Eastern Caribbean Volcanic Hazards

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Abstract

Because of the short period of recorded history in the eastern Caribbean, essentially since the 17th century, the reconstruction of the eruptive history of the potentially active Lesser Antillean volcanoes, and thus their volcanic hazards, has to be based on indirect methods such as recognition of eruptive activity based on the deposits it produced and strtigraphic correlation. These studies have shown that volcanic activity can be grouped into Pelean-, St.Vincent-, Plinian-, Asama-style, and phreatic/phreatomagmatic, explosive eruptions, or non-explosive activity-which has produced domes, and lava flows, and generated volcano-seismic crises. Pyroclastic flows, surges and falls produced by the explosive erptions have dominated both the historic and pre-historic record. The pyroclastic flows are commonly tne high aspect-ratio variety, although more widespread and destructive low aspect-ratio flows have occurred on many volcanoes. The hazards produced by these different styles of activity can be grouped into three categories based on increasing magnitude and decreasing frequency of the event:

Category I - occur every few decades and affect only a volcano's immediate flanks;

Category II - occur every few hundreds to thousands of years and often affect most of an island;

Category III- occur every few tens to hundreds of thousands of years and could affect several islands.

The historic activity is dominated by Category I eruptions on three volcanoes, Soufriere (Guadeloupe), Soufriere (St.Vincent), and Mt. Pelée (Martinique). Volcanic hazard assessments, including maps that illustrate the areas affected by the different styles of volcanic activity, have been prepared for most of the potentially active volcanoes. However, the mitigation of future volcanic disasters requires that local governments utilize these assessments in conjunction with long-range planning and a vigorous programme of education. Without such programmes even small future eruptions could result in unnecessary loss of life and/or property.

Introduction

The present day active volcanic arc of the Lesser Antilles extends from the island of Grenada in the south to the island of Saba in the north (Figure 1). Since the permanent arrival of Europeans in the region, around the middle of the 17th century, there have been approximately 25 subaerial eruptions, of which three have caused loss of life, 10 submarine eruptions and 10 volcano-seismic crises (Table 1). Although most of the historic activity has occurred on three volcanoes: Soufriere (Guadeloupe), Mt Pelée (Martinique), and Soufriere (St. Vincent), all volcanic centres showing evidence for recent activity have to be regarded as potentially active.

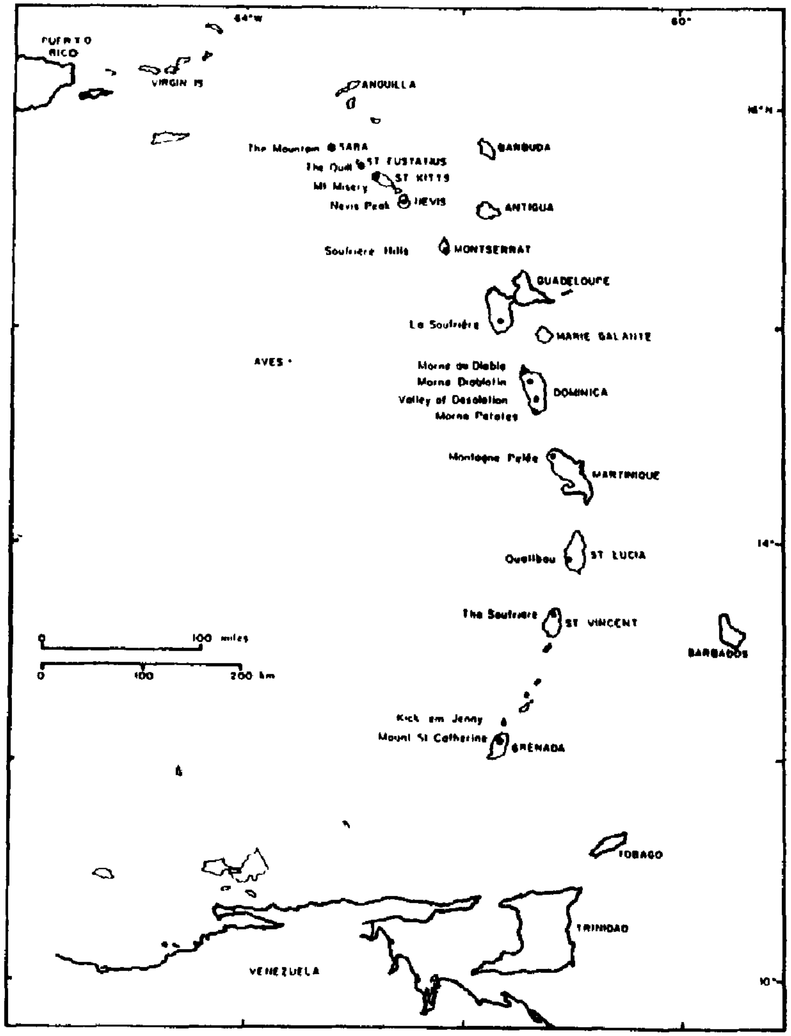

Figure 1. Map of the Eatern Caribbean showing the locations of the potentially active volcanoes of the Lesser Antilles.

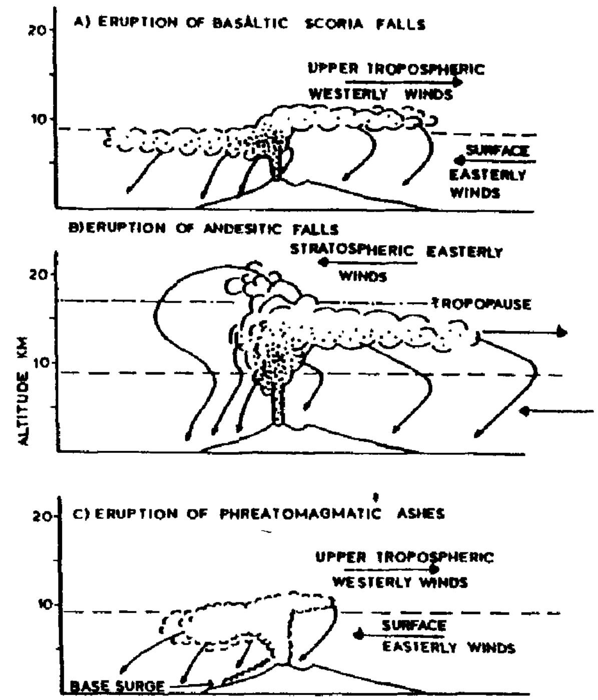

Figure 2. Schematic diagrams showing the effects of a layered atmospheric system and eruptive styles on the dispersal of airfall ejecta. The heights given correspond to data from today's wind systems where the lower Tropospheric easterlies are confined to altitudes below 5-9 km depending on the season. The tropopause is shown at about 17 km. The trajectories are schematic transport paths of airfall ejecta (after Roobol et al, 1985).

TABLE 1 HISTORIC ACTIVITY OF THE VOLCANOES OF THE LESSER ANTILLES

Date	Volcano	Type of Activity
1680	Soufriere, Guadeloupe	Phreatic
1692?	Mt. Liamuiga, St. Kitts	Phreatic
1696	Soufriere, Guadeloupe	Phreatic
1718	Soufriere, St. Vincent	St. Vincent-style
1766	Qualibou, St. Lucia	Phreatic/Phreatomagmatic
1784	Soufriere, St. Vincent	Dome
1792	Mt. Pelée, Martinique	Phreatic
1797	Soufriere, Guadeloupe	Phreatomagmatic
1798-99	Soufriere, Guadeloupe	Pelean-style
1809	Soufriere, Guadeloupe	Phreatomagmatic
1812*	Soufriere, St. Vincent	St. Vincent-style
1837	Soufriere, Guadeloupe	Phreatic
1843?	Mt. Liamuiga, St. Kitts	Phreatic
1843	Soufriere, Guadeloupe	Phreatic/Phreatomagmatic
1851	Mt. Pelée, Martinique	Phreatomagmatic
1880	Valley of Desolation	Phreatic
1880?	Soufriere, St. Vincent	Dome
1897-98	Soufriere Peak, Montserrat	Volcano-seismic
1902-03*	Soufriere, St. Vincent	St. Vincent-style
1902-05*	Mt. Pelée, Martinique	Pelean-style
1903	Soufriere, Guadeloupe	Phreatic
1929-32	Mt. Pelée, Martinique	Pelean-style
1933-36	Soufriere Peak, Montserrat	Volcano-seismic
1939	Kick-'em-Jenny	Submarine
1943	Kick-'em-Jenny	Submarine
1950	Nevis Peak, Nevis	Volcano-seismic
1953	Kick-'em-Jenny	Submarine
1956	Soufriere, Guadeloupe	Phreatic
1961-62	Nevis Peak, Nevis	Volcano-seismic
1962	Soufriere, Guadeloupe	Volcano-seismic
1965	Kick-'em-Jenny	Submarine
1966	Kick-'em-Jenny	Submarine
1966-67	Soufriere Peak, Montserrat	Volcano-seismic
1971-72	Soufriere, St. Vincent	Dome
1972	Kick-'em-Jenny	Submarine
1974	Kick-'em-Jenny	Submarine
1976	Micotrin, Dominica	Volcano-seismic
1976-77	Soufriere, Guadeloupe	Phreatic
1977	Kick-'em-Jenny	Submarine
1979	Soufriere, St. Vincent	Phreatomagmatic/Dome
1986	Morne Patates, Dominica	Volcano-seismic
1988	Mt. Liamuiga, St. Kitts	Volcano-seismic
1988	Kick-'em-Jenny	Submarine
1990	Kick-'em-Jenny	Submarine
1990	St. Lucia	Volcano-seismic

Data sources Robson and Tomblin (1966), Simkin et al. (1981), McCelland et al. (1986,1988,1989,1990)

* Denotes an eruption in which loss of life occurred.

The assessment of volcanic hazards involves a number of different factors which are summarized in Table 2. Of these factors, the determination of the eruptive history of a volcano is the most important. For the eastern Caribbean, because of the relatively short historic period, the reconstruction of the eruptive histories has to be based mainly on indirect methods such as the measurement and correlation of stratigraphic sections, the identification of the different types of deposits, the generation of maps showing the extent of these deposits, and the radiometric dating of the deposits. The results of these studies have shown that the historic and pre-historic subaerial activity can be grouped into explosive eruptions that have produced pyroclastic flows, surges and airfalls, and non-explosive activity that has produced lava flows, domes, and volcano seismic activity (Table 3).

Volcanic Activity

Explosive eruptions can be classified based on the composition of the magma and on the characteristics of the eruptions with their deposits, into Pelean-, Plinian-, St.Vincent-, Asama- and phreatic/phreatomagmatic-types (Table 3).

Pelean-style activity

Pelean-style eruptions, as exemplified by the 1902-05 eruption of Mt. Pelée (LaCroix, 1904; Roobol and Smith, 1975; Fisher et al., 1980; Smith and Roobol, 1991), are characterized by the active growth of a dome thoughout the eruption which, based on historic examples, usually last from 2 to 4 years, although growth of the accompanying dome may last longer. Partial or complete destruction of this dome by gravity collapse or explosions produces the large angular blocks that give the pyroclastic flow deposits generated by these eruptions their characteristic appearance - block and ash flow deposits. Most block and ash flows move down valleys and their deposits are restricted to these valleys and can thus be regarded as being of high-aspect ratio (HAR), where thick deposits cover a small area. Finer grained low-aspect ratio (LAR) block and ash flows and dense andesite surges, produce thinner, less conspicuous deposits which cover a wider area and as such represent a greater hazard than the HAR flows. It was, for example, LAR block and ash flows that destroyed the town of St. Pierre in 1902 with the death of approximately 28,000 people. Pelean-style eruptions also generate ash-falls and dust-falls (Smith and Roobol, 1991) produced by the fallout of the finer particles from vertical explosions and from the clouds overriding the block and ash flows. Most Pelean-style eruptions tend to affect only a limited sector of a volcano's flanks (see Figures 15 & 57, Smith and Roobol, 1991).

Plinian-style activity

Plinian-style eruptions, which have not occurred during the period of European occupation of the West Indies, but which were witnessed by the pre-Columbian inhabitants (Roobol et al., 1976; Smith and Roobol, 1991), are generated by a series of sustained explosions from open craters producing high eruption columns. Fallout from these columns produce coarse to fine pumiceous fall deposits, whereas their collapse generate pumice and ash flows, ash hurricanes and pumiceous surges (Smith and Roobol, 1991). The pumice and ash flows based on the distribution of their deposits, which can reach up to 50 m in thickness, flowed down valleys often on all flanks of a volcano. In contrast, ash hurricanes (LAR flows), which are not generally restricted to valleys, can affect very extensive areas of a volcano's flanks and their deposits have been identified tens of kilometres from a volcano (Figures 45 & 56, Smith and Roobol, 1991). Fall deposits are relatively thick and coarse close to the crater and show a progressive decrease in thickness and grain size with distance.

St. Vincent-style activity

These eruptions are produced by discrete explosions from an open crater, and are exemplified by the 1902 eruption of Soufriere, St Vincent (Roobol and Smith, 1975). Fallout

TABLE 2 Factors involved in the assessment of volcanic hazards

PAST ACTIVITY OF THE VOLCANO	
- Historic eruptions	Examination of records - style and course of the eruptions - distribution of the products
- Prehistoric	Study of stratigraphic sections - sampling of volcanic units & charcoal - age determination by ^{14}C & thermoluminescence methods - chemical analysis of rocks
	Detailed geological mapping
	Geophysical surveys
REGIONAL METEOROLOGICAL DATA	
- Winds and rain patterns	Examination of long-term records
TOPOGRAPHIC AND STRUCTURAL CHARACTERISTICS OF THE VOLCANO	
- Relief and structural features	Examination of topographic maps & aerial photographs
- Degree of alteration	Recognition of present and relict fumerole fields Geochemistry of active fumeroles
- Surficial and underground water	Hydrogeologic studies Geochemistry of cold and hot springs
ACTIVITY OF OTHER VOLCANOES	Examination of well-documented historic eruptions from equivalent volcanoes

TABLE 3 VOLCANIC ACTIVITY FROM LESSER ANTILLEAN VOLCANOES

VOLCANIC ACTIVITY	ERUPTIVE STYLE	PRODUCTS
Explosive	Pelean	Block & ash flows (HAR/LAR); Surges; Airfalls
	Plinian	Pumice & ash flows (HAR); Ash hurricanes (LAR); Surges; Airfalls
	St. Vincent	Scoria & ash flows (HAR) Surges; Airfalls
	Asama	Semi-vesicular block & ash flows (HAR)
	Phreatic/phreatomagmatic	Block flows; Base surges; Airfalls
	Submarine	Tsunamis
Effusive	Lava	Lava flows Domes
Seismic	Volcano-seismic activity	Earthquakes

from the eruption cloud give rise to scoriaceous fall deposits, whereas the partial collapse of the column generates scoria and ash flows which move down valleys. As with Plinian eruptions, all flanks of a volcano can be affected by these flows and their associated surges (Figure 34, Smith and Roobol, 1991).

Asama-style activity

On many islands, semi-vesicular block and ash pyroclastic flow deposits occur which show characteristics between block and ash flow and pumice and ash flow deposits (Roobol and Smith, 1980; Smith and Roobol 1991). Such deposits are thought to have been produced by pyroclastic flows welling over the rim of an open crater without the generation of an eruptive column. No surge or airfall deposits associated with this style of activity have been recognized.

Phreatic/phreatomagmatic-style activity

Since European settlement in the Lesser Antilles the most frequent type of volcanic activity has been phreatic or phreatomagmatic explosions (Table 1). Such explosions are generated by the interaction of groundwater with magma or heated rocks and produce block flows, base surges, and falls. This activity has probably been the most common eruptive style thoughout the history of all Lesser Antillean volcanoes. The deposits from these eruptions are usually of limited lateral extent.

Submarine eruptions

The most active volcanic centre in the Lesser Antilles at the present time is the submarine volcano of Kick-'em-Jenny, which has erupted ten times since 1939 (Table 1). Future eruptions from this volcano could generate tsunamis which would affect all islands in the easten Caribbean. The height of the resulting tsunami wave on individual islands would depend on the topography of the sea floor of the eastern Caribbean, local topographic features, and the size of the eruption, and could reach up to tens of metres. Other sources for the generation of tsunamis are the entry of pyroclastic flows into the sea and the rapid sector collapse of the flanks of a volcano. Features which are thought to represent the head scarps of such collapses have been identified on the islands of St. Vincent, St. Lucia, and Dominica (Roobol et al., 1983).

Airfall activity

The distribution of fall deposits from all eruptive styles depends on the interaction of the eruptive column with the local atmospheric conditions, especially the strength and direction of the winds at different levels. For the eastern Caribbean the atmosphere can be divided into the lower Troposphere dominated by surface easterly winds (Trades), the upper Troposphere affected by westerly winds (anti-Trades) and the Stratosphere which is characterized by easterly winds (Easterlies) (Roobol et al., 1985). Although the boundaries between these different wind systems varies in height depending on the time of the year Roobol et al., 1985), for simplicity, they are drawn in Figure 2 at 9 and 17 km respectively. Based on such an atmospheric structure, low eruption columns (<9 km) are affected by the Trades, intermediate columns (between 9 and 17 km) are affected by the anti-Trades, whereas the highest eruption columns (>17 km) reach the Easterlies. Thus deposits from eruption clouds lower than 10 km tend to be thicker towards the west of the volcano, whereas deposits from higher eruption clouds are mainly deposited towards the east.

Non-explosive activity

Effusive central and flank eruptions have generated both lava flows and domes. The former are dominantly of basaltic or andesitic composition, whereas the latter vary in composition from basalt to rhyolite. All lava flows are of the HAR variety, but with the more basic generally showing longer runouts. Domes have been extruded both without any associated explosive activity, for example, the 1971 dome of Soufriere, St. Vincent, and intimately associated with such activity, for example the 1902-05 dome of Mt. Pelée, Martinique. For most of the potentially active centres from the Lesser Antilles effusive eruptions producing lava flows have generally occurred less frequently than explosive eruptions.

Volcano-seismic activity
In some cases magma may rise into the volcanic edifice without actually causing an eruption. This rise of magma usually generates an intense local earthquake swarm known as a volcano-seismic crisis. Ten such crises have affected the Lesser Antilles this century (Table 1).

Non-volcanic activity
In addition to volcanic eruptions, surficial processes acting on the unconsolidated products of recent eruptions can also have hazardous results. Such hazards include the flooding of rivers, and the generation of landslides and the production of lahars. Evidence from historic eruptions has shown that such activity can cause considerable property damage and loss of life, e.g. the 1902-05 eruption of Mt . Pelée.

Percursory activity
Based on the evidence from historic eruptions from the LesserAntilles, the most important precursors of an impending eruption appear to be an increase in fumerolic activity, the generation of shallow earthquakes, and in some cases the flooding of rivers (Roobol and Smith, 1975; Smith and Roobol, 1991). For those volcanoes that have had long repose periods between magmatic eruptions, it is possible that phreatic/phreatomagmatic explosions may occur decades or centuries before a major magmatic eruption e.g. the 1792 and 1851 eruptions of Mt. Pelée, Martinique, were probably the precursors to the 1902-05 magmatic eruption (Smith and Roobol, 1991).

Volcanic Hazards

Potential hazards from pyroclastic flows and surges, lava flows and lahars are loss of life, destruction of property, and agricultural losses. As a consequence of their high velocities, which can reach up to 200 km/h, pyroclastic flows, surges, and lahars offer a greater danger to the population than do lava flows. HAR pyroclastic flows and lahars usually are channelled down valleys, whereas LAR flows and surges are ofen not topographically controlled and can thus affect much wider areas of a volcano's flanks. For large eruptions, LAR flows can travel for relatively long distances and surmount relatively high topographic barriers (Smith and Roobol, 1991). The major danger from aifall eruptions is the destruction of buildings by the collapse of roofs due to the weight of the accumulated ash. Other hazards that are often associated with volcanic activity include the cutting of roads by lava flows, pyroclastic flows and lahars, the disruption of communication systems, the contamination of water supplies, and the effects of ash on the health of the local population. Volcano-seismic activity can cause structural damage to buildings in the immediate vicinity of the volcano, and volcanic generated tsunamis can also cause considerable damage and loss of life to coastal areas.

Hazard Assessment

The hazards produced by the different types of volcanic activity can be groupd into three categories based on increasing magnitude and decreasing frequency of the event:

Category I - occur every few decades and affect only a volcano's immediate flanks. All of the historic activity belongs to this category;

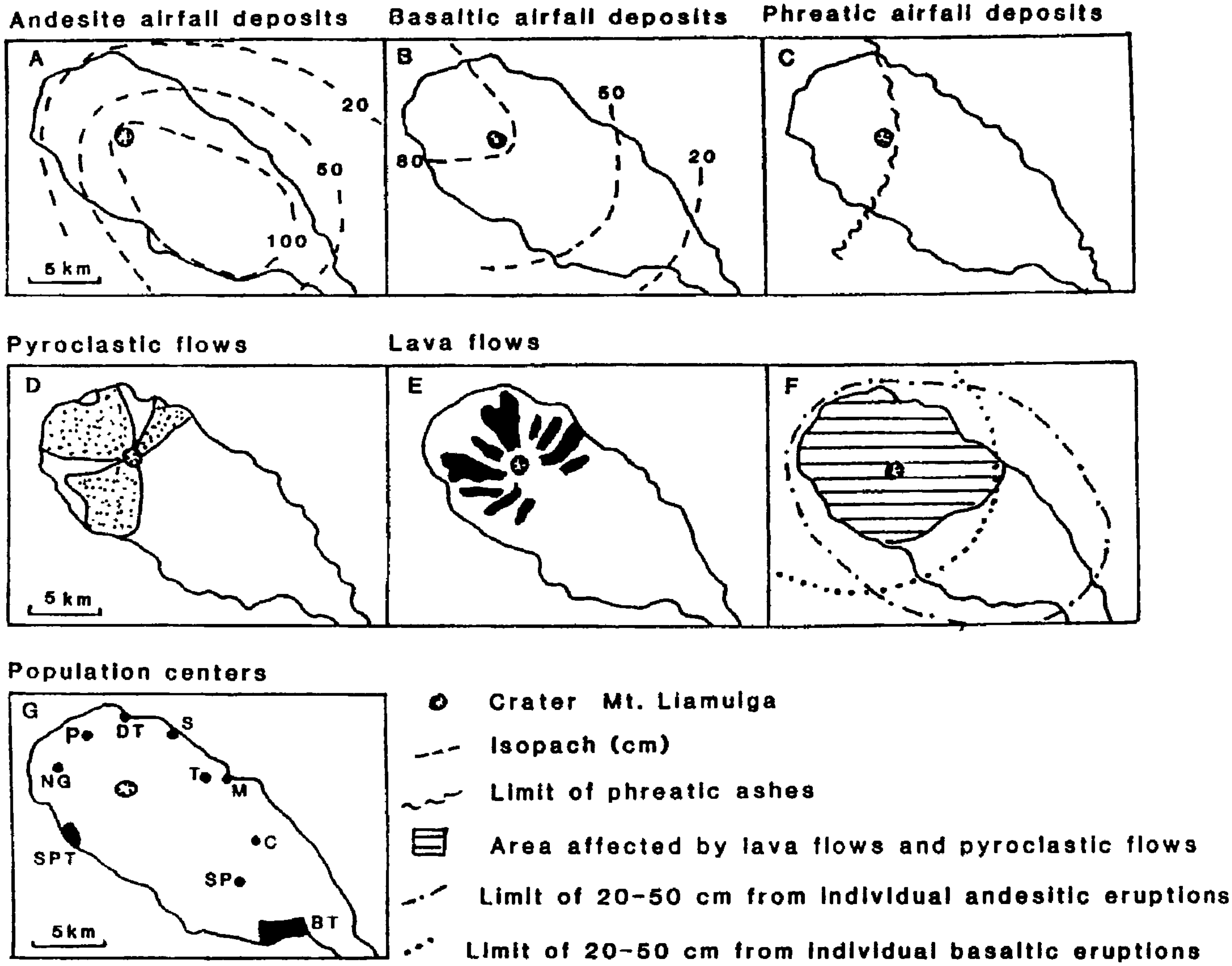

Figure 3. Distribution of volcanic products from Mt. Liamuiga, St. Kitts (maps A-E); map F shows the approximate maximum extents of the areas affected by pyroclastic flows and lavas flows, and the different types of airfall eruptions; population centers in map G are BT-Basse Terre, SPT-Sandy Point Town, NG-Newton Ground, P-St. Paul's, DT-Dieppe Bay Town, S-Sadlers, T-Tabernacle, M-Mansion, C-Cayon, SP-St. Peter's. Sources of data: Baker, 1969; Roobol et al, 1985, 1987.

Category II - occur every few hundreds to thousands of years and often affect a major part of an island;

Category III - occur every few tens to hundreds of thousands of years and could affect several islands.

The exception to this division are the submarine eruptions of Kick-'em-Jenny, which fall under Category I in terms of their frequency of occurrence but could fall under Category III in terms of the number of islands that could be affected.

In order to evaluate the volcanic hazard for a particular volcano, the data obtained from the various studies undertaken on a volcano can be combined to produce hazard assessment maps showing the areas affected by the different types of volcanic activity, and the relative risks imposed by these activities. Examples of such maps for the island of St. Kitts are given in Figure 3.

Recommendations -

The fundamental steps to reduce the effects of future volcanic eruptions include an understanding of what an individual volcano is capable of producing, and the means to predict the onset of future activity. For the Lesser Antilles this entails determining the volcanic histories and the preparation of hazard assessments for all potentially active volcanoes, as well as a programme of geological, geophysical and geochemical monitoring and surveillance. Seismic monitoring of most of the potentially active volcanoes has been undertaken for a number of decades. However, in order to provide the potential for significant advanced warning, new monitoring techniques such as continuous GPS measurements, the measurement of temperatures of fumeroles and hot springs, and the determination of the compositions of fumerolic gases should be implemented.

No matter how thorough or sophisticated these scientific studies are, they would be of only minimum value if the local governments do not utilize them to produce effective contingency plans and to undertake long range planning and a vigorous progamme of education to all levels of the population. Without such programmes even small eruptions in the future could result in unnecessary loss of life and property.

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References

Baker, P.E. (1969). The geological history of Mt. Misery volcano, St. Kitts, West Indies. Overseas Geol. Min. Resources, 10: 207-238.

Fisher, R.V., Smith, A.L. and Roobol, M.J. (1980). The destruction of St. Pierre, Martinique, by ash-cloud surges, May 8 and 20, 1902, Geology, 8: 472-476.

LaCroix, A. (1904). La Montagne Pelée et ses eruptions. Mason et Cie, Paris.

McClelland, L., Nielsen, E., Summers, M. and Wainger, L., (1986). Morne Patates Volcano. SEAN Bulletin, 11 (10): 6-7.

McCelland, L., Nielsen, E., Summers, M. and Wainger, L. (1988). Mt. Liamuiga Volcano. SEAN Bulletin, 13 (10): 2-3.

McCelland, L. and Dunker, K. (1989). Kick-'em-Jenny. SEAN Bulletin, 14 (5): 12.

McClelland, L., Romanak, K., Stein, T.C. and Kivimaki, K. (1990). Kick-em'-Jenny. Bulletin Global Volcanism Network, 15 (3): 2.

McClelland L., Romanak, K., Stein, T.C. and Kivimaki, K. (1990). Earthquake swarm, St.Luica, West Indies. Bulletin Global Volcanism Network, 15 (5): 9-10.

Robson, G.R. and Tomblin, J.F. (1966). Catalogue of the active volcanoes of the World, including Solfatara Fields, Part XX, West Indies. International Assciation of Volcanology, Rome.

Roobol, M.J. and Smith, A.L., (1975). A comparison of the recent eruptions of Mt. Pelée, Martinique and Soufriere, St. Vincent. Bull. Volcanol., 39: 1-27.

Roobol, M.J. and Smith, A.L. (1980). Pumice Eruptions of the Lesser Antilles. Bull. Volcanol., 43: 277-276.

Roobol, M.J., Petitjean Roget, H. and Smith, A.L., (1976). Mt. Pelée and the island population of Martinique. Proc. 6th Inter. Congress on Pre-Columbian cultures of the Lesser Antilles. Florida State Museum.

Roobol, M.J. Smith, A.L. and Wright, J.V. (1985). Dispersal and characteristics of pyroclastic fall deposits from Mt. Misery volcano, West Indies. Geol. Rundschau, 74: 321-335.

Roobol, M.J., Wright, J.V. and Smith, A.L. (1983). Calderas or gravity-slide structures in the Lesser Antilles arc?. J. Volcanol. Geotherm. Res., 19: 121-134.

Simkin, T., Siebert, L., McCelland, L., Bridge, D., Newhall, C. and Latter, J.H. (1981). Volcanoes of the World. Smithsonian Institution, Washington, D.C.

Smith, A.L., and Roobol, M.J. (1991). Mt. Pelée, Martinique. A study of an active island-arc volcano. Geol. Soc. Amer. Memoir 175.