Estimating Volcanic Risk in the Lesser Antilles

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Abstract

The potential catastrophic effects of future volcanic eruptions in the Lesser Antilles can be decreased by the utilisation of effective risk quantification measures and their subsequent incorporation into disaster risk reduction strategies. A volcanic risk study conducted by the Norwegian Geotechnical Institute (NGI) in collaboration with Bristol Environment Risk Research Centre (BRISK) on priority countries of the Global Facility for Disaster Risk Reduction (GFDRR) of the World Bank provides a possible way for this to be achieved. The study produced a simple estimate of the risk posed to any one country by combining numerically assigned hazard levels and their related uncertainty with population exposure indices for each volcano. Our study applied this methodology to countries in the Lesser Antilles to establish risk levels and assess its usefulness for preparing for the threat of upcoming eruptions.

A database of past eruptions and their characteristics was compiled using data from the Volcanic Hazard Atlas of the Lesser Antilles, Smithsonian Global Volcanism Program, Global Database of Large Magnitude Explosive Eruptions (LaMEVE) and other published literature for the region. This, together with population distribution data was used to calculate risk levels (ranging 1 to 3) for volcanoes of the English-speaking islands of the Eastern Caribbean. The results assigned more than 60% of the volcanoes to Risk Level 2 and 25% to Risk Level 3. However, applying the risk estimation method has its limitations. The hazard component of the method was found to be heavily dependent on the quality and quantity of eruptive data. The paucity of eruption records for this region made it easy for the hazard level to be underestimated. To account for this, future eruption scenarios were used in tandem with past eruption details to determine volcano hazard levels. Also, the exposure component only considered the physical threat to the surrounding population. It is recommended that other exposed human elements such as infrastructure and communication routes be incorporated into the estimation.

Table of Contents

List of Tables

List of Figures

1.0 Introduction

The Lesser Antilles volcanic island arc outlines the eastern margin of the Caribbean Sea and marks the zone of westward subduction of the North American Plate below the Caribbean Plate. The active or potentially active volcanic islands displayed in Figure 1 are known as the Volcanic Caribbees. North of Dominica the arc is split into two, where the eastern arc (Limestone Caribbees) no longer exhibits volcanism because of changes in subduction geometry (Lindsay et al., 2005). The volcanic islands spanning Grenada to Saba pose a threat because of the potential of eruptions to impact life and property. Finding a way to effectively quantify risk can help in mitigating the potential catastrophic effects.

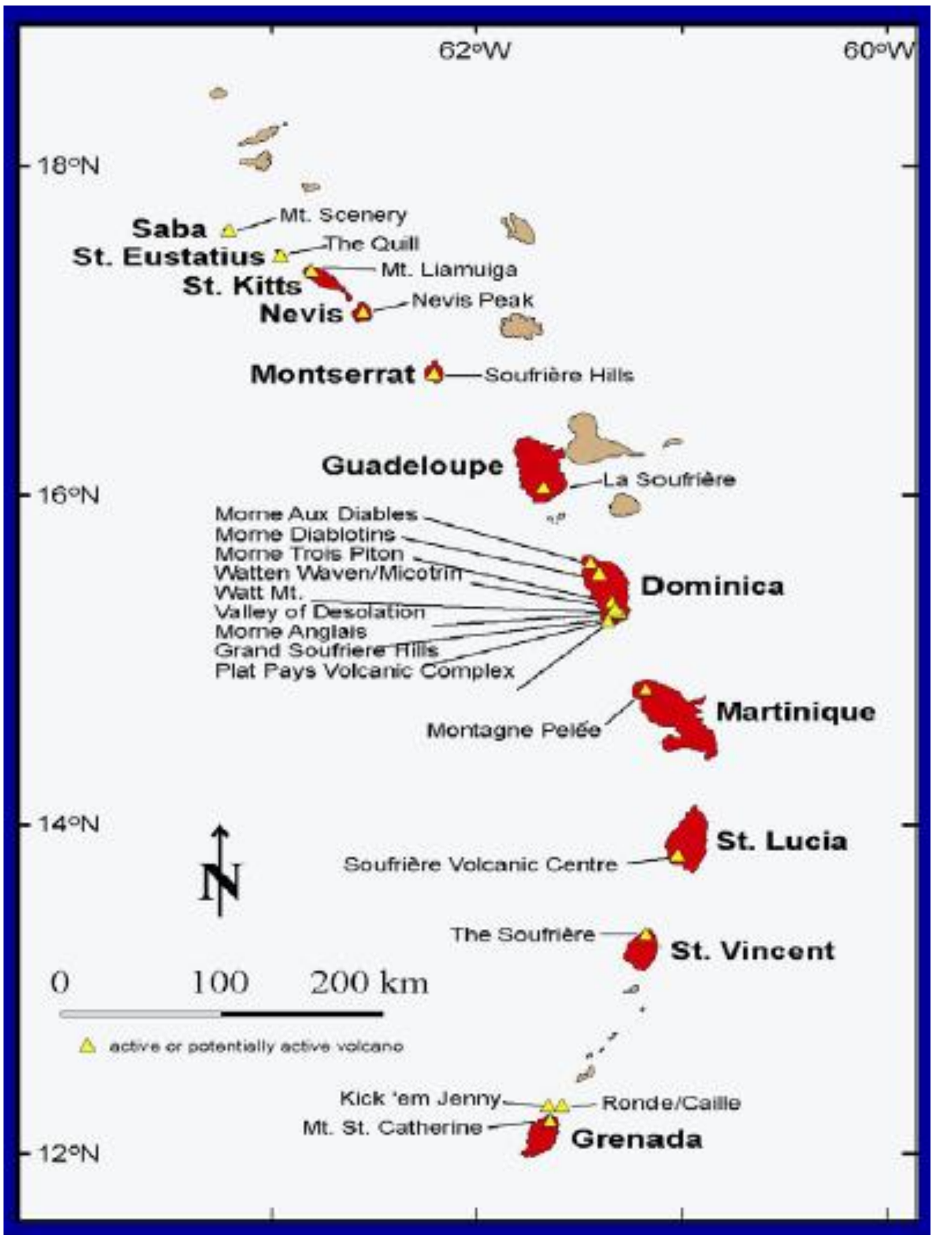

Figure 1: Live volcanoes of the Lesser Antilles (Lindsay et al., 2005)

In 2011, a study published by the Norwegian Geotechnical Institute (NGI) and the Bristol Environment Risk Research Centre for the Global Facility for Disaster Reduction and Recovery (GFDRR) Priority Countries provided a simple estimate of risk (NGI, 2011). A major aim of their study was to "establish science based evidence for better integration of volcanic risk in national disaster risk reduction programs" in these countries. Our study has applied their risk quantification methodology to the English-speaking islands of the Lesser Antilles to assess its transference capabilities and usefulness for future risk reduction strategies.

It should be noted that the NGI (2011) study involved a broader approach to assessing risk, details of which were not utilised in this report. In addition to deriving a method that produced a numerical value for risk, they considered hazard-specific exposure assessments which highlighted the elements exposed such as ports, roads, railways and airports to pyroclastic flows, lahars and ash. This was done using ArcGIS to estimate the proportion of these elements exposed, as well as producing maps showing potential hazard zones in relation to population and infrastructure. The average return periods for different magnitude eruptions were also addressed for eruptions related to a particular country. Finally, the national capacity of the relevant countries for coping with volcanic risk was investigated.

Most of the volcanoes in the Lesser Antilles are potentially active and have not had historically recorded eruptions[1]. Of the 16 volcanoes being studied, only the Kick 'em Jenny, The Soufriere, Soufriere Volcanic Centre, Valley of Desolation and Soufriere Hills have been historically active. This trend continues to be observed when all volcanoes of the Lesser Antilles (including those in the French and Dutch islands) are considered. As a result, many residents have not experienced the negative effects of this hazard and may have the mentality that eruptions will not occur in their lifetimes. This does not auger well for disaster preparedness initiatives since it gives people a low perception of risk. Quantifying the risk posed by individual live volcanoes allows for mitigation measures to be put in place not only for areas that are of major concern but also for communities surrounding volcanoes that are not currently erupting.

This report starts by summarising related research to provide context, followed by outlining the application of the NGI (2011) risk estimation methodology to the Lesser Antilles. The challenges encountered in using this method are explained, along with some recommendations for future applications of this methodology.

[1] Eruptions occurring after European settlement and the introduction of written records into the region. Although most European settlement began in the early 1600s, this period varies amongst the islands so there is some difficulty in defining the start of historically recorded eruptions for the entire Eastern Caribbean.

2.0 Review of Volcanic Risk Methodologies

The hazards associated with volcanic eruptions pose an ongoing physical threat to people and property in the vicinity of individual volcanoes or volcanic fields. To reduce the negative environmental effects of these hazards, assessing the level of danger faced to affected regions in terms of risk becomes important. Studies evaluating volcanic risk have been done with the sole purpose of guiding risk reduction activities by scientists and decision makers. Many of these studies have been volcano specific, while others have been geared towards comparing the relative risk of regional volcanoes. This review summarizes some of the previous works on quantifying volcanic risk, ending with the methodology applied in this study.

Volcanic risk has been defined as: R= Value x Vulnerability x Hazard (UNESCO, 1972), where value is the total amount of lives or property at risk in volcanic area, vulnerability is the percentage of value likely to be lost because of a given volcanic event and hazard is the probability that a given area may be affected by a volcanic phenomenon. Risk can be quantified using this equation as a template. A recent study has suggested that the resilience of communities must be included in this equation to effectively tackle risk reduction (MIAVITATeam, 2012). A method that quantifies volcanic risk must therefore consider all of these facets to accurately represent the different components of risk.

Volcanic risk studies require databases of eruption record details, population/property exposure statistics and information on land features. Therefore besides the methodology used, the reliability of these studies is dependent on the integrity of existing records. Geographic Information Systems (GIS) are the computer based software that can be used to manipulate such data and compile risk maps (Pareschi et al., 2000), which then aid decision makers in identifying the problem areas surrounding an individual volcano or volcanic field. Scandone et al (1993) produced a risk map of Vesuvius rating the potential for losses of human lives from an eruption of VEI 3-5 in areas surrounding the volcano. Their methodology utilised the UNESCO (1972) equation for risk but focused only on human life. The hazard parameter was given by the probability of occurrence of each magnitude of eruption (VEI 3, 4 or 5) over a ten year time span (Scandone et al., 1993). Alberico et al (2002) used the same formula proposed by UNESCO (1972), but instead applied it to the Campi Flegrei caldera and focused on the effect of one volcanic hazard: pyroclastic flows. Their study came up with a methodology for displaying risk levels in areas lacking a central vent (Alberico et al., 2002).

Apart from risk mapping, volcanic risk ranking is another quantitative contributor to risk reduction activities. Here, relative threat values are the end products instead of visually perceptive maps. A ranking system can be applied to volcanic regions with the similar aim of assessing risk. Magill and Blong (2005) proposed a method for ranking the risk posed by individual volcanic hazards with respect to a given eruptive event from the Auckland Region, New Zealand (Magill and Blong, 2005a). The risk was calculated using the following equation: Risk = likelihood x extent x impact x probability. Likelihood was the probability of the particular hazard in question conditional on the volcanic event occurring, extent was the area affected, effect was the outcome (to buildings or humans) within the area affected and probability was the relative probability of the event occurring. The similarity between the parameters included in this equation and the UNESCO (1972) definition can be observed. The risk was calculated separately for building damage and human loss and then combined to determine the total risk from each hazard and event. The results were then ranked in order of importance and normalised for easy comparison (Magill and Blong, 2005b).

Another application of the risk ranking system is to systematically rank the relative threat of one volcano to another in an attempt to prioritise mitigation efforts. Yokoyama et al. (1984) came up with a system to rank all volcanoes in the world, as part of an international initiative to better cope with volcanic crises. Their methodology identified high risk volcanoes based on the summed scores of 10 hazard factors and 7 risk factors (Yokoyama et al., 1984). Unfortunately, the criteria used and scores obtained were heavily dependent on the availability and quality of existing information, and so low risk values did not necessarily reflect low volcanic risk but rather insufficient data.

A ranking system was later developed by Ewert et al. (2005) to determine the relative threat of United States volcanoes as part of the establishment of a National Volcano Early Warning System (Ewert et al., 2005). Their methodology involved calculating threat scores to rank each volcano in terms of risk. Numerical values were assigned to 15 hazard and 10 exposure factors. These were then summed into separate hazard and exposure scores and multiplied to produce an overall threat score. The resulting threat scores were divided into 5 threat categories, from very high to very low. Threat is clearly observed to be a combination of hazard and exposure, in keeping with the UNESCO (1972) definition of risk. An effort was made for the method to be general enough to be applied to volcanoes other than the ones considered in this study. Also, to account for variations in data availability, many factors were used to ensure that any deficiencies in data would not have a large effect on the final score.

The methodology being applied in this study was taken directly from a pilot study on the risk posed by volcanic eruptions to GFDRR priority countries of the World Bank (NGI, 2011). A method for measuring the physical threat posed by these volcanoes was developed by assigning each volcano a hazard and uncertainty level and a population exposure index. The hazard estimation was adopted from the work of Ewert et al. (2005), modifying it slightly with the incorporation of an uncertainty level. This was done in an effort to clarify data availability. The weightings for the hazard factors were also modified in this study to better reflect the threat levels of each hazard. They quantified population exposure adopting the Volcano Population Index method (Ewert and Harpel, 2004). A simple estimate of population risk for each volcano was determined by combining the hazard level and population exposure index. The simplicity of this method must be emphasised as the effect of ash hazard is rudimentary, and the impact to infrastructure and the coping capacity of populations are not at all considered in calculations.

Barring these limitations, this methodology was applied to the Lesser Antilles to test its usefulness in quantifying the unmitigated threat these volcanoes pose.

3.0 Method

The NGI (2011) risk assessment methodology was applied to the following English-speaking Lesser Antilles territories: Grenada, St Vincent, St Lucia, Dominica, Montserrat and St Kitts Nevis. A numerical value for the risk posed by each volcano was calculated by combining each volcano's Hazard Level (HL) and Population Exposure Index (PEI). Details of the methodologies for volcano hazard, exposure and risk are described in the NGI report (NGI, 2011). An outline of its application to this region is presented below.

3.1 Hazard and Uncertainty Determination

To measure the physical threat posed by individual volcanoes, a database of eruptive history was first collated to provide the raw material for the hazard calculation. The following sources of information were pooled together: Smithsonian Global Volcanism Program (Simkin and Seibert, 2002-), Volcanic Hazard Atlas of the Lesser Antilles (Lindsay et al., 2005), Global database on large magnitude explosive volcanic eruptions (LaMEVE) (Crosweller et al., 2012), and other more recent published literature for this region (Stuiver et al., 2009). This was done in an effort to ensure that the information incorporated into this study was as extensive as possible. The different databases expressed the dates either as years BP (Before Present) or BC (Before Christ). For standardization, all the eruption dates were converted to BP following the standard convention of treating 1950 as 'present'.

Eight hazard elements or factors were assessed, each given a defined score range (Table 1) for each volcano considered.

Hazard Factor	Hazard Score Range	Uncertainty Score Range
Volcano type	0,1	0, 0.13, 0.27, 0.4
Crater lake	0, 1	N/A
Pyroclastic flow	0, 1, 2	0, 0.23, 0.47, 0.7
Lahar	0, 1, 2	0, 0.23, 0.47, 0.7
Lava flow	0, 0.2	0, 0.13, 0.27, 0.4
Number of subfeatures	0.1 for first 15 subfeatures, 0.05 for each thereafter	N/A
Maximum Volcano Explosivity Index (VEI)	1, 2, 3, 4	0, 0.13, 0.27, 0.4
Eruption frequency	1, 2, 3, 4	0, 0.15, 0.45
Total	2 to 14.55	0 to 3.05

Table 1: Hazard and uncertainty score ranges

The resulting hazard scores were summed and then assigned to one of three hazard levels (Table 2), with level 1 being the lowest hazard and level 3 the highest hazard.

Summed Hazard Score	Hazard Level
0 - 5	1
5 - 9	2
9+	3

Table 2: Hazard scores and levels

Six uncertainty scores directly related to all of the hazard factors except crater lake presence and number of subfeatures, each with its own score range (Table 1) were also applied to each volcano. As with the hazard factors, the scores were summed and then assigned to one of three uncertainty levels (Table 3).

Summed Uncertainty Score	Uncertainty Level
0 - 1	1
1 - 2	2
2 - 3	3

Table 3: Uncertainty scores and levels

Limitations and adjustments to methodology

The hazard and uncertainty scores were heavily dependent on the eruption records available for any one volcano. The records in the Lesser Antilles are comparatively less extensive than those in the GFDRR priority countries. Fortunately, the eruption characteristics were far more useful than the actual numbers of recorded eruptions in this scoring system. Where eruption details were unavailable due to an absence of recorded eruptions, future eruption scenarios proposed in the Volcanic Hazard Atlas of the Lesser Antilles (Lindsay et al., 2005) were instead used where possible to determine the scores. It is important to note that the use of these future eruption scenarios gave a corresponding increase in the uncertainty score for that volcano.

One hazard factor that was notably missing from most eruption episode details was the Volcano Explosivity Index (VEI) magnitude. To overcome this, the VEI was estimated for recorded eruptions using Table 4, based on the written accounts of recorded eruptions. Of the eruption episode details stated, the one with the highest VEI assignment was used as the magnitude for that eruption. This method was checked with eruptions that had recorded VEI's to validate its accuracy.

Eruptive Feature	VEI Assignment
Lava flow	1
Explosive eruption	2
Phreatic eruption	2
Scoria fall	2
Dome eruptions	3
Pyroclastic flow	3
Caldera large volume collapse	3
Plinian eruption	4

Table 4: VEI magnitude estimation for recorded eruptions

3.2 Population Exposure Determination

Population vulnerability was calculated by measuring the proportion of people threatened by each volcano. Population census data at the enumeration district level combined with ArcGIS software capabilities were used to calculate the numbers of people living within 10 km and 30 km of the volcano. Geographic coordinates of the vents and volcanic fields were obtained from the Volcanic Hazard Atlas of the Lesser Antilles files stored at the University of the West Indies Seismic Research Centre. Population data were obtained from the statistics departments and websites of the relevant countries. Table 5 shows these data sources. The population figures for each aerial extent were multiplied by two respective weightings: 0.9375 for the 10 km region and 0.0625 for the 30 km region. These empirically calculated weightings cater for differences in proximity and areal extent when moving away from the vent (NGI, 2011). The results were then summed and assigned a PEI using Table 6. The PEI was further grouped into three levels (Table 7).

Country	Population Data Source
Grenada and Carriacou	2011 Population Census
St Vincent	2001 Population Census
St Lucia	2010 Population Census
Dominica	November 2011 Electorate Statistics
Montserrat	2011 Population Census
St Kitts Nevis	2011 Population Census (Parish Preliminary Count)

Table 5: Population data sources

Weighted Summed Population	Population Exposure Index
0	0
<3,000	0.5
3,000 – 9,999	1
10,000 – 29,999	1.5
30,000 – 99,999	2
100,000 – 300,000	2.5
>300,000	3

Table 6: PEI conversion

Population Exposure Index	Population Exposure Index Level
0, 0.5	1
1, 1.5	2
2, 2.5, 3	3

Table 7: PEI level conversions

3.3 Population Risk

The risk posed by each volcano was calculated by taking the product of the HL and PEI and assigning the numerical result to one of three Risk Levels as shown in Table 8.

Population Exposure Index	**Volcano Hazard Level**		
	1	**2**	**3**
0, 0.5	1	1	1
1	1	2	2
1.5	1	2	3
2	2	2	3
2.5, 3	2	3	3

Table 8: Population Risk Level cohorts

4.0 Results

The eruption record database for the Lesser Antilles that was utilised in the hazard and uncertainty calculations can be found in the Appendix. The results of the risk assessments for each volcano are summarised in the following sections.

4.1 Grenada

<u>Hazard and Uncertainty Assessment</u>

The only volcano in Grenada considered to have the potential to erupt in the future is the Mt St Catherine volcanic centre (Lindsay et al., 2005). No eruptive records were available for this volcano, so this part of the assessment was calculated using written accounts of past eruptive activity, together with future eruption scenarios. Table 9 shows its calculated hazard and uncertainty scores.

Hazard Factor	**Hazard Score**	**Uncertainty Score**
Volcano type	1	0
Crater lake	0	-
Pyroclastic density current	2	0.47
Lahar	0	0.7
Lava flow	0.2	0.27
Number of subfeatures	0	-
Maximum VEI	1	0.4
Eruption frequency	0	0.45
Total	**4.2**	**2.29**

Table 9: Mt St Catherine hazard and uncertainty scores

Table 10 shows the hazard-uncertainty class to which Mt St Catherine was assigned.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1			Mt. St.Catherine
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 10: Mt St Catherine hazard-uncertainty cohort

<u>Exposure Assessment</u>

The results of the population exposure calculation Grenada are shown in Table 11.

PEI	2
PEI Level	3

Table 11: Mt St Catherine population exposure results

Table 12 shows the assignment of Mt St Catherine across the hazard-PEI levels

Hazard level 3			
Hazard level 2			
Hazard Level 1			Mt St Catherine
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 12: Soufriere hazard-PEI cohort

<u>Risk Assessment</u>

Combining the HL and the PEI gave the Mt St Catherine volcano a Risk Level 2.

4.2 Kick ‘em Jenny

Hazard and Uncertainty Assessment

Kick ‘em Jenny is a submarine active volcano located about 8 km north of Grenada. Table 13 shows its calculated hazard and uncertainty scores.

Hazard Factor	Hazard Score	Uncertainty Score
Volcano type	0	0.4
Crater lake	0	-
Pyroclastic density current	2	0
Lahar	1	0.47
Lava flow	0	0
Number of subfeatures	0	-
Maximum VEI	1	0
Eruption frequency	3	0
Total	**7**	**0.87**

Table 13: Kick ‘em Jenny hazard and uncertainty scores

Table 14 shows the hazard-uncertainty class to which Mt St Catherine was assigned.

Hazard level 3			
Hazard level 2	Kick 'em Jenny		
Hazard Level 1			
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 14: Kick ‘em Jenny hazard-uncertainty cohort

Exposure Assessment

Kick ‘em Jenny, though not located on any island, is close enough to Grenada and Carriacou, to affect their populations. The proportions of both territories affected by the 10 km and 30 km radii were included in calculations. The results of these calculations are shown in Table 15.

PEI	1.5
PEI Level	2

Table 15: Kick ‘em Jenny population exposure results

Table 16 shows the assignment of Kick ‘em Jenny across the hazard-PEI levels.

Hazard level 3			
Hazard level 2		Kick 'em Jenny	
Hazard Level 1			
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 16: Kick ‘em Jenny hazard-PEI cohort

Risk Assessment

Combining the HL and the PEI gave the Kick ‘em Jenny volcano a Risk Level 2.

4.3 St Vincent

Hazard and Uncertainty Assessment

Soufriere is the only active volcano on St Vincent (Lindsay et al., 2005). Table 17 shows its hazard and uncertainty scores.

Hazard Factor	Hazard Score	Uncertainty Score
Volcano type	1	0
Crater lake	1	-
Pyroclastic density current	2	0
Lahar	2	0
Lava flow	0.2	0
Number of subfeatures	0	-
Maximum VEI	2	0
Eruption frequency	4	0
Total	**12.2**	**0**

Table 17: Soufriere hazard and uncertainty scores

Table 18 shows the hazard-uncertainty class to which Soufriere was assigned.

Hazard Level 3	Soufriere		
Hazard Level 2			
Hazard Level 1			
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 18: Soufriere hazard-uncertainty cohort

Exposure Assessment

The results of the population exposure calculation for St Vincent are shown in Table 19.

PEI	1.5
PEI Level	2

Table 19: Soufriere population exposure results

Table 20 shows the assignment of the Soufriere volcano across the hazard-PEI levels.

Hazard Level 3		Soufriere	
Hazard Level 2			
Hazard Level 1			
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 20: Soufriere hazard-PEI cohort

Risk Assessment

Combining the HL and the PEI gave the Soufriere volcano a Risk Level 3.

4.4 St Lucia

Hazard and Uncertainty Assessment

The Soufriere Volcanic Centre is the only active volcanic centre in St Lucia (Lindsay et al., 2005). Table 21 shows its hazard and uncertainty scores.

Hazard Factor	Hazard Score	Uncertainty Score
Volcano type	1	0
Crater lake	0	-
Pyroclastic density current	2	0.47
Lahar	2	0.47
Lava flow	0.2	0.27
Number of subfeatures	0	-
Maximum VEI	3	0
Eruption frequency	1	0
Total	**9.2**	**1.21**

Table 21: Soufriere Volcanic Centre hazard and uncertainty scores

Table 22 shows the hazard-uncertainty class to which the Soufriere Volcanic Centre was assigned.

Hazard Level 3		Soufriere Volcanic Centre	
Hazard Level 2			
Hazard Level 1			
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 22: Soufriere Volcanic Centre hazard-uncertainty cohort

Exposure Assessment

The results of the population exposure calculation for St Lucia are shown in Table 23.

PEI	2
PEI Level	3

Table 23: Soufriere Volcanic Centre population exposure results

Table 24 shows the assignment of the Soufriere Volcanic Centre across the hazard-PEI levels.

Hazard level 3			Soufriere Volcanic Centre
Hazard level 2			
Hazard Level 1			
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 24: Soufriere Volcanic Centre hazard-PEI cohort

Risk Assessment

Combining the HL and the PEI gave the Soufriere Volcanic Centre a Risk Level 3.

4.5 Dominica

Hazard and Uncertainty Assessment

Hazard Factor	Valley of Desolation		Plat Pays		Morne Anglais	
	Hazard Score	Uncertainty Score	Hazard Score	Uncertainty Score	Hazard Score	Uncertainty Score
Volcano type	1	0	1	0	1	0
Crater lake	0	-	0	-	0	-
Pyroclastic density current	1	0.47	2	0	2	0
Lahar	2	0	0	0.23	0	0.23
Lava flow	0	0.27	0.2	0.27	0	0.27
Number of subfeatures	0	-	0	-	0	-
Maximum VEI	1	0.13	2	0	2	0.4
Eruption frequency	2	0	2	0	0	?
Total	**7**	**0.87**	**7.2**	**0.5**	**5**	**0.9**
Hazard Factor	**Micotrin**		**Morne Watt**		**Grand Soufriere Hills**	
	Hazard Score	**Uncertainty Score**	**Hazard Score**	**Uncertainty Score**	**Hazard Score**	**Uncertainty Score**
Volcano type	1	0	1	0	1	0
Crater lake	0	-	0	-	0	-
Pyroclastic density current	2	0	2	0	2	0.47
Lahar	0	0.23	2	0	0	0.7
Lava flow	0	0.27	0.2	0.27	0	0.27
Number of subfeatures	0	-	0	-	0	-
Maximum VEI	3	0	2	0.4	2	0.4
Eruption frequency	2	0	2	0	0	?
Total	**8**	**0.5**	**9.2**	**0.67**	**5**	**1.84**
Hazard Factor	**Morne aux Diables**		**Morne Trois Pitons**		**Morne Diablotins**	
	Hazard Score	**Uncertainty Score**	**Hazard Score**	**Uncertainty Score**	**Hazard Score**	**Uncertainty Score**
Volcano type	1	0	1	0	1	0
Crater lake	0	-	0	-	0	-
Pyroclastic density current	2	0.47	2	0	2	0
Lahar	0	0.7	0	0.23	0	0.23
Lava flow	0	0.27	0	0.27	0.2	0.27
Number of subfeatures	0	-	0	-	0	-
Maximum VEI	2	0.4	2	0.4	2	0.4
Eruption frequency	0	?	0	?	0	?
Total	**5**	**1.84**	**5**	**0.9**	**5.2**	**0.9**

Table 25: Hazard and uncertainty scores for Dominica's nine volcanoes

Dominica has nine potentially active volcanic centres (Lindsay et al., 2005). Table 25 above shows their hazard and uncertainty scores.

Table 26 shows the hazard-uncertainty classes to which the Dominican volcanoes were assigned.

Hazard Level 3	Morne Watt		
Hazard Level 2	Valley of Desolation Plat Pays Micotrin	Morne Diablotins	
Hazard Level 1		Morne Anglais Morne Trois Pitons	Grand Soufriere Hills Morne aux Diables
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 26: Dominica's volcanoes across hazard-uncertainty cohorts

<u>Exposure Assessment</u>

The results of the population exposure calculation for Dominica in relation to the eight volcanic vents and one volcanic centre (the Valley of Desolation includes a number of phreatic/phreatomagmatic explosion craters concentrated in one area) are shown in Table 27.

	Valley of Desolation	**Morne Plat Pays**	**Morne Anglais**	**Micotrin**	**Morne Watt**	**Grand Soufriere Hills**	**Morne aux Diables**	**Morne Trois Pitons**	**Morne Diablotins**
PEI	2	1.5	2	2	2	1.5	1.5	2	1.5
PEI Level	3	2	3	3	3	2	2	3	2

Table 27: Population exposure results for Dominica's volcanoes

Table 28 shows the assignment of Dominica's volcanoes across hazard-PEI levels.

Hazard level 3			Morne Watt
Hazard level 2		Morne Diablotins Morne Plat Pays	Morne Trois Pitons Micotrin Valley of Desolation
Hazard Level 1		Morne aux Diables Grand Soufriere Hills	Morne Anglais
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 28: Distribution of Dominica's volcanoes across hazard-PEI cohorts

Risk Assessment

Table 29 gives the risk levels of Dominica's volcanoes:

Risk Level 1	**Risk Level 2**	**Risk Level 3**
Grand Soufriere Hills	Morne Plat Pays	Morne Watt
Morne aux Diables	Morne Anglais	
	Micotrin	
	Morne Trois Pitons	
	Morne Diablotins	
	Valley of Desolation	

Table 29: Risk levels of Dominica's volcanoes

Figure 2 summarises the distribution of Dominica's volcanoes across the different risk levels. The background colours represent red for Risk Level 3, yellow for Risk Level 2 and green for Risk Level 1. The graph may appear to show only 8 volcanoes, but this is only because two of the volcanoes have the same hazard and PEI values.

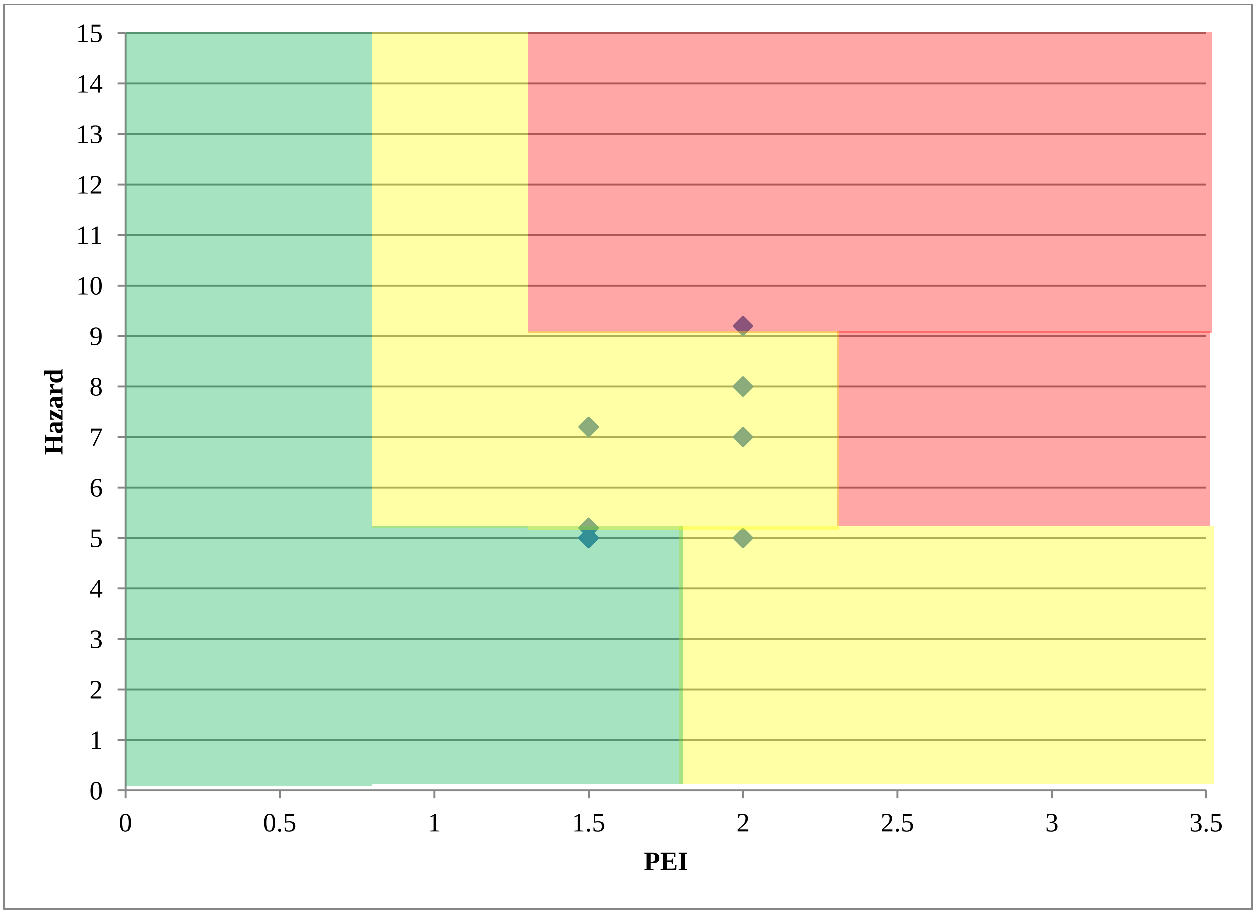

Figure 2: Risk Levels of Dominica's volcanoes

4.6 Montserrat

Hazard and Uncertainty Assessment

The active volcanic centre on Montserrat is the Soufriere Hills volcano. Table 30 shows its hazard and uncertainty scores.

Hazard Factor	**Hazard Score**	**Uncertainty Score**
Volcano type	1	0
Crater lake	0	-
Pyroclastic density current	2	0
Lahar	2	0
Lava flow	0	0.27
Number of subfeatures	0	-
Maximum VEI	2	0.13
Eruption frequency	2	0
Total	**9**	**0.4**

Table 30: Soufriere Hills hazard and uncertainty scores

Table 31 shows the hazard-uncertainty class to which the Soufriere Hills was assigned.

Hazard Level 3			
Hazard Level 2	Soufriere Hills		
Hazard Level 1			
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 31: Soufriere Hills hazard-uncertainty cohort

Exposure Assessment

The results of the population exposure calculation for Montserrat are shown in Table 32.

PEI	1
PEI Level	2

Table 32: Soufriere Hills population exposure results

Table 33 shows the assignment of Soufriere Hills across the hazard-PEI levels.

Hazard Level 3			
Hazard Level 2		Soufriere Hills	
Hazard Level 1			
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 33: Soufriere Hills hazard-PEI cohort

Risk Assessment

Combining the HL and the PEI gave the Soufriere Hills a Risk Level 2.

4.7 St Kitts

Hazard and Uncertainty Assessment

The potentially active volcano on St Kitts is Mt Liamuiga which is the most likely location for future eruptions (Lindsay et al., 2005). Table 34 shows its hazard and uncertainty scores.

Hazard Factor	**Hazard Score**	**Uncertainty Score**
Volcano type	1	0
Crater lake	0	-
Pyroclastic density current	2	0
Lahar	2	0
Lava flow	0.2	0.27
Number of subfeatures	0	-
Maximum VEI	2	0.13
Eruption frequency	2	0
Total	**9.2**	**0.4**

Table 34: Mt Liamuiga hazard and uncertainty scores

Table 35 shows the hazard-uncertainty class to which Mt Liamuiga was assigned.

Hazard Level 3	Mt. Liamuiga		
Hazard Level 2			
Hazard Level 1			
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 35: Mt Liamuiga hazard-uncertainty cohort

Exposure Assessment

The population exposed to Mt Liamuiga included portions of Nevis and St Eustatius in addition to St Kitts. However, population data could not be obtained from St Eustatius since they have not yet completed and updated their census database. The PEI estimate obtained for this volcano was therefore an underestimate of the actual numbers of person exposed to this physical threat.

The results of the population exposure calculation for St Kitts are shown in Table 36.

PEI	2
PEI Level	3

Table 36: St Kitts population exposure results

Table 37 shows the assignment of Mt Liamuiga across the hazard-PEI levels.

Hazard Level 3			Mt. Liamuiga
Hazard Level 2			
Hazard Level 1			
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 37: Mt Liamuiga hazard-PEI cohort

Risk Assessment

Combining the HL and the PEI gave the Mt Liamuiga a Risk Level 3.

4.8 Nevis

Hazard and Uncertainty Assessment

Nevis Peak is the only potentially active centre on the island of Nevis. No eruptive records were available for this volcano, so this part of the assessment was calculated using written accounts of past eruptive activity, together with future eruption scenarios. Table 38 shows its hazard and uncertainty scores.

Hazard Factor	Hazard Score	Uncertainty Score
Volcano type	1	0
Crater lake	0	-
Pyroclastic density current	2	0.47
Lahar	2	0.47
Lava flow	0	0.27
Number of subfeatures	0	-
Maximum VEI	1	0.4
Eruption frequency	0	0.45
Total	**6**	**2.06**

Table 38: Nevis Peak hazard and uncertainty scores

Table 39 shows the hazard-uncertainty class to which Nevis was assigned.

Hazard Level 3		Nevis Peak	
Hazard Level 2			
Hazard Level 1			
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Table 39: Nevis Peak hazard-uncertainty cohort

Exposure Assessment

The population exposed to Nevis Peak included part of St Kitts which was incorporated into the estimation. The results of the population exposure calculation for Nevis are shown in Table 40.

PEI	1.5
PEI Level	2

Table 40: Nevis population exposure results

Table 41 shows the assignment of Nevis Peak across the hazard-PEI levels.

Hazard Level 3			
Hazard Level 2		Nevis Peak	
Hazard Level 1			
	PEI Level 1	**PEI Level 2**	**PEI Level 3**

Table 41: Nevis Peak hazard-PEI cohort

Risk Assessment

Combining the HL and the PEI gave the Nevis Peak a Risk Level 2.

4.9 Results Summary

Figure 3 summarises the hazard and uncertainty assessment results for all the volcanoes studied. The background colouring is used to show the Hazard Level and the colour intensity to show the Uncertainty Level.

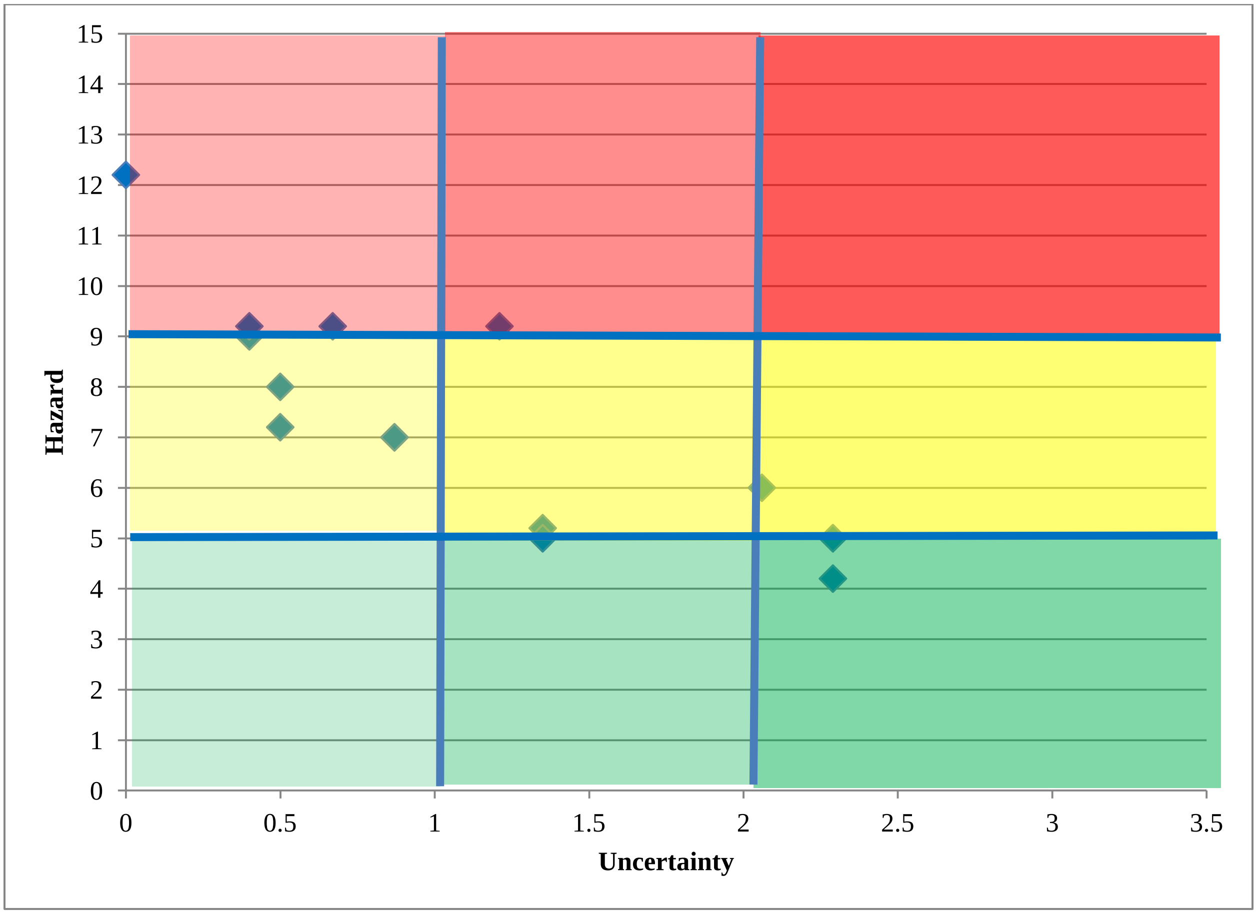

Figure 3: Distribution of all the volcanoes studied across Hazard and Uncertainty Levels

Table 42 and Figure 3 summarise the Risk Level results for all the volcanoes studied.

Island	Volcano	Hazard	PEI	Risk Level
Grenada	Mt St Catherine	4.2	2	2
	Kick 'em Jenny	7	1.5	2
St Vincent	Soufriere	12.2	1.5	3
St Lucia	Soufriere Volcanic Complex	9.2	2	3
Dominica	Valley of Desolation	7	2	2
Dominica	Morne Plat Pays	7.2	1.5	2
Dominica	Morne Anglais	5	2	2
Dominica	Micotrin	8	2	2
Dominica	Morne Watt	9.2	2	3
Dominica	Grand Soufriere Hills	5	1.5	1
Dominica	Morne aux Diables	5	1.5	1
Dominica	Morne Trois Pitons	5	2	2
Dominica	Morne Diablotins	5.2	1.5	2
Montserrat	Soufriere Hills	9	1	2
St Kitts	Mt Liamuiga	9.2	2	3
Nevis	Nevis Peak	6	1.5	2

Table 42: Summary of Risk Level results for all volcanoes

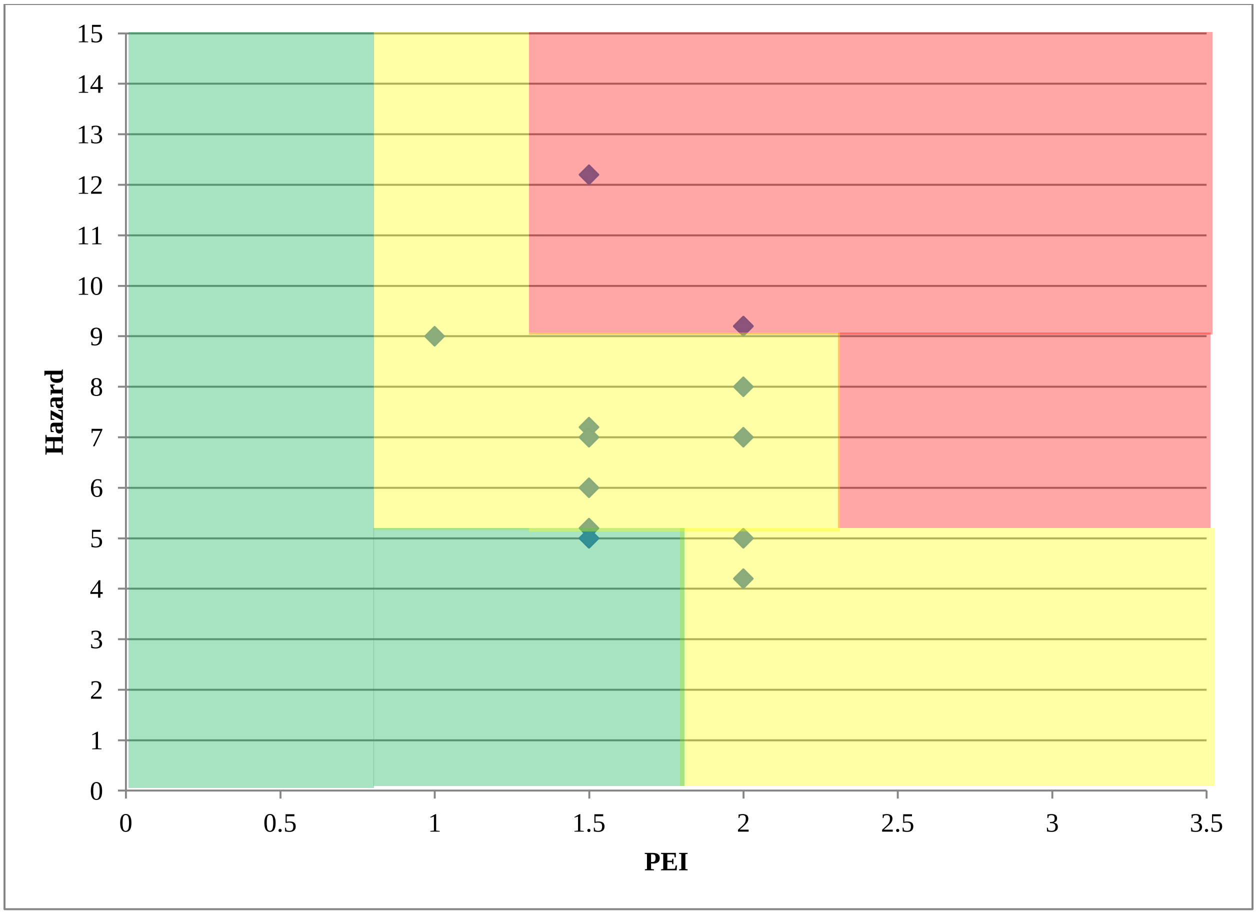

Figure 4: Risk Level results for all the volcanoes studied

In this figure, the background colours represent red for Risk Level 3, yellow for Risk Level 2 and green for Risk Level 1. Less than 16 volcano points are distributed on the graph because hazard and PEI values were duplicated in certain instances (see Table 42). Most of the volcanoes studied fell into the Risk Level 2 cohort.

5.0 Discussion

Applying the NGI methodology to the Lesser Antilles has emphasised its inherent simplicity as well as the importance of having databases (whether eruptive or demographic) of significant quality and quantity to incorporate into risk assessments. However, to avoid unwarranted criticism, it must be highlighted that the writers of the report stated that their method was in its preliminary stages and more work still needed to be done to refine it. The following sections outline some of the challenges faced in the different components of this study while explaining its results. Recommendations are given where possible, for better integration of this method into the region.

Data availability in the Lesser Antilles

The Lesser Antilles volcanic arc is geologically young, and has had few historical eruptions in comparison to other volcanic arcs of the world. Of the volcanoes that have been historically active (Kick ‘em Jenny, Soufriere, Soufriere Volcanic Centre, Mt Pelee, La Soufriere, Soufriere Hills), only three have been considered in this study due to our focus on the English-speaking islands. To make things more difficult, the geological record of pre-historic eruptions is scarce. This can be attributed to a lack of in-depth scientific study (field surveys, mapping and dating of deposits) and erosion of deposits. Additionally, there is a disparity in the eruptive records for different volcanoes in the region due to a concentration of research in some areas and neglect in others.

However, in spite of the limited research, the trend of eruptive activity for this region seems to be comparatively mild. Using the data from the Smithsonian Institution website database, there have only been 50 eruptions for the Holocene period, with the highest magnitude being VEI 4 and the majority being VEI 3 and below. This can be explained by the proclivity of the region for dome forming eruptions rather than Plinian eruptions which are more likely to leave behind lasting deposits. More importantly it suggests that it is possible that the number of recorded eruptions would not change significantly even with the intervention of rigorous scientific study.

In terms of data on population statistics, some difficulties arose in the quality of information from the different island inventories. Of the countries that were willing to share their data, the most recent statistics were dated, some more so than others. Also, data was not only given from the population census at the enumeration district level, but in one case it was obtained as electorate statistics. The data in the latter case are dependent on persons registering to vote. The standardisation of this component of the study is therefore limited by the methods in which population statistics are recorded and distributed in the respective islands.

Hazard and Uncertainty Assessment

The following limitations to this component of the NGI methodology were observed:

- Because the hazard estimation method is heavily dependent on the integrity of the eruptive history database being used, for volcanoes where a lot of data is available, the method works well. This is especially true for Soufriere, St Vincent, which has a comparatively extensive database of historic and pre-historic eruptions with a corresponding uncertainty level of zero for the hazard score. However, even for Soufriere Hills, Montserrat, where a lot of research is concentrated due to the establishment of the Montserrat Volcano Observatory, the uncertainty level though low, is not zero because of reduced numbers of recorded eruptions and their details. Mentioning the hazard level with its associated uncertainty level for all the volcanoes, highlights and accounts for this limitation.

- The method focussed on assessing the risk from individual volcanoes and did not consider the risk from volcanic fields. This was highlighted when it was applied to the Soufriere Volcanic Centre of St Lucia which consists of a series of volcanic vents associated with the Qualibou depression. Evaluating the physical threat from volcanic fields lacking a central vent is tricky because an eruption can potentially occur from any vent within the field. This 'unknown' in a possible future eruption should make the hazard level faced greater. The method however, does not make a distinction between volcanoes and volcanic fields and so the Soufriere Volcanic Centre was given the same hazard level as Soufriere, Morne Watt, Mt Liamuiga and Nevis Peak.

- No distinction was made between active and potentially active/dormant volcanoes in the hazard-uncertainty calculations. This distinction will help to decipher the kinds of disaster risk reduction strategies that need to be employed. Clearly a volcano that is active requires immediate attention as opposed to one that is not which would benefit from a different type of proactive preparedness to be introduced to the population. Factors such as type of unrest observed or frequency of seismic swarms can be added to the hazard element parameters to account for this distinction. This may help make up for ambiguities in the lack of recent eruption records and determine how soon eruptions are likely to occur in the future.

- Many of the GFDRR priority countries have multiple volcanoes within their boundaries, but none had volcanoes in such close proximity to each other as in Dominica. The method does not take into account the increased threat in areas where the overlap of volcanic hazards is a real possibility.

Population Exposure Assessment

The following limitations to the exposure assessment were observed:

- An obvious limitation to this study is the restriction of the method to population vulnerability. The major elements at risk to volcanic hazards correspond to exposed financial, environmental as well as human assets (MIAVITATeam, 2012). Had the impact to infrastructure and property been considered, a more balanced assessment of risk would be produced. A similar assessment of the distribution of infrastructure and communication routes in relation to the volcano using ArcGIS should be attempted.

- The method for measuring population exposure was developed from the idea of the Volcano Population Index (VPI) (Ewert & Harpel, 2004). Their method used a LandScan population database which is gridded with a resolution of 1 km. Population census data are distributed using models to match the data conditions and geographical nature of each individual country. Unfortunately, this level of detail in terms of population distribution was not obtained in this study, because of the limitations of data availability in the region. The uncertainty associated with the data used in the Lesser Antilles study would be greater than the LandScan data, if it were to be quantified.

- It was unclear as to why regions spanning 10 km and 30 km were chosen to calculate the PEI. In almost all instances, the 30 km radial circle surrounding the vent covered the entire island and in the case of St Kitts, also covered part of the neighbouring island of St Eustatius. The VPI estimation (from which the NGI method is based) used areas of 5 km and 10 km with the justification that small-medium sized eruptions of <VEI 4 would not have severe hazards reaching further than 10 km. However, they did state that in areas where lahar hazard were perceived to be severe, this distance would have to be extended. Still, a maximum extent of 30 km in this risk analysis was not adequately explained.

Volcanic Risk

More than 60% of the volcanoes studied were assigned a Risk Level of 2, with approximately 25% having a Risk Level of 3. This has reinforced what is already known about the high volcanic risk the Lesser Antilles region faces and the need for proactive risk reduction programmes. Of the 5 volcanoes labelled historically active, only Soufriere and Soufriere Volcanic Complex were assigned a Risk Level of 3. However, other potentially active volcanoes (Mt Liamuiga and Morne Watt) were highlighted by this method to be of Risk Level 3, which should make them priority volcanoes for risk reduction measures to be implemented.

6.0 Future Work

The following areas of research on volcanic risk in the region came out of this study, all of which are avenues for continued research by the authors:

- The Lesser Antilles volcanic eruption database needs to be expanded to include patterns and features of unrest periods at volcanoes.

- The exposure component of the risk estimation method should be widened to consider the impact to infrastructure and communication lines, using a method similar to the one outlined in the NGI (2011) study. The proportion of these elements at different distances from the volcano can be estimated using GIS. This can then be used to produce an exposure index using further empirical calculations.

- The risk results obtained gave a value for the risk (to population) posed by an individual volcano, which was ultimately the aim of the NGI methodology. Knowing the relative risk of volcanoes may be useful for global and by extension regional comparisons of risk. However, smaller regions such as the Lesser Antilles and individual countries may better benefit from small-scaled estimations of risk. This could entail the comparative risk posed to towns, cities or enumeration districts within the country by a particular volcano (or volcanoes, if multiple volcanoes occur in the country). This more detailed approach may better assist in implementing disaster risk reduction programs into these countries.

- The risk to non-volcanic islands or countries should also be considered. The effect of ashfall can be far-reaching and, depending on the proximity of a neighbouring island and the intensity of eruption, pyroclastic flows can be a potential hazard.

7.0 References

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Appendix

Lesser Antilles Volcanic Eruption Database

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
Dominica	Valley of Desolation	Stratovolcano	08-Jul-97	09-Jul-97	Historical records	phreatic, flank vent, explosive	1	VHA, GVP	
			04-Jan-1880		Historical records	phreatic, flank vent, explosive, mudflow	2?	VHA, GVP	
			2900 ± 370 BP		14C	phreatic		VHA	2
			2900 ± 300 BP		14C	flank vent, explosive, phreatic		GVP	2
			3750 ± 100 BP		14C	phreatic		VHA	2
			3750 ± 300 BP		14C	flank vent, explosive, phreatic		GVP	2
			4,050 ± 80 BP		14C	phreatic		VHA	2
	Plat Pays Volcanic Complex	Stratovolcano	1270±50		14C	central vent, explosive, pyroclastic flow, dome		GVP	3
			390±40		14C	central vent, explosive, pyroclastic flow, dome		GVP	3
			2380 BP?		14C	explosive, pyroclastic flow		GVP	3
			6690 BP?		14C	explosive, pyroclastic flow		GVP	3
			39 Ka BP	450 BP	14C	formation of domes		VHA	3
			39 Ka BP		14C	Grand Bay Ignimbrite		(Lindsay et al., 2003)	4
			43516±349 BP		14C (corrected)	Grand Bay Ignimbrite	4	LaMEVE	
	Morne Anglais	Stratovolcano	26,400 ± 2,500 BP?		14C	scoria fall		VHA	2

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
			28,450 ± 1,500 BP?		14C	scoria fall		VHA	2
			0.43 Ma* BP		K-Ar	block and ash flow (pyroclastic flow deposit)		VHA	3
	Micotrin	Complex volcano	790 ± 50		14C	central, explosive, pyroclastic flow, dome		GVP	3
			920 ± 50		14C	central, explosive, pyroclastic flow		GVP	3
			≈1000 BP		14C	small Plinian and Pelean dome forming eruptions: block and ash flows, pumiceous pyroclastic flows		VHA	4
			36,385±1555 BP		14C (corrected)	Roseau Tuff	6	LaMEVE	
			40 Ka BP	20 Ka BP	14C	Plinian eruptive sequences of activity		VHA	4
	Morne Watt		640±150		14C	flank vent, explosive, pyroclastic flow, mudlfow		GVP	3
			1,270 ± 75 BP		14C	cryptodome extrusion: blockand ash flows		VHA	3
			1,350 ± 75 BP		14C	cryptodome extrusion: blockand ash flows		VHA	3
			10,290 ± 60 BP		14C	Plinian eruptions		VHA	4
			0.46 Ma BP		K-Ar	andesite lava flow		VHA	1
	Morne Trois Pitons	Complex volcano	17,240 ± 720 BP		14C	eruption associated with dome growth		VHA	3
			25,310 ± 230 BP		14C	eruption associated with dome growth		VHA	3
			>40,000 BP		14C	Plinian style activity: pumiceous pyroclastic flows		VHA	4

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
	Grand Soufriere Hills	Complex volcano	10,320 ± 40 BP		14C	block and ash flow deposit		VHA	3
			11,000 ± 85 BP		14C	block and ash flows deposit		VHA	3
	Morne Diablotins	Stratovolcano	>40,000 BP	>22,200 BP	14C	plinian style eruptions: pumiceous falls, ignimbrites		VHA	4
			0.72 ± 0.11 Ma BP	>46,620 BP	K-Ar, 14C	pelean style eruptions: block and ash flows		VHA	3
			1.77Ma Ma			Pelean activity: block and ash flows, lava flows		VHA	3
	Morne aux Diables	Stratovolcano	>46,740 BP		14C	block and ash flow deposit		VHA	3
Grenada	Mt. St. Catherine	Stratovolcano							
Grenadine Islands	Kick 'em Jenny	Submarine volcano	04-Dec-01	06-Dec-01	Hydrophone	earthquakes	0	VHA, GVP	
			26-Mar-90	05-Apr-90	Hydrophone	earthquakes		VHA, GVP	
			26-Mar-90	28-Mar-90	Hydrophone	explosive	0	GVP	
			29-Dec-88	30-Dec-88	Hydrophone	earthquakes, dome destruction, explosive, pyroclastic flow	0	VHA, GVP	
			11-Nov-77		Hydrophone		0	GVP	
			14-Jan-77	14-Jan-77	Hydrophone	dome formation	0	VHA, GVP	
			06-Sep-74		Hydrophone	material ejected into air		VHA	
			05-Sep-74	06-Sep-74	Hydrophone	explosive	0	GVP	
			05-Jul-72	05-Jul-72	Hydrophone		0	VHA,	

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
								GVP	
			03-Aug-66	06-Aug-66	Hydrophone			VHA	
			05-May-66	07-May-66	Hydrophone	earthquakes		VHA	
			05-May-66	06-Aug-66	Hydrophone		0	GVP	
			24-Oct-65	24-Oct-65	Hydrophone	earthquakes	0	VHA, GVP	
			30-Oct-53	30-Oct-53	Hydrophone	earthquakes	0	VHA, GVP	
			05-Oct-43	06-Oct-43	Hydrophone	earthquakes	0	VHA, GVP	
			24-Jul-39	24-Jul-39	Witnessed	explosive, earthquakes felt	1	VHA, GVP	
Guadeloupe	La Soufriere	Stratovolcano	08-Jul-76	01-Mar-77	Historical records	explosive, pyroclastic flows, phreatic, mudflow, radial fissures	2	VHA, GVP	
			19-Oct-56	27-Oct-56	Historical records	explosive, pyroclastic flows, phreatic, mudflow, radial fissures	1	VHA, GVP	
			1903?		Uncertain eruption		2	GVP	
			03-Dec-1836	12-Feb-1837	Historical records	explosive, pyroclastic flows, phreatic, mudflow, radial fissures	2	VHA, GVP	
			Apr-1812	10-May-1812	Historical records	explosive, phreatic, radial fissures	1	VHA, GVP	
			29-Sept-1797	26-Apr-1798	Historical records	explosive, pyroclastic flows, phreatic, mudflow, radial fissures	2	VHA, GVP	
			Apr-1696		Historical records	explosive, phreatic	1	GVP	
			1690		Historical records	explosive, phreatic, radial fissures	1	VHA, GVP	
			1600±50		14C (corrected)	explosive, pyroclastic flows		GVP	3
			1530		14C	last magmatic eruption, sub-plinian phase with scoria fallout and column collapse pyroclastic flows, growth of lava dome		(Boudon et al., 2008)	3
			1440±100		14C (corrected)	explosive, pyro flow,caldera large vol collapse, dome eruption, plinian deposits		GVP, LaMEVE	4

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
			1370±150		14C (corrected)	explosive, pyroclastic flows, mud flow, plinian deposits		GVP, LaMEVE	4
			1340±50		14C (corrected)	explosive	3	GVP	
			370±75		14C (corrected)	lava flows associated with L'Eschelle and La Citerne cones		GVP	1
			after 2530 BP		14C	south flank (Morne Lenglet)explosive,lava flow	2	GVP	
			2770±100 BP		14C (corrected)	explosive, pyro flow, phreatic, caldera large vol collapse, dome erution	3	GVP	
			2930±200 BP		14C (corrected)	explosive, caldera large vol collapse		GVP	
			3260±150 BP		14C (corrected)	explosive, pyroclastic flow, dome eruption, caldera large vol collapse	3	GVP	
			3760±150 BP		14C (corrected)	south flank, explosive, pyro flow, phreatic, caldera large vol collapse, mudflow		GVP	3
			4000 BP ?		Uncertain eruption	south flank		GVP	
			5260±150 BP		14C (corrected)	south flank (Gros Fougas), explosive, pyroclastic flow, lava flow, dome eruption		GVP	3
			8400±150 BP		14C (corrected)	explosive, pyroclastic flow, mudflow, caldera collapse		GVP	3
			9440±150 BP		14C (corrected)	formation of Amic crater: explosive, pyroclastic flow, mudflow, caldera collapse		GVP	3
			8500 BP		not available	formation of Amic crater		VHA	
			46465±1132 BP		14C (corrected)	Pintade Unit	5	LaMEVE	
			110000 BP		not available	Montval caldera	4?	LaMEVE	
			140000 BP		not available	Anse des Peres caldera formation	4?	LaMEVE	

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
Martinique	Montagne Pelee	Stratovolcano	16-Sep-29	01-Dec-1932 ±30 days	Historical records	explosive, pyro flow, dome forming eruption, spine, mudlfow, damage	3	VHA, GVP	
			23-Apr-02	05-Oct-05	Historical records	explosive, pyro flow, phreatic, dome forming eruption, spine, crater lake, mudflow, tsunamis, fatalities, damamge	4	VHA, GVP, LaMEVE	
			05-Aug-1851	01-Feb-1852 ±30days	Historical records	explosive, phreatic, mudflow	2	VHA, GVP	
			22-Jan-1792	Apr-1792	Historical records	phreatic, mudflow	1	VHA, GVP	
			before 1635		Historical records	explosive, pyroclastic flows, dome		GVP	3
			1460±20		14C	explosive, pyroclastic flows		GVP	3
			1370?		14C	explosive, pyroclastic flows		GVP	3
			1341±84		14C (corrected)		4	LaMEVE	
			1340±50		14C (corrected)	explosive, pyroclastic flows	4	GVP	
			1337±53		14C (corrected)			(Stuiver et al., 2009)	
			1260±20		14C	explosive, pyroclastic flows		GVP	3
			1190?		14C	explosive, pyroclastic flows		GVP	3
			910?		14C	explosive, pyroclastic flows		GVP	3
			1068±100		14C (corrected)			(Stuiver et al., 2009)	
			890±100		14C (corrected)	explosive, pyroclastic flows, dome, Plinian deposits		GVP	4
			881±166		14C (corrected)		4?	LaMEVE	
			720?		14C	explosive, pyroclastic flows		GVP	3
			650?		14C	explosive, pyroclastic flows		GVP	3
			514±247		14C (corrected)			LaMEVE	

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
			450?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			350±75		14C (corrected)	explosive, pyroclastic flows	4	GVP	
			280±40		14C (corrected)		4	LaMEVE	
			419±126		14C (corrected)		4?	LaMEVE	
			300?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			280±40		14C (corrected)		4	LaMEVE	
			239±287		13C (corrected)		4?	LaMEVE	
			220±75		14C	explosive, pyroclastic flow, dome		GVP	3
			130?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			117±144		14C (corrected)		4?	LaMEVE	
			50?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			10±50		14C (corrected)	explosive, pyroclastic flows	4	GVP	3
			1980±130 BP		14C (corrected)		4	LaMEVE	
			2051±235 BP		14C (corrected)			(Stuiver et al., 2009)	
			2150 BP?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			2170±210 BP		14C (corrected)		4?	LaMEVE	
			2250±100 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			2390 BP?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			2513±288 BP		14C (corrected)		4?	LaMEVE	
			2537±262 BP		14C (corrected)		4	LaMEVE	

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
			2540±200 BP		14C (corrected)	explosive, pyroclastic flow, dome	4?	GVP	
			2550 BP?		14C	explosive, pyroclastic flows		GVP	3
			2570 BP?		14C	explosive, pyroclastic flows		GVP	3
			2680 BP?		14C	explosive, pyroclastic flows		GVP	3
			2840±50 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			3340±150 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			4050±200 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			4230 BP?		14C	explosive, pyroclastic flows, dome		GVP	3
			4310 BP?		14C	explosive, pyroclastic flows, dome		GVP	3
			4380 BP?		14C	explosive, pyroclastic flows, plinian deposits		GVP	4
			4410±100 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			4594±300 BP		14C (corrected)		4?	GVP	
			4613±188 BP		14C (corrected)			(Stuiver et al., 2009)	
			4610± 200 BP		14C (corrected)	explosive, pyroclastic flows	4?	LaMEVE	
			4932±674 BP		14C (corrected)		4?	GVP, LaMEVE	
			4960 BP?		14C	explosive, pyroclastic flows, dome		GVP	3
			5070±200 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			5200 BP?		14C	explosive, pyroclastic flows dome		GVP	3
			5240 BP?		14C	explosive, pyroclastic flows		GVP	3
			5371±138 BP		14C (corrected)		4	GVP, LaMEVE	
			5380±75 BP		14C (corrected)	explosive, pyroclastic flows	4	GVP, LaMEVE	
			5450±200 BP		Tephrochronology	explosive, pyroclastic flows, Plinian deposits		GVP, LaMEVE	4

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
			5770 BP?		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			6564±214 BP		14C (corrected)		4?	LaMEVE	
			5880±100 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			6460±500 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			7450±200 BP		14C (corrected)	explosive, pyroclastic flows, Plinian deposits	4?	GVP, LaMEVE	
			7750 BP?		14C	explosive, pyroclastic flows		GVP	3
			8170±200 BP		14C (corrected)	explosive, pyroclastic flows, Plinian deposits	4?	GVP, LaMEVE	
			8400 BP?		14C	explosive, pyroclastic flows, dome		GVP	3
			8560±150 BP		14C (corrected)	explosive, pyroclastic flows	4?	GVP, LaMEVE	
			9000±1000 BP		Uranium series	Sans Nom lava dome		GVP	3
			9270±1000 BP		14C (corrected)	explosive, pyroclastic flows, dome		GVP	3
			9700±500 BP		Uranium series	Aileron lava dome		GVP	3
			10160±200 BP		14C (corrected)	explosive, pyroclastic flows	4?	GVP, LaMEVE	
Montserrat	Soufriere Hills	Stratovolcano	1995-present		Historical records	explosive, pyro flow, phreatic, dome, spine, mudlfow, tsunamis, large vol debris avalanche, damage, fatalities	3?	VHA, GVP	
			1667±40		Uncertain eruption	dome forming		VHA	3
			1630±50		14C	Castle Peak lava dome formed		GVP	3
			3950±75 BP		14C	English's Crater formed, explosive, pyro flow		VHA, GVP	3
			≈31000 BP	16000BP		pyroclastic flows		VHA	3
Nevis	Nevis Peak	Stratovolcano							

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
Saba	Saba	Stratovolcano	1670		14C	explosive		VHA	2
			before 1640		Historical records	explosive, pyroclastic flows		GVP	3
			after ≈100,000 BP			dome formation		VHA	3
			≈100,000 BP			gravitational sector collapse		VHA	3
			≈400,000 BP	≈100,000 BP		Plinian style activity		VHA	4
			≈500,000 BP			Pelean domes, dome flows		VHA	3
St. Eustatius	The Quill	Stratovolcano	250±150		14C	explosive, pyroclastic flows		GVP	3
			2500 BP?		14C	explosive, pyroclastic flows		GVP	3
			8090±200 BP		14C	explosive, pyroclastic flows, Plinian deposits		GVP	4
			8968±305 BP		14C (corrected)		4?	LaMEVE	
St. Kitts	Mt. Liamuiga	Stratovolcano	08-Feb-1843?		Historical records			VHA, GVP	
			1692?		Historical records			VHA, GVP	
			160±200		14C	explosive, pyroclastic flows, phreatic, Plinian deposits		GVP	4
			173±84		14C (corrected)		4?	LaMEVE	
			60±100		14C	explosive, pyro flow		GVP	3
			3960±150 BP		14C	explosive, pyroclastic flows, mudflow, Plinian deposits		GVP	4
			4470±314 BP		14C (corrected)		4?	LaMEVE	

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
St. Lucia	Soufriere Volcanic Centre	Qualibou = Caldera	1766		Historical records	phreatic eruptions from Sulphur Springs	1	VHA, GVP	
			42264±1376		14C (corrected)	formation of Qualibou caldera?? (forming Chioseul Tuff)	6	LaMEVE	
St. Vincent	Soufriere	Stratovolcano	13-Apr-79	26-10-1979 ±5 days	Historical records	explosive, pyro flow, phreatic, dome, mudflow, damage	3	VHA, GVP	
			04-Oct-1971 ±6 days	20-Mar-72	Historical records	lava flow, crater lake, dome	0	VHA, GVP	
			06-May-02	03-Mar-03	Historical records	explosive, pyro flow, phreatic, mudlfow, crater lake, tsunamis, fatalities, damage, ashfall	4	VHA, GVP, LaMEVE	
			1880?		Historical records	increased fumarolic activity with possible development of lava dome	0	VHA, GVP	
			09-Jan-1814	09-Jan-1814	Historical records	phreatic, crater lake	1?	VHA, GVP	
			27-Apr-1812	09-June-1812 ?	Historical records	explosive, pyro flow, mudflow, crater lake, fatalities, damage	4	GVP, LaMEVE	
			Mar-1784		Historical records		0	GVP	
			1780		Historical records	fumarolic activity possibly accompanied by lava emissions		VHA	1
			26-Mar-1718 (26-May-1718)	29-Mar-1718 (29-May-1718)	Historical records	explosive	3	VHA, GVP	
			1640±50		14C	explosive, pyroclastic flows		GVP	3
			1550±50		14C	explosive, pyroclastic flows		GVP	3
			1480±150		14C	explosive, pyroclastic flows		GVP	3
			1395±75		14C	explosive, pyroclastic flows		GVP	3

Island	Volcano	Volcano Type	Eruption Episode Details					Source	Estimated VEI
			Start Date	End Date	Dating Method	Description	VEI		
			1325±75		14C	explosive, pyroclastic flows		GVP	3
			905±75		14C	explosive, pyroclastic flows		GVP	3
			2480±75 BP		14C	explosive, pyroclastic flows		GVP	3
			2700±100 BP		14C	explosive, pyroclastic flows		GVP	3
			3550±75 BP		14C	explosive, pyroclastic flows		GVP	3
			3970±75 BP		14C	explosive, pyroclastic flows, mudflows		GVP	3
			4085±50 BP		14C	explosive, pyroclastic flows, mudflows		GVP	3
			4150±150 BP		14C	explosive, pyroclastic flows		GVP	3
			4260±100 BP		14C	explosive, pyroclastic flows		GVP	3
			4330±100 BP		14C	explosive, pyroclastic flows, lava flow, mudflows		GVP	3

KEY	
GVP	Smithsonian Global Volcanism Program
VHA	Volcanic Hazard Atlas of the Lesser Antilles
LaMEVE	Global database on large magnitude explosive volcanic eruptions
	Same eruption?
VEI	Volcano Explosivity Index
14C	Uncorrected radiocarbon
14C (corrected)	Corrected radiocarbon
K-Ar	Potassium-Argon
Hydrophone	Submarine hydrophone detection (T-phase)