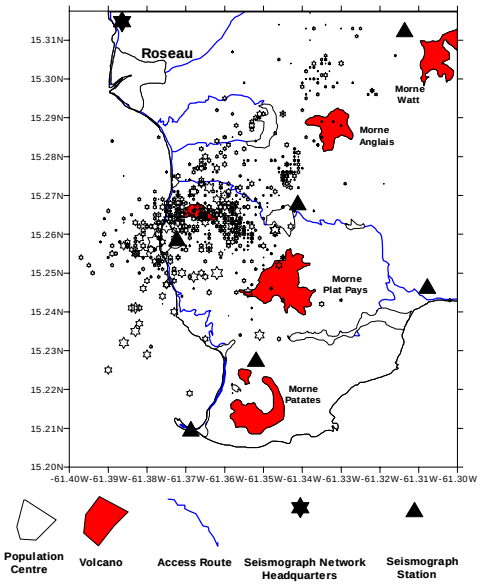
Seismic Research Unit

THE UNIVERSITY OF THE WEST INDIES

Volcano Hazard Report for Southern Dominica:

Interpretation of 1998-2000 Earthquakes
and
Hazard Mapping Results



8 May, 2000

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1. PROJECT SUMMARY

Point-form summary of scientific achievements since October 1998*:*

- Continuous monitoring of earthquake swarm using a 9-station seismograph network
- 19-station GPS network established and used for monitoring ground deformation across 6 of 8 volcanoes in Dominica (all volcanoes south of the Layou and Pagua Rivers)
- Detailed volcanological observations made at 147 sites allowing prehistoric eruption behaviours established to be established for volcanoes within the area of the recent earthquake swarm
- 93 rock samples taken for chemical analyses

Point-form summary of scientific results since October 1998:

- Seismicity at 1-5 km depth beneath southern Dominica reflects magma movement [1]
- Swarms are reaching closer to the surface, producing stronger earthquakes, and lasting longer with each re-occurrence since the 1960s
- Earthquake characteristics provide strong evidence of the presence of magma within 3 km of the surface in the area of Bellevue Chopin-Pointe Michel-Loubiere
- No changes in geothermal activity and no ground deformation have been observed during swarm
- 13 new C-14 dates obtained on pre-historic eruption deposits allow determination of the frequency of eruptions in southern Dominica as 300-1500 years.
- Approximately 20 previously-unrecognized eruption episodes discovered in southwestern Dominica with ages less than 50,000 years
- Of the newly-discovered eruption episodes, 6 happened less than 10,000 years ago

[1] Where technical jargon is used in this report it is marked [G] and explained in the glossary

- The recent volcanic histories of Plat Pays, Anglais and Micotrin have been determined in detail

- Plat Pays, Anglais, Micotrin, Trois Pitons, Watt, Valley of Desolation and Grande Soufriere Hills have all erupted within the last 50,000 years. All can now be confirmed as "live": all are possible locations of future eruptions

- Most likely next hazardous volcanic event: a phreatic [G] (water only, no magma) explosion in the Valley of Desolation (radius of high hazard 2 km)

- Most likely next magmatic eruption: a dome eruption in the Bellevue Chopin-Pointe Michel-Loubiere area within the next 100 years, with related hazards persisting for 10-50 years after the start of eruption

- Preliminary versions of eruption scenarios and hazard maps for the five most-likely magmatic eruption cases completed

- A preliminary integrated volcanic hazard level map for southern Dominica has been completed.

Executive Summary

From September 1998 to May 1 2000, Dominica experienced 1650 earthquakes associated with two southwestern volcanic centres: Morne Plat Pays and Morne Anglais. The activity was monitored using a network of 9 short-period seismographs. Most events were typical volcanic earthquakes. 80% of the 700 locatable events were 2-5 km deep, and 96% were between 1 and 9.4 km deep. The activity peaked on October 23rd 1998, with 180 earthquakes, then decayed nearly exponentially. Most seismicity occurred within 19 pulses, each 1-3 days long, with smaller, more widespread events between pulses. Pulse hypocenters[G] defined paths starting at about 5 km depth in the central southwest (between Anglais and Plat Pays) and shallowing to 1 km while trending up to 10 km west from the starting point.

Geothermal activity, which is widespread on the island, did not change during the swarm period. GPS[G] measurements were made on a new 19-station network every 1-2 months, starting in October 1998. No ground deformation was measured during the swarm period. New mapping and 13 new ^{14}C ([G]) dates reveal at least 20 previously unrecognized eruption episodes from the last 50,000 years, 6 of which occurred within the last 10,000 years from 4 different centers – Morne Plat Pays, Morne Anglais, Micotrin and Valley of Desolation/Morne Watt. Over the last 50,000 years there have been a total of at least 50 eruptions in southwestern Dominica. Morne Anglais' 4 most-recent episode were summit eruptions producing airfall, pyroclastic flows and dome extrusions[G]. Morne Plat Pays, after a major explosive eruption about 50,000 years ago which generated a 4.5 km-diameter caldera[G], produced at least 16 lava domes and related minor explosive activity, up to as recently as 685 years ago, when Morne Patates last erupted. Domes were extruded along caldera-related faults and centrally on the caldera floor. The recent pulses of seismicity underlie the northern part of the Morne Plat Pays dome field.

The association of shallow earthquakes with volcanic features and the patterns of the seismicity indicate a volcanic origin, probably from repeated intrusions of magma. The stability of the geothermal system and lack of ground deformation suggest that the intruded volume was small, and deeper than the level at which groundwater circulates. Seven previous swarms in the same area between 1967 and 1998 show that southwestern Dominica is underlain by an active magma plumbing system. In addition, the seismic swarms have become increasingly energetic, long lived and shallow with time. All factors taken together indicate the next eruption of magma in southern Dominica could occur at any time within the next 100 years. The occurrence of two phreatic explosions in the last 120 years (1880 and 1997) in the Valley of Desolation shows that this area presents a more localized, separate hazard. Similar explosions in this area are considered to be the most likely next volcanic event.

The location of the seismic swarm and its inferred volcanic origin, together with intensive geologic mapping in southern Dominica has led to the identification of the Bellevue Chopin-Pointe Michel-Loubiere area as the most likely location of the next magmatic eruption. Past volcanic activity in this area indicates that future activity will most likely take the form of a dome-eruption, which will create hazards similar to those experienced on Montserrat during the recent eruption there. Hazard maps relating to this scenario, along with four other possible eruption locations and scenarios, are discussed and presented in this report. A weighted compilation of these 5 most likely scenarios is used to develop a map of relative volcanic hazard levels.

Given the existence of a magma plumbing system ready to erupt and the possibility that the eruption could occur anywhere from Morne Trois Pitons south, continuous intensive monitoring and hazard re-assessment are critically important.

2. INTRODUCTION

The Seismic Research Unit is the regional institution in the Commonwealth eastern Caribbean responsible for the monitoring of earthquakes and volcanoes, and for their hazards mitigation. Since 1953 Dominica has been closely monitored for earthquake activity and has proven to be the most seismically active location in the region, both in terms of deep, tectonic (non-volcanic) earthquakes and shallow volcanic events. The island is the only one in the Caribbean to have more than one major volcano; at present, we consider it to have 8.

Table 1. Volcanoes of Dominica

Volcano[1]	Age of most recent eruption known	Number of eruptions in the last 50,000 yrs	number of eruptions in the last 10,000 yrs	latest characteristic eruption behaviour
Morne Plat Pays	685	20-40	2	lava dome
Morne Anglais	6700	5-10	1	pyroclastic
Morne Trois Pitons/Micotrin	1160	10-20	1	lava dome
Valley of Desolation/Morne Watt	1020	3-6	2	pyroclastic
Grande Soufriere Hills	11000	1-?	0 ?	pyroclastic
Morne Diablotins	<40000	2-?	0 ?	pyroclastic
Morne aux Diables	?	?	?	lava dome
Foundland	?	?	?	lava flow
Total eruptions		> 80	~ 10	

[1]Yellow: the level of information is considered sufficient for a preliminary hazard assessment, and the volcano is considered a potentially serious hazard. Pink: level of information considered insufficient for a preliminary hazard assessment but the volcano considered a potentially serious hazard (further work needed). Grey: volcano not currently considered a potentially serious hazard.

These volcanoes have generated the largest eruptions in the region, most of them have erupted in the last few millenia, all have associated vigorous geothermal ('soufriere' or 'hot spring') activity and all have had clusters of shallow earthquakes beneath them in the last century. It is therefore considered by us and many scientists worldwide to be one of the most volcanically hazardous countries in the world. Amongst all scientists who have studied it, there is no doubt that Dominica will experience a powerful eruption in the future; the relevant questions are when? where? how? Unfortunately, the high cost of volcanic fieldwork and of associated analytical work plus Dominica's steep topography and dense vegetation have inhibited scientific studies. As a result Dominica was, until two years ago, one of the least-studied Caribbean islands. Since then the situation has changed completely. The intense efforts of the recent and ongoing work are making Dominica one of the best-studied of the eastern Caribbean islands.

Despite Dominica's inevitable volcanic future, it has equally unstoppable growth in population and industry. Without taking great care, the situation represents a collision between man and nature. There are many locations on the planet in the same situation, and it has been found elsewhere that two steps to ensure sustainable development are

(1) to determine the magnitude, type and frequency of past volcanic events, and
(2) to monitor relentlessly for early signs of impending volcanic events.

In addition, monitoring for sufficiently long periods yields critical, current information that feeds into the hazard assessment. In this report we provide first a summary of the recent seismic activity and a description of its meaning for Dominica's future, then an overview of hazard mapping results giving volcanic highlights of Dominica's past. We then use all the information at hand to produce a series of likely volcanic eruption scenarios and resulting hazards maps for southern Dominica. Finally a composite hazard map is presented which is relevant to land-use planning and future infrastructural distribution. We provide a glossary containing definitions of common volcanological terms and descriptions of eruption processes and hazards.

This report results from a project motivated by the most recent seismic swarm, which started in September 1998 and was largely over by May 1999, although it continued at a low level through April 2000. Details of the swarm will be considered in Section 3. Because of the seriousness of the situation the Seismic Research Unit stationed a volcanologist in Dominica continuously for six months, from March to August 1999. He was backed up by frequent visits by specialists not only from the Seismic Research Unit but also from the United States Geological Survey and from other US institutions. The monitoring efforts were stepped up by expanding the seismic network and installing an extensive ground deformation network for Global Positioning System (GPS) and other surveying techniques. Dominica is now the most heavily instrumented and intensely monitored island in the OECS. In the southwestern area of intense seismicity, a major hazard mapping project was completed during the seismic swarm. With the end of that project and the delivery of this report, however, we are not turning our attention away from Dominica. In fact we are a long way from being satisfied with what is known, and are continuing in a number of ways. We are performing extensive chemical analyses on rock samples collected during the previous work, we are expanding the seismic monitoring network into the north, we will begin additional hazard mapping, rock sampling and analytical work in the next 4 months, and we are reexamining all existing seismic records..

It is important to note that this report discusses the volcanoes of southern Dominica almost exclusively, and focuses on a subset of these. The reason for this is simple: we focus on the area which is showing early signs of volcanic activity. By comparison, the northern volcanoes are currently of far less concern. Nevertheless, the northern volcanoes are young enough and seismically active enough to be considered live. Hence they also represent a future hazard, and therefore a hazard assessment of them is a future requirement. Despite a paucity of information on the north, we consider that our current results provide a reasonably accurate assessment of the current volcanic hazards, and cover 6 of Dominica's 8 volcanoes.

3 SCIENTIFIC RESULTS

Earthquake Activity

Background

In the Caribbean there are two sources of earthquakes: plate tectonics and volcanic systems. Plate tectonics generally produces earthquakes at a range of depths (up to 200 kilometers below the Earth's surface), which are one-off events or short-lived sequences associated with major faults in the Earth's lithosphere[G]. Volcanic earthquakes are shallow (less than 15 km), tend to occur in swarms lasting months or years, and are associated with volcanoes. Both types occur commonly beneath Dominica. In this hazard assessment we will be concerned purely with volcanic earthquakes.

Earthquakes before 1953

Dominica is known to have experienced frequent intense swarms of volcanic earthquakes for at least the last two hundred years. Sequences of felt earthquakes were reported in February-June 1765, October 1841, January-April 1849, February-March 1893 and October 1937 to April 1938. Some of these sequences were associated with the northern and central Dominican volcanoes but those of 1849 and 1937-38 were certainly centered in the south. Before 1952 there were no seismographs in the island so that all knowledge of these swarms comes from accounts of felt earthquakes.

Earthquakes 1953-1998

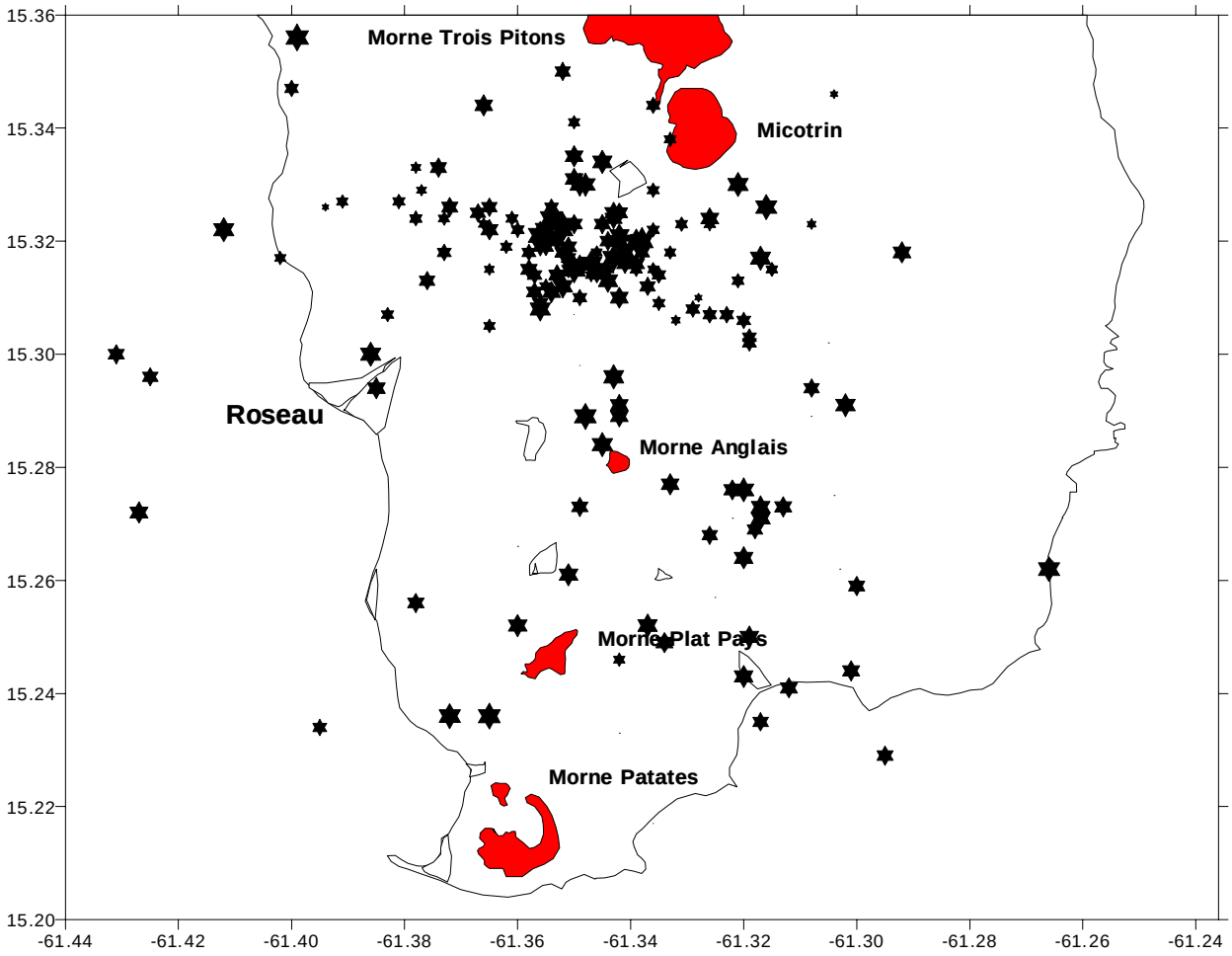
The first instrument was installed in the Botanical Gardens in Roseau in 1953 and operated continuously until it was destroyed by hurricane David in 1979. This instrument was capable of detecting small volcanic earthquakes and determining their distance from Roseau but was not capable of determining their precise location. Significant swarms occurred in southern Dominica in September to December 1959, June 1967, January 1971, April-November 1974, February-June 1976, November 1985 to June 1986, December 1994 - January 1995 and November-December 1997. In 1959, 1974 and 1976 (the 1967 swarm lasted for a single day only) extra, temporary seismograph stations were installed in Dominica as soon as it was known that a swarm was in progress but in each case the swarm was over, or almost over, by the time that the instruments arrived. The reason for this was that the Dominica seismograph recorded data locally and the records were sent to Trinidad by post for further analysis. Even at the best of times it could be several weeks before the records reached Trinidad and at the worst of times it could be up to three months.

The situation improved considerably in 1980 when the original station was replaced by two more-modern stations at Morne Daniel and Morne Espagnol (Barbers Block) which transmitted data continuously to Trinidad and Guadeloupe respectively.

When the next swarm occurred in 1985 temporary stations were again established (and again arrived too late to collect significant quantities of data) but this time they were left in operation

after the swarm ended and continued to transmit data continuously to Trinidad. This network was capable of locating all local earthquakes which occurred in southern Dominica. Figure 1 shows the epicentres of all earthquakes which were located by the temporary networks between 1959 and 1985 and the permanent network between 1985 and 1998.

Figure 1 Shallow earthquakes 1952-1997

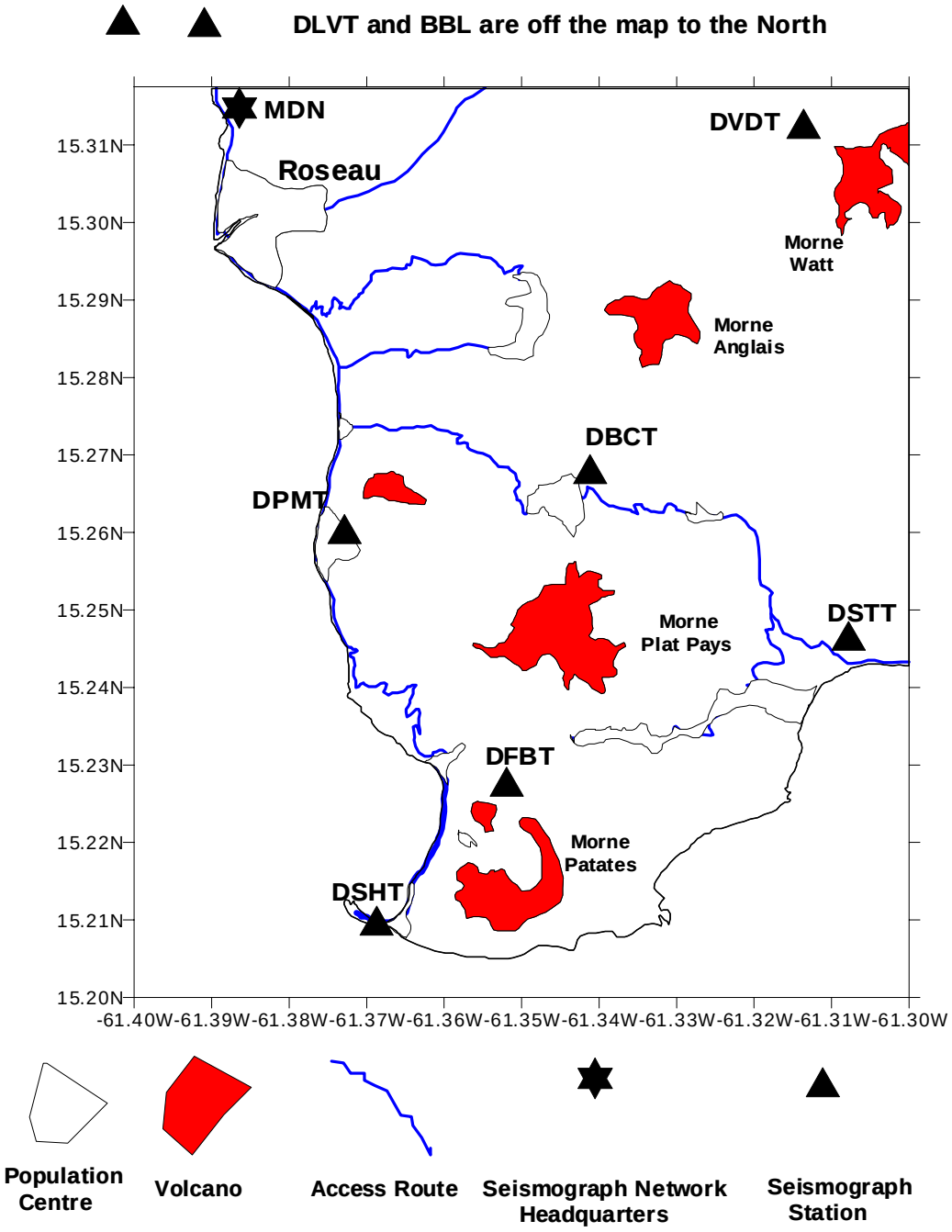


This map is not fully representative since it includes only those earthquakes which occurred when there happened to be a full network in operation. The cluster of earthquakes between Roseau and Micotrin volcano for example almost all occurred during a single period of eight hours in October 1974. However the general pattern illustrates the major problem of volcanic hazard assessment in Dominica. The earthquakes are not unequivocally associated with any single volcanic centre.

The ongoing swarm

In September 1998 the most recent southern swarm began, by which time there was a network of instruments in southern Dominica to provide high-quality monitoring; as soon as the swarm began, the stations were reconfigured and improved slightly to suit the situation. The current network configuration is shown in Figure 2.

Figure 2: Current seismograph network in Dominica



The base of the network is at Morne Daniel (MDN) north of Roseau. This station is equipped with a three component short-period seismometer whose signals are recorded digitally on a Personal Computer (PC). Signals are digitized at a resolution of 16 bits with a sampling rate of 100 samples per second. Gain ranging produces a nominal dynamic range of 143 db. All other stations (except BBL in the extreme north of the island) are linked to MDN by radio telemetry, telephone lines or a combination of both. The records can be read directly at MDN or downloaded by direct telephone link or internet connection to any remote location. Routinely the signals are transmitted to Trinidad through the internet at 6AM each day and subsequently updated by telephone interrogation every few hours. BBL records separately in Guadeloupe but data are available rapidly from the Guadeloupe Volcano Observatory.

There are a number of reasons for having a network of instruments rather than a single seismograph: first, most of the small shallow earthquakes which characterize volcanic swarms cannot be detected by instruments more than about 10 kilometers from the earthquake location (epicentre[G]); second, in order for us to calculate the locations of earthquakes they must be recorded on at least three seismographs. For accurate determination of focal depths, the nearest station to the earthquake should be no further away from the earthquake epicentre than the depth of the earthquake below the Earth's surface and for accurate location of the latitude and longitude of the earthquake the stations should surround the earthquake epicentre. There should also be stations at greater distances (100 km or more) from the volcano to allow detailed study of any larger events which may occur. To keep down costs, most stations record only the vertical component of ground motion but the network should include one or more stations which record two horizontal components of ground motion in order to help identify seismic shear waves.

For this investigation we knew from figure 1 that volcanic earthquakes were likely to happen almost anywhere in southwestern Dominica at focal depths[G] of between three and five kilometers. The requirements of the previous paragraph indicate that the ideal seismograph configuration for Dominica would include stations evenly distributed with a spacing of about 3 kilometers between stations with more stations in adjacent islands. The network of figure 2, which includes a three-component station at MDN and is reinforced by more distant stations in the rest of the Lesser Antilles, does not quite achieve this objective but it is considerably better than is usually achieved before volcanic earthquakes start. The earthquakes in this swarm ranged in size from very tiny ones which could be detected only if there happened to be a seismograph station very close by to larger ones which were recorded by all of the stations of figure 2 plus some in Martinique and Guadeloupe as well[2].

Basic features of the recent swarm are shown graphically in Figures 3-4. Daily numbers of earthquakes peaked on 22/23 October 1998, and then gradually tailed off. The level of activity has now dropped back the level in the months prior to September 1998 of 5-10 events per month. Of the total number of earthquakes (including those which were detected at only one or

[2] Non seismologists often ask how big the earthquakes were "on the Richter scale". The Richter scale has in fact not been used by seismologists since about 1950 and is inapplicable to Dominica anyway. We use different and more useful methods to measure the size of earthquakes. In familiar terms the smallest earthquakes detected in Dominica were about equivalent to moderate quarry blasts. The largest was equivalent to the explosion of a moderate-sized nuclear weapon.

two stations and therefore could not be located) almost all occurred in the first 12 months, with a total of 1599 and an average of 133 per month from Sept. 1998 to Sept. 1999. From September 1 1999 to April 30 2000 there were 50 earthquakes for an average of 6 – 7 per month.. The most recent brief renewal of activity occurred as this report was being written.

The swarm consisted mainly of about 19 earthquake sequences lasting a few days and spaced at intervals of a few weeks to months. The earthquakes between these pulses were generally small in magnitude and scattered more or less randomly across southwestern Dominica. During pulses, earthquakes tended to occur in organized patterns in which the hypocentres defined paths beneath Dominica. Earthquakes at the onset of a pulse occurred at depths of 5-10 km beneath the area of Bellevue Chopin, and with time during each pulse they occurred at shallower depths and ever farther west, reaching depths of 1-3 km and positions west of Pointe Michel. With time, the summation of these paths delineated a central corridor to the seismic swarm stretching from Bellevue Chopin to Pointe Michel and Loubiere.

Figure 3:Earthquake numbers, September 1998 to April 2000

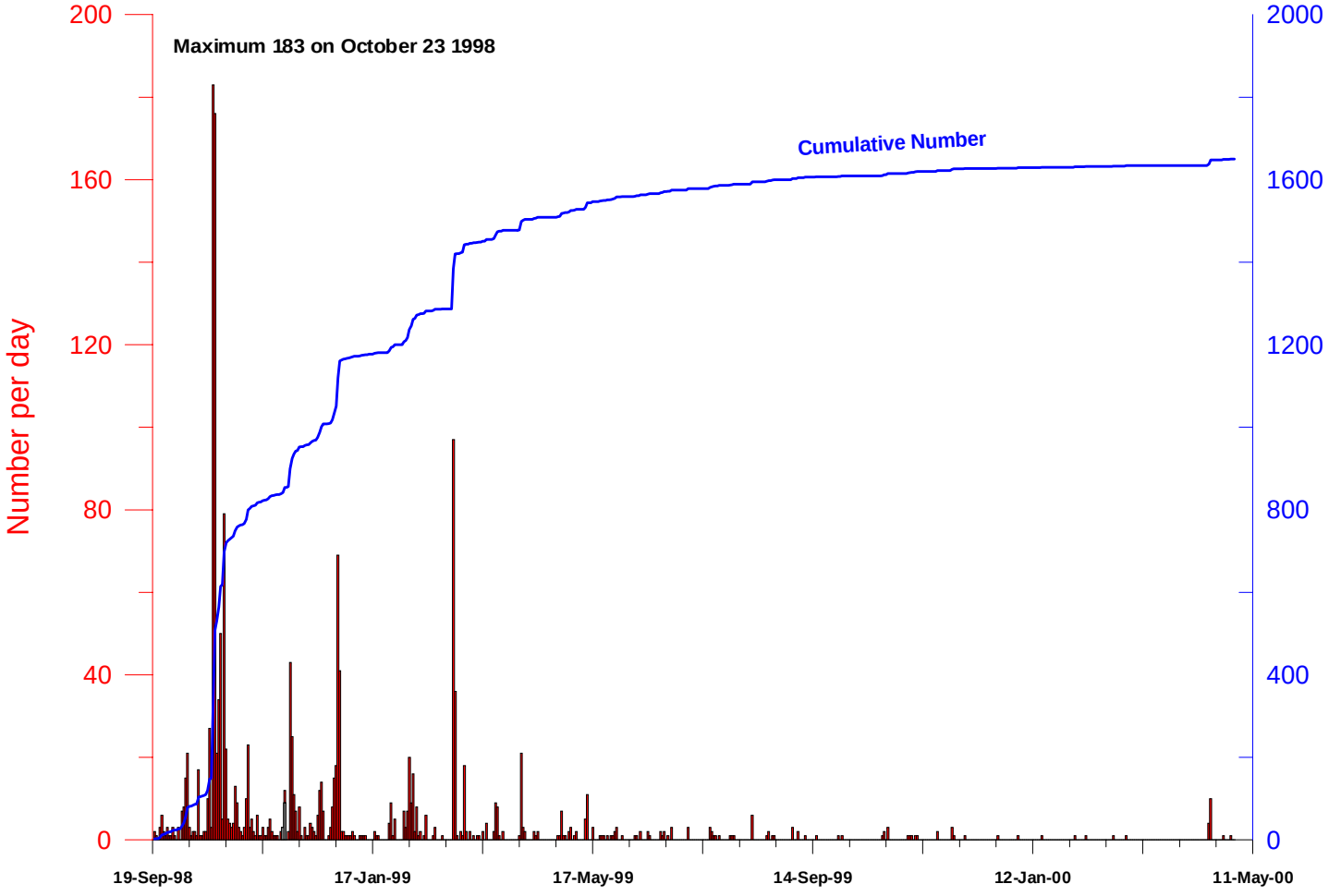
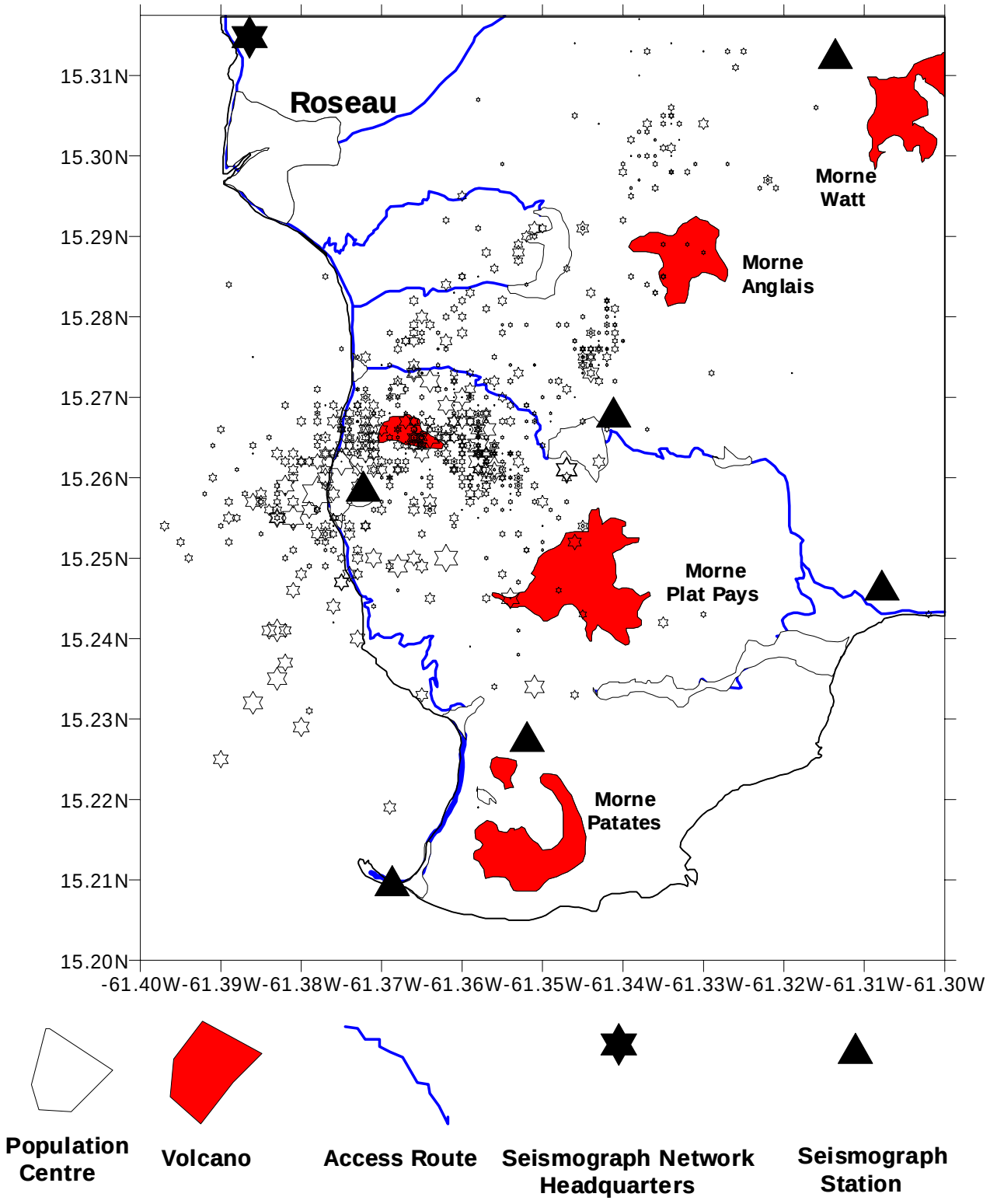


Figure 4: Earthquake epicentres, September 29 1998 to May 1 2000



Previous swarms showed generally similar patterns and occurred in essentially the same areas (Figure 1). It is likely, therefore, that all the southern swarms in the last few decades have had the same cause. In addition, it is important to recognize that of the activity since seismographs were first installed in Dominica, the recent swarm included the biggest earthquakes, the greatest total number of earthquakes, the shallowest earthquakes, and lasted longer than any other.

The patterns seen in the recent swarm are characteristic of volcanic earthquake sequences. Our preliminary interpretation is that the paths defined by earthquake locations during pulses are the approximate paths that magma (molten rock) is being squeezed along as it moves away from some pressurized reservoir region through cracks in the surrounding solid rock. This is consistent with the rapid start of the swarm followed by a gradual decay, a specific pattern which can be shown to result when a pressurized reservoir of liquid gradually leaks out its contents and thereby depressurizes. The similarities to previous swarms indicate that there is currently a single, dominant magma reservoir system which becomes periodically pressurized, breaks open and leaks magma into a favoured weak zone. This zone of weakness extends upward and westward toward the Pointe Michel area. All this suggests strongly that future activity will originate in the same reservoir and will take advantage of the same zone of weakness. In the case of the recent swarm, the reservoir pressure was insufficient to push magma to the surface, but it is valid and relevant to ask “how close did it get?”. The magma reservoir under Dominica is apparently at a depth of approximately 6 km, where most of the deeper seismic activity was located. From there, magma reached to depths of about 1 km. Therefore magma was able to climb 5/6 of the way to the surface. Once the right conditions are achieved, sufficient reservoir pressure for example, the process will not stop before the magma reaches the surface, and an eruption will occur. The fact that the most recent swarm was the most energetic and approached the surface more closely than at any other time in the last 50 years suggests that with time this volcanic system is moving toward eruption conditions. The geological studies which will be reported here indicate that in the recent past, eruptions in this region have occurred about every 300-1500 years and that it has been 685 years since the last one. Over the past 50 years the rate of shallow earthquake activity in southwestern Dominica has gradually accelerated so that the probability of an eruption is increasing with time and is now much higher than is suggested by the longer-term geological record. It is therefore reasonable to expect an eruption in the Bellevue Chopin-Pointe Michel area in the next 1-100 years.

The earthquakes suggest when and where the next eruption will occur, but do not provide clues about what kind of eruption to expect in the future, nor its size. Furthermore, since Dominica’s volcanic history stretches back far beyond our seismic monitoring, a more complete picture of what may happen must be developed by incorporating additional forms of observation.

Ground Deformation Measurements

Shallow seismic activity is only one type of precursor to a volcanic eruption. As magma pushes its way to the surface, it must force aside the surrounding rock and in general this causes the ground surface to deform, normally in a swelling sense. The amount of the deformation depends on how large a volume of magma is moving, and the depth of the movement. Large

magma volumes and shallow depths generate larger amounts of deformation. At other volcanoes, the amount of deformation preceding eruptions varies widely, but often is in the region of centimeters to tens of centimeters of ground movement over areas of a few to a few tens of square kilometers.

There are a variety of methods for monitoring ground deformation, all involving high-precision surveying equipment and techniques. We chose to apply Global Positioning System (GPS) equipment because it can measure position to within a few millimeters, and allows surveys to be performed quickly, even in remote locations. The basic idea is to install solidly-embedded bolts in the ground at locations throughout the area where an eruption may occur, and measure the position of each pin at intervals of 1-6 weeks. Significant changes in these positions can define magma movement. The GPS method uses signals from a group of satellites orbiting the Earth to determine position by a method of triangulation.

In order to monitor possible ground deformation in southern Dominica, a 6-site network of GPS pins was installed in the southwest from October 25 to 31 1998. The network was first measured using equipment borrowed from the Montserrat Volcano Observatory, from 1 to 5 November 1998, and again with the same equipment in January 1999. At that point the Seismic Research Unit purchased its own state-of-the-art GPS equipment and software, which it used to re-measure the network in April 1999. From early April, the network was expanded to 19 sites covering all volcanic centers south of the Layou River valley. During the expansion, the network was measured over the period 4 May to 26 June 1999.

Over the entire campaign no significant ground deformation was measured, which means that the ground did not deform by more than a few millimeters during the seismic swarm. This fact stands in stark contrast to the level of earthquake activity during the same period, and provides an extremely useful constraint on what was happening. Essentially, the lack of ground deformation shows that the combined magma reservoir and upward-migrating pulses of magma emanating from it were too small in volume and too deep significantly to deform the ground surface. This is also consistent with the earthquake data, which show that the magma did not approach closer than 1 km to the surface of the Earth

These results have some positive implications. For example, a useful measure of the magnitude of a volcanic eruption is the volume of magma erupted. Typically, large-volume eruptions are also extremely violent and hence impact a larger area. In order for a large volume of magma to be erupted, it must have a proportionally larger reservoir volume. Dominica, with its long history of volcanism, has had all sizes of eruption from very small to extremely voluminous, information which by itself leaves open the possibility of the next eruption being large magnitude. The earthquake data and interpretation, coupled with the ground deformation results, indicate that the currently active magma system under Dominica is small in volume and hence the most likely future eruption will be small in magnitude. This is a result which is consistent with geological observations made during the hazard mapping phase of the project (Sections 4 and 5).

Another major outcome of the ground deformation campaign was the establishment of a network of GPS pins with precisely-measured locations. This network covers all volcanoes in

southern Dominica (6 of 8 in the country). Such baseline measurements, taken prior to ground deformation actually happening, are very rare in the Caribbean and extremely useful for monitoring purposes. We now have the capability of quickly detecting an increase in activity at depth with full confidence. The GPS network will be re-measured every 6-12 months to monitor for early signs of activity and maintain our baseline data.

An incidental result of our ground deformation measurements was the determination of Dominica's true position on the Earth. We found that our GPS locations were displaced from the apparent map locations by slightly more than 1 km, which was extremely problematic for accurately locating seismic stations, earthquake hypocenters, GPS pins and sample sites. This is a problem which is fairly common in the West Indies and appears to have resulted from minor errors in very early surveys done by the U.K. Department (now Directorate) of Overseas Surveys. Locations in Dominica are correct relative to each other, it is simply that they are as a group placed in the wrong place on the Earth's surface. We have resolved this problem by working closely with the Dominica Department of Lands and Surveys. By using GPS to measure a series of Lands and Surveys survey locations, we have calculated a method of transforming all Lands and Surveys locations to their true positions. The results of this work have been reported to the Department of Lands and Surveys.

Hydrothermal Activity

Dominica has an abundance of hot springs and fumaroles[G], the most famous example being the Boiling Lake. The vigorous venting and associated sulphurous odors and heat make it tempting to believe that these areas are where magma is most likely to rise, and that it may even be just a few meters below the surface. These are misconceptions. An equally serious misconception, widespread in Saint Lucia but thankfully not in Dominica, is that hot springs provide a safety valve which means that an eruption cannot happen. Hot springs are not necessarily the most likely locations for future eruptions but they do indicate that hot rock exists not too far below the surface.

Wherever volcanoes exist in wet climates, there are hot springs and fumaroles. The current understanding of such systems is that water from rain, lakes, rivers and the surrounding sea percolates into the ground to depths of hundreds of meters, and sometimes thousands of meters, in narrow cracks, where it comes into contact with rock which itself has been heated by yet more deeply-seated magma. The water is heated, and before it penetrates much deeper it becomes buoyant and rises back to the surface. If heated sufficiently, it rises as steam. Only a small amount of the hot spring water or fumarole gas comes from the molten rock below the surface, or even has had contact with magma. While hot, this circulating water dissolves and reacts with the surrounding rock, altering the water chemistry typically by making it acidic and rich in sulfur, calcium, silicon and iron. The hot water appears at the surface to form hot springs and fumaroles, and when it cools it releases its dissolved minerals to form red-stained (iron) deposits and deposits of sulphur, calcium carbonate and chalcedony (hydrated silica). The hot, acidic water breaks down minerals in the near-surface rocks, forming large amounts of clay.

In detail, hydrothermal fields show considerable variability with time. One hot spring may become sealed up with sulphur or clay while a new one forms nearby, or particularly wet weather

or high tides may provide extra water and lead to increased hydrothermal activity. In addition, from time to time some water may become trapped, and if it is heated to steam it may burst the encasing rock with little or no warning, producing a sudden, minor steam explosion. Explosions such as these, particularly if a number occur in succession are known as phreatic eruptions. Small phreatic eruptions occurred in the Valley of Desolation in 1880 and 1997. In such explosions, there is often no direct involvement of magma. When magma finally does fracture upward, perhaps on its way to erupting, it intersects the shallow wet zone and provides yet more heat to the circulating water. The result is a highly localized increase in hydrothermal activity directly prior to an eruption. The overall sequence of observations that has played out repeatedly at other volcanoes is:

(1) Significant earthquake activity which migrates toward the surface with time, accompanied by accelerating ground deformation;
(2) Increasing hydrothermal activity, including the creation of new hot springs and fumaroles, in a specific area coinciding with the earthquakes and ground deformation;
(3) Magma eruption at the surface.

This is a particularly common eruption precursor sequence in the West Indies, and usually the changes in the hydrothermal system immediately prior to eruption are so vigorous that they are impossible to miss. However, subtle changes in the water and gas chemistry and water temperature of hydrothermal fields have been observed to occur over wide areas surrounding volcanoes many months before they erupt. This possibility of early detection warrants regular monitoring of Dominica's hydrothermal system. In cooperation with external scientists we are organizing such a programme.

The major soufrieres of southwestern Dominica have been monitored at long intervals by French scientists from the Guadeloupe Volcano Observatory, whose dominant interest has been the chemistry of the gases and waters. The areas normally sampled are the hydrothermal fields of Morne Patates, Soufriere, Champagne, Wotten Waven, Trafalgar and Valley of Desolation (including the Boiling Lake). During our monitoring efforts we made examinations and temperature measurements of hot springs on a more frequent basis. No significant changes were observed by either group throughout the seismic swarm. This is further evidence that the magma that pushed upward did not reach closer than about 1 km from the surface. That is, the magma never penetrated into the shallow wet zone in which hot water circulates.

4 Prehistoric volcanic eruptions

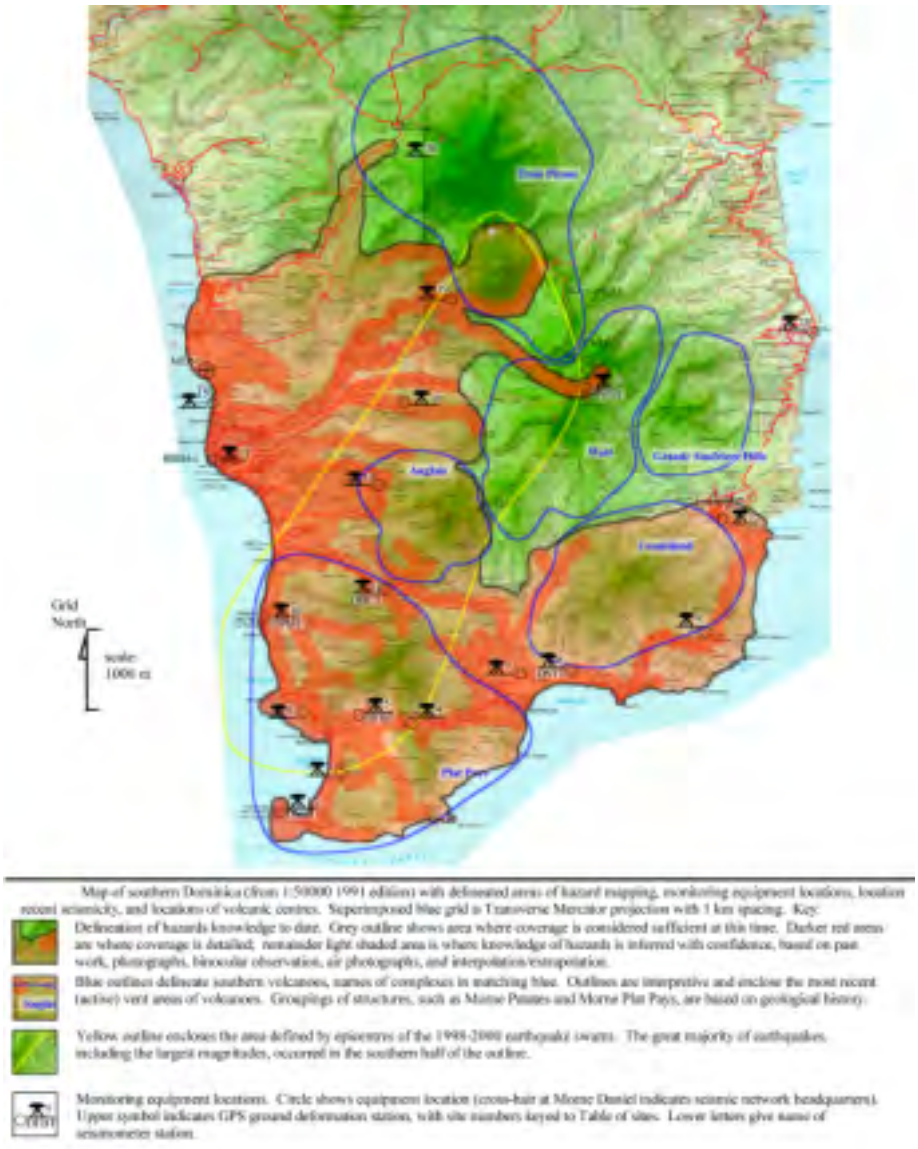
Background

It has been found that the best predictor of a volcano's future behaviour is its most recent behaviour. Therefore, constructing a hazard map requires unraveling a volcano's history, which is done by volcanological mapping. Mapping consists of various tasks, including

- Identification of separate, recent eruptions based on their deposits.
- Deduction of what sort of volcanic activity produced them, and
- Tracing out deposit extents to determine the areas impacted.

These activities are time-consuming, detailed work because even very thin or small-volume deposits can have great significance for hazards. For example, pyroclastic surge eruptions may leave deposits only a few centimeters thick, which can be largely and rapidly removed by wind, rain and streams. However, such eruptions are extremely violent and devastate all areas impacted, making it important to recognize their probability of occurrence. Although there have been a number of previous volcanological projects on Dominica which involved mapping, the compiled results were insufficient to allow construction of a reliable hazard map. Therefore we proceeded with new mapping, and have integrated the previous results. 147 locations were selected at which detailed observations were made. The general area covered by the investigation is shown in figure 5

Figure 5: Location map for Dominica investigations



Another important task in constructing hazard maps is the absolute dating of young eruptions. This allows us to assign a time frame to the volcanic history, providing such critical information as the average time between eruptions and the time since the last eruption. The most common method of obtaining eruption dates on young deposits is by Carbon-14 (^{14}C) dating of charcoal fragments in deposits. When explosive eruptions overrun vegetation, they break it up, incorporate the fragments and bake them to charcoal. The charcoal fragments are then preserved in the deposits. Not all deposits incorporate and preserve dateable material, so each deposit must be searched carefully. Sometimes entire tree trunks, branches or twigs can be found, but most often the charcoal comes in the form of millimetric flakes dispersed throughout the body of the deposit, and to collect enough for dating (about a thimble-full) may take half a day of carefulsearching with a pocketknife and tweezers. During mapping it is also usual to sample rocks from deposits. The chemistry of volcanic rocks can discriminate between otherwise similar deposits, give information on how a volcano is evolving on a long time scale, yield the recent conditions and depth of the magma reservoir, and provide clues as to the causes of eruption. During the mapping, 93 rock samples were taken, of which 20 are being analyzed chemically. A further 60 samples will be analyzed over the next 6 months. The results of the analyses will be presented in a later report.

Carbon-14 Dating

During the seismic swarm of 1998-2000, 13 deposits from prehistoric eruptions were sampled for dateable material (charcoal, charred wood and coral). The results are shown in Table 1, a compilation of all the known dating results for deposits in southern Dominica.

Table 1. Compilation of Carbon-14 Dates for Southern Dominica

age, ybp[1]	error	Sample no.[2]	type[3]	volcano[4]	locality
685	55	DOM678*	PPF	MPP	Soufriere, nr. school, 150 m from sulphur springs rd.
1020	40	DOM642*	PPF		tram line
1025	45	DOM698*	PPF	MW/VD ?	trail 1/3 to VofD from Titou
1160	45	DOM696*	LPF	MTP/M	Laudat
1560	40	DO30c*	LPF	MPP	Soufriere, nr. turn to sulphur springs
6650	50	DOM636c*	LPF	MA	Mt. Lofty Rd., nr. Refuge Estate
6825	75	DOM673*	PPF	MA	Grand Bay quarry
10290	60	D137c	PPF	MW/VD ?	Perdu Temps trail, at divide to River Jack
11000	85	DOM90-05	BLST	GSH	Corossol
17240	720	DTP-2	LPF	MTP/M	Bells bridge
19500	500	D24011	PPF	MTP/M ?	En Bas Petit Fond
>22200	--	DOM036*	SRG	MTP/M ?	Grande Savanne
25310	230	--	LPF	MTP/M	Bells
25370	120	D103c*	LPF	MTP/M	Bath Estate
26380	190	DOM664*	PPF	MTP/M	Micotrin ring road
26500	900	DM-2	LPF	MTP/M	Laudat
>27200	--	DOM067	PPF	MPP ?	Stowe
27600	600	D24404	PPF	MTP/M	Grand Fond
28400	900	D24021	PPF	MTP/M	Goodwill quarry
28400	900	D24358	PPF	MTP/M	Goodwill
28450	1500	DMP-54	AFS	MPP ?	Soufriere road
29000	4000	DOM056	SRG	MTP/M	Goodwill quarry

31000	4000	DOM085	PPF	MTP/M	Tete Grand Fond
34600	1500	D24011	PPF	MTP/M	Rosalie
35000	2200	DM-1	AFP	MTP/M	Goodwill
35800	260	DO77c*	AFP	MPP	Pt. Guignard Estate road
>36800	--	D24442	AFP	MPP ?	Fond St. Jean
38610	350	D009c*	PPF	MA	Wall House quarry
>40000	--	DTP-4	PPF	MTP/M	Layou
46000	4500	D24160	PPF	MTP/M	Goodwill quarry
>47330	--	D004C*	DCB	MPP	coral, nr. La Falaise quarry

[1]C14 ages: radio carbon years before present. Results are collated from recent results from Beta Analytic Inc. and USGS C14 lab, and past results with unknown data specifics.
[2] Samples archived in the Seismic Research Unit, UWI, St. Augustine (* indicates samples collected since 1998.)
[3]LPF=lithic pyroclastic flow, PPF=pumiceous pyroclastic flow, SRG=surge, AFP=airfall pumice, AFS=airfall scoria, DCB=dome carapace breccia, BLST=lateral blast
[4]MTP/M=Morne Trois Pitons/Micotrin, MW/VD=Morne Watt/Valley of Desolation, GSH=Grande Soufriere Hills, MPP=Morne Plat Pays, MA=Morne Anglais

The mapping and dating revealed 6 previously unknown eruption episodes in the last 10,000 years. Before 1998 only 1 eruption was known to be so recent. Other, older dates establish an additional 4 newly-discovered episodes. It should be kept in mind that there is an abundance of deposits between the dated deposits which do not contain dateable material but do represent separate eruptions. In addition, there are almost certainly more eruption episodes whose deposits have not been found, are not currently exposed, or have been removed by erosion. Therefore our estimate of the number of eruptions is a minimum. Through a combination of inference, mapping and dating we conclude that there have been at least 20 more eruptions in southern Dominica in the last 50,000 years than was previously acknowledged, raising the number from about 30 to 50 eruptions. This information shows that Dominica's volcanoes have been about twice as active as previously thought.

With the dating and mapping results together, an average eruption frequency is calculated at about 1000 years. Unfortunately, volcanic systems generally do not behave with perfect regularity, so actual repose periods between eruptions in the south can be expected to be between 300 and 1500 years. The dating results also show that there has been no tendency for a particular volcano to erupt, nor for eruption locations to migrate systematically with time, nor for separate volcanoes to erupt simultaneously. Eruptions have occurred at approximately random locations. This means that it is possible for the next eruption to occur almost anywhere in the south, although the earthquake activity of recent decades allows us to favour some locations over others

False eruptions

One highly misleading phenomenon sometimes results from fumarolic activity. Hot fumarolic gases deposit native sulphur around the fumaroles and over time large amounts of sulphur can accumulate. Native sulphur is inflammable and burns in a slightly peculiar way. Once ignited it burns slowly, usually without a visible flame, and melts at the same time to form a hot, viscous liquid. In all of the West Indian Islands where there are fumaroles ordinary bush fires occasionally ignite accumulated fumarolic sulphur which continues to burn for a long time and may flow over and destroy significant areas of vegetation. To the untrained eye the slowly flowing,

glowing, molten sulphur looks like molten lava, and false rumours of volcanic eruptions may result. Such an incident occurred at the fumarole field to the east of Soufriere village in 1994 and there is a graphic description of this "eruption" together with samples of the "lava" in the small nearby museum. We emphasize that this incident was a sulphur fire not a volcanic eruption.

5 Individual volcanic centres

Morne Plat Pays

The Morne Plat Pays volcano is better described as a volcanic complex as it is not a classical cone-shaped volcano with a central, summit vent. It has had a complicated history involving at least 3 stages of development, and encompasses a broad area. We consider that Morne Patates (previously considered to be a separate volcano) and a number of other domes such as Morne Canot, La Falaise and La Sorciere are part of the Morne Plat Pays complex.

The earliest phase of Morne Plat Pays' growth is not well understood, mainly because of limited exposure of deposits. Essentially it consisted of the build-up above sea level of a volcano similar in size to Morne Trois Pitons. The summit was probably near the area of Gallion, but at a greater elevation. This phase is relatively unimportant to the current hazard assessment except in setting up conditions for the second phase.

At some point after building up a large structure – probably in the region of 30-60 thousand years ago – there was a major eruption which produced the Soufriere valley and which represents the second phase of development. The precise origin of the valley has been a topic of debate amongst scientists for the last two decades or so, but our recent work appears to have resolved the issue. A violent explosive eruption occurred which produced an airfall pumice[G] deposit (seen at Fond St. Jean) and coated the flanks of the volcano with thick accumulations of hot pyroclastic flows, devastating a large area around the volcano. The eruption was sufficiently energetic that material moved over significant topographic barriers to coat much of the lower flanks of Foundland, on its eastern side from Dubuc to Bagatelle, and on its western side up the Perdu Temps valley to the Perdu Temps Estate. On all sides of the volcano, these flows poured into the sea. The deposit has been covered by deposits of later eruptions in areas west of Pichelin. It is, however, partially exposed east of Pichelin, especially prominent in the high, light-colored cliffs south of the main road between Bellevue Chopin and Grand Bay. Grand Bay itself is built on top of the deposit. In such voluminous eruptions it is typical that the magma reservoir region at depth is partially emptied, causing a collapse of the volcano's summit area and forming a large central depression called a caldera. The northern and eastern walls of the Soufriere valley represent original parts of the caldera scarp. The remainder of the caldera rim has been eroded down or altered by later eruptions and is less obvious. To the south the rim approximately follows the coast from Morne Fous to Scotts Head. From Scotts Head the caldera rim curves north and extends as a submarine ridge from Scotts Head to Point Guignard. The caldera has a diameter of 4.5 km. This eruption probably devastated most of the southern half of the island, while the northern half would have been uninhabitable for weeks to months afterward. An eruption of this size and type in the near future is considered extremely unlikely, but the possibility is discussed in more detail below.

We are currently in the third phase of Morne Plat Pays' development, involving the slow rejuvenation of the volcanic plumbing system which was largely destroyed by the caldera-forming eruption. In the thousands of years following caldera formation, magma has flowed back into the system, along paths of least resistance: fracture faults generated during the caldera eruption. Such faults commonly are concentric to the caldera rim, and surround a central area of fracturing corresponding to the original eruptive vent location. Manifestation of these fracture faults can be seen where they intersect the roadside rocks on the coastal road south of Loubiere. Magma flowing along these fractures has leaked to the surface in two main zones: the central part of the caldera and in the vicinity (and slightly beyond) the caldera rim. The resulting eruptions have consisted of the slow extrusion of small parcels of magma to form a series of approximately 16 lava domes. The quarry just south of Loubiere is actually dug into one of these domes (La Falaise) and another dome (Morne Canot) is prominent to the west of Belle Vue. At least one dome eruption occurred completely underwater, and was visited for observations and sampling by scuba diving. We believe the most recent dome activity to be the last eruption of Morne Patates, 685 years ago, which is also the most recent eruption in which magma breached the surface in Dominica – unlike the phreatic explosions in the Valley of Desolation in 1883 and 1997, which involved only water and solid, hot, near-surface rocks.

There are three important features of the recent dome eruptions that are particularly relevant to the current volcanic hazards. First, the eruptions were small in volume and energy, so that they generally did not devastate large areas and their effects were mostly constrained by local topography. For example, most of Morne Patates' activity would have affected only the Soufriere valley. Second, the previous domes show evidence of episodic, long-duration eruptions, or multiple reactivations, over a long time scale. Morne Patates, for example, erupted in a similar way 685 years ago, 1560 years ago, and up to 4 times before that, probably with similar time spacing. Third, deposits associated with the domes show that relatively small, but quite violent, explosions are common features toward the end of their growth. These come in the form of small volume airfall, pyroclastic flow and surge deposits mantling the flanks of the domes Morne Patates, La Falaise, La Sorciere and Morne Cabrits. During much of their growth, lava domes can appear calm and quiet and hence give the impression of not being particularly hazardous. Observations of domes worldwide, however, show that this is dangerously misleading: domes commonly generate minor explosions with little warning and no clear pattern. The demonstrated tendency of Dominica's past lava domes to suffer explosions indicates similar activity should be expected in the future.

Morne Anglais

Compared to Morne Plat Pays, the Morne Anglais volcano is smaller and apparently simpler. Its proximity to Roseau and close association with the seismic swarms of recent decades makes it highly relevant to our hazards assessment. The exposed deposits show evidence of two phases of development. The first phase, like that of Morne Plat Pays, was constructional and consisted mainly of lava dome eruptions and their associated fragmental aprons. There is little known about this early phase.

The second and most recent phase consisted of 4 to 5 explosive eruptions with vents located centrally on the volcano (at or near the summit), and occurring from 38,000 to 6,600 years ago. These eruptions were the opposite of the most recent events on Morne Plat Pays as they began with explosive activity and generally ended with quiet extrusion of lava domes. The early parts of these eruptions included airfall, pyroclastic flows and surges, which impacted all slopes of the volcano. The deposits from these eruptions vary in detail but all were apparently intermediate in volume. During at least the most recent eruption, the pyroclastic flows had sufficient energy to flow partway up the opposing slope of Morne Plat Pays and to cross a low area on Morne Eloi's shoulder, thus accessing the valley leading to Pointe Michel.

Although there have been only a few major eruptions of Morne Anglais in the last 38,000 years, there is a strong possibility that more frequent, minor eruptive activity has occurred but is not preserved or exposed. On Dominica, where erosion is very efficient, such deposits would have a high likelihood of removal. As a result, the frequency of eruptions for this volcano of once per 10,000 years must be considered an absolute minimum.

Other Relevant Volcanoes

The majority of the historic seismicity has been in the vicinity of Morne Plat Pays and Morne Anglais, placing the focus on these volcanoes for the future eruption. However, during our mapping we have uncovered relevant facts about the south-central volcanoes of Morne Trois Pitons/Micotrin and Morne Watt/Valley of Desolation which warrant their inclusion in the discussion.

Morne Micotrin/Morne Trois Pitons

Morne Micotrin is included as part of the Morne Trois Pitons volcano because it is essentially a cluster of flank lava domes of Trois Pitons. During field work we discovered evidence that there was a significant time gap between an early phase of Micotrin dome growth, and its most recent activity. Both periods of activity produced pyroclastic flows due to collapse of the lava dome flank. Charcoal obtained from the older pyroclastic flow in Laudat has been dated at about 26,000 years, and that from the most recent flow dated at 1,160 years. This shows that Micotrin reactivated after a period of inactivity of 25,000 years, leaving open the possibility that it may erupt again. This is supported by the fact that a small fraction of the recent seismicity was clustered beneath the Micotrin dome, suggesting it continues to harbour an active magmatic system. As a result, we mapped the extent of the dome collapse pyroclastic flows. Although such flows are too dense to cross significant topography or even flow beyond about 10 km, the basic discovery was that at least the older flows were sufficiently mobile to reach the Canefield airport and industrial estate, and Roseau. Indeed, the houses of Bath Estate are built upon charcoal-bearing pyroclastic flow deposits from the Micotrin dome.

Morne Watt and the Valley of Desolation

These areas are grouped together largely because there is little reason at this point to separate them. Very little is known about this area because there is only minimal exposure of the underlying deposits. Historical seismicity has occurred at the fringes of this complex, making it a

possible future vent area. In addition, the extreme vigor of hydrothermal activity of the Valley of Desolation and Boiling Lake, and the youthful morphology of the Boiling Lake crater, make this area a potential eruption location. Two youthful pyroclastic flow deposits have been found which probably originate somewhere in this area. One flow mantles the area of the Valley of Desolation trail from Laudat, and was erupted 1,020 years before present. The other coats the surface on the opposite side of the volcano and appears to have descended the valley of the River Jack leading to Delices about 10,000 years ago. At this point the evidence suggests that these eruptions were similar to those of Morne Anglais. The Valley of Desolation has exhibited another hazard which is less far-reaching but still potentially lethal, that of phreatic explosions. Trapping of hot water in the shallow subsurface resulted in explosions in 1880 and 1997, and more can be expected in the future. This hazard is discussed further in Section 6.

The Grande Soufriere Hills

This volcano is displaced significantly from the historical seismicity and so remains of less immediate concern. Its history is not well understood and it is relatively inaccessible. Previous studies have indicated in a preliminary way that it has the capacity for explosive activity. Fortunately, however, any pyroclastic flows from this volcano would be relatively well-constrained by a series of high ridges to the north, and by the line of volcanoes to the north-west, west and south.

Foundland

This volcano is also displaced from the historical seismicity, and in addition shows no evidence of activity in the last 50,000 years.

6 FUTURE VOLCANIC HAZARDS

Here we focus on the three critical questions:

(1) When will an eruption occur?
(2) What kind of eruption will it be?
(3) Where will it happen?

Time to Next Eruption

Phreatic eruptions

The active hydrothermal fields in Dominica and frequency of phreatic explosions in the Valley of Desolation of about once per century indicate that such explosions are in fact the most probable next volcanic event. We consider such activity even more likely given the high level of activity of the magmatic system, which is injecting hot magma into the near-surface rock. Therefore we consider it highly probable that a phreatic explosion will occur within the next 30 years, and almost certain within 100 years. Historical phreatic eruptions in Dominica have occurred exclusively in the Valley of Desolation and have consisted of single explosions. Phreatic

explosions in other locations or more than one phreatic explosion within a short period of time should be regarded as strong precursors of magmatic activity

Magmatic eruptions

The work done thus far permits us to approach the question of when the next magmatic eruption in Dominica will be. The Carbon-14 dating and mapping results show that magmatic eruptions have occurred about every 300 to 1500 years in the past, and that it has been 685 years since the last eruption (Morne Patates) big enough to leave a geological signature. Using this information alone would indicate the next eruption could happen at any time within the next 800 years. In addition it is necessary to consider the current state of the magma plumbing system under southern Dominica in order to refine the time estimate. The increase in magnitude and number, and decrease in depth, of the earthquakes over the last 50 years indicates that the conditions in the magma plumbing system are changing on a decadal time scale in a way that favours an eruption. It is therefore prudent to conclude that the probability of a magmatic eruption within the near future is higher than is indicated by the long-term eruption frequency of this group of vents. Table 2 gives our estimate of the probability of an eruption on increasing time scales

Table 3: Estimates of the probability of magmatic eruptions on various time scales

Time scale (From May 1 2000)	**Probability**	**Remarks**
One Month	Very low	Intensification of precursory phenomena expected before eruption
One Year	1 in 50	This probability will change when precursor phenomena resume.
Ten Years	1 in 5	“
100 years	More likely than not	“
800 years	Certain	

Expected Types of Eruptions

Volcanic hazards are determined by the type and location of eruption. The larger the eruption magnitude, the larger will be the areas of devastation and damage. Fortunately large magnitude events are relatively rare. For example on Dominica there have been three very large-volume eruptions in the last 50,000 years, so that the probability of a large magnitude event occurring in the next few centuries is very small. This is particularly true given the lack of evidence for a large magma reservoir at depth. The great majority of eruptions in the last 50,000 years have been small in volume.

The volcanological mapping has shown that each volcano in southern Dominica has a characteristic eruption type, so that the type of eruption we expect depends on where the eruption occurs. Probable vent locations are discussed in the next sections. In general, however, two basic type of eruption have occurred on Dominica in the recent past and can be expected in the fu-

ture: dominantly dome-forming eruptions (Morne Plat Pays, Morne Trois Pitons/Micotrin), and dominantly explosive eruptions (Morne Anglais, Morne Watt/Valley of Desolation).

Dome-forming Eruptions

A good example of a dome-forming eruption is the current Soufriere Hills eruption in Montserrat. There, after many years of precursor seismic activity and several months of increased hydrothermal activity, viscous magma quietly breached the surface. The day on which the magma reached the surface, in fact, is not known with confidence. The lava, too viscous to flow away from the vent, piled up over the vent to form a dome. Lava dome eruptions tend to occur over a prolonged period, from months to decades, during which magma may continuously or episodically flow to the surface, as seen on Montserrat. Typically lava domes grow to heights of a few hundred metres and attain diameters of about 1 km.

When domes grow on steep topography, over-steepened parts of their cooler, more brittle margins collapse away from time to time, generating small, dense pyroclastic flows that move down surrounding river valleys at speeds up to about 100 km/h. The pyroclastic flows generate more dilute, ashy surges which are more mobile and may overtop minor ridges, pour up side valleys and flow over the top of the sea for hundreds of meters.

Domes also tend to exhibit minor and difficult to predict explosive behaviour, especially toward the end of eruption, apparently because of gas that becomes trapped in the lava dome structure. The explosions generate ash-rich eruption columns up to about 10 km above the dome, and may launch dome blocks up to 2 m in diameter as far as 5 km from the dome. Parts of the eruption column are denser than air and so collapse from great heights, producing pyroclastic flows with enough mobility to overtop minor hills and ridges.

Domes are a long-lived source of ash, producing it through the grinding action of the dome's outer margins, persistent ashy fumaroles on the dome structure, pyroclastic flows and infrequent explosive eruption columns. Generally the ash remains in the lower atmosphere and in Dominica would fall mainly to the west. Ash injected into a wet atmosphere commonly triggers rain and hence the ash falls as mud. As dome eruptions are long-duration events, downwind ash accumulation can reach many centimeters especially within a few kilometers of the vent. The dome in Montserrat has shown all these patterns of behaviour.

After the eruption ends (once magma stops flowing to the surface), the hazards do not. For decades after eruption domes continue to cool and fracture, leading to further collapses and pyroclastic flows, and also explosions. The accumulated fragmental material in river valleys becomes mobilized during wet periods, forming lethal mudflows.

One mitigating feature of dome eruptions compared with predominantly explosive eruptions is that they tend to develop slowly, providing opportunity for emergency response. Overall, however, hazard mitigation during dome eruptions is made difficult by their long duration and irregular, episodic behaviour. Dome eruptions can cause the permanent displacement of popula-

tions from the areas affected, and yet can appear benign one day – leading to a dangerous level of complacency – and produce a devastating explosion the next.

Explosive Eruptions

The second type of eruption common in Dominica's recent past are relatively short, sharp, explosive eruptions. The best modern analogy for this type are the historic eruptions of the Soufriere of St. Vincent, for example in 1902 and 1979. In these eruptions magma rapidly flows to the surface, leading to a sharp onset of explosive behaviour. Although we use the term explosive, these eruptions are not instantaneous. It appears that gas held in the magma blows it apart in the shallow subsurface, and a rapid flow of magma from below continually replaces that which just exploded, forming a sustained explosion analogous to the jet of a rocket. The fragmenting magma forms an ashy eruption column typically 5-20 km in height. Usually these events are episodic over a period of a few weeks to months, generating a series of events of which each lasts a few minutes to a number of hours.

These events are more energetic than dome explosions and inject ash into the upper atmosphere, where the wind direction is approximately the reverse of the surface winds (Anti-Trades). The majority of the ash plume would drift east, while ash entrained from the lower parts of the eruption column would move west with the Trade winds. Therefore these events can drop significant ash both east and west of the vent. All local air traffic would be prevented. The upper ash plume would force diversion of international air traffic from routes to the east of the island.

The eruption columns are of course accompanied by the violent ejection of ballistic blocks. Typically these eruptions climax in one particularly violent episode. During each explosive event, it is common for parts of the eruption column, or sometimes the entire column, to collapse back onto the volcano slopes and form devastating, highly mobile pyroclastic flows. These move down all surrounding valleys at high speeds and can overtop ridges up to about 200 m high. The accompanying, less dense surges are even more mobile and generally coat ridges between valleys. These surges can travel distances of 5 to 10 km over the sea surface, remaining lethal over their entire distance.

Atmospheric effects may cause the ash to fall as water-saturated mud as in dome eruptions. There are also likely to be abundant lightning strikes. The rain of wet ash and that supplied from pyroclastic flows and surges interacts with rivers to generate large mudflows.

Once the explosions stop, it is typical any magma which remains to flow more gently to the surface and form a dome within the explosion crater. Typically these post-explosion domes grow for periods of a few months to a few years, and are usually less prone to form collapse-related pyroclastic flows and explosions, particularly if they are constrained on all sides by a crater.

Explosive eruptions may produce secondary mudflow hazards for many years after the eruption has stopped. In fact Dominica presently suffers from this secondary hazard in the Layou Val-

ley area, where the incorporation of ash-rich deposits from a large-magnitude explosive eruption into the Layou River continues to produce mudflows fully 30,000 years after the eruption.

Eruption Scenarios

Unfortunately, there are a number of volcanoes in Dominica any one of which may erupt next. The available evidence permits us to favor certain vent locations and eruption styles, indicated below on a case-by-case basis. However, we emphasize that volcanoes are not perfectly predictable; so that an event outside our list of cases is a possibility that should be allowed for in the emergency plans. This also emphasizes the importance of constant volcano surveillance, since only the most current information will allow accurate forecasts.

The cases given below lead to the delineation of hazard zones for times of crisis, and in order of what we believe is most likely to happen in the future. They pose the question, "Given an eruption at volcano X, what are the hazards?" The resulting hazard maps should be used as a guide to planning emergency measures such as evacuation areas and routes, evacuee staging and shelters, placement of communications, security, rescue and road-clearing personnel and equipment. With changing conditions, the cases and resulting hazard maps will almost certainly need significant revisions. Since any of these cases may happen, each specific case's hazard map does not represent long term volcanic hazards relevant to sustainable development, an aspect discussed in Section 4.4. Since our hazard zonation is designed to address the issue of evacuation, we consider only the land area. Nevertheless it should be understood that ballistic fragments, ash fall and pyroclastic surges will strike at sea and hence appropriate marine vessel no-go areas would need to be established and enforced during any eruption.

In the case of a volcanic emergency, three zones will be declared whenever it becomes clear (more likely than not) that an eruption will occur in the near future.

Devastation Zone

In this zone it is expected that all life and human structures will be destroyed. All people should be evacuated from this zone. A single team of informed emergency workers may be permitted for brief periods of high priority work, depending on volcano conditions, and requiring: (1) constant radio communication and/or accompaniment by monitoring scientists, (2) dedicated, appropriately fast and reliable motorized transport for fast escape (e.g. helicopter), and (3) appropriate safety equipment (helmets, goggles, gas masks, boots, fire-resistant suits, first aid kits, etc.).

Danger Zone

In this zone structures are likely to be damaged, and resident people and livestock have a significant likelihood of serious injury, or possibly death. We recommend evacuation to the boundary of this zone. Multiple teams of emergency workers may be permitted for prolonged daylight periods, depending on conditions, requiring: (1) constant radio communication with monitoring scientists, (2) dedicated, reliable transport for fast escape (e.g. jeep), and (3) appropriate safety equipment. No non-scientific personnel should be stationed within this zone on a daily work basis unless the work is high priority, in which case appropriate safety precautions must be taken.

Disruption Zone

Normal social activities may occur but are likely to be episodically and severely disrupted (e.g. disruptions to communications, power, water supply, transport and travel), mainly by significant deposition of ash. The chances of injury or death are relatively low. People living in this zone should prepare for disruptions in the same way that would prepare for a hurricane. They must be well-informed of the state of the volcano, and should be ready to seek adequate shelter or temporarily evacuate at short notice if conditions change. The size and position of this zone can change since it exists wherever there is significant ash falling, and that in turn depends on wind direction and other meteorological conditions.

The boundaries of these zones must never be considered to be sharp, narrow lines. Rather, zone boundaries must be thought of as locations where the volcanic hazards change rapidly. One important implication is that, where an evacuation boundary cuts across a community, it should be adjusted to enclose the entire community; for an evacuation boundary covering an area 10 km across, a house or school a few meters outside it cannot be considered safe. The zones may also expand outward or collapse inward as conditions change. Zone expansions will normally occur at short notice because of sudden, unpredictable increases in activity, whereas zone collapses tend to occur after prolonged periods of minimal activity and careful consideration. A good example of this zone expansion comes from the 1991 eruption of Mt. Pinatubo, Philippines, which reached a climax in its explosive activity on 15 June 1991. This is a larger magnitude event than is expected for Dominica, but illustrates the point: the evacuation zone was set to a radius of 10 km from the summit in April 1991, and 5,000 people were evacuated. It was expanded to 20 km on June 9, when15,000 more people were evacuated and finally placed at 30 km on June 12 when 30,000 *more* were evacuated as the eruption grew in vigor.

Outside the **Disruption Zone**, it is tempting to create a final zone labeled as “safe”. We do not favour the use of this zone, nor the label “safe”. To most people, “safe” means there is essentially zero chance of injury or death, whereas in reality “safe” means a level of risk that people are willing to live with. During a major natural disaster such as an eruption, the level of risk to people everywhere in Dominica would increase, by direct (eruption) effects such as minor windblown ash, and indirect effects such as disruption in traffic flow, power and water supply, and population pressure due to displaced persons.

7 Possible eruptions

In this section we consider a number of possible eruption scenarios, starting with the most likely scenario and working downwards to less likely ones. For each scenario we present two maps. The first map shows areas likely to be affected by the main volcanic effects. We describe these maps as eruption scenarios. The second map shows the zones of devastation, danger and disruption (as defined in the previous section) to be expected in the event of this type of eruption. These are referred to as hazard maps. Note that the versions included in this report have been reduced in resolution in order to fit within the standard A4 page format. Larger versions at higher resolution are available.

Size of eruptions

Regarding the size of the eruptions we have taken as models eruptions which have occurred in the Caribbean in historical time. The model for dome-building eruptions is that of the Soufriere Hills volcano in Montserrat. This began to erupt in July 1995 and is continuing to erupt as this report is prepared. Similar eruptions occurred at Mt Pelé in Martinique in 1902-1907 and 1929-33. The total volume of erupted material in each of these eruptions was a few hundred million cubic metres. The model for explosive eruptions is the Soufriere of St. Vincent which erupted explosively in 1718, 1812, 1902 and 1979. The volume of erupted material ranged from about 100 million cubic meters in 1979 to 1 cubic kilometer (1,000 million cubic meters) in 1902. The models considered are at the upper end of this range. It should be noted nevertheless that the Dominican volcanoes considered here are capable of very much larger eruptions than this. The biggest known in the geological record have erupted volumes in the range 20 to 40 cubic kilometers. The premonitory symptoms identified so far do not suggest that such mega-eruptions are likely within the near future.

Specific Scenarios

Case 1: Dome Eruption in Bellevue Chopin-Pointe Michel-Loubiere Area (Morne Canot)

This is considered the most likely case for the next magmatic eruption in Dominica, based on the location and pattern of seismicity in recent decades, and the types and youth of lava dome deposits located above the earthquakes. The fact that the recent swarm appeared to inject magma from the reservoir toward this area is a further indication that it is the most likely next vent location. The small volume of magma injected is consistent with that which would produce a lava dome. We select the summit of Morne Canot for the vent because it is centrally located in the area of shallowest and energetic seismicity. However, the area in which the vent could occur is broader and the vent for the next eruption may not coincide exactly with a preexisting volcano Shifts in the vent location within this area would not greatly alter the scenario unless the vent was displaced considerably west of Bellevue Chopin or at sea. This would reduce the likely impact on the Geneva River valley.

The eruption scenario (Figure 6 page 30) outlines in red the areas likely to be impacted by pyroclastic flows and surges. Dome-collapse pyroclastic flows are almost certain down the valleys leading to Pointe Michel, Loubiere, Bellevue Chopin, Pichelin and Grand Bay. The surges from these would extend to higher elevations and may overtop valley walls, spread out at the coast, cross the sea surface to a distance of about 1000 m, or pour up side valleys for distances of a few hundred meters. Infrequent explosions could generate more mobile pyroclastic flows and surges that could additionally reach Castle Comfort and the southern part of Giraudel. Lethal ballistic fragments could reach to a radius of 5 km, reaching Roseau, Morne Prosper, Grand Bay and Soufriere within 60 seconds of the explosion. These would fall within the black circles on the eruption scenarios. Fist and head-sized ballistic blocks would plunge through the walls and roofs of buildings while still red-hot, and start fires within the buildings after impact. Atmospheric effects in the eruption column would generate frequent lightning strikes to about the radius of the ballistic trajectories. Millimeters to centimeters of ash – sometimes wet ash - would fall at least to the range of ballistics in the upwind direction and farther in the downwind direction – that is within the area enclosed by the grey line, and ash fall sufficient to cause respiratory problems might occur anywhere south of the white line depending on wind conditions. Local air traffic would be prevented wherever the ash plume went, and explosions may force diversion of international air traffic from routes to the west of the island. Likely duration of an eruption of his sort is between one and ten years.

The hazard map (Figure 7 page 33) for this case reflects the above hazards, in that the **Devastation Zone** (1) includes areas likely to be impacted by the dome, pyroclastic flows, pyroclastic surges and ballistics. The **Danger Zone** (2) further includes areas likely to receive heavy ash and pumice fall, anomalously energetic pyroclastic flows, surges and ballistics, and mudflows. The Disruption Zone includes areas likely to receive frequent and significant ash and minor mudflows. Small amounts (a few millimeters) of ash can be expected to fall from time to time, depending on weather and eruption conditions, in almost any part of the island.

Figure 6: Eruption scenario, dome-forming eruption, Morne Canot

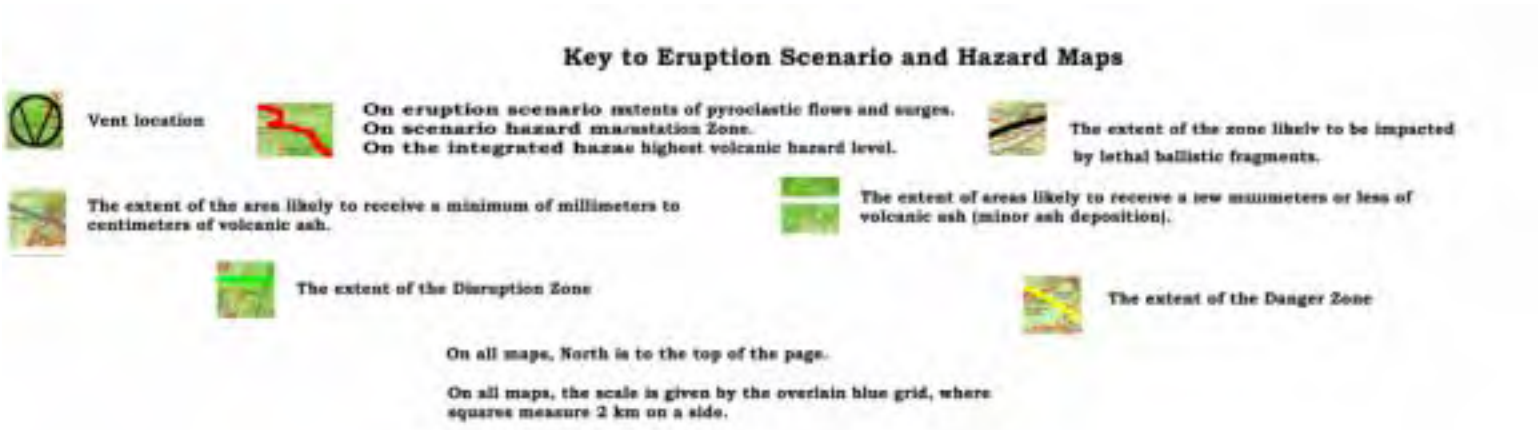


Figure 7: Hazard map, Dome-forming eruption, Morne Canot

Case 2: Dome Eruption in Soufriere Valley

An eruption on or near Morne Patates is considered the second most likely location of the next eruption, because it has erupted numerous times in the past, is the site of the island's most recent eruption and is located in close proximity to the recent earthquake swarm. Given the past behaviour in this area, we would expect a dome eruption. The hazards and expected duration would be the same as for Case 1.

The eruption scenario map for this case is shown in figure 6. The confining Soufriere valley walls would constrain all the dome collapse pyroclastic flows and surges, but ballistic fragments, ash fall and possibly pyroclastic flows generated by explosive column collapse could reach beyond the valley walls. The hazard zones resulting from this scenario are shown in Figure 7.

Figure 8: Eruption scenario, dome-forming eruption, Morne Patates

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Figure 9: Hazard map, dome eruption, Morne Patates

Case 3: Explosive Eruption at Morne Anglais Summit

The proximity of Morne Anglais to the recent swarm, and in particular the cluster of earthquakes directly beneath its summit, make this another possible eruption site. However the apparently low frequency of eruptions from Anglais (every 5,000 to 10,000 years) and much greater concentration of seismicity further south suggest it is not the most likely location.

In this case (Figure 10) the vent would be expected to be at or near the summit, as in past eruptions. The eruption style would be explosive, probably followed by rapid extrusion of a lava dome. Because the eruption column would be much higher ash could fall from the plume in almost any direction. Collapse of parts of the column would produce mobile pyroclastic flows and surges in all directions from the summit. These flows could overtop significant topography, and would be accompanied and followed by mudflows down major drainages. Figure 11 shows the delineated hazard zones.

Figure 10: Eruption Scenario: Explosive eruption, Morne Anglais

Figure 11: Hazard map, Explosive eruption, Morne Anglais

Case 4: Dome eruption on Morne Trois Pitons/Micotrin

The new Carbon-14 dating results showing Micotrin's ability to reactivate, the generally high level of activity exhibited by this area, and the proximity to historic seismicity prompt us to make this our fourth most likely case. The relatively recent eruption of Micotrin suggests it would be the vent location, and its past behaviour indicates it would be a dome eruption. This is equivalent to moving the vent for Case 1 to the Micotrin dome, and the duration and hazards would be similar. Most rockfall and pyroclastic flows would be directed down valleys to the west, toward Canefield and Roseau, but the dome may overtop the low ridge to the east, thus endangering both the east and west of the island (Figures 12 and 13)

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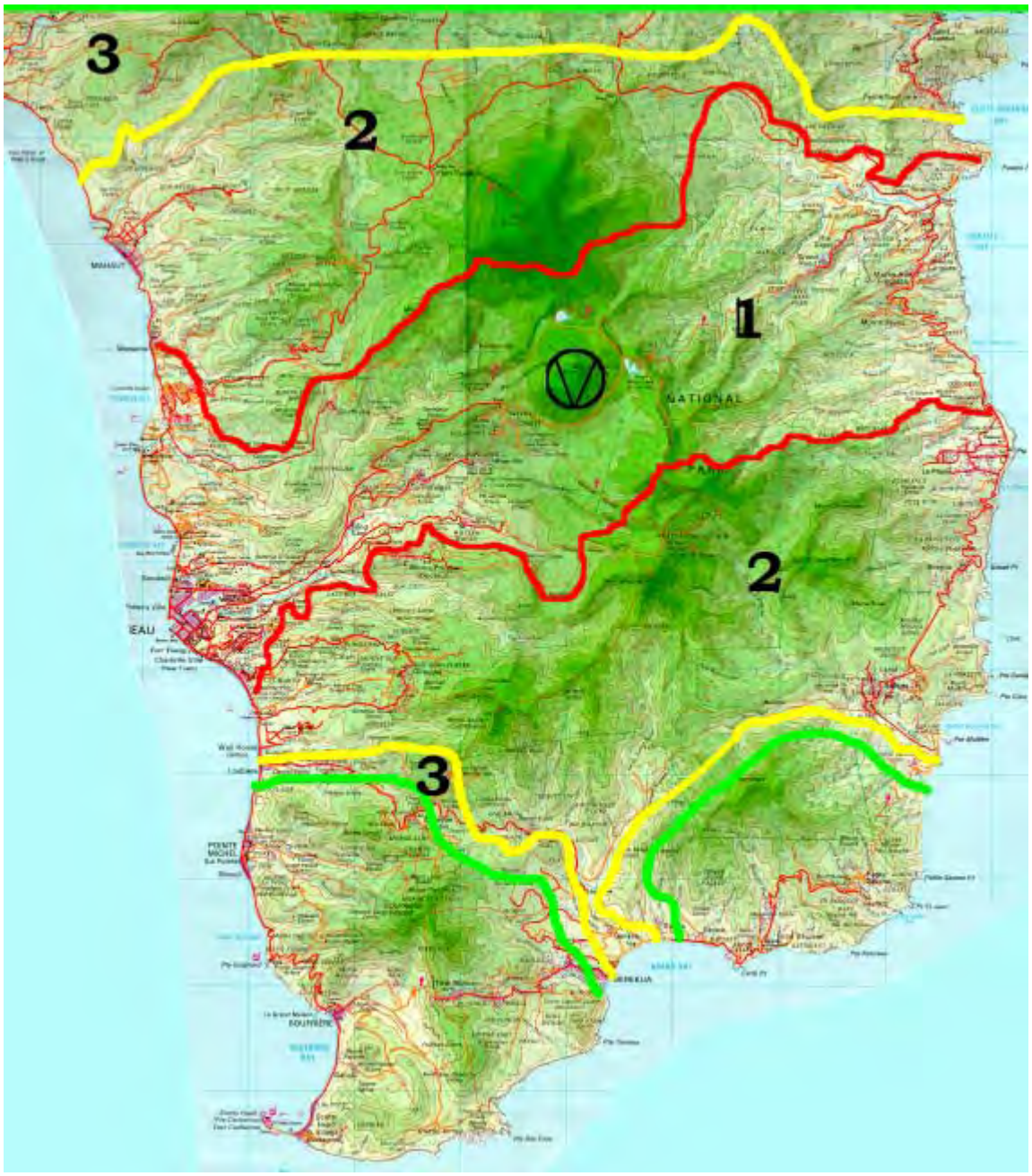
Figure 12: Eruption scenario: Dome eruption on Morne Trois Pitons/Micotrin

Figure 13: Hazard map, Dome eruption, Morne Trois Pitons/Micotrin



Case 5: Explosive Eruption in Valley of Desolation

Two newly discovered young pyroclastic flow deposits which apparently originated in this area, plus the proximity of recent seismicity and vigor of the hydrothermal fields makes this our fifth most likely case. We place the vent at the Valley of Desolation, but it could be placed anywhere from the Boiling Lake to the summit of Morne Watt. The eruption style, duration

and hazards would be the same as Case 3; see Figure 14 for the scenario, and Figure 15 for the hazard zones.

Figure 14: Eruption scenario: explosive (magmatic) eruption in the Valley of Desolation.

Figure 15: Hazard map, Explosive magmatic eruption, Valley of Desolation

Significant Remote Cases

Three of Dominica's volcanoes (Morne Diablotins, Morne Trois Pitons/Micotrin, and Morne Plat Pays) have produced large-volume explosive eruptions in the last 50,000 years, so another

event of this type is a probability for the future. Given that we have no evidence of a sufficiently voluminous magma reservoir which could produce such an event, and their low frequency of about one per 20,000 years, the probability of another happening over a relevant time scale is considered remote. However, as such an event is a possibility and would devastate the majority of Dominica, it is worth developing contingency plans for total evacuation.

8 Integrated Volcanic Hazard Levels

Overall levels of hazard

The various eruption cases are useful for defining the areas of southern Dominica which have the greatest and least overall volcanic hazards at this time. If Dominica had a single volcano, these zones would be the same as the eruption scenario hazard zones. With 5 most-likely cases to consider, appreciating the long-term hazard for a particular location on the map is a more complicated question since it depends on which volcano erupts. In the case of a Morne Canot eruption, life would continue in La Plaine without major change, but if the Valley of Desolation erupted it would be destroyed. For purposes of sustainable development, it is an appropriate question to ask “Just how hazardous is location X?”.

One approach to answering this question would be to simply compile all the hazard zones of the 5 scenarios. This would, however, give undue weight to zones in cases that are considered less likely than other cases. The result would be an exaggeration of the overall volcanic hazards. Instead, we choose to reduce the weighting of cases 3 to 5 to reflect the fact that they are currently considered significantly less likely than cases 1 and 2. The zone definitions are:

H – Highest volcano hazard level

(Devastation Zones for cases 1 and 2): property and structures in this zone have a significant (more likely than not) probability of destruction due to volcanic eruption within the next 100 years.

I – Intermediate volcano hazard level

(Devastation Zones for cases 3,4, or 5 and danger zones cases 1 and 2) property and structures are likely to be damaged (more likely than not) , and may be destroyed (greater than 10% probability), within the next 100 years.

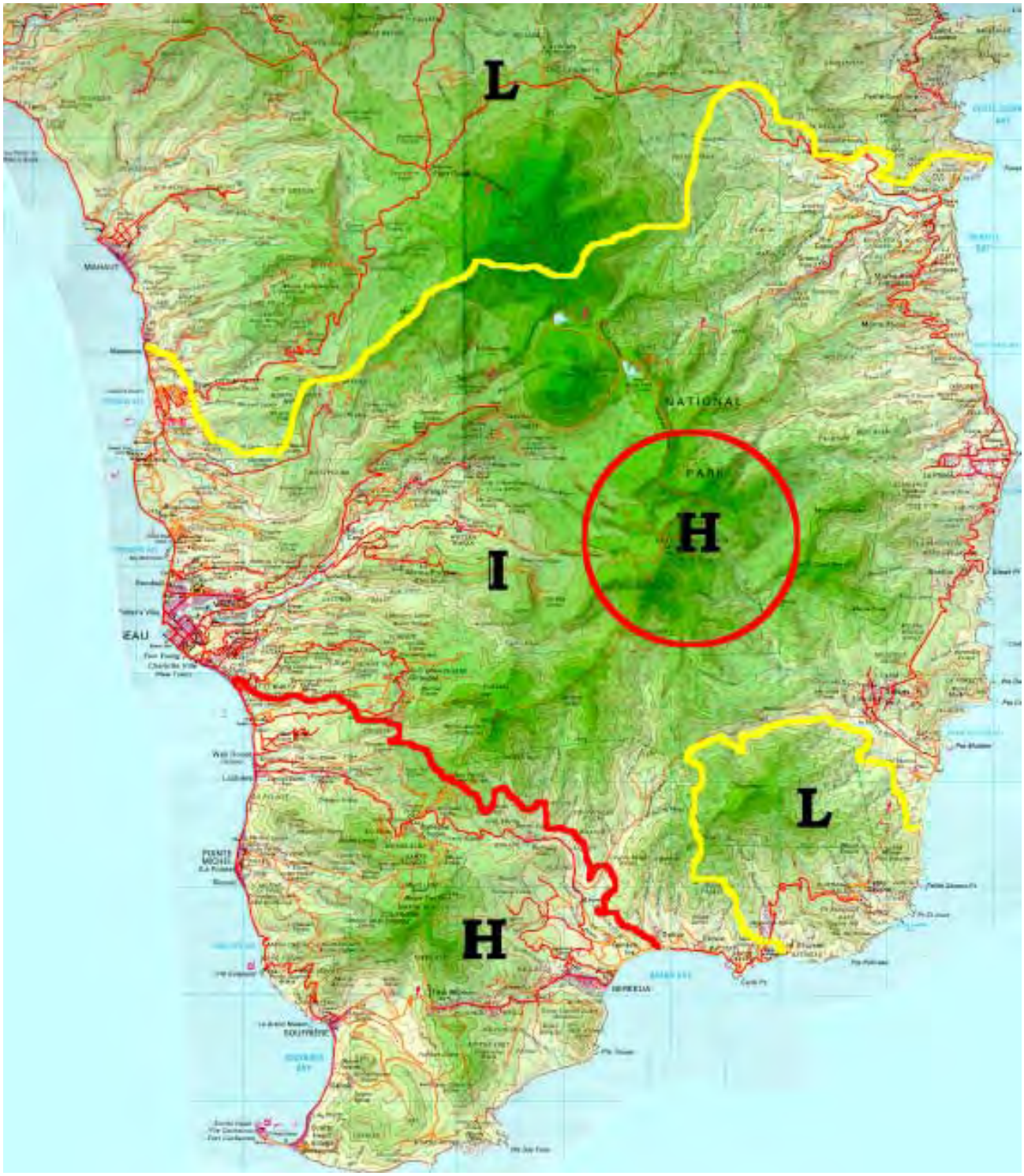
L – Lowest volcano hazard level:

(Disruption Zones cases 1 and 2, Danger Zones, 3,4, and 5) : property and structures may be damaged, but destruction is unlikely.

In constructing these zones, all possible vent areas for the 5 eruption scenarios were considered, along with the future high probability of phreatic explosions in the Valley of Desolation. The

results are shown on Figure 16. It must be remembered that this hazard level delineation is reliant on current information on the volcanoes and is likely to be revised in the future.

Figure 16: Integrated hazard zones



Discussion

The implications of figures 4 to 14 are serious for the Commonwealth of Dominica and we wish to make it clear that we have not reached these conclusions lightly. The clear implication is that on the time scale of the next century the southwestern corner of Dominica – all areas southwest of the road from Loubiere to Grande Bay and a strip approximately one kilometer wide to the northeast
of this road – are extremely hazardous volcanically. The level of hazard in the Valley of Desolation and its immediate surroundings is equally high. In these regions it is more likely than not that within the next century there will be widespread destruction of property by volcanic action; these regions will be rendered immediately uninhabitable and may remain uninhabitable for many years particularly if the eruption leaves a large dome of hot unstable rock perched on one of the existing domes in the Morne Plat Pays complex and a mantle of unstable ash on the steep slopes surrounding the complex.. If this happens then the hazard from further collapses of hot rock from the new dome and the hazard of mud flows as heavy rains mobilize the residual ash will remain for years, decades or even centuries.

There are different schools of thought amongst scientists with responsibility for volcanic monitoring about the limits of their responsibility. Some scientists believe that they have a direct responsibility to the public to advise them about the level of volcanic hazards and to urge them to take actions to mitigate the possible effects of volcanic activity. The position of the Seismic Research Unit is that our responsibility is to the governments which provide our funds. In reports like this one we will describe the level of hazard based on experience at other volcanoes and on the available scientific evidence. We will not communicate these conclusions to the general public – including the general scientific community – until it is clear that the government has no objection. At all times we are prepared to discuss the implications of our findings with government officials and to present a united front to the general public and the scientific world.

9 Future work

When the level of earthquake activity in southwestern Dominica declined in mid 1999 the question was asked whether the level of vigilance established in late 1998 could now be relaxed. The answer to this question is “no”. The pattern which has been established in Dominica is that we are on the path to an eruption. There is no doubt whatsoever that the earthquakes will resume and that eventually one of these earthquake swarms will not stop but will escalate into an eruption. The investigations carried out since September 1998 have enabled us to come much closer to answering the crucial questions of where?, when? and how? Successive earthquake swarms and investigations carried out between swarms will refine the answers to these questions and we have a high confidence that when the eruption does happen there will be ample

time to take appropriate action. The main monitoring techniques which will be applied are as follows

- The reinforced seismograph network established in 1998 will continue in operation for the indefinite future
- The programme of ground deformation measurements begun in 1998 will continue indefinitely.
- As funds become available further analyses will be made of rocks collected during the recent field investigation.

10 Contributors

The Head of Seismic Research, Dr. John Shepherd takes full responsibility for conclusions and recommendations expressed in this report. Fieldwork has been a group effort of the Seismic Research Unit, with major contributions from Paul Jackson, Chan Ramsingh, Joan Latchman, Jan Lindsay, Lloyd Lynch, John Shepherd and Mark Stasiuk. The contents also gained significantly from input by Joseph Devine, Rick Hoblitt and Dan Miller. In Dominica we have benefited greatly from the cooperation of Mr. Cecil Shillingford and his staff and from successive Permanent Secretaries in the Ministry of Communications and Works, Mrs. J. Astaphan and Mr. S. Carrette. The Lands and Surveys Department cooperate so closely with us that they should be considered joint investigators and many other Dominicans too numerous to mention have assisted us in the field. Christian Antenor-Habezac and Jean-Paul Viodé of the IPGP observatories in Guadeloupe and Martinique provided crucial seismograph data.

11 Acknowledgements

The work described here is part of the ongoing programme of work of the Seismic Research Unit of the University of the West Indies and is therefore basically a regional effort supported by the governments of Trinidad and Tobago, Barbados and the OECS countries. It has been acknowledged since the mid-1980's at least that the level of volcanic risk in Dominica is higher than anywhere else in the Lesser Antilles, and the government of the Commonwealth of Dominica has provided extra funds to the Unit over and above its regional contribution to support special studies. During the recent crisis extra funds were provided by the UK Department for International Development (DFID) and by the United States Agency for International Development, Office of Foreign Disaster Assistance (USAID-OFDA). Rapid provision of helicopter support by DFID at a time when it appeared that an eruption might be imminent probably avoided precautionary evacuation of part of Dominica and the provision of expert volcanologists by USAID (OFDA) considerably lightened the load. We are grateful for all of this support.