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## Prediction in relation to Seismo-volcanic Phenomena in the Caribbean Volcanic Arc

(With 2 Figures)

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### Introduction

Observations and inferences made in Martinique and Montserrat (Lesser Antilles) by Mr. F. A. PERRET and others from 1929 to 1937, and by Dr. C. F. POWELL and the writer in 1936, have suggested the compilation of a review of evidence potentially useful for predicting the time and place of future earthquakes, soufrière activity or volcanic eruptions in this part of the West Indies.

The objects of the following notes are: 1) to summarise facts relating to seismo-volcanic disturbances in the Caribbean region (with special reference to the Caribbean volcanic arc: Fig. 1) and inferences drawn from them; 2) to indicate exactly where scattered records of facts and inferences are to be found in the literature, additions to which during the last dozen years include three un-indexed monographs each exceeding seventy pages in length (PERRET 1935, 1939; MACGREGOR 1938). The summary

includes accounts of premonitory symptoms known to have heralded eruptions at various centres.

The methods developed by Mr. PERRET for « feeling the pulse » of an active volcano, as applied in particular to Montagne Pelée (Mt. Pelée or Mt. Pelé) in Martinique (PERRET 1935, pp. 8-14), will be referred to only so far as they concern general seismo-volcanic conditions in the Caribbean volcanic arc.

The circumstances that gave rise to the work of Mr. PERRET, Dr. POWELL and the writer in Montserrat are as follows. This island experienced a series of local « volcanic » earthquakes of considerable violence, accompanied by abnormal soufrière activity, from 1897 to 1899. Disturbed conditions are said to have lasted until 1902 (MACGREGOR 1938, p. 6; PERRET 1939, p. 64), but they were not renewed after the great eruptions of the Soufrière of St. Vincent and of Mt. Pelée in Martinique, which began almost simultaneously in that year. Towards the end of 1933 there was a renewal of local earthquakes in Montserrat, again accompanied by increased soufrière activity. In 1934 and 1935 the frequency of the shocks (some of which were violent and caused much damage), and the abnormal gas-emission from the soufrières, gave rise to anxiety. Mr PERRET visited the island in 1934 and 1935, submitted to the Governor of the Leeward Islands a number of valuable reports, and initiated continuous observational work. In 1936, the Royal Society sent Dr POWELL and the writer to continue and extend Mr. PERRET's study of the nature and location of the earthquake shocks and of the conditions at the soufrières, and to work out the morphology and volcanic history of the island. In 1936, earthquakes and soufrière activity were on a much reduced scale, and the decline of activity continued.

### **Evidence of earthquakes**

#### **The Caribbean Region as a whole.**

TEMPEST ANDERSON and FLETT mention records of earthquakes and volcanic eruptions that led them to believe there is some kind of interconnection between volcanic activity in the Lesser Antilles and major earthquakes in other parts of the



Fig. 1 — Map of the Caribbean Volcanic Arc

Caribbean region, including the Greater Antilles and the Central American mainland (1).

For instance they cite records (mainly from HUMBOLDT) of the approximate contemporaneity of (a) a great earthquake in Jamaica, and the eruption of Mt. Misery in St. Kitts, in 1692; (b) earthquakes in Venezuela, Trinidad, Jamaica, etc., and the eruption of Qualibou volcano in St. Lucia in 1766; (c) great earthquakes in Ecuador and Venezuela, and the eruption of the Soufrière volcano in Guadeloupe in 1796/7; (d) a violent earthquake in Venezuela, and the eruption of the Soufrière volcano in St. Vincent in 1812; (e) many earthquakes in the Greater Antilles, and the eruption of the Grande Soufrière volcano in Dominica in 1880; (f) a violent earthquake in Guatemala in 1902, just before Mt. Pelée began to emit steam.

The duration of the eruptive activity in Martinique and St. Vincent in 1902 (exceptionally prolonged when judged by previous Caribbean standards) was attributed to the continuation of crustal adjustments affecting the whole border of the Caribbean Sea (ANDERSON and FLETT 1903, pp. 533-4).

It is clearly desirable that critical and authoritative documented statements should be prepared, in order to compare the dates, locations, and degrees of violence of all seismic, fumarolic and volcanic activity known to have occurred in the Caribbean region in historic times. Such a compilation, made from all available original records, would involve a lengthy piece of research in European libraries and in Caribbean archives. A provisional graphical compilation for the Caribbean volcanic arc (up to 1938), based only in part on original records, is provided in Fig. 2; it is discussed in a later section of this paper (pp. 79-82).

#### **Martinique and St. Vincent.**

Before the 1902/7 eruption of Mt. Pelée in Martinique, the submarine cable to Guadeloupe was broken on 22 April; the rupture may or may not have been due to seismic activity (2).

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(1) See also p. 77 for examples of contemporaneity of eruptions throughout the Caribbean region.

(2) The prolonged eruptions of Mt. Pelée and of the Soufrière of St. Vincent which began almost simultaneously early in May 1902, were accompanied by the repeated rupture of all submarine cables west of the

Slight earthquake shocks occurred, however, on the western flanks of the volcano on 23, 25 and 30 April, that is to say about the time of *initiation* of explosive phenomena on 24 April. During the eruptions, earthquakes did not coincide with explosive paroxysms (LACROIX 1904, pp. 35, 90).

Before the 1929/32 eruption of Mt. Pelée, the records of seismic activity at the volcano observatory on Morne des Cadets showed no abnormality in the number and intensity of tremors. In September and November of 1928, however, seismograph records resembling those produced by mine-explosions had been obtained; it is thought that these tremors may have been connected with the internal activity of the volcano (ROMER 1936, p. 92).

In the twelve months before the eruption of the Soufrière of St. Vincent in 1812, over 200 earthquake shocks were counted in the island (ANDERSON and FLETT 1903, p. 533).

A series of earthquakes in St. Vincent in 1901/2 proved to be a premonitory symptom of the eruption of 1902/3. In February and March 1901 tremors became much more numerous than usual on the north side of the Soufrière volcano. Shocks continued for the ensuing twelve months; they increased in number and in violence in the latter part of April 1902, that is to say shortly before the initiation of eruptive activity on 6/7 May. Severe local shocks recurred during the eruptive period, and were sometimes contemporaneous with explosive activity at Mt. Pelée (ANDERSON and FLETT 1903, pp. 378-9, 532-5).

### **Montserrat.**

The earthquakes of the years 1933 to 1937 in Montserrat proved to be mostly of shallow origin, the majority of the foci being below the island and between one and two kilometres from the surface (MACGREGOR 1938, pp. 14-5; POWELL 1938, Fig. 11 and p. 31; PERRET 1939, pp. 26-8, 48, 58).

The seismic disturbances were of volcanic origin, that is to say intimately connected with local soufrière activity (see p. 74) and general magmatic conditions along the Caribbean volcanic arc. Mr. PERRET regarded the earthquakes as « subvolcanic »

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two volcanoes. The causes, or cause, of the ruptures are not clear (LACROIX 1904, pp. 92-107).

(MACGREGOR 1938, pp. 14, 39, 83; POWELL 1938, pp. 28-32; PERRET 1939, pp. 2, 19, 36-7, 47-9, 53-4, 62, 72).

Dr POWELL's map of the distribution of earthquakes in Montserrat in 1936 shows an elongated clustering of epicentres (Region II) that is almost coincident with a line of soufrières mapped by the writer. This suggested that here the earthquake and soufrière activity was connected with a plane of crustal weakness or of deep-seated fracture (POWELL 1938, Fig. 11; MACGREGOR 1938, pp. 14-5, 40). Mr. PERRET also connected the earthquakes with crustal fractures, but his views on the origins of the earthquake and soufrière activity differ considerably from those of Dr POWELL and the writer (PERRET 1939, Fig. 3 and pp. 36, 48, 57, 72).

The foci of the 1936 earthquakes in Montserrat were distributed beneath parts of three of the seven volcanic centres of the island, including the youngest (POWELL 1938, Fig. 11). This distribution might perhaps have been used as evidence that no local eruption was imminent; for had such been the case epicentres would more probably have been confined to the area occupied by the Soufrière Hills, the youngest volcano and the only one with active soufrières on its flanks.

One of the earthquakes (10 November 1935) was recorded over a large part of the world (POWELL 1938, pp. 26, 31). After this major shock, the epicentre of which was north of Montserrat, seismo-volcanic disturbances in the island began to decline; in 1936 the shocks were fewer and much less violent than in 1934 and 1935, and the decline in activity continued. This suggests that a major shock in a series of local volcanic earthquakes may be a sign that the peak of activity has passed (POWELL 1938, pp. 26-9, 32; MACGREGOR 1938, p. 15).

### **Evidence of soufrière activity**

#### **Martinique and St. Vincent.**

Premonitory symptoms of the eruption of Mt. Pelée in Martinique in 1902/7 were apparent, it is said, as early as 1889, when small hydrosulphuric fumaroles appeared in the crater. In 1900, in 1901, and in February 1902 increases in soufrière

activity were observed; explosive phenomena began on 24 April 1902 (LACROIX 1904, p. 34).

In the case of the eruptions that began at Mt. Pelée in 1929, the only warning appears to have been a slight increase in the number and activity of the fumaroles on the dome of 1902/7. These *soufrières* showed signs of increased gas-emission in March and May 1929, and began to emit sulphur dioxide instead of (or in addition to) hydrogen sulphide on 23 August 1929; this was about a month before the commencement of explosive phenomena, which at first were mild (ROMER 1936, pp. 89, 92, 115).

In relation to St. Vincent before the eruptions of 1902/3, there are apparently no records concerning *soufrière* activity. According to Dr. JAGGAR, the water in the crater lake was noticed to be warm in January 1902 (ANDERSON and FLETT 1903, p. 532).

### **Montserrat.**

During the seismo-volcanic « crisis » in this island in 1933/37, it was found that temporary intensifications of *soufrière* activity coincided with « seismic storms » of the earthquake series (MACGREGOR 1938, pp. 39, 83; PERRET 1939, pp. 19, 37, 62, 72). According to Mr. PERRET, increased gas-emission at the *soufrières* was the only normal presage of a considerable shock; but a severe shock occurred without such a premonitory symptom (PERRET 1939, pp. 58, 62); moreover, increased gas-emission did not always herald a shock or shocks (PERRET 1939, Fig. 20).

The gas-emission, although abnormal in pressure and quantity, remained normal in type (mainly hydrogen sulphide (1) and steam), and *soufrière* temperatures remained low from a volcanological point of view—close to the boiling point (of water) corresponding to the barometric pressure. These facts, and the continued absence of acid gases such as sulphur dioxide, hydrogen

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(1) Mr. PERRET believes that eye-stinging gaseous polysulphides of hydrogen were also emitted at the *soufrières*, and that they were decomposed into hydrogen sulphide and sulphur at a distance from their points of origin. He also recorded carbon dioxide in comparatively small quantities (PERRET 1939, pp. 42-5, 72).

fluoride and hydrochloric acid, were regarded as indicating that a local eruption was unlikely (POWELL 1937, pp. 490-1; MAC-GREGOR 1938, pp. 39-46, 84; PERRET 1939, pp. 36, 41, 43, 46, 72).

### **Significance of peléean domes in volcano craters**

According to Mr. PERRET, dome-building (accompanied by the production of *nuées ardentes*) marks a late, decadent, stage in the evolution of a volcano such as Mt. Pelée, characterised by acidic lava, and this fact is valuable in volcanological diagnosis and prediction (PERRET 1935, p. 106, 112). The duration of such a late phase, although short from a geological point of view, may be protracted when regarded from the human standpoint. Thus, at Mt. Pelée, the explosive dome-building of the 1902/7 eruptions was renewed during 1929/32, *though on a less catastrophic scale*; and it may well recur. The Soufrière of Guadeloupe, according to HOVEY and LACROIX, has a crater containing a pre-historic peléean dome (LACROIX 1904, p. 56; 1908, p. 60). Several eruptions of minor character have occurred since 1696. But, because there have been no very violent eruptions during this long period, it may be argued that the volcano supports PERRET's generalisation (MAC-GREGOR 1938, p. 85).

HOWEL WILLIAMS, in commenting on a similar generalisation made earlier by FRIEDLAENDER and by POWERS, states that it is subject to « many exceptions »; he does not analyse these exceptions, and names only one of the volcanoes concerned - Saishu in Japan (WILLIAMS 1932, p. 146). From his account of Saishu, it seems likely that some, at least, of WILLIAMS's « many exceptions » concern recrudescence of activity *not at the same volcano* but at other eruptive centres in the vicinity (WILLIAMS 1932, p. 99). It is also possible that other important factors, such as the time and the violence of the recrudescence, are not comparable in all the exceptions that he has in mind.

Castles Peak in Montserrat was found to be a peléean dome in the breached crater of an eroded volcano which, apart from



soufrière activity on its flanks, has been inactive since 1493, and probably for a much longer period (MACGREGOR 1938, pp. 28-30, 83). This volcano (Soufrière Hills) is the youngest in the island, and its eruptions were proved to have been predominantly of *nuée ardente* type (MACGREGOR 1938, pp. 30-4); petrologically its rocks closely resemble those involved in the 1902/7 and 1929/32 eruptions of Mt. Pelée (MACGREGOR 1938, p. 72). In view of Mr. PERRET's generalisation, and of the Guadeloupe evidence, the writer inferred that, in Montserrat, a renewal of violent explosive activity was improbable (MACGREGOR 1938, p. 85).

Because a dome has not yet formed in the crater of the Soufrière of St. Vincent, Mr. PERRET has stressed the probability that this volcano may still retain a great store of potential energy. He points out: 1) that conditions at the Soufrière of St. Vincent are not fully comparable with those at Mt. Pelée before the dome-building of 1902, because the lava of the Soufrière is of a rather more basic character; 2) that, nevertheless, activity in St. Vincent in 1902 was of an explosive type having much in common with that of Mt. Pelée (1). Mr. PERRET therefore considered it probable that a dome will eventually form in the crater of the Soufrière of St. Vincent, where eruptions have occurred at intervals of about ninety years since 1718. (PERRET 1935, pp. 112, 115; 1939, p. 34, Fig. 1, and p. 2). Few volcanologists are likely to disagree with this prediction.

### **Records indicating short-term « Periodicity » of seismo-volcanic phenomena at local centres of disturbance**

Records of earthquake and related soufrière activity in Montserrat from 1933 to 1937 (e. g. PERRET 1939, Fig. 20), when considered in relation to the succession of events during previous volcanic episodes in St. Vincent and Martinique, and elsewhere in the Caribbean region, indicate that, in the Caribbean volcanic arc, seismo-volcanic disturbances tend to be part-

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(1) For a summary of current opinions regarding the mechanism of various types of *nuée ardente* eruptions, at Mt. Pelée, at the Soufrière of St. Vincent, and elsewhere, see MACGREGOR 1946, p. 305.

icularly violent at certain periods of the year - early in May and between October and December (1). The evidence is as follows.

The most violent outbursts of the 1812/14 eruption of the Soufrière of St. Vincent were at the beginning of May (LACROIX 1904, p. 47). The major paroxysms in St. Vincent and Martinique in 1902 occurred on the 7 and 8 May respectively (ANDERSON and FLETT 1903, p. 392; LACROIX 1904, pp. 49, 37). On 10 May 1902, Izalco volcano in Salvador renewed its customary activity after a fifteen months pause (SAPPER 1905, p. 82). In Montserrat, in 1934, 1935 and 1936, markedly increased earthquake and soufrière activity were experienced early in May (MACGREGOR 1938, p. 84; PERRET 1939, Fig. 20). As early as March 1935 MR PERRET successfully predicted that, if the bi-yearly crises of 1934 were to be repeated in 1935, it would be in May that stronger conditions would prevail (PERRET 1939, p. 27 and Fig. 20).

In commenting on Montserrat crises in May, the writer has pointed out that May was a critical period at Lassen Peak volcano in California, where the main eruptions of 1914/17 occurred in that month in 1914, 1915 and 1917 (MACGREGOR 1938, footnote p. 84).

The most violent activity of the 1851/2 eruption of Mt. Pelée occurred in late October to early November (LACROIX 1904, p. 32). During the Montserrat earthquake series of 1897 onwards, particularly strong shocks occurred in mid-October 1900 (PERRET 1939, p. 64). An outburst of considerable violence occurred at Izalco volcano in Salvador on 28 September 1902, following on the renewal of activity of 10 May of that year (SAPPER 1927, p. 127). At the Soufrière of St. Vincent, after the May eruption of 1902, the most violent recrudescence of activity was in the middle of October of the same year (ANDERSON 1908, p. 290). On 24 October 1902 a violent eruption occurred at the volcano of Santa Maria in Guatemala, which was believed to be extinct (SAPPER 1905, p. 82). At Mt. Pelée

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(1) For a discussion of 1) the legitimacy of regarding this recurrence of events as «periodic», and of 2) a postulated lunisolar causation, see: LENOX-CONYNGHAM 1937, p. 908; PERRET 1939, pp. 62, 75 and Fig. 20.

in 1929-32 the most violent phase of the eruption began on 20 November 1929 (ROMER 1936, pp. 94-6, 115). In Montserrat, during the period 1933-36, peaks of earthquake and soufrière activity occurred in December of 1933 and 1934 and in November of 1935 (MACGREGOR 1938, p. 84; PERRET 1939, Fig. 20).

As regards the Caribbean volcanic arc (and other parts of the Caribbean region) it must not be inferred that minor disturbances or violent eruptions may not occur in the future, as they have in the past, at other periods of the year. In the volcanic arc serious eruptions have, for instance, taken place in March, and between 30 August and 31 September. Nevertheless it would clearly be most imprudent to ignore the fact that the beginning of May and the last quarter of the year (particularly October-November) have been periods especially liable to unrest (MACGREGOR 1938, p. 84; PERRET 1939, pp. 27, 62-4).

#### **Records indicating oscillation of seismo-volcanic phenomena within the volcanic arc**

The writer's « space-time » method of graphical representation of past records of seismo-volcanic episodes in the Lesser Antilles (Fig. 2) indicates that there has been a tendency for the centre of disturbance to oscillate back and forth along that part of the volcanic arc between St. Kitts and St. Vincent (cf. MACGREGOR 1938, Fig. 2 and pp. 6-7, 84). On the evidence provided by his original graphical record (1938 Fig. 2) the writer suggested (early in 1937) that the next manifestation of activity would probably be in Guadeloupe or St. Vincent or in one of the intervening islands, and that it would occur at an early date (MACGREGOR 1938, pp. 83, 85). A series of earthquake shocks occurred shortly afterwards in Dominica, an island between Guadeloupe and St. Vincent (PERRET 1938).

#### **Records of long-term intervals between seismo-volcanic phenomena in the volcanic arc**

Records of seismo-volcanic events in the Caribbean volcanic arc (1) mentioned by TEMPEST ANDERSON and FLETT, LACROIX,

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(1) Dr. T. A. JAGGAR, as an appendix to a report submitted to the Royal Society after his visit to Montserrat in 1936, gave a résumé of

SAPPER, VON WOLFF (1929), PERRET and ROMER were tabulated in 1937 (MACGREGOR 1938, p. 6 and Fig. 2). They led the writer to point out, in 1937, that 1) since 1692 the longest period that has elapsed without the occurrence of a seismo-volcanic disturbance somewhere in the arc is 47 years; 2) since 1766 the longest period of tranquillity (1) has been 28 years; 3) on seven occasions the interval between eruptions or minor volcanic activity has been seven years or less; 4) there is thus every reason to believe that eruptions or earthquakes will be renewed in the volcanic arc at no distant date, and probably more than once in the lifetime of the present generation (MACGREGOR 1938, pp. 83-4).

Mr PERRET has inferred from his own compilation of seismo-volcanic records in the volcanic arc (sources unspecified: PERRET 1929, Fig. 1) that there is a periodicity approximating to 30 years (or to some multiple of this such as 60 or 90) connected with a « magmatic expansion » which occurs about three times a century and gives rise to localised concentrated effects under and through the various previously formed island centres (PERRET 1939, p. 2).

The exact meaning of these statements is not clear to the writer. This is partly because Mr PERRET quotes in their support time-intervals between selected events in various islands, while ignoring eruptions etc. which occurred in other islands during the same periods (2). Time-intervals so computed do not seem to have a bearing on *periodicity*, either in the arc as a whole or in individual islands. Nevertheless a tabular statement compiled by the writer (Table I: based on Fig. 2: see below) indicates that Mr PERRET has done a useful service in drawing attention to the tendency towards gaps approximating to 30.

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the seismic history of the West Indies in the preceding 250 years. This report is filed for reference at the Royal Society rooms.

(1) « Tranquil » years were reckoned from the end of the *last* year of one episode to the beginning of the *first* year of the succeeding episode.

(2) In computing two of these intervals Mr. PERRET has made a slip in assigning an eruption at Qualibou in St. Lucia to the year 1756. Qualibou erupted in 1766, as recorded by himself in his table of seismo-volcanic events (PERRET 1939, Fig. 1). This eruption has also been recorded erroneously as having taken place in 1776 (ANDERSON and FLETT, 1903, p. 535).

60, or 90 years between the initiations of successive notable seismo-volcanic incidents *in individual islands*. There is an even greater tendency for gaps to approximate to a multiple of 15 years; but with so small a basic period the approximation is not close enough to be of much value for purposes of prediction.

Mr PERRET includes in his table of seismo-volcanic events a number of episodes of which the writer was unaware when he prepared the diagram for his 1938 paper (MACGREGOR 1938, Fig. 2); Mr PERRET omits, however, without comment, two records of submarine eruptions (between Guadeloupe and Marie Galante in 1843, and between St. Vincent and Barbados in 1831) and some minor events, all of which were recorded by the writer on the authority of previous publications. A new graphical space-time diagram of seismo-volcanic events in the Caribbean volcanic arc, up to 1938, has therefore been prepared, combining Mr PERRET's new data, from unspecified sources, with all events previously quoted by the writer (Fig. 2). In this graphical statement intervals between events are calculated from the *first* year of one episode (even though it be prolonged: e. g. Mt. Pelée 1902/7) to the *first* year of the next (e. g. Mt. Pelée 1929/32).

It will be seen from the last column of Fig. 2 that, if the volcanic arc is considered as a whole, there is no tendency for intervals approximating to 30, 60 or 90 years to occur between the initiation of successive eruptions; nor have eruptions occurred only three times a century since 1692, even if we ignore submarine eruptions, and the Montserrat disturbances of 1897/9 and 1933/7 which Mr. PERRET (1939, p. 2) appears to class as eruptive periods corresponding to magmatic expansions: see also under 1c), p. 83.

Consideration of all the evidence available leads to the following general indications of the seismo-volcanic prospects *in individual islands*, after a relatively serious episode, which need not necessarily include a volcanic eruption.

1) Recurrence of serious trouble within 12 to 15 years of a given incident will be most exceptional.

TABLE I

ISLAND	INTERVAL BETWEEN SEISMO-VOLCANIC INCIDENTS	INTERVAL AS APPROXIMATE MULTIPLE OF 30	INTERVAL AS APPROXIMATE MULTIPLE OF 15	NUMBER OF RECORDED INTERVALS THAT DO NOT APPROXIMATE TO MULTIPLES OF 30 OR 15
MONTSERAT	1897 - 1933 (36 years)	--	--	1 (36 years)
GUADELOUPE	1837 - 1896 (61 years)	30 × 2	15 × 4	2 (103 and 38 years)
	1673 - 1765 (92 years)	30 × 3	15 × 6	
DOMINICA	1765 - 1809 (44 years)	--	15 × 3	None, but the approximation to 15 × 5 in the case of the 1809-1880 interval is poor.
	1809 - 1880 (71 years)	--	15 × 5	
	1880 - 1938 (58 years)	30 × 2	15 × 4	
	1727 - 1771 (44 years)	--	15 × 3	
MARTINIQUE	1771 - 1816 (45 years)	--	15 × 3	4 (70, 23, 12 and 24 years)
	1851 - 1878 (27 years)	30 × 1	15 × 2	
	1902 - 1929 (27 years)	30 × 1	15 × 2	
St. Lucia	1766 - 1906 (140 years)	--	--	1 (140 years)
St. Vincent	1718 - 1812 (94 years)	30 × 3	15 × 6	None
	1812 - 1902 (90 years)	30 × 3	15 × 6	

2) There is a good prospect of between 23 and 30 years of freedom from serious disturbance.

3) If there has been no recurrence of trouble after 30 years, the approximate time of the initiation of the next danger period is likely to be after an *additional* 6 to 8, 15, 30, 40, or 60 to 65 years, or after an even longer period.

It is hardly necessary to say that too much reliance should not be placed on such generalisations. In the writer's opinion, however, they will definitely serve a useful purpose in giving a general idea of the future probabilities of seismo-volcanic troubles throughout the Lesser Antilles: see also under 1d), p. 83.

In assessing the prospects of the nature and violence of future disturbances at any one centre, not only must the past records of the island concerned be considered, but also the age and structure of its volcanoes and the oscillation-phase of the migration of disturbances along the volcanic arc.

### Summary of evidence and inferences

This paper summarises facts relating to seismo-volcanic disturbances in the Caribbean region, and brings together evidence used by Mr F. A. PERRET, Dr C. F. POWELL and the writer for prediction in relation to such disturbances in the Caribbean volcanic arc of the Lesser Antilles. Facts and inferences may be summarised as follows.

1) Historical records of seismo-volcanic events in the Caribbean region indicate that. —

a) The beginning of May and the last quarter of the year (particularly October-November) are periods at which especially violent seismo-volcanic events are liable to occur (PERRET, POWELL, MACGREGOR).

b) There is a tendency for the main centre of disturbance to oscillate back and forth along that part of the Caribbean volcanic arc between St. Kitts and St. Vincent. The phase of the oscillation gives some indication of the most likely locus of the next disturbance (MACGREGOR).

c) Since 1657 volcanic eruptions have occurred at different places in the Caribbean volcanic arc at intervals ranging from 4 to 48 years. On six occasions the interval between the initiation of successive sub-aerial eruptions has been between 22 and 31 years. If records of strong earthquakes, of earthquake series, and of submarine eruptions are taken into account, the interval between the initiation of seismo-volcanic disturbances has on nine occasions been 4 years or less, on five occasions between 15 and 17 years, on four occasions between 23 and 28 years, and on one occasion 38 years (MACGREGOR).

d) On any one island in the Caribbean volcanic arc there has often been an interval of at least 23 to 30 years between the initiation of one relatively serious seismo-volcanic disturbance and the beginning of the next. Intervals of *about* 8, 12, 37, 45, 60, 70, 92, 103 and 140 years have also been recorded in different islands (MACGREGOR).

e) Some idea of the probability of the nature and violence of future disturbances at any one centre may be gained by consideration of the past records of the island concerned, the age and structure of its volcanoes and the oscillation-phase of the migration of disturbances along the volcanic arc (MACGREGOR).

f) Serious eruptions are most unlikely to take place without premonitory symptoms at the volcano in question. These symptoms have included (i) unusually numerous and increasingly violent local earthquakes for over a year before the initiation of explosions: Soufrière of St. Vincent 1902; (ii) increased gas-emission at soufrières, commencing at least two years before the eruption: Mt. Pelée 1902; (iii) change of soufrière gases from hydrogen sulphide to sulphur dioxide, beginning about a month before the initiation of explosions: Mt. Pelée 1929 (ANDERSON and FLETT, LACROIX, ROMER). There is thus no need to stress the desirability of *continuous* observation of seismo-volcanic phenomena.

g) While eruptions are taking place in one island of the Caribbean volcanic arc, earthquakes, earthquake series, increased gas-emission at soufrières, or even a simultaneous eruptive period may be initiated in another island (Fig. 2).



h) There is a general interconnection *throughout the whole Caribbean region* between volcanic activity, severe earthquakes and adjustments of crustal stability (ANDERSON and FLETT).

2) Other evidence used for purposes of prediction is as follows.

a) The foci of shallow local earthquakes in Montserrat in 1936 were distributed below parts of three of the seven old volcanoes of the island. If a local eruption had been imminent the epicentres would more probably have been confined to the area covered by the youngest volcano, the only one with active *soufrières* on its flanks (MACGREGOR).

b) On Caribbean evidence of 1935/36 it is suggested that a major (world-wide) shock in a series of local volcanic earthquakes may be a sign that the peak of activity has passed (POWELL, MACGREGOR).

c) In Montserrat temporary intensifications of *soufrière* activity accompanied « seismic storms » of the earthquake series 1933/7. Abnormal gas-emission at *soufrières* usually preceded a shock of considerable violence; but a severe shock occurred without such a premonitory symptom; and increased gas-emission did not always herald shocks (PERRET).

d) In Montserrat (1933/7) gas-emission at *soufrières* remained normal in type (mainly hydrogen sulphide and steam; no acid gases such as sulphur dioxide) and temperatures remained close to the boiling point (of water) corresponding to local barometric pressure. It was inferred that a local eruption was unlikely (PERRET, POWELL, MACGREGOR; but see footnote p. 74).

e) Previous dome-building (accompanied by the production of *nuées ardentes*) was taken as an indication that the 1929/32 eruption of Mt. Pelée represented a late, decadent, stage in the evolution of this volcano. In general, dome-building represents a late, decadent, phase of all volcanoes of peléean affinities, characterised by somewhat acidic lava (PERRET). The validity of this inference in the Lesser Antilles is discussed, and upheld.

The occurrence of a peléean dome in the crater of a long



inactive volcano of peléean type in Montserrat was taken as evidence of volcanic decadence and of the improbability of a future violent eruption in the island (MACGREGOR).

f) The Soufrière volcano in St. Vincent resembles Mt. Pelée in many ways, but has no peléean dome in its crater. It is therefore suggested that dome-building (and, by implication accompanying eruptions of *nuée ardente* type) will probably take place in due course at this volcano, where eruptions have occurred at intervals of about ninety years since 1718 (PERRET).

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