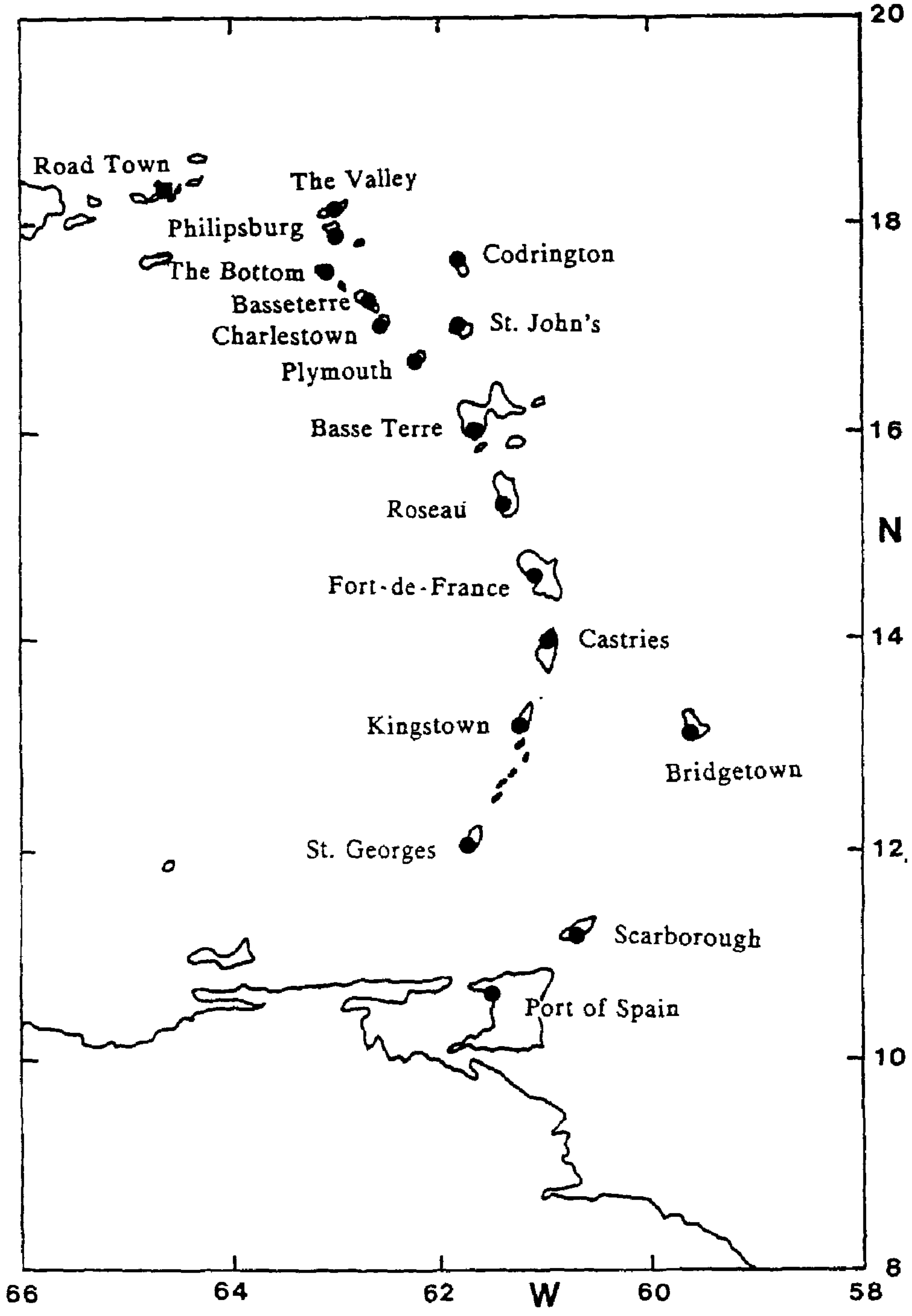

Figure 1: The Eastern Caribbean (Towns for which seismic hazard was estimated are shown).

Magnitude

Magnitude estimates for the earthquakes are required for the seismic hazard analysis and are necessary if any completeness analysis of the earthquake data is to be undertaken. The surface wave magnitude, M_s, has been selected as the standard magnitude. However, since many data sources assign magnitudes which are different from M_s, equivalent M_s values were calculated for earthquakes for which M_s values were not available using the regression relationships derived by Ambeh (1994).

Completeness

Since the main purpose of the compilation of the catalogue is its use in seismic hazard analysis, it is necessary to examine its completeness. Attempts made to achieve a certain degree of homogeneity of the data cannot generally prevent incompleteness at the lower magnitudes, particularly in the earlier years. Examination of completeness was made by both the simple process of plotting maximum numbers of earthquakes in different magnitude ranges per decade and using the analytical technique of Stepp (1971). The results of this examination suggest that eastern Caribbean earthquakes within the defined region may be complete for the following periods: $M_s \geq 4.0$ (1953 - 1992); $M_s \geq 5.5$ (1918 - 1992); $M_s \geq 6.0$ (1913 - 1992); $M_s \geq 6.5$ (1903 - 1992). That is, only earthquakes of magnitude $M_s \geq 6.5$ are completely reported for the whole period of investigation.

Seismicity

No relocations were done as part of this study but it is obvious that earthquake location accuracies have improved with time since the beginning of instrumental recordings during the last part of the 19th century because of the increase in the number and quality of seismic stations and the development of better velocity models.

In the eastern Caribbean, pre-1953 epicentres, which were generally computed from teleseismic data, probably have accuracies not better than ±100 km. Focal depths are either unknown or highly uncertain. The creation of the Seismic Research Unit in 1953 saw the establishment of more seismograph stations in the region and a consequent improvement in hypocentral precision (to better than ±100 km). Further improvement resulted in 1964 with the inception of the World Wide Standardized Seismograph Network (WWSSN) while the introduction of radio telemetry and additional stations in the eastern Caribbean from 1978 probably reduced the mislocation errors to about ±20 km. Of course, errors in focal depth determination may exhibit the same trend albeit with different values.

Figure 2 shows epicentres of magnitude $M_s \geq 4.0$ earthquakes for the eastern Caribbean for the period 1906 -1992 based on the compiled catalogue. A well-defined arcuate seismic belt occurs parallel to the Lesser Antilles arc with the shallowest earthquakes occuring about 100 - 150 km to the east of the arc platform. Focal depths increase in a westward direction to maximum values of about 200 km at distances about 50 km to the west of the islands. In general, this belt exhibits a variable density of epicentres, with the northern region (north of about 14 °N) being more active than the southern region. The distribution of the hypocentres is represented by a westward dipping Wadati-Benioff zone whose dip seems to vary along the arc, possibly indicating segmentation (e.g. Wadge and Shepherd, 1984). Further south, seismicity is mainly concentrated to the west and northwest of Trinidad and focal depths range from near surface to about 180 km.

Method and Application

Method

The statistical analysis of earthquake data can generally be grouped into two broad areas: "whole process" methods which utilize the whole data set (e.g. Cornell, 1968) and "part process" methods which use only part of the data set, such as annual extremes (e.g. Gumbel,

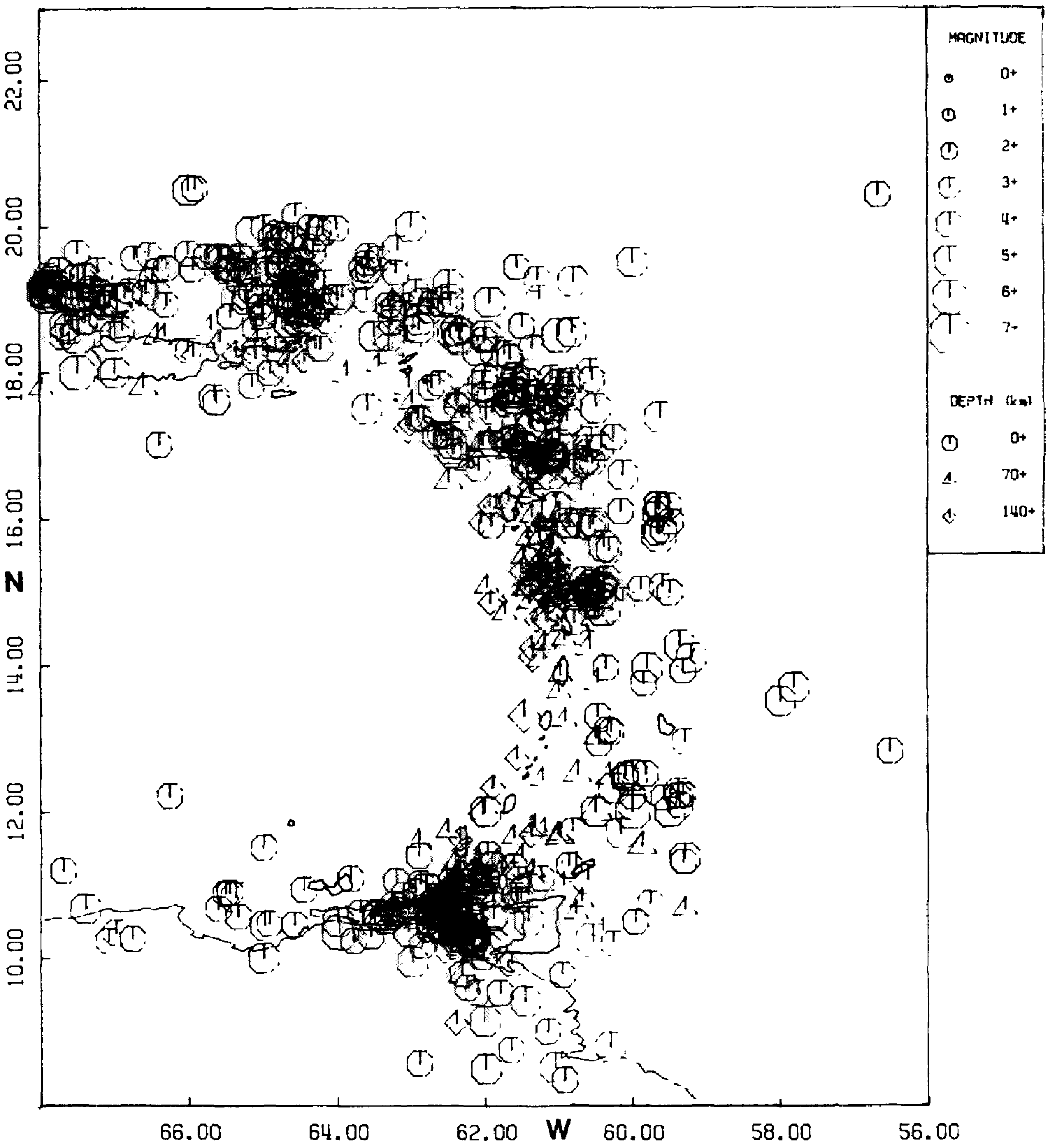

Figure 2: Seismicity of the Eastern Caribbean: 1906-1992 (Ms >= 4.0).

1966). Yegulalp and Kuo (1974) and Burton (1979) provide detailed discussions of the advantages and limitations of both approaches.

This study utilizes the extreme value method of Gumbel (1966) to estimate seismic hazard in the area bounded by 8 - 20 °N and 58 - 66 °W. This method has been applied to earthquake hazard analysis by several other workers (e.g. Burton, 1979; Ahjos et al., 1984, Makropoulos and Burton, 1985 a,b). Some advantages of using extreme value analysis include:

(a) detailed knowledge of the parent distribution is not required,

(b) the extreme values themselves are usually better known than the smaller events in a catalogue,

(c) use of extreme values will also eliminate most significant aftershocks from the analysis and maintain emphasis on what are held to be independent events.

According to Davis (1970), the distribution from which extremes are sampled must take one of three forms, irrespective of the parent distribution:

$$P^{I}(x) = \exp[-\exp(-\alpha(x-u))], \quad \alpha>0 \qquad (1)$$

$$P^{II}(x) = \exp\{[(u-\gamma)/(x-\gamma)]^{k}, \quad k>0, \ x\geq\gamma, \ u>\gamma\geq 0 \qquad (2)$$

$$P^{III}(x) = \exp\{-[(\omega-x)/(\omega-u)]^{k}\}, \quad k>0, \ x\leq\omega, \ u<\omega \qquad (3)$$

where I, II and III represent the first, second and third type asymptotic distributions of Gumbel and $P(x)$ in each case the probability that x (which may represent magnitude, ground acceleration or gound velocity) is an annual extreme. In all three situations, the parameter u is a characteristic value of the variable x and has the probability $P(u) = 1/e$ of being an annual extreme.

Gumbel type I holds for the initial whole-process distributions unlimited in both directions of x and has a second parameter α . Gumbel type II arises when the initial distribution is bounded at $x\geq\gamma$ while Gumbel type III results when the initial whole process distribution is bounded at $x\leq\omega$. The parameter k present in types II and III relates to the distribution curvature.

The type III distribution is used for maximum magnitudes where physically realistic curvature at higher magnitudes is taken into account whereas type I is recommended for use with peak ground acceleration or peak ground velocity calculations (Makropoulos and Burton, 1986). Gumbel type II is generally ruled out for the purpose of maximum earthquakes.

Introducing the 'reduced variable'

$$y = -\ln(-\ln P(x)) \qquad (4)$$

results in equation (1) becoming a straight line of the form

$$\hat{x} = u - y/\alpha \qquad (5)$$

with u and α being estimated by linear least squares regression.

Equation (3) can be rewritten as

$$x = \omega - (\omega-u)\ (-\ln\ (P\ (x)))^{\lambda} \qquad (6)$$

where $\lambda = 1/k$ but the parameters ω, u and λ would need to be estimated by non-linear least squares analysis.

The hazard value with probability P of not being exceeded in T-years, X(T,P), is given by,

$$X(T,P) = u - (1/\alpha)\ln(-\ln P) + (1/\alpha)\ln T \qquad (7)$$

for Gumbel type I and

$$X(T,P) = \omega - (\omega-u)(-(1/T)\ln P)^{\lambda} \qquad (8)$$

for Gumbel type III distributions.

Application

A slightly modified version of the computer program HAZAN (Makropoulos and Burton, 1986) was used in the hazard analysis. The region bounded by 8-20 °N and 58-66 °W was gridded at 0.25° intervals of latitude and longitude. For each grid point, all earthquakes of magnitude $Ms \geq 4.0$ in the catalogue within a 2° radius of the grid point were collected. For acceleration or velocity hazard, expected values at the grid point were first calculated using attenuation relationships given below and then the parameters of the Gumbel I distribution obtained by fitting equation (5) to the ranked annual extremes. For magnitude hazard, the process involved the straight forward use of equation (6) and the ranked annual magnitude extremes to get the Gumbel III parameters. Equations (7) and (8) were then used to calculate hazard values with 90% probability of being the maximum occurrence in 50 years. Contour maps showing the spatial distribution of hazard were then prepared for acceleration and velocity.

Attenuation relationships

The determination of seismic hazards in terms of acceleration and velocity usually necessitates the use of attenuation relationships linking these parameters to, for example, magnitude and distance from source. The very few earthquake strong ground motion recordings available for the eastern Caribbean are generally of poor quality and are not adequate for generalizing attenuation characteristics in the region. Consequently, recourse has to be made to using attenuation relationships determined for other environments considered to be tectonically similar to the eastern Caribbean, i.e. subduction zone - island arc. For this hazard assessment, the preferred attenuation relationships are those proposed by Krinitzsky et al. (1988) based on a selected world-wide data set of 987 strong motion accelerograms from source areas that represent seismically active plate boundaries. The relationships for hard sites are:

$$\log A = 1.23 + 0.385M - \log r - 0.00255r \qquad (9)$$

$$\log V = -0.67 + 0.489M - \log r - 0.00256r \qquad (10)$$

$$\log A = 2.08 + 0.35M - \log(\Delta^2 + 100^2)^{0.5} - 0.0025r \qquad (11)$$

$$\log V = 0.63 = 0.38M - \log (\Delta^2 + 100^2)^{0.5} - 0.0025r \qquad (12)$$

where A is mean peak horizontal acceleration in cm/s^2, V is velocity in cm/s, r is focal distance in km and Δ is epicentral distance in km. M is magnitude which is equivalent to local magnitude for $M < 5.9$, to surface wave magnitude for $5.9 \leq M \leq 8.0$ and to moment magnitude for $M > 8.0$. Equations (9) and (10) are valid for earthquakes with focal depths less than or equal to 19 km while equations (11) and (12) are for earthquakes deeper than 19 km. Appropriate conversions from M_s to M were made before using these equations in this study.

For comparison, hazard estimates for four towns were also made using the attenuation relationships proposed by Woodward-Clyde Consultants (1982) and Fukushima and Tanaka (1990).

The Woodward-Clyde relationships appear to fit Alaskan and Japanese data very well and are of the form :

$$\ln (A) = 5.347 + 0.5\, M_s - 0.85 \ln [\, R + 0.864 \exp (\, 0.463\, M_s)\,] \qquad (13)$$

$$\ln (V) = 1.673 + 0.72\, M_s - 1.05 \ln [\, R + 0.864 \exp (\, 0.463\, M_s)\,] \qquad (14)$$

where A is acceleration in cm/s^2, V is velocity in cm/s, M_s is surface wave magnitude and R is the closest distance to the rupture area.

Fukushima and Tanaka's (1990) relationship was developed from mean peak horizontal ground acceleration values from 28 Japanese earthquakes supplemented with near-source data from 15 earthquakes in other countries. The relationship is:

$$\log A = 0.41\, M_s - \log (R + 0.032\, (\, 10^{0.41M_s}) - 0.0034\, R + 1.30 \qquad (15)$$

where A is the mean peak acceleration in cm/s^2, R is the shortest distance between the site and fault rupture in km and M_s is surface wave magnitude.

Results

Magnitude

Table 1 shows the results of the magnitude hazard analysis using the Gumbel III distribution for 18 eastern Caribbean towns and the eastern Caribbean region as a whole. It includes the estimated parameters and their uncertainties, the most probable maximum magnitude during the next fifty years (Mp), the maximum magnitude with 90% probability of not being exceeded in the next 50 years (Mm), the maximum observed magnitude in the area under investigation (Mo) and the number of years during the 87 year period of the earthquake data catalogue for which no extremes were available (MY). For each of the towns, earthquakes analyzed were taken from an area with a radius of 2.0° centred on the town.

Figure 3 shows some examples of fits of Gumbel III curves to observed magnitude extremes. In general, the Gumbel III parameters obtained were found to be relatively good approximations to the magnitude distributions in almost all cases although the quality of the fits varied considerably as seen in Table 1 and Figure 3. In particular, the towns in the central and northeastern part of the region (Bridgetown, Kingstown, Castries, Fort-de-France, Roseau, Basse Terre, Plymouth, St. John's, Charlestown, Basseterre and Codrington) seem to exhibit the highest magnitude hazards although these values are associated with larger uncertainties and hence may not necessarily be a true reflecton of the expected hazard. On the other hand, The Bottom, Philipsburg, Road Town and The Valley have moderately well defined parameters while for the whole eastern Caribbean, Port of Spain, Scarborough and St. George's, the parameters seem to be well defined and have small uncertainties. For some of the towns, the poor estimates of the hazard parameters may be attributable to the limited

Table 1: Estimated Gumbel III Parameters and Associated Magnitude Hazard

Town	ω	σ_ω	u	σ_u	λ	σ_λ	Mp	Mm	Mo	MY
Port of Spain, Trinidad	7.52	0.17	3.44	0.14	0.468	0.051	7.03	7.29	7.20	40
Scarborough, Tobago	8.08	0.34	3.75	0.10	0.308	0.047	6.93	7.44	7.20	37
St. Georges, Grenada	7.51	0.17	3.52	0.12	0.459	0.050	7.02	7.28	7.20	38
Bridgetown, Barbados	11.56	1.69	3.29	0.14	0.148	0.044	7.04	8.24	7.5	47
Kingstown, St. Vincent	10.08	0.72	2.96	0.15	0.227	0.040	7.33	8.33	7.5	46
Castries, St. Lucia	13.15	1.51	3.13	0.13	0.125	0.030	7.10	8.50	7.5	49
Fort-de-France Martinique	9.49	0.48	3.09	0.14	0.276	0.039	7.50	8.33	7.5	43
Roseau, Dominica	9.36	0.43	3.44	0.12	0.273	0.038	7.50	8.26	7.5	40
Basse Terre, Guadeloupe	9.34	0.46	3.57	0.11	0.270	0.039	7.50	8.25	7.5	39
Plymouth, Montserrat	10.99	1.55	3.83	0.11	0.147	0.045	7.05	8.10	7.4	40
St. John's, Antigua	9.71	0.80	3.85	0.10	0.201	0.044	7.16	8.01	7.4	38
Charlestown, Nevis	10.15	1.11	3.82	0.11	0.175	0.047	7.06	8.00	7.4	40
Basseterre, St. Kitts	10.10	1.72	3.96	0.12	0.143	0.058	6.67	7.56	7.3	42
Codrington, Barbuda	10.22	1.17	3.91	0.11	0.168	0.047	7.06	7.99	7.4	39
The Bottom, Saba	8.13	0.46	3.80	0.12	0.277	0.056	6.80	7.35	7.3	40
Philipsburg, St. Maarten	8.89	0.79	4.03	0.10	0.200	0.052	6.76	7.47	7.3	37
Road Town, Tortola	7.51	0.49	3.64	0.14	0.277	0.070	6.32	6.81	6.5	42
The Valley, Anguilla	8.77	0.62	4.01	0.10	0.223	0.049	6.89	7.57	7.3	36
Eastern * Caribbean	7.97	0.14	4.83	0.05	0.443	0.038	7.55	7.77	7.5	22

*(5° radius centred at 14N, 62W)

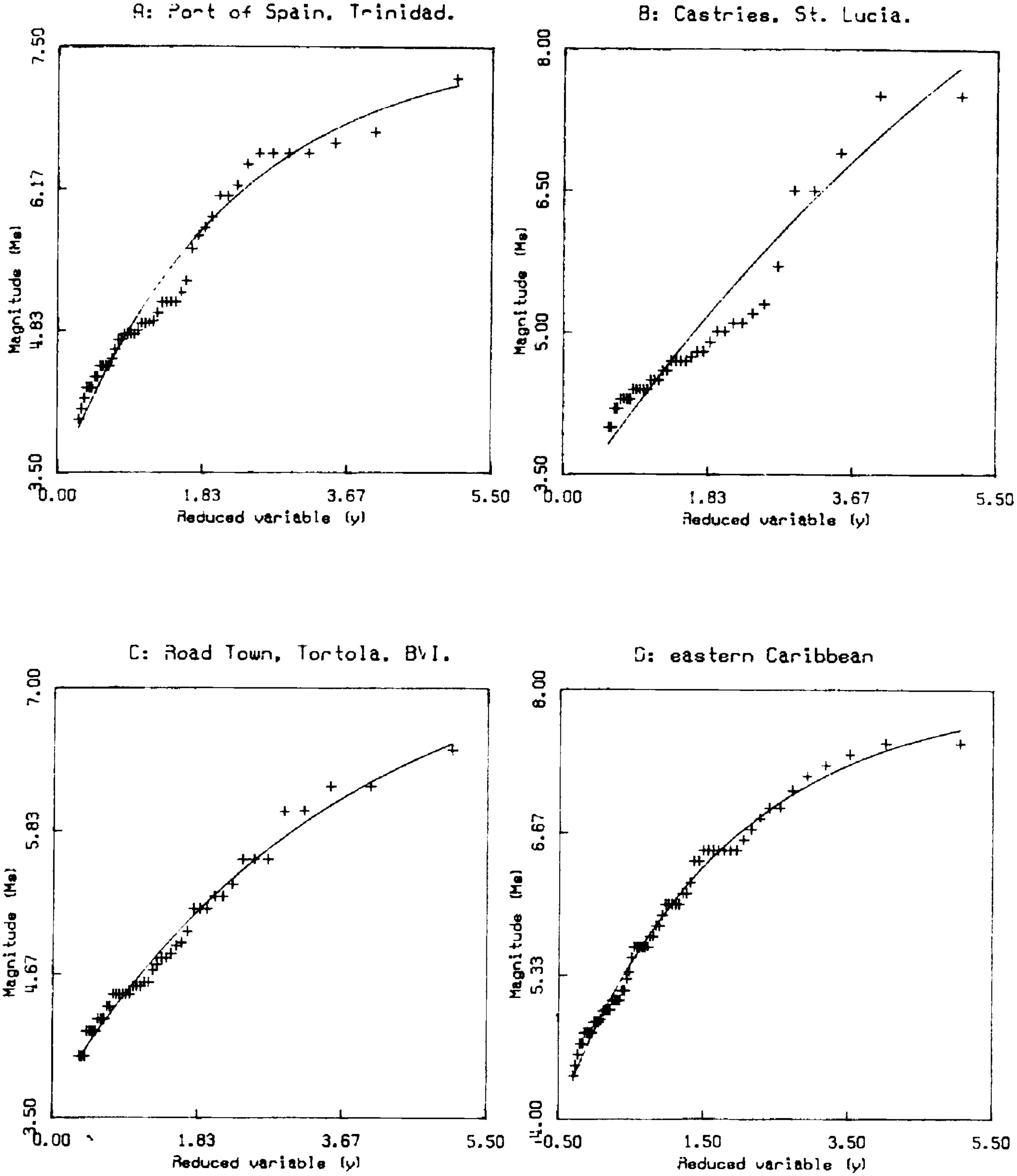

Figure 3: Gumbel III asymptotic distribution of extremes for four eastern Caribbean sites (+ represents observed annual magnitude extreme)

number of data or to the presence of two natural but different earthquake populations as reflected, for example, in the plot for Castries (Figure 3B). The latter effect has been reported for some areas such as the Aleutians and Alaska region (Burton and Makropoulos, 1983), the New Madrid Zone, USA (Burton et al., 1983), and the Thessaloniki area, Greece (Makropoulos and Burton, 1985a).

Table 2 lists values of the average return periods together with predicted and observed exceedances for various magnitudes for the eastern Caribbean and three towns. The return periods, T(M), were calculated from the relevant Gumbel III parameters in Table 1 using the following equations:

$$P(M) = \exp[-((\omega-M)/(\omega-u))^k] \quad (16)$$

$$T(M) = 1/(1-P(M)) \quad (17)$$

The upper bound to earthquakes obtained for the whole of the eastern Caribbean using the Gumbel III method is $\omega = 7.97 \pm 0.14$, which compares reasonably well with the maximum observed earthquake magnitude of 7.5 recorded during the 87 year data period. The return period for magnitude Ms 6.5 earthquakes, which is the minimum magnitude considered to be completely reported for the 87 year period, is about 6.1 years for the eastern Caribbean. The predicted and observed exceedances for earthquakes of at least this magnitude, and even lower, show good agreement (Table 2).

Acceleration and Velocity hazards

As has already been mentioned, acceleration and velocity hazards were evaluated using the first type asymptotic distribution only since attempts to apply the type III distribution led to poor convergence in all cases. Also, search areas involved in the selection of earthquakes for each grid point are of 2° radius·

Table 3 lists the peak ground acceleration and peak ground velocity with 90% probability of non-exceedance in 50 and 100 year periods for the eastern Caribbean towns for which magnitude hazards were evaluated. The corresponding return periods for each of these events are about 475 and 950 years for the 50 and 100 year period respectively.

The patterns of acceleration and velocity variations amongst the different towns are similar. St. George's, Bridgetown, The Bottom, Philipsburg and The Valley are characterized by the lowest acceleration and velocity hazards (accelerations and velocities for the 50 year period less than about 150 cm/s^2 and 8 cm/s respectively) while Fort-de-France and Roseau have the highest hazards (50-year accelerations and velocities greater than about 300 cm/s^2 and 17 cm/s respectively).

Figures 4a, b are iso-hazard contour maps for the maximum expected acceleration and velocity respectively with 90% probability of non-exceedance in 50 years. The pattern of spatial variation of acceleration and velocity hazards is generally similar. Areas of high seismic hazard include northeastern Venezuela, from St. Lucia to Barbuda, just north of the British Virgin Islands and between Barbados and Tobago, with the highest hazards generally occurring out at sea.

Discussion and Conclusions

Seismic hazard in the eastern Caribbean has been assessed in terms of maximum expected magnitudes, accelerations and velocities using extreme value analysis. Gumbel's third type asymptotic distribution of extreme fits the observed magnitude extremes well while for acceleration and velocity, the Gumbel I distribution provides a better representation.

Table 2: Return Periods (T) and Number of Exceedances Expected during the next 50 and 100 Years for various magnitudes.

	Eastern Caribbean No of exceedances				Port of Spain, Trinidad No. of exceedances				Castries, St. Lucia No. of exceedances				St. Johns, Antigua No. of exceedances			
	T	Predicted		Observed	T	Predicted		Observed	T	Predicted		Observed	T	Predicted		Observed
Ms	(yr)	50yr	100yr	87yr	(yr)	50 yr	100yr	87 yr	(yr)	50 yr	100 yr	87 yr	(yr)	50yr	100yr	87yr
5.0	1.7	29-30	58-59	52	3.3	15-16	30-31	22	5.7	8-9	17-18	12	3.5	14-15	28-29	25
5.5	2.3	22-23	44-45	40	5.0	9-10	19-20	15	9.2	5-6	10-11	6	5.7	8-9	17-18	17
6.0	3.4	14-15	29-30	28	8.8	5-6	11-12	11	15.4	3-4	6-7	5	10.2	4-5	9-10	9
6.5	6.1	8-9	16-17	18	19.8	2-3	5-6	7	27.1	1-2	3-4	5	20.5	2-3	4-5	4
7.0	14.7	3-4	6-7	6	82.1	0-1	1-2	1	50.1	1-2	1-2	2	46.9	1-2	2-3	2
7.5	73.3	0-1	1-2	2					98.3	0-1	1-2	2	128.4	0-1	0-1	-
8.0									205.8	0-1	0-1	-	458.8	0-1	0-1	-

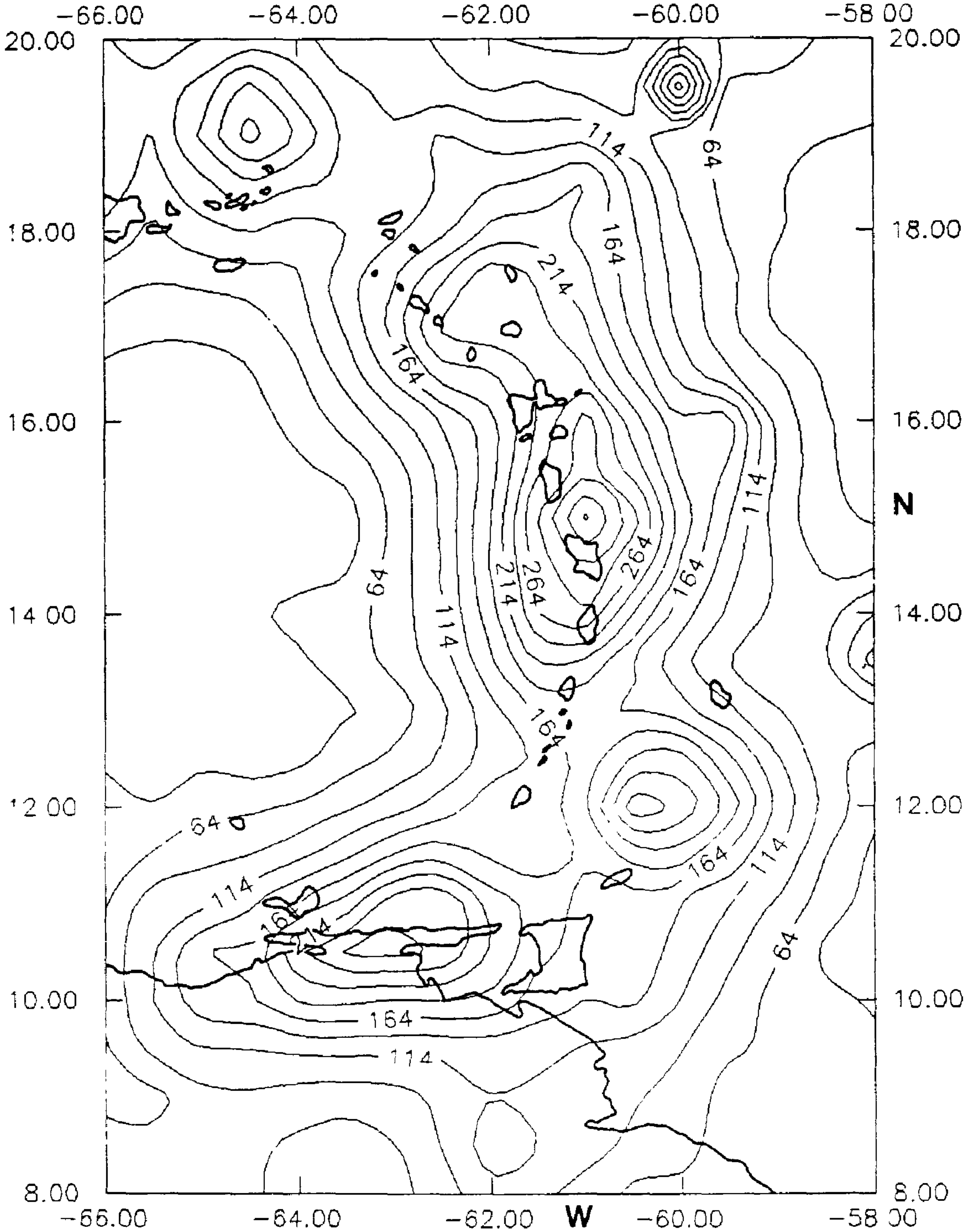

Figure 4a: Maximum acceleration with 90% probability of non-exceedance in 50 years (contour interval = 25 cm/s^2).

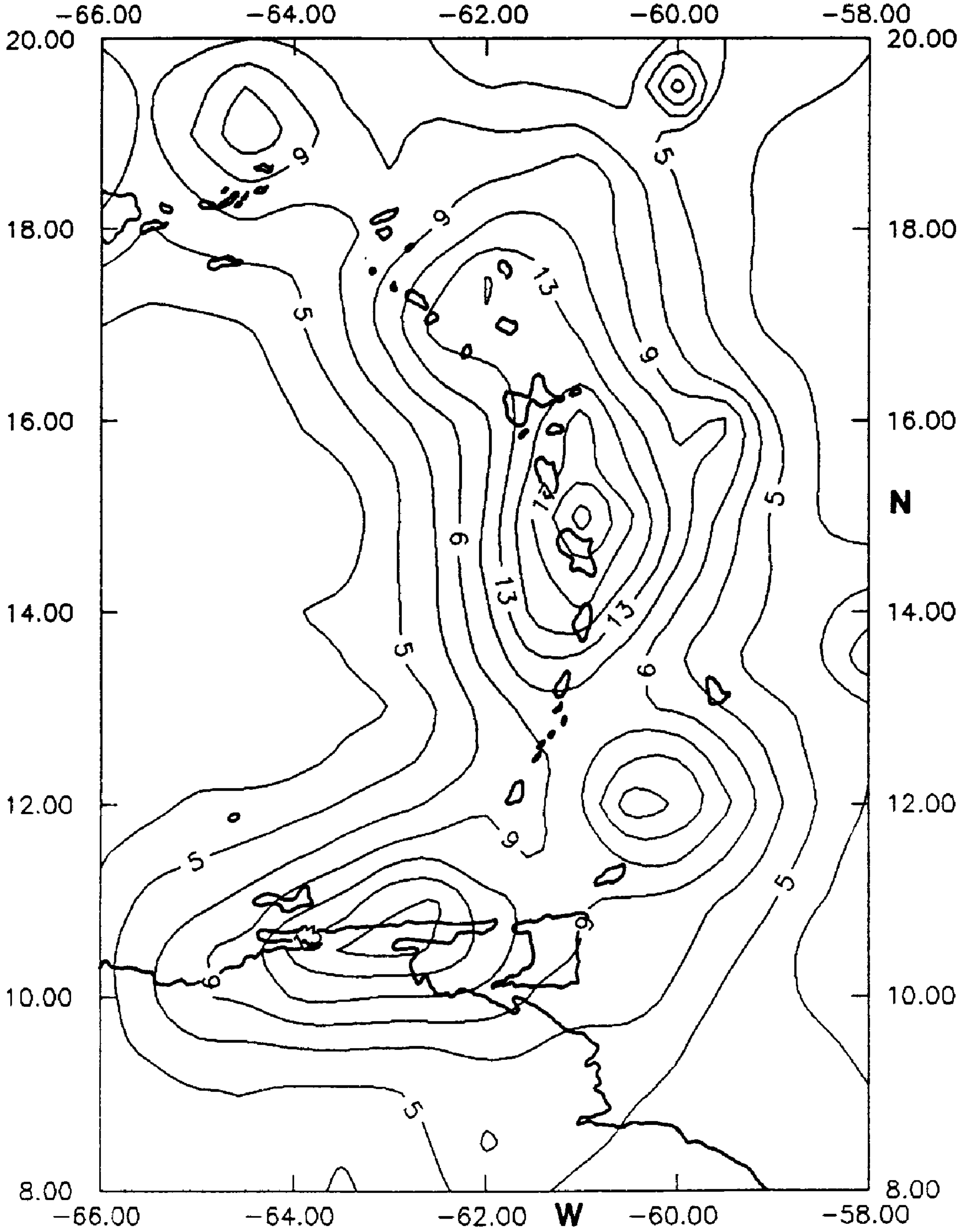

Figure 4b: Maximum velocity with 90% probability of non-exceedance in 50 years. (Contour interval = 2 cm/s).

The application of Gumbel III to the whole eastern Caribbean region yielded an upper bound magnitude $\omega = 7.97 \pm 0.14$, with earthquakes of magnitude M_s 6.5 having a return period of about 6.1 years.

Table 3: Peak Ground Accelerations and Velocities for Eastern Caribbean Towns with 90% Probability of not being exceeded in 50 and 100 years.

Amplitude of:	Acceleration	(cm/s^2)	Velocity	(cm/s)
Period T years:	50	100	50	100
Port of Spain, Trinidad	177.22	197.25	9.98	11.13
Scarborough, Tobago	168.34	187.87	9.26	10.35
St. George's, Grenada	142.61	158.66	7.99	8.91
Bridgetown, Barbados	116.41	130.19	6.52	7.31
Kingstown, St. Vincent	187.50	210.90	10.81	12.17
Castries, St. Lucia	282.82	318.67	16.46	18.57
Fort de France, Martinique	350.07	393.00	20.46	23.01
Roseau, Dominica	305.03	341.84	17.73	19.90
Basse Terre, Guadeloupe	213.22	238.07	12.43	13.91
Plymouth, Montserrat	237.83	266.07	13.40	15.01
St. John's, Antigua	258.54	288.40	14.73	16.46
Charlestown, Nevis	229.65	256.93	12.82	14.37
Basseterre, St. Kitts	207.15	231.99	11.57	12.98
Codrington, Barbuda	237.88	265.18	13.47	15.04
The Bottom, Saba	136.15	151.82	7.56	8.44
Philipsburg, St. Maarten	127.68	141.76	7.06	7.85
Road Town, Tortola	150.27	166.96	8.17	9.10
The Valley, Anguilla	123.38	136.66	6.82	7.57

The iso-hazard maps for acceleration and velocity generally agree well with each other and reveal the high hazard areas as northeastern Venezuela, the region from St. Lucia to Barbuda, just north of the British Virgin Islands and between Tobago and Barbados, with the highest hazards generally occurring out at sea.

Although seismic hazard patterns estimated using different models and hazard variables are not generally expected to be totally compatible, those obtained in this study seem to exhibit similar spatial features. Differences between the magnitude hazards and those for acceleration and velocity are probably attributable to the fact that focal distance is important in the evaluation of acceleration and velocity from attenuation relations.

Very few studies have been done on quantitatively estimating eastern Caribbean earthquake hazards. Taylor et al. (1979) prepared a preliminary map of peak horizontal ground acceleration with 90% probability of non-exceedence in 50 years for the same area as this study using the "whole process" approach of Cornell (1968). Both the hazard amplitudes and the patterns of spatial distribution seem to agree fairly well with those of this study. However, the studies of Shepherd and Aspinall (1983) and Shepherd et al. (1994b) for the Trinidad and Tobago area using Cornell-type approaches produced maximum acceleration values which are generally larger than those in this study by more than 50%. A site specific seismic hazard analysis for the Roseau Dam site, St. Lucia, by Aspinall et al. (1994) yielded peak ground acceleration and velocity values with 90% probability of not being exceeded in 50 years of 262 cm/s^2 and 12.9 cm/s respectively. These agree very well with values of 283 cm/s^2 and 16.5 cm/s obtained using extreme value analysis although it must be pointed out that the attenuation relations used in the two cases are different. If the same attenuation relationship used by Aspinall et al. (1994) is employed, the extreme value results are 50% less: for example, peak ground acceleration is now 138 cm/s^2.

The differences between the hazard levels defined by the "whole process" studies and the extreme value analysis may be attributable to the differences in approach, especially the definition of the source zones. For the Cornell methodology, a maximum magnitude earthquake is defined for each source zone and the final hazard contribution from the zone is due to the integrated effect of this maximum earthquake being moved around spatially throughout the source zone. In most cases as well, this maximum magnitude earthquake is assumed to have a fixed focal depth which is often the average of the focal depths for sources in that zone. Such an approach is overall definitely more conservative and would obviously lead to higher hazard estimates. On the other hand, the extreme value method does not define source zones but simply uses the individual earthquake focal parameters as is. Since it is possible that large earthquakes may occur in the future in some areas that have not been active during the instrumental period, the hazard values obtained in this study for some areas may be considered as minimum values. This, together with the fact that earthquake location errors, which may be quite considerable for earlier events, are not taken into account, point to potential limitations in the use of extreme value analysis in earthquake hazard assessment. A further study in the near future will evaluate hazard in this region using the Cornell approach.

The acceleration hazard would generally be applicable in considerations involving the earthquake resistant design of short-period structures, such as 1-3 storey buildings, since most peak horizontal acceleration values occur at frequencies of about 2-5 Hz. The peak ground velocity hazard is more suitable for considerations involving high-rise buildings for which longer period ground motion is important.

The lack of eastern Caribbean strong ground motion data and hence appropriate attenuation relationships probably results in the largest uncertainty in the numerical analysis. The results of applying the attenuation formulae given by Woodward-Clyde Consultants (1982) and Fukushima and Tanaka (1990) for four eastern Caribbean towns are listed in Table 4. For Port of Spain, for example, the acceleration values range from a minimum of 66 cm/s^2 obtained using the Fukushima and Tanaka (1990) relationship to a maximum of 177 cm/s^2 for the Krinitzsky et al. (1988) formula, with the Woodward-Clyde Consultants (1982) relation yielding an intermediate value of 142 cm/s^2. The differences are even larger for the other towns. This range of variation is quite significant and points to the absolute importance of acquiring local strong gound motion records in the long term.

Table 4: Acceleration Amplitudes (cm/s^2) with 90% probability of non-exceedance in 50 years obtained for four Eastern Caribbean Towns using Different Attenuation Relationships.

Attenuation Relation	Port of Spain	Castries	Roseau	St. Johns
Krinitzsky et al. (1988)	177.22	282.82	305.03	258.54
Woodward-Clyde (1982)	142.50	137.96	143.95	188.64
Fukushima & Tanaka (1990)	66.09	50.99	61.46	110.08

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