Volcano Monitoring and Hazard Assessment in the Eastern Caribbean

by Richard E. A. Robertson*

Abstract

The paper starts with the geological setting, explaining the current state of volcanic activity in the Eastern Caribbean and the need for hazard assessment. Attention is given to volcano monitoring in the Lesser Antilles and the characteristics of hazardous volcanic events expected during future eruptions in the region. The author contends that public authorities and planners need to be provided with information on volcanic hazards so as to reduce their impact and enable the formulation of disaster preparedness and management plans.

Introduction

The Lesser Antillean island arc is a 740km long chain of volcanic islands that stretches from the Anegada Passage, in the north, to the South American continental margin (Figure 1). The area is one of high seismicity, tectonism and active volcanism dating back as far as the Eocene epoch.[1] The arc is convex towards the Atlantic and asymmetrical, with steeper slopes present on the western side.

Seismic evidence indicates that the Lesser Antilles arc is the surface manifestation of a subduction zone, with the North American plate under-thrusting the Caribbean plate. Active subduction with under-thrusting of the Caribbean plate, by the North and/or South American plate, occurs along the axis of the Lesser Antilles. Plate subduction with volcanism commenced along the arc after cessation of similar activity along the Aves Ridge to the west [2]

North of Martinique the arc bifurcates to form a double arc [3] The islands of the northeastern branch (Marie Galante, Grande Terre of Guadeloupe, La Desirade, Antigua, Barbuda, St. Bartholemew, St. Maarten, Dog and Sombrero) are relatively low-lying and partially or completely capped by mid-Miocene to Pleistocene limestones.[4] They have been named the Limestone Caribbees. The islands of the northern branch (Dominica, Les Saites, Basse Terre, Montserrat, Redonda, Nevis, St. Kitts, St Eustatius and Saba) are dominantly composed of late Miocene or younger volcanic rocks and their epiclastic derivatives.[4] South of Martinique the islands form a single arc which includes St Lucia, St. Vincent, the Grenadines and Grenada. The arc which stretches from Saba to Grenada and contains the active volcanoes is called the Volcanic Caribbees (Figure 1).

Volcanic Activity

Lesser Antillean volcanoes are noted for low frequency, high magnitude explosive eruptions related to the production of viscous, water saturated magma. The extreme violence of these eruptions poses a threat to lives and property, which is far greater than the threat posed by any other natural hazard.

There are approximately 25 Lesser Antillean volcanic centres which are thought to be potentially active. Major eruptions at two of these centres (Soufriere, St. Vincent, 1812, 1902; Mt Pelée, Martinique, 1902-05, 1929 to 32) during the last 300 years have been responsible for at least 31,000 deaths. In addition to this toll in human lives is the damage due to three major evacuations (Soufriere, St. Vincent, 1971, 1979; Soufriere, Guadeloupe, 1976), costing many millions of Dollars, in the last 20 years. At the present time there are over 250,000 people living on the flanks of active volcanoes in this region. The timely evacuation of population living within high risk areas is the most effective way of coping with most types of volcanic hazard Accomplishment of this goal is largely dependant on adequate monitoring as well as on the demarcation of volcanic hazard/risk zones before an eruption.

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The volcanoes of the Lesser Antilles have produced a wide variety of eruptive products These range from the rare rhyolites of the central and northern islands of St. Lucia, Guadeloupe, Dominica and St. Eustatius to the nepheline basalts of Grenada at the southern end.[5,6,7] The most abundant rock types are those which fall within the intermediate ranges of andesitic compositions.[6,8,9,10,11]

The Need for Hazard Assessment

Despite over a century of investigations into the geology of the Lesser Antillean region, there has as yet been no detailed study carried out of the volcanic hazard. Most of the early geological work in the region has concentrated on efforts aimed at identification and interpretation of the geophysical, petrological and geochemical characteristics of the arc.[2,5,6,8,9,10,12] These studies provide the basis upon which predictions of future activity can be based. Later research efforts made some provision for hazard assessment at various levels, for some of the volcanoes which are commonly believed to be the most active and hence pose the greatest immediate threat.[11,13,14,15,16] The first stage in the loss reduction process – identification of volcanoes with the potential for future eruptions – has therefore been completed. The next stage: detailed hazard assessment of each of these volcanoes and preparation of emergency management plans has still to be completed.

Empirical vs Deterministic Hazard Assessment

A wide variety of methods have been used in volcanic hazard assessment. For the most part these may be classified as belonging to one of two basic types; an empirical approach, based essentially on the eruptive history of the volcano; and a deterministic approach based on modelling of the volcanic eruption process

The empirical approach has been used by several workers at a variety of volcanoes.[13,17,18,19,20] The hazard in all cases was assessed by thoroughly investigating the volcanic history with particular reference to morphology and to the frequency, magnitude and intensity of past eruptions A reconstruction of past events then enabled a quantitative assessment of the most likely effects of future eruptions.

Geological field work and radiocarbon dating help to identify the volcanic centres most likely to be the sites of future eruptions and allow estimation of the likely magnitude and geographical extent of specific volcanic events from these centres. Patterns of events likely to occur once an eruptive sequence begins can also be determined.

The deterministic method combines empirical and theoretically based modelling of the volcanic eruption mechanism with knowledge of the volcano's history. It has often been used in recent times to determine hazards from volcanoes.[15,21,22] The method combines diagnostic information on the specific volcano with knowledge of the volcanic process in order to model future activity, as well as possible future changes in the volcano's behaviour pattern. However, it is limited in that the assumptions made in the modelling may be too simplistic to allow for the complex volcanic processes that come into play during an eruption.

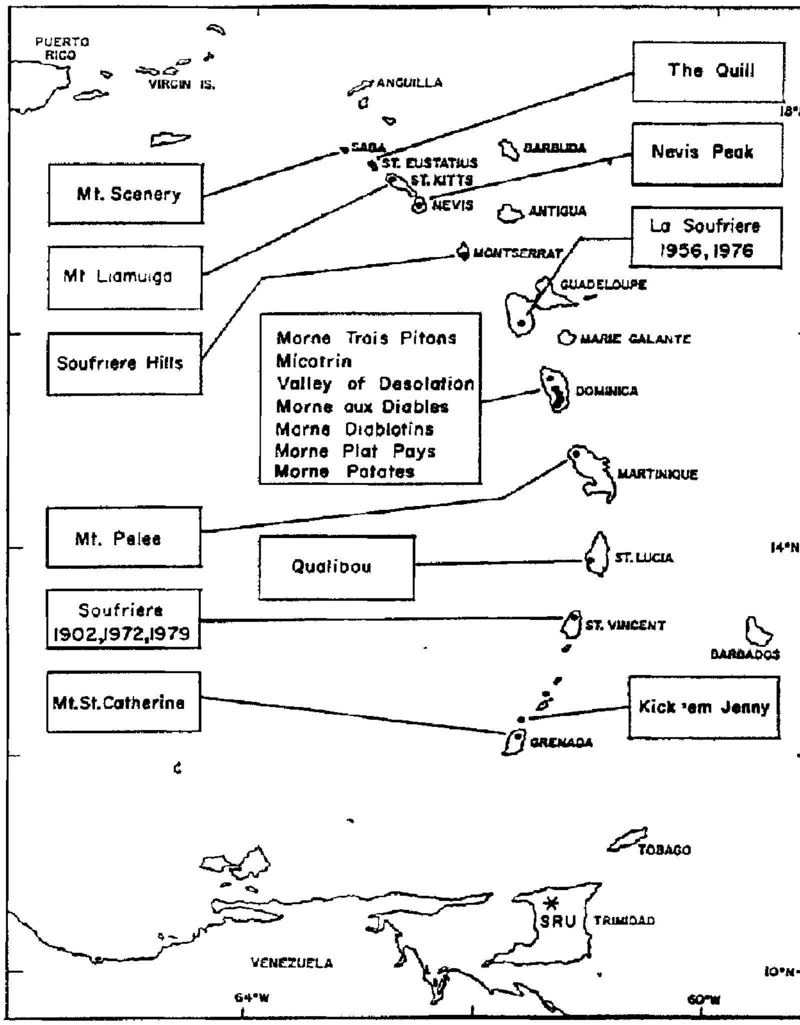

Figure 1: Map of the eastern Caribbean and Lesser Antilles island arcs. Isobaths in metres; proposed faults after Westercamp (1979). Mont = Montserrat; Ant = Antigua; Nev = Nevis (taken from Smith & Roobol, 1990)

Volcanic Activity and Volcanic Monitoring

A review of the literature indicates that varying degrees of hazard assessment have been done at several volcanic centres in the region. These include: the Soufriere of St. Vincent,[11,16] St. Eustatius, Montserrat and Saba,[22,23] Montserrate[14,15], Morne Plat Pays and Morne Patates, Dominica[24,25] and Kick 'em Jenny, Southern Grenadines[26]. However, these have all used different approaches and as such may need some additional work in order for hazard maps to be prepared.

The outline presented below summarises the main characteristics of the active and potentially active volcanoes in the Lesser Antilles (Figure 2). The information is obtained from a variety of sources.[27,28] The main methods used in monitoring these centres is also outlined. Apart from the islands of Guadeloupe and Martinique, all monitoring activities carried out throughout the eastern Caribbean is done by the Seismic Research Unit based at the University of the West Indies, St. Augustine, Trinidad.

Saba and St. Eustatius: *The Mountain* (17.63°N, 63.23°W, elevation 887m), on the island of Saba, has had no known historical eruptions. Recent surface manifestations of activity include hot springs and local earthquake swarms (June, 1992). Future eruptions at this centre would be expected to generate pyroclastic flows, mudflows and ashfalls. The monitoring system at present consists of a single seismograph.

The Quill (17.48°N, 62.95°W, elevation 601m), on the island of St. Eustatius (Statia), has also had no known historical eruptions, however, there is a distinct possibility of future eruptions within the next few decades. Pyroclastic flows, mudflow and ashfalls would be generated during such events.

St. Kitts: It is possible that there was increased thermal activity or phreatic eruptions about 1690-1692 and February 1843 at *Mt. Liamuiga* in St. Kitts. This centre is located at 17.37°N, 62.80°W and has an elevation 1,157m. Rare local earthquakes and hot springs are presently the only signs of volcanic activity. There is a possibility of further eruptions within the next few decades. These could generate pyroclastic flows, ashfalls and mudflows. Two seismographs, one approximately nine km from the summit, are used to monitor this volcano.

Nevis: *Nevis Peak* (17.15°N, 62.58°W, elevation 985m), has had no known historical eruptions. However hot springs have been present throughout the historical period. Occasional shallow earthquakes with severe swarms occurred in 1831 to 35, 1926, 1947 to 48, 1950 to 51, 1961 to 62. There is a possibility of further eruptions within the next few decades. These would most likely be phreatic with the possibility that they may develop into magmatic events. Pyroclastic flows, mudflows, ashfalls and projectiles may be produced. The monitoring system consists of one seismograph two km from the summit. In addition, baseline ground tilt measurements have been conducted.

Montserrat: *Soufriere Hills* (16.72°N, 62.18°W, elevation 914m), has had hot springs and fumaroles throughout historical times. Occasional shallow earthquakes have been experienced with severe swarms in 1897 to 1902, 1933 to 1938, 1966 to 1967, each accompanied by increased fumarolic activity. The volcano was observed to inflate during the period 1966 to 67. Minor earthquake swarms occurred in May 1985 with occasional swarms from September 1992 to present. There have been no known historical eruptions. Future eruptions would most probably be phreatic with the possibility of these developing into magmatic events involving the growth of domes. Pyroclastic flows, mudflows and ashfalls may be produced. The current monitoring system consist of two seismographs three km from the summit. In addition ground tilt measurements have been conducted.

Guadeloupe: *La Soufriere de la Guadeloupe* (16.05°N, 61.67°W, elevation 1,467m) on the island of Basse-Terre (Guadeloupe proprement-dite), French Antilles has hot springs, fumaroles and frequent shallow earthquakes. A major magmatic eruption occurred in 1580 ± 50 AD while phreatic eruptions occurred in 1690, 1797, 1809 to 12, 1836 to 1837, 1956, 1976 to 1977. There is a high probability of future eruptions in the next few decades. An extensive monitoring network using geophysical (seismographic stations), geo-magnetic (magnetometers), geo-electrical and geochemical (temperature and gas analysis) methods is operated by the Institut du Physique du Globe de Paris.

Dominica: Young volcanics form the north-south trending axial ridge of the island with deposits of andesitic breccias, dacitic andesite domes, pyroclastic flows and rare basic andesite lavas. Seven centres make up this north-south trend, Morne aux Diable (861m), Morne Diablotin (1,421m), Morne Trois Pitons (1,387m), Micotrin (1,380m), Grand Soufriere Hills (1,040m), Watt Mountain (1,224m), Morne Anglais (1,122m), Foundland (970m), Morne Plat Pays (960m) and Morne Patates (520m).

The two most significant symptoms of continuing volcanic activity in Dominica are active hot springs and frequent local earthquakes. Hot springs are found mainly in the southernmost third of the island where the chain of volcanoes is almost unbroken from Morne Trois Pitons to Morne Patates. Severe earthquake swarms have occurred at several of the centres in the past. At Morne aux Diable there may have been severe earthquake swarms in October 1841 and February to March 1893. At Morne Diablotin there may have been swarms during 1841 and 1893. At Morne Plat Pays severe swarms occurred in February to April 1849, and October 1937 to April 1938. At Morne Patates there were severe swarms in February to April 1849, October 1937 to April 1938 and June to December 1974. The only volcanic eruption recorded in Dominica in historic time was a phreatic explosion in the Valley of Desolation in 1880. Seven seismic stations, operated by the Seismic Research Unit are located near to the volcanic centres on the island.

Martinique: *Montagne Pelée* (14.82°N, 61.17°W, elevation 1,397m), on the island of Martinique, French Antilles, has had phreatic eruptions on January 22, 1792, August 5, 1851 to 1852. Explosive magmatic eruptions began April 24, 1902 and continued to 1905 with a dome-building eruption punctuated by explosions and pyroclastic flows. Similar eruptions occurred from September 16, 1929 to 1932. There is usually an increase in fumarolic activity a few weeks before onset and minor earthquakes a few days before onset. There is a high probability of further eruptions in the next few decades. Block and ash flows, mudflows and ashfalls would be generated. Flooding rivers and volcanic earthquakes may also pose hazards. An extensive network of seismic stations, magnetometers, geo-electrical indicators, and geo-chemical measurements is operated by the Institut du Physique du Globe de Paris.

St. Lucia: *Sulphur Springs* (13.83°N, 61.05°W, elevation 77m), in St. Lucia is an area of hot springs and solfataras. Occasional single shallow earthquakes have occurred but no severe swarms are known. A single steam explosion may have occurred in or about 1766. The possibility of future eruptions is less compelling than in the other islands since the volcano appear to be in a later stage of development. However, the possibility of future phreatic or magmato-phreatic activity cannot be entirely excluded. There is a single seismic station on the inner flank of the depression.

St. Vincent: Major magmatic eruptions with vertical explosions and pyroclast flows occurred at the *Soufriere volcano* (13.33°N, 61.19°W, elevation 1,178m), on March 26 to 29, 1718, April 27, 1812 to 1814, May 2, 1902 to 1903 and April 13 to 27, 1979. The eruption of 1979 was followed by the extrusion of a dome which continued to October 1979. A similar dome-building eruption took place from October 1971 to March 1972. Another eruption of this type may have occurred in about 1780. Thermal activity has been continuous throughout historic time but apparently confined to the summit crater and one location on the outer crater wall. A strong increase in thermal output to the crater lake occurred in 1780 and 1880 possibly accompanied by minor lava extrusion or phreatic eruption. Seismic activity is usually negligible except before and during eruptions but an earthquake swarm occurred in 1945 to 46.

There is a high probability of further eruptions during the next few decades. Pyroclastic flows and surges, mudflows, projectiles and ashfalls would be generated. A network of seismographs stations, ground deformation sites using dry tilt and occasional thermal and chemical measurements all comprise the monitoring system.

Grenada and the Grenadines: *Kick 'em Jenny* located at 12.30°N, 61.63°, elevation 160m (1983), in the southern Grenadines islands, Grenada, is a submarine volcano. This volcano was first recognised in 1939. Eruptions detected by underwater acoustic signals occurred on July 24, 1939, October 5 to 6 1943, October 30, 1953, October 25, 1965 to August 6, 1966, July 5, 1972, September 5 to 6, 1974 and November 4, 1977. The eruptions of 1939 and 1974 were also observed to break the sea surface. There is a high probability of further eruptions in the next few decades. The volcano is monitored by a seismograph located nine km from the summit.

Mount St. Catherine (12.15°N. 61.67°W, elevation 840m), on the island of Grenada has had no historic eruptions. Hot springs and solfataras are the current manifestations of volcanic activity. A single seismograph station located nine km from the summit is used to monitor the volcano.

A number of explosion craters are located in the southern Grenadines and Grenada, from Ile de Caille (12.18°N, 61.58°W) to St. George Harbour (12.07°N, 61.73°W). There have been no recorded historical eruptions, but all craters are very youthful and future activity may include formation of further examples. Hot springs are present. These centres are monitored by the seismograph located at St. Catherine.

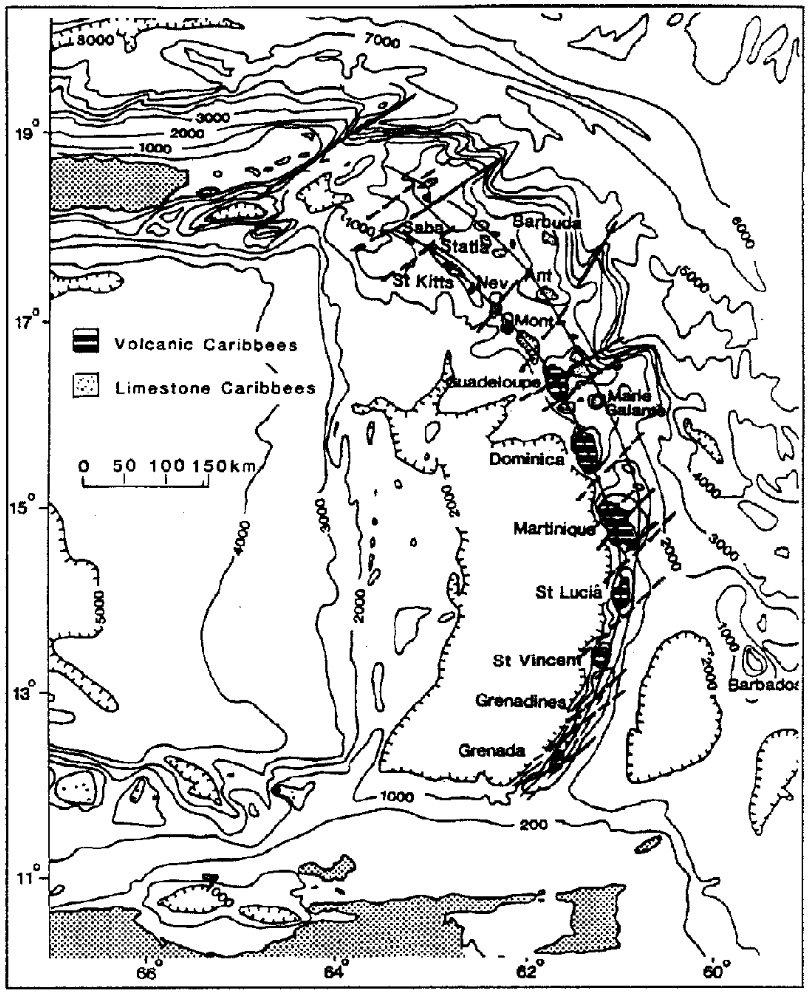

Figure 2: Map of the active and potentially active volcanic centres in the eastern Caribbean.

Characteristics of Future Eruptions at Lesser Antillean Volcanoes

Ballistic projectile and tephra falls: Projectiles are volcanic bombs, blocks and lapilli which leave the vent of a volcano with ballistic trajectories. Tephra falls include all airborne pyroclastic fragments that emanate from volcanic eruption columns. Both are the products of explosive volcanism and owe their origin to the fragmentation and forceful ejection of volatile-rich pyroclasts from a volcanic vent.

Hazards from airfall tephra occur principally from burial, impact of falling fragments and high temperature.[29] The extent of hazard impact is dependant upon distance from the volcanic centre and grain-size. The hazard resulting from ashfalls is proportional to the amount that accumulates and usually decreases exponentially, away from the volcanic centre.[30]

The hazard from projectiles stems from their potentially high impact energies and temperature, rather than their size or density alone. The energy of impact of a projectile is largely a function of diameter and density. Only relatively large projectiles with high kinetic energy will arrive with high temperature. Close to the volcano the impact of projectiles can injure and kill.

Pyroclastic flows and surges: Pyroclastic flows and hot, gravity-controlled, concentrated gas-solid dispersion of fragmented material (pyroclasts) which flow over the ground surface accumulating in topographic lows.[31] Flows can originate through a number of causative mechanisms (eg dome collapse, inclined blast or gravitational column collapse). Pyroclastic surges are turbulent, lateral movements of expanded low-concentration gas-solid dispersions [32] Surges are unsteady streams of tephra that are unable to maintain their kinetic energy for a very long time. They form thin, continuous beds, accumulate in depressions but also mantle the topography.

Asphyxiation, burial, incineration and impact damage may all be caused by flows.[29] Deaths result largely from the extreme mobility and high temperatures of the flow, while damage and destruction of buildings and crops result primarily from the very high kinetic energies as well as from the high temperature. The spatial impact varies widely depending on the topography of the volcano and magnitude, intensity and dispersive power of the eruption.

A hot pyroclastic surge destroys plant life, demolishes structures, causes severe abrasion impact damage (by rock fragments) and burial (by ash and coarser rock debris). People in its path are killed by asphyxiation, heat, the presence of noxious gases and lack of oxygen. Evacuation of the areas most likely to be affected, at the start of an eruption with surge generating potential, is therefore the only mitigation effort possible.

Lahars: Lahars (mudflows and debris flows), represent a continuum of flow processes that extend from stream flow through hyperconcentrated flow to mudflow and finally debris flow. As the proportion of rock debris increases and particularly as the silt and clay contents increase, turbulent flow is replaced by laminar flow.

Flows threaten people, agriculture and structures on valley floors and may displace and transport very large and heavy objects. They generally cause rivers to inflate resulting in subsequent floods to higher and broader areas of the valley floor. They cause river channels to shift and may form lakes damming tributary valleys.[29] They may reach further downstream than pyroclastic flows but delayed arrival, especially for secondary flows, often allows for adequate warning to be given.

Lava flows: Lava flows are mobile, viscous mixtures of silicates that are discharged effusively from a volcano. The distance reached and the morphology of a lava flow are determined by the total volume of lava extruded, its viscosity, temperature, yield strength and effusion rate, as well as the topography and slope of the land over which it flows.[33]

Flows can cause damage or total destruction by burning, crushing or burying everything in their paths. The very high temperatures of flows, 880° to 1,050°C for basaltic andesites, compared to the ignition temperature of cloth, paper and wood (approximately 250°C), indicates their potential for damage. The rate of effusion and velocity are the two main factors determining the level of hazard posed by lava flows. Flow velocity is a function of the same factors which influence the morphology and distance travelled. Flows seldom threaten human life directly due to their generally slow rate of movement.

Volcanic gases: Volcanic gases are volatile components of magma which are spread during an eruption and are spread as acid aerosols, components absorbed on tephra and as salt particles.[30] Acid rain forms as gases absorbed in volcanic plumes are washed out by rainfall. The distribution and amount of rainfall relative to the formation of the eruption plume is of great importance in terms of the volcanic hazard caused.[30] Volcanic gases can endanger life and health, can damage property and crops and may kill animals that eat these crops Gas injuries to people occur mainly because of the effects of acid compounds on eyes, skin and the respiratory system. The damage to vegetation differs according to the type of plant and the kind of gas.[29]

Earthquakes: Volcanoes produce a wide variety of seismic signals, the origin of which are in some cases still a matter of debate. Four types of earthquakes have been identified based on the location of the focal mechanism and the nature of the earthquake motion.[34] Earthquakes are important from a hazard perspective since they may cause significant damage and injury and may be a premonitory sign of an impending eruption.[30] Damage from volcanic earthquakes is usually confined to a fairly small area due to their relatively shallow hypocentres.[35,36]

Atmospheric phenomena: Atmospheric phenomena include atmospheric sound and shock waves and electrical discharges associated with volcanic eruptions. When they occur within the eruption plume, electrical discharges create a hazard only to the communication systems. However, discharges between the plume and the earth around a volcano are not uncommon and pose a threat to life and property. Shock waves can cause physical damage to buildings.[30]

Laterally directed blasts and structural collapse: Directed blasts occur in some explosive volcanic eruptions when the pyroclastic material is not ejected vertically upwards but is directed in a horizontal or near horizontal direction.[37] Supersonic speeds may be attained due to extreme pressures with the blast, compared to the surrounding atmosphere [38] Structural collapse involves failure of a major segment of the volcano. This may be triggered by tectonic earthquakes and often involves movement along some pre-existing line of weakness.[38] Directed blasts may have similar impact to pyroclastic flow but are less restricted by topography. Damage occurs due to the physical momentum of the blast and may result in destruction of both natural and man-made features within an irregular defined blast zone. Since structural collapse may involve large portions of the land surface around a volcano it can result in destruction of vital aspects of infrastructure within the volcanic region.

Phreatic explosions: These are steam explosions that occur within the country rock above a magmatic heat source. They are ground water steam eruptions that are characterised by a pure or almost pure steam discharge, without the involvement of fresh lava.[39] Phreatic explosions are limited in their impact to areas immediately around the volcanic centre. Explosions may throw rock debris of various sizes outward on ballistic trajectories and produce minor ash plumes that can be carried downwind.[29]

Landslides: Landslides occur in volcanic landscapes due to the additional potential energy created by the deposition of large volumes of tephra on steep slopes flanking volcanic centres. In tropical areas the abundance of heavy rainfall is an additional factor contributing to the easy mobilisation of tephra from unstable upper slopes to more stable positions in the lower outlying valleys. Damage to all aspects of the natural and man-made environment can result from slides. Damage to infrastructure (mainly buildings and roads) and to agriculture is most common, particularly in tropical volcanic areas with abundant rainfall.

Conclusion

The islands of the region, with their dense population often located well within areas affected by past hazardous events, are quite vulnerable to the hazardous effects of future volcanic eruptions. The presence of large population centres, active volcanoes, valuable property and infrastructure, and increasing pressures on governments to develop marginal, area makes a good case for loss reduction measures based upon detailed hazard assessment of volcanism in the region.

Public authorities and planners need to be provided with information on volcanic hazards so as to reduce their impact and enable formulation of disaster preparedness and management plans. In addition, geological maps are needed in areas where the geological and volcanic history is still incomplete. Volcanic hazard maps must be produced and volcanic hazard information provided in a manner which could be widely disseminated to a vulnerable population. Finally, an effective monitoring system capable of providing early warning and responding to the particular needs of individual islands, must always be in operation so as to minimise the impact of hazardous volcanic events.

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