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Seismicity and seismic gap in the Lesser Antilles arc and earthquake hazard in Guadeloupe

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Summary. A seismic study of the Lesser Antilles arc has been carried out, first for the period 1950–1978, for which we can use local seismic networks to draw maps of instrumental seismicity, then for the period 1530–1950, for which we have catalogues of felt earthquakes. The striking feature of the spatial distribution of foci is the cluster of epicentres in the northern half of the arc; all large earthquakes ($M > 7.5$) are located north of 14° latitude. Seismicity cross-sections through the arc show a variable dipping subduction zone along the arc; the deep seismic zone is steeper in the centre of the arc than on the extremity.

The time–space diagram for historical seismicity, and the evidence of a seismic gap at the east of Guadeloupe lead us to consider the northern half arc as a likely site for a large earthquake in the near future.

The seismic slip rate calculated from all major earthquakes since 1530 is of much greater value than that obtained from recent plate tectonic models, suggesting that the recurrence rate of earthquakes is more than many hundreds of years with a possible aseismic creep.

1 Introduction

The Lesser Antilles arc is the eastern part of the Caribbean plate. The existence of this plate, suggested by Morgan (1968), was definitively proved by Molnar & Sykes (1969), who studied the seismicity of the periphery of the plate.

The advance in our understanding of the focal mechanisms of earthquakes allows us to treat in greater detail the relative motions of plates surrounding the Caribbean plate.

The Lesser Antilles arc is the result of the subduction of the American plate under the Caribbean plate. Fig. 1 shows plate boundaries in the Caribbean region with the relative motion between plates indicated. The most recent plate motion model RM2 by Minster & Jordan (1978) yields a slip rate of about 2 cm yr^{-1} along the arc. The slip vector azimuth is nearly perpendicular to the arc. In this RM2 model, a very small relative motion (< 0.5 cm yr^{-1}) between the North and South American plates is predicted, but the position of the boundary between these two plates is questionable. Arguments exist (Dorel 1978) which

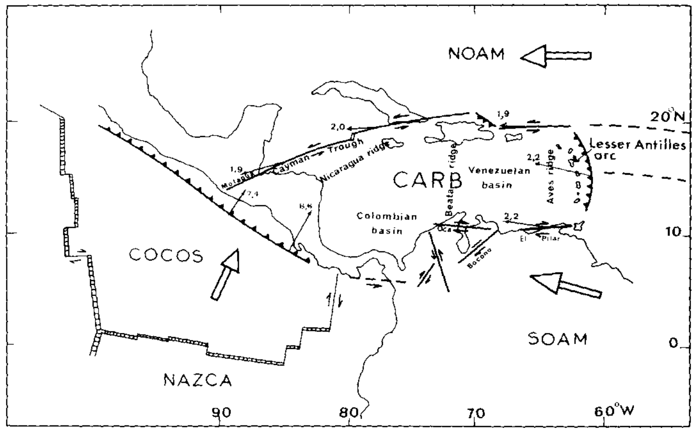

Figure 1. Boundaries of the Caribbean plate. In the north and south there are transform fault systems, and at the east and west two subduction zones. Arrows indicate direction of surrounding plates with respect to the Caribbean plate, supposed stationary. Numbers indicated near arrows are slip rates in cm yr^{-1} (after Molnar & Sykes 1969; Jordan 1975; Minster & Jordan 1978).

put this limit nearer 20° N of latitude; so we should have the South American plate in front of the Lesser Antilles arc. An alternative, however, is the presence of a broad zone of deformation without a single boundary. The aim of this study is to investigate the seismicity of the Lesser Antilles arc and the implications for seismic hazard in Guadeloupe.

The analysis of the occurrence of earthquakes in a specified interval of time and space has shown, that in many regions earthquakes are not randomly distributed throughout this space–time interval. Such studies led to the concept of 'seismic gap' and to evidence of migrations of epicentres along plate margins. This concept of seismic gap was introduced a few years ago to identify seismic areas which have not been active during the past years, although there is a relative motion of adjacent blocks. These quiescent regions are therefore the most likely sites of large earthquakes in the future. This method was developed by many investigators, among them Fedotov (1965), Mogi (1968), Sykes (1971), Kelleher (1970), Kelleher, Sykes & Oliver (1973) and some regions identified as gaps have been the locations of large earthquakes. This method is a long-range prediction and does not provide an estimate of the time of occurrence of future large earthquakes. For this it is necessary to find the duration of quiescence in a seismic gap. Until now only very crude empirical methods have been developed (Acharya 1979; Molnar 1979).

2 Seismicity

Instrumental recording of earthquakes in the Lesser Antilles arc began in 1936 with the installation of the first permanent seismic station in Martinique. This station was followed in 1947 by another on the island of Guadeloupe. In 1950 stations were set up on each mean island by the seismic research unit of Trinidad. Finally, in 1973 a French telemetry network of nine stations was set up on the three islands of Martinique, Guadeloupe and Dominique (Fig. 2). Only short-period seismographs (1 Hz) are in operation. The output of seismometers is recorded on a visible ink-paper recorder and on magnetic tape for signals exceeding a certain threshold, so the observational material based on instrumental recordings is essentially limited to the last 30 yr. For the period before that, only larger earthquakes ($M > 6.5$) are known from records at distant stations; the data sources used have been the catalogue of Gutemberg & Richter (1954) and the bulletin of the International Seimological

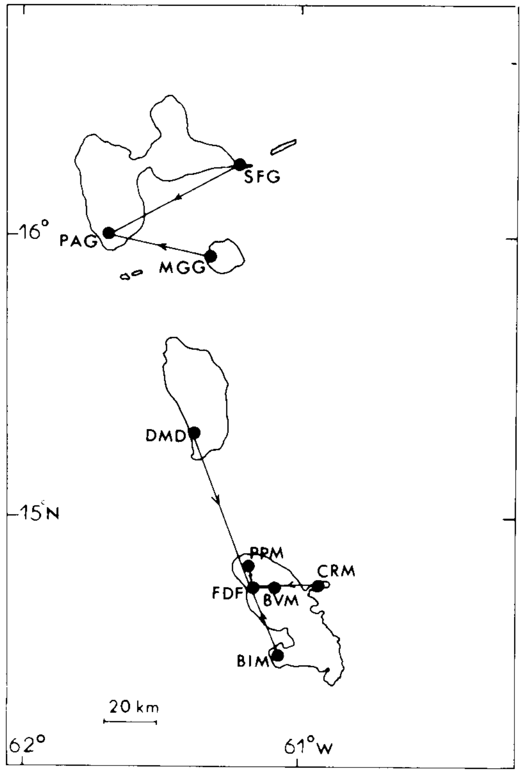

Figure 2. French seismic telemetry network for the study of regional seismicity. Two other networks, not represented, are set up around the two volcanoes: La Soufriere de Guadeloupe, and Montange Pelée of Martinique for volcanologic studies.

Summary (ISS) for the period 1900–1950. Before 1900, for historical seismicity, we have searched all available catalogues and publications on the seismicity of this area as far back in time as possible. But the catalogue is not homogeneous for the whole interval of time covered: the abundance of data in more recent years is important compared to the earliest ones and the catalogue can be considered as homogeneous only above an assigned magnitude limit ($M > 7$?).

2.1 INSTRUMENTAL SEISMICITY

For the period 1950–1978, the epicentre determinations have been carried out using data from the stations of the Lesser Antilles arc and from global teleseismic networks.

For earthquakes with magnitude (m_b) greater than or equal to 5, the determination of ISC (International Seismological Center of Edimbourg) or the recomputation of Sykes & Ewing (1965) for the period 1953–1965, have been kept because we assume that the determination of the focus from distant stations is probably more reliable than that calculated from local network when the structure is not well known. This is supported by the study of Barazangi & Isacks (1979) which shows that for depths greater than 50 km the results based on teleseismic data give no substantial bias of the spatial distribution.

For earthquakes with magnitude less than 5, location of the events is obtained from the local data, using an approximate Earth structure determined by Dorel, Eschenbrenner & Feuillard (1974, 1979) along the arc; the crustal structure is characterized by a three-layers

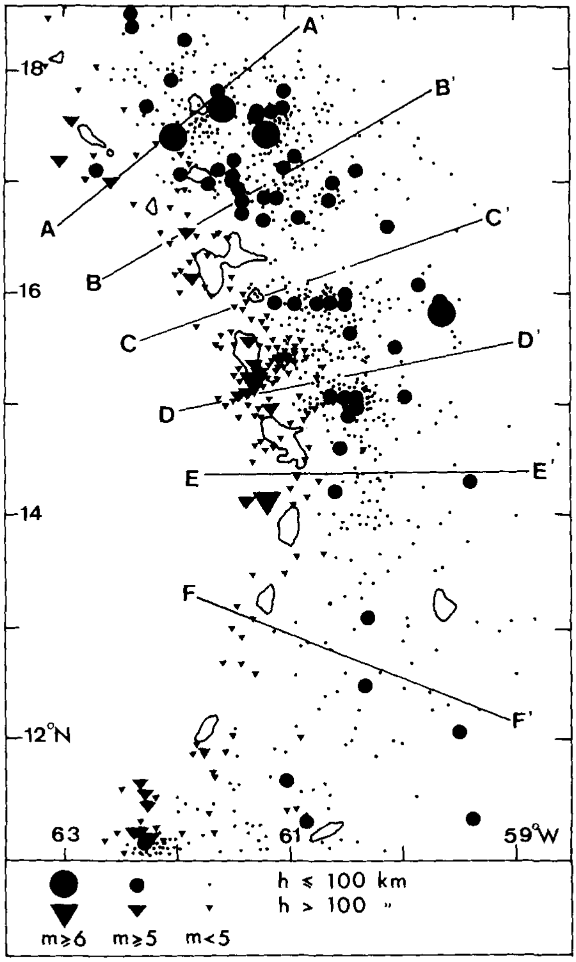

Figure 3. Distribution of earthquake epicentres in the period 1950–1978. Shallow focus earthquakes ($h < 30$ km) on volcanic islands are omitted to avoid overcrowding of the figure. Magnitude m_b is taken from NOAA, PDE list or ISC.

Six seismicity cross-sections (AA′, BB′, ...) are taken perpendicular to the arc and presented in Fig. 4.

model: the compressional velocity is about 3.5 km s^{-1} down to a depth of 3 km. Below this the velocity is 6.0 km s^{-1} in a layer whose thickness is about 12 km. Under this layer we found a 7.0 km s^{-1} layer with a thickness of 15 km. The crust is underlain by a mantle whose mean velocity has been taken to 8.0 km s^{-1}.

A recent shot calibration in sea at 120 km east of Dominique (15°.5 N) has shown that for a superficial focus the error in epicentral determination was less than 5 km in this region.

Fig. 3 shows the distribution of earthquakes in the Lesser Antilles arc between 11° and 18°.5 north, and 59° and 63° west, for the period 1950–1978.

The foci are classified in two groups: a first group of events in which depths are less than 100 km and a second group in which depths are greater than 100 km. The shallow seismicity spreads between the trench represented by the negative gravimetry anomaly and the arc. The intermediate depth earthquakes (up to 190 km) exist under and along the arc defined by the active volcanic front but most of these events are concentrated in a zone located beneath the island of Dominique in the centre of the arc near 15°.2 N. The cluster of foci

Table 1. Earthquakes of the Lesser Antilles arc with magnitude (m_b) greater than 5.0 between 1950 and 1979.

Date	Origin Time	Lat. (N)	Long. (W)	depth	M (>6)	Reference
1950 Mar.09	10 03 37	15.6	60.4	0		Sykes
1950 Dec.29	20 16 27	17.0	62.5	100		"
1951 May 03	04 08 51	15.5	61.3	150		"
1951 Nov.12	09 36 32	16.7	61.4	61		"
1951 Dec.23	06 57 20	14.9	61.2	172		"
1952 Jun.18	00 59 38	16.5	61.8	111		"
1952 Aug.19	14.03.10	15.9	61.1	70		"
1952 Dec.31	01 38 13	11.4	59.3	9		"
1953 Mar.19	08 27 53	12.1	61.2	134	6.8	"
1953 Jun.25	21 19 08	11.3	62.4	124		"
1954 Apr.21	18 41 13	15.1	61.4	150		B.C.I.S.
1954 Sep.18	04 55 20	15.5	60.0			Sykes
1958 Jan.02	22 35 36	11.5	60.9	15		"
1958 May 21	11 08 18	17.5	61.9	117		"
1958 Aug.15	00 22 41	12.1	58.3	62		"
1958 Nov.24	22 27 02	17.1	61.6	51		"
1959 Jan.08	01 55 57	15.7	61.3	114	6.2	"
1959 Mar.27	07 02 09	17.2	63.0	123		"
1959 Apr.02	01 52 54	14.6	60.5	83		"
1959 May 26	05 27 45	17.0	61.7	46		"
1960 May 31	11 02 20	17.7	61.6	27	6.0	"
1961 Jan.09	19 22 08	17.2	61.5	38		"
1961 Jul.05	05 02 27	15.1	60.4	52		"
1961 Sep.11	22 15 03	11.2	62.3	121		"
1961 Nov.02	23 03 50	17.1	62.7	–		"
1962 Jan.15	08 22 13	13.1	60.3	60		"
1962 Feb.10	19 31 53	17.9	62.0	49		"
1962 Apr.07	23 04 12	15.0	60.6	65		"
1962 Sep.08	13 02 24	16.0	60.5	–		"
1962 Sep.13	14 33 02	11.7	61.0	72		"
1962 Dec.26	06 12 54	15.2	61.3	144		"
1963 Dec.10	20 03 13	17.1	60.4	33		"
1964 Mar.14	15 12 22	15.9	60.5	31		"
1964 Aug.20	08 37 03	14.9	60.5	82		I.S.C.
1965 Fev.25	06 28 21	15.1	59.9	42		"
1965 Jul.17	15 52 28	17.8	61.6	45		"
1965 Jul.29	08 54 01	16.6	60.1	33		"
1966 Jan.09	09 11 31	11.5	62.3	163		"
1966 Feb.13	06 07 25	14.1	61.4	188		"
1966 Apr.16	07 12 37	18.3	61.9	28		"
1966 Jul.15	07 59 59	17.0	61.5	62		"
1966 Nov.13	02 51 53	17.1	61.9	92		"
1967 Apr.26	10 47 51	11.2	62.3	127		"
1967 May 31	11 38 39	12.5	60.3	70		"
1967 Sep.25	08 51.50	17.6	61.6	57		"
1967 Oct.14	03 31 07	17.3	60.9	42		"
1967 Oct.26	12 21 35	17.7	61.0	46		"
1967 Oct.26	13 44 48	17.6	61.1	59		"
1967 Nov.04	15 11 22	17.8	61.0	33		"
1967 Nov.28	03 21 32	18.5	62.4	45		"
1967 Nov.29	01 23 34	18.4	62.4	52		"
1967 Dec.24	20 03 14	17.4	61.2	42	6.4	"
1967 Dec.24	21 52 50	17.6	61.5	5		"
1968 Mar.19	02 19 15	15.1	60.5	57		"
1969 May 15	20 35 51	16.8	61.1	57		"
1969 Dec.07	22 15 54	16.7	60.8	17		"
1969 Dec.25	21 32 27	15.8	59.6	1	6.3	"
1969 Dec.25	12 31 02	16.1	59.8	6		"
1970 Feb.09	11 26 56	16.8	61.2	60		"
1970 Mar.17	19 04 59	16.8	60.6	59		"

Table 1 – *continued*

Date	Origin Time	Lat. (N)	Long. (W)	depth	M (>6)	Reference
1971 Mar.20	02 59 09	14.2	60.6	82		"
1971 Mar.30	03 11 37	15.9	59.6	33		"
1971 May 06	01 11 21	15.9	60.6	54		"
1971 Dec.25	13 17 08	15.1	61.4	178		I.S.C.
1973 Feb.17	16 02 49	17.0	61.5	63		"
1973 Mar.22	14 00 43	15.3	61.3	151		"
1973 Jul.08	16 59 09	15.9	60.7	26		"
1974 Sep.07	19 40 52	15.1	60.6	58		"
1974 Oct.08	09 50 58	17.4	62.0	41	6.4	"
1974 Nov.20	08 33 12	17.3	59.4	45		"
1975 Mar.03	09 43 23	17.2	61.0	39		"
1975 Jun.08	23 59 32	11.5	62.2	142		"
1976 Fev.09	02 33 05	11.6	62.3	161		"
1976 Mar.10	09 04 59	16.8	61.1	56		"
1976 Jun.11	03 41 58	17.0	60.6	36		"
1976 Jul.01	03 38 12	16.6	61.2	38		"
1976 Aug.23	13 56 12	11.1	62.3	90		"
1977 Feb.24	14 24 45	17.2	61.5	33		N.E.I.S.
1977 Nov.28	00 30 58	15.9	60.9	62		"
1978 Jun.08	23 43 51	16.2	61.8	111		"
1979 Jun.07	07 25 33	17.7	62.3	17		"

draw a line perpendicular to the arc. The most striking effect of this distribution is the great cluster of epicentres in the northern half of the arc at latitude 14° N. All large earthquakes ($m_b > 6$) are located in this portion of the arc. The total seismic energy released for this period is relatively poor; only five earthquakes have a magnitude (m_b) greater or equal than 6 with a maximum of 6.6, and about 80 earthquakes have a magnitude greater than 5. Their epicentres are listed in Table 1. The average annual energy released is about 4×10^{20} erg for the last 30 yr. The seismic activity arises from the subduction of the South American plate beneath the Caribbean plate. The dipping zone of seismic activity normally associated with subduction may be presented by vertical cross-sections along the arc. Fig. 4 shows six cross-sections along profiles of Fig. 3. The sections are 100 km wide. From the seismicity we can try to draw the boundary of the plates and the shape of the slab. But this is difficult because of crustal seismicity and hypocentral uncertainties whose consequence is the scattering of the focus.

Yet the distribution of events with depth seen on the different cross-sections show a relatively fairly well-defined Benioff zone and suggest a variable dipping slab along the arc. The cross-section AA′ in the north of the arc gives an angle of about 30° for the plunge of the slab. The section BB′ gives an angle of 45°.

In the centre of the arc with the cross-sections CC′, DD′ we obtain 60°. In the south (section FF′) the subduction is very badly defined because of poor seismicity, but it seems that the angle of subduction has a low value (≃ 30°), as in the north.

The distance between the front volcanic arc and the trench is almost constant along the arc with a value of 180–190 km, except in the south (section FF′) where this distance is about 160 km. Hence the depth of the subduction zone under the active volcanos is variable; about 90 km to the north this depth increases to 120 km under the centre of the arc (profile DD′).

The variations of the dip of the slab in the north and south of the arc may be related to the transformation of movement from a pure subduction in the centre of arc to a transform trench fault zone in the north and a transform strike-slip fault zone in the south. The values found for dips along the arc are low, 30°–60°, and do not agree with the relation of

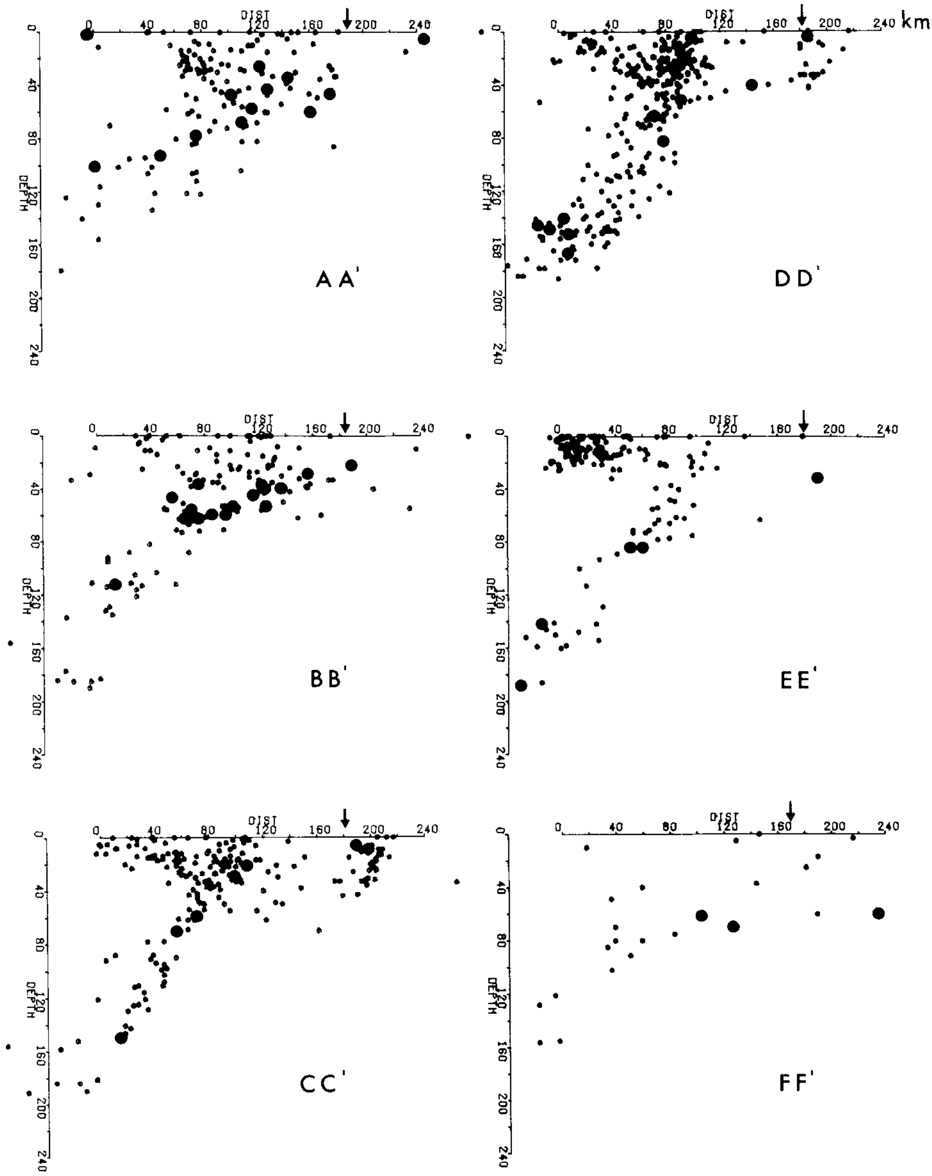

Figure 4. Distribution of foci in a vertical plane perpendicular to the arc axis, along profiles of Fig. 3. The sections are 100 km wide. Shallow foci on volcanic islands (except volcanic earthquakes) are represented here. Origin on the horizontal axis indicates the active volcanic front. Arrows show the position of the negative gravity anomaly.

Luyendyk (1970) who found a relationship between the dip and the relative rate of convergence of plates.

The observation of seismicity on cross-sections suggests a bend of the underthrusting plate at about 40 km depth. This is particularly obvious on the profiles BB′ to EE′. The shallow seismic zone between the upper end of the Benioff zone, near a depth of 40 km, and the trench is defined as the main thrust zone where the two plates overthrust. The contact spreads over a width of 100 km.

It does not seem (Fig. 4) that a double planned structure of the deep seismic zone exists as on other arcs (Hasegawa, Umino & Takagi 1978), although on the section CC′ the existence of a double sheet of seismicity is not out of the question. A further investigation with an improvement of location of the foci will be necessary.

2.2 HISTORICAL SEISMICITY

This seismicity is studied with the catalogues of felt earthquakes during the past.

A chronological historical listing of earthquakes can be found in Poey (1837), Perrey (1845) and Robson (1964). All these catalogues list the earthquakes which were felt or caused damage and have been reported in the seismological literature in West Indian newspapers or European sources, since 1530.

In Robson's catalogue the intensity in different islands of the arc is given for each earthquake.

Because of scattered population centres and poor communications between the islands, the historical accounts of earthquakes provide only approximate estimates of location and magnitude of the earthquakes.

Relationships between macroseismic and instrumental data are used to obtain the location and magnitude of earthquakes.

General relationships between intensity at epicentral zone (I_0), magnitude M, depth h and intensity I_n at the hypocentral distance D, have the following form:

$$I_0 - I_n = \gamma \log \frac{D}{h} \qquad 3 < \gamma < 6$$

$$M = \frac{2}{3} I_0 + 1.2 \log h - 1.1 \qquad \text{(Kârnik 1969).}$$

The major problem in the case of the Lesser Antilles arc is the small area of emerged lands with respect to the total area concerned with earthquakes.

The previous relationships have been applied to recent earthquakes (1974 October 8, 1969 December 25) for which we know the parameters of the focus, location, magnitude, and the intensity which has been pointed out on every island. The agreement is quite good. The application of these relationships to the past earthquakes for which we know only the intensity on the islands, provides an estimation of the location and magnitude for major earthquakes. Fig. 5 shows the isoseismical maps for great earthquakes ($M > 6.5$) in the Lesser Antilles arc since 1530 and Table 2 is a list of these earthquakes. Fig. 6 displays the location of epicentres of great historical earthquakes. We can observe a similar concentration of earthquakes in the northern half arc as we pointed out for instrumental seismicity in the last 30 yr. The two major earthquakes ($M > 8$) in 1690 and 1843 have taken place in the north of Guadeloupe where the seismicity at the present time is also the most important on the arc. In the south of 14° N no earthquake has a magnitude greater than 7.5.

In our presentation of historical seismicity (Fig. 6) we distinguish between two groups of earthquakes according to their depth. It is a striking feature to observe that in the north of the arc all great earthquakes have depths less than 100 km and consequently seem to be correlated to thrust motion, whereas in the south of the arc only three moderate superficial earthquakes occurred. This contrast between the northern and southern parts of the arc suggests a different tectonic process in the two parts of the arc.

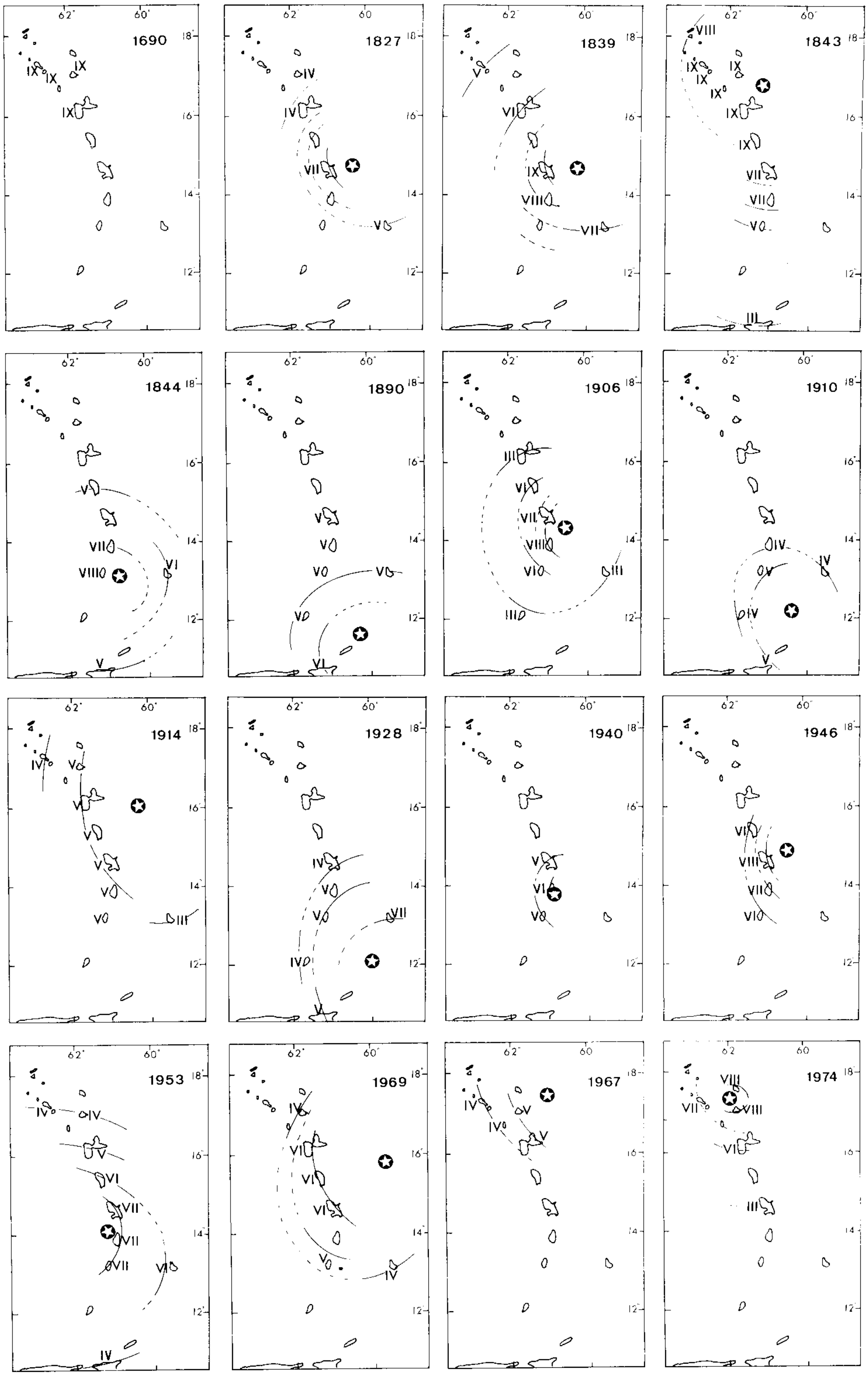

Figure 5. Macroseismic maps of historical seismicity for larger earthquakes in the Lesser Antilles arc since 1530. A star indicates the epicentre.

Table 2. Earthquakes of the Lesser Antilles arc with magnitude (M_S) greater than 6.5 between 1530 and 1979.

Date	Coordinates N	W	Depth (km)	Magnitude (M_S)	Seismic moment M_0 (10^{27} dyne cm)
1690 April 5	17.5	61.5*	—	8.0(?)*	13
1827 Dec. 1	14.5	60.5*	—	~6.5*	0.07
1839 Jan. 11	14.5	60.5*	—	~7.8*	6.4
1843 Feb. 8	17.0	61.0*	50*	>8.0*	>13
1844 Aug. 30	13.0	61.0*	150*	~7.0*	0.4
1888 Jan. 9	11.5	62.0*	150*	~7.5*	2.2
1890 Oct. 6	11.5	60.5*	50*	~7.0*	0.4
1906 Feb. 16	14.2	60.5*	50*		
	15.0	61.0†	100†	7.5†	2.2
1910 Jan. 23	12.0	60.5†	100†	7.2†	0.8
1914 Oct. 3	16.0	61.0†	100†	7.4†	1.6
	16.0	60.5*	50*		
1928 Sep. 26	12.0	60.0†	—	6.5†	0.07
1940 July 5	13.0	61.2†	100†	6.5†	0.07
1946 May 21	14.5	60.5†	50†	7.0†	0.4
	14.8	60.5**			
1953 March 19	14.1	61.2‡	134‡	7.5‡	2.2
1967 Dec. 24	17.4	61.1§	24§	7.0¶	0.4
1969 Dec. 25	15.8	59.6§	1§	7.2**	0.8
1974 Oct. 8	17.4	62.0§	41§	7.5**	2.2

Origin of epicentre determination.
*From isoceists.
† From Gutemberg & Richter (1954).
‡ Sykes & Ewing (1965).
§ ISC.
¶ Pasadena.
** USCGS or NEIS.

3 Space–time distribution of earthquakes

Many authors, e.g. Kelleher *et al.* (1973) have studied space–time patterns of earthquakes. A suggestion of linear trends has been found in circum-Pacific seismic zones.

In the Lesser Antilles arc, the study of the space–time seismicity pattern is handicapped by the short time period of instrumental data and by the low seismicity in historical time.

Fig. 7 displays in space and time the distribution of earthquakes for the whole period between 1530 and the present time. Only earthquakes whose magnitude M_s is greater than 6.5 have been reported.

Evidently the relative abundance of earthquakes in the last century is a consequence of better communications and reports about the effects of earthquakes. For previous centuries only the major earthquakes can be reliable sources of information. Fig. 7 suggests three periods of active seismicity: the first at the end of the seventeenth century with the great earthquake of 1690, the second period in the first half of the nineteenth century with the 1839 and 1843 earthquakes and the third period in the twentieth century, with several moderate earthquakes but without any great earthquake until now.

The two earthquakes of 1690 and 1843 were important enough to affect all the northern half of the arc. We have no direct indication about the rupture zone of these large

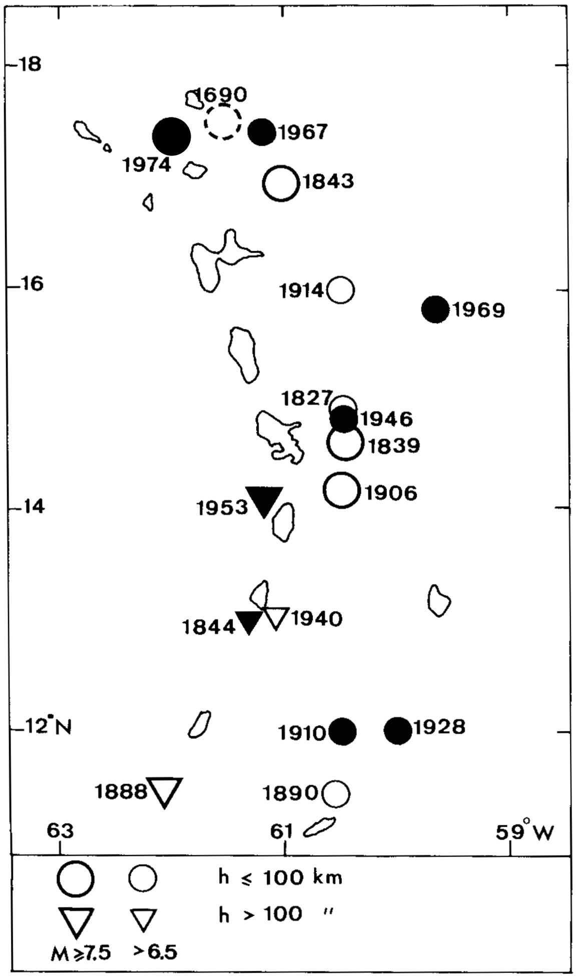

Figure 6. Map of epicentres (with the date) of large earthquakes listed in Table 2. Magnitude is M_S. (Black circles and triangles are instrumental determinations, open circles and triangles are macroseismic determinations.)

earthquakes, but the seismic intensity pointed out in every island suggests a magnitude probably equal to or greater than 8.

For the last period, the twentieth century, there has been no large earthquake similar to those of 1843 and 1690. Several earthquakes with magnitudes between 6.5 and 7.5 occurred. The 'pseudo-period' of 150 yr defined by the interval between the two great earthquakes seems to suggest that the next great earthquake will possibly occur at the end of this century.

Contrary to the northern part we can point out that no important earthquake occurred in the south of 14° N. Fig. 7 shows no recurrent seismic period in this part of the arc.

The graph of the time–space distribution for earthquakes of magnitude greater than 5 and during the period 1950–1978 is shown in Fig. 8. If we consider only the part of the arc north of latitude 14° we see a very noticeable gap at the east of Guadeloupe between 16°.1 and 16°.6 of latitude during this period.

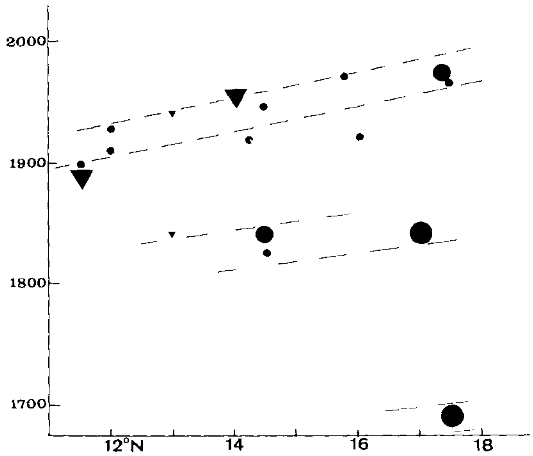

Figure 7. Graph of the space–time distribution of large earthquakes of the Lesser Antilles arc since 1530. Circles represent focal depths less than 100 km and triangles represent focal depths greater than 100 km. The size of the symbols is a function of magnitude, the smaller size for magnitudes between 6.5 and 7.5, and the larger size for magnitudes greater than 8.0. An intermediate size is for magnitudes between 7.5 and 8.0.

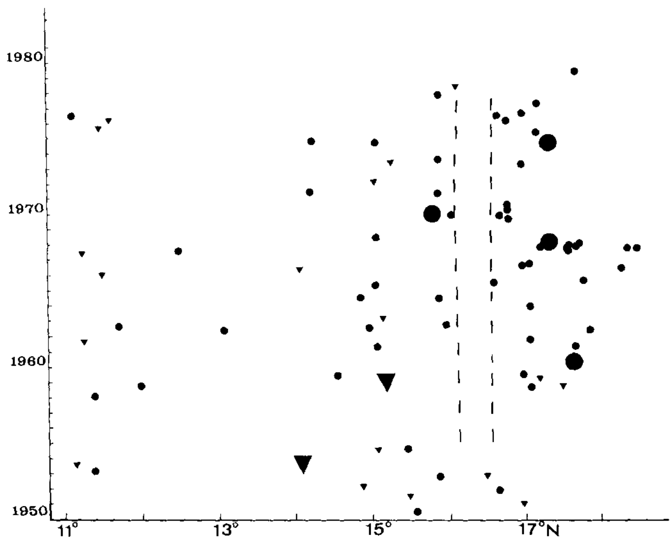

Figure 8. Graph of space–time distribution of earthquakes with magnitude $m > 5$ for the period 1950–1978. (For symbols see Fig. 7.)

Except for this gap, no obvious trend can be observed except for a possible recurrence of $M = 6$ earthquakes near latitude 17°.25 N. The evidence of this gap is also suggested by the seismicity map (Fig. 9).

4 Seismic slip rate

A model for the earthquake mechanism is provided by dislocation theory. From this several physical quantities can be defined; the faulting parameters are the dimension of fault area S,

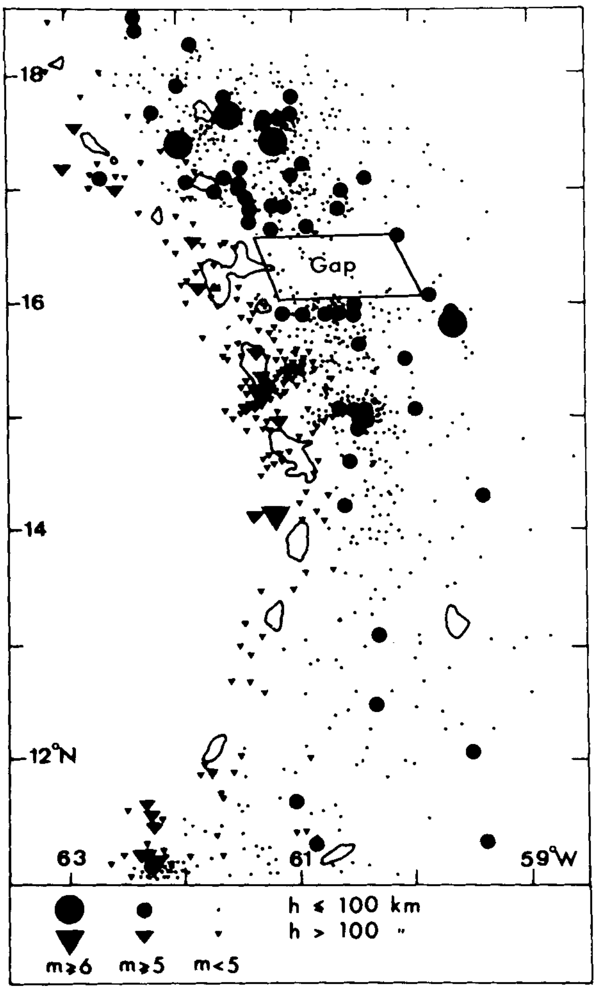

Figure 9. Evidence of a seismic gap at the east of Guadeloupe during the period 1950–1978.

or when the source is deep the aftershock area, and the average offset D. From these we can calculate the static moment M_0 by the relation:

$$M_0 = \mu SD \qquad (1)$$

where μ is the rigidity in dyne cm^{-2}, S is in cm^2, D is in cm. In terms of the stress drop σ and fault area S the seismic moment M_0 can be written:

$$M_0 = \xi \sigma S^{3/2} \qquad (2)$$

where ξ is the parameter associated with the fault geometry. In the case of a dip-slip fault we have:

$$\xi = \frac{3\pi}{16}\sqrt{\frac{W}{L}} \qquad \text{(Aki 1966).}$$

L and W are the length and width of the fault. Abe (1975) has studied the best possible values of ξ and σ from a number of large earthquakes on the Pacific coast. The data show that the fault length is approximately twice as large as the fault width. Then

$$L = 2W, \quad \xi = 0.40.$$

Besides, the relationship between fault area, seismic moment and stress drop shows that the stress drop is almost constant and independent of the seismic moment and fault area. Its value does not differ from one region to another, and is about 30 bar.

So with $\xi = 0.40$ and $\sigma = 30$ bar we obtain from equation (2)

$$M_0 = 1.23 \times 10^{22} S^{3/2} \quad (3)$$

where S is in km^2 and M_0 is in dyne cm.

Davies & Brune (1971) using relation (1) have computed the slip rate u along plate boundaries by summing seismic moments (ΣM_0) of individual earthquakes over a period of time T.

If $\langle u \rangle$ is the dislocation, the elementary moment for an earthquake i will be:

$$M_0^i = \mu \langle u \rangle dS$$

where dS is the area of the fault slip and the total seismic moment will be:

$$M_0 = \Sigma M_0^i = \int_S \mu \langle u \rangle dS = \mu US. \quad (4)$$

U is the average dislocation on the total area of the shear zone S. So we obtain:

$$u = \frac{U}{T}$$

for an average slip rate. The estimation of M_0 can be calculated from the magnitude M_s with the following formula:

$$\log M_0 = 1.5\, M_s + 16.1 \quad \text{(Kanamori 1977)}. \quad (5)$$

In Table 2 seismic moments have been computed with this relation. The summation of M_0 for all earthquakes of the Lesser Antilles arc yields 46×10^{27} dyne cm.

An approximate value of the surface S will be obtained by taking 100 km for the thrust contact between plates and 800 km for the length of the arc. So relation (4) gives $U =$ 100 cm.

If we consider that almost all earthquakes are in the northern part of the arc, the surface S must be divided by 2 and U becomes 200 cm.

Over a period of more than four centuries we obtain a slip rate of 0.25 cm yr^{-1} for the whole arc, or 0.50 cm yr^{-1} for the northern part and less than 0.1 cm yr^{-1} for the southern part. All these values have been computed with $\mu = 7 \times 10^{11}$ dyne cm^2 for mantle rigidity. With a half value for crust rigidity the slip rates will be double.

Whatever values are chosen, the seismic slip rate is less important than that computed from the plate motion model.

Many reasons may be put forward to explain the difference:

A great deal of creep is occurring without associated earthquakes. This is probably important in the southern half of the arc where a great accretion prism of sediments in front of the arc, the Barbados ridge, may play a prominent part in subduction.

The calculated rate of slip depends on the time sample. If the recurrence time of strong earthquakes is greater than many hundreds of years the results obtained from a time period of only 400 yr will be erroneous.

The calculated rate of slip is affected by the area of the shear zone.

The seismic moments are estimated from earthquake magnitudes and are therefore subject to large errors for individual earthquakes. If we have many great earthquakes an average value over several earthquakes will be more accurate. But in the Lesser Antilles arc we have only two major earthquakes with a great uncertainty of their magnitude.

Slip rates predicted from the plate motion model are determined from magnetic anomalies and are therefore averaged over the past several million years, whereas seismic slip rares are correlated with the present state of plate motions.

Davies & Brune (1971) showed that many seismic slip rates agreed to within a factor of about 2 with the predicted slip rates from slip rates greater than 5 cm yr^{-1}. But for regions with predicted slip rates less than this value the agreement is very poor and a factor greater than 2 must be considered.

5 Seismic gap

In 1973 Kelleher *et al.* studied the distribution of past major earthquakes ($M > 7$) along plate boundaries of the circum-Pacific seismic belt in an attempt to forecast the locations of large earthquakes that may occur in the next decade. Three criteria are appled to define the areas where a high seismic risk exists: first, the segment must be a part of a major seismic belt; secondly, the segment must not have broken for at least 30 yr; thirdly, one or more additional criteria, for instance a historic record of at least one large earthquake, having occurred along that segment.

The northern half of the Lesser Antilles arc answers these three criteria and can therefore be classified as a likely site of large earthquakes in the near future.

In addition it has been pointed out that periods of relative quiescence in seismicity occur before the largest earthquakes in a general area, except for increased seismicity in the epicentral zone.

The indication of a seismicity gap many years before the major earthquake has been observed for Kuril in 1963, Alaska in 1964 and Rat Island in 1965 by Kelleher (1970).

In general the following sequence of four seismic episodes can be distinguished: normal seismicity, the precursory swarm, the precursory gap and the major event. The time interval between the precursory swarm and the major event, i.e. the logarithm of the duration of gap, is proportional to the magnitude of the main shock. This sequence is observed for superficial earthquakes but it can also be pointed out on subduction zones (Engdhal & Kisslinger 1977).

The lack of seismicity at the east of Guadeloupe during the past 30 yr may be interpreted as a gap before a major earthquake.

Two assumptions may be put forward on the consequences of this gap:

First, this gap may be considered as the third episode of the sequence described above. So we are expecting an earthquake similar to the 1690 or 1843 earthquakes. The magnitude may be about 8. The fault area will spread over all the northern half of the Lesser Antilles arc.

Secondly, we can assume that this gap shows a temporarily locked section of plate limited to the area of the gap, with respect to the rest of plate in the subduction motion, since a few decades ago. So it is possible that only this section will be reactivated in the next earthquake.

If we assume that an earthquake will eventually fill the gap, we can calculate the seismic moment by relation (3) and therefore the magnitude M_s by relation (5). The surface of the seismic gap is approximately $S = 6000\,\text{km}^2$ for which we have $M_0 = 6 \times 10^{26}$ dyne cm and $M_s \simeq 7.1$.

6 Seismic hazard in Guadeloupe

The earthquake hazard may be defined as the probability of occurrence of an earthquake with magnitude M during a specified period, while the seismic risk at a certain site will be defined as a probability of occurrence of an earthquake of given acceleration (or intensity) during a given period. Alternatively the seismic risk may be the largest expected intensity in a given region of the maximum observed intensity. In this latter case the seismic zoning map summarizes the observations on past earthquake effects and the assumption is made that the same pattern of seismic activity will be valid for the future. It is true only if the time of observation is long before the recurrence time of the earthquake; if not, the maximum expected intensity may be different from maximum observed intensity and its calculation implies an empirical attentuation function of intensity with distance and depth, the definition of source regions, and relationships of geological and soil properties to strong ground motion.

In Guadeloupe and Martinique we have catalogues of felt earthquakes since 1530. If we consider only those earthquakes which have been felt with an intensity greater or equal to six we obtain a list (Table 3) of about 20 earthquakes over a period of four centuries. Among them three have been felt in Guadeloupe with an intensity of IX. Very crudely, we can say that an intensity of IX is probable every century. This does not mean that a greater intensity will never occur. The possibility of a great earthquake ($M > 8$?) at the east of Guadeloupe implies a risk of an intensity greater than 9 for this island, but the damages will probably not be the same in all parts of the island. It will be of great interest to define the zoning map and then draw up a seismic micro-zoning. Recently, strong motion instruments

Table 3. Earthquakes felt in Guadeloupe or Martinique with an intensity greater than or equal to VI.

Date	Intensity	
	Guadeloupe	Martinique
1690 April 5	IX	
1702 Sept.		VIII
1727 Nov. 7		IX
1766 Aug.		VIII
1771 Feb.		VII
1787 July 21		VIII
1823 Nov. 11		VI
1827 Dec. 1		VII
1839 Jan. 11	VI	IV
1839 Jan. 21		VI
1843 Feb. 8	IX	VII
1851 May 16	VII	
1897 April 29	IX	
1906 Feb. 16		VII
1914 April 17		VI
1953 March 19		VII
1946 May 21		VIII
1969 Dec. 25	VI	VI
1974 Oct. 8	VII	

have been set up in Guadeloupe. The data obtained from these will improve the knowledge of the dynamic characteristics of surface soil layers and will lead to significant improvement of the assessment of damage to structures.

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