MONITORING VOLCANIC ACTIVITY AT THE SOUFRI�RE VOLCANO � A MODEL FOR VOLCANO MONITORING OPERATIONS IN SMALL-ISLAND NATIONS

R. E. A. Robertson[1], Aisha Samuel[2], John Shepherd[1], Lloyd Lynch[1] and Joan Latchman[1]

[1] Seismic Research Unit, University of the West Indies, St Augustine Campus, Trinidad.

[2] Soufri�re Monitoring Unit, Ministry of Agriculture, Richmond Hill, St. Vincent.

Keywords:� Soufri�re volcano, St. Vincent, volcano monitoring, volcanic eruption, volcanic hazards.

Table of Contents

Abstract

Since its devastating eruption in 1902, the Soufri�re volcano of St. Vincent has been kept under surveillance by a varied assemblage of local individuals and overseas-based scientists.� The establishment of the Seismic Research Unit in 1952 led to the development of a sustained program of volcano monitoring that has evolved in response to changing conditions at the volcano and to improvements in technology.� The volcano monitoring program in St. Vincent currently comprises two components: a small locally staffed volcano monitoring unit and a regionally based scientific organisation.� Funding is provided by the government of St. Vincent and the Grenadines through contributions made to the regional organisation and as recurrent expenditure for the operations of the local unit.� The monitoring program has worked well in the past and can serve as a model for regions similar to the Eastern Caribbean in which small island nations with limited resources are exposed to a volcanic hazard.

This paper traces the development of volcano monitoring operations on St. Vincent and provides an overview of its current composition.� It makes a case for the �St. Vincent model� to be used as a template for similar operations in other islands that may require a similar level of surveillance at their volcanic centre.

Introduction

Effective reduction of risks from volcanic eruptions depends on identification of volcanoes that have the potential to erupt in the future and on the establishment of an early warning system well in advance of any possible eruption.� Basic geoscience studies of volcanoes enable the identification of these so-called �live� (likely to erupt) volcanoes and allow the preparation of volcanic hazards-zonation maps to guide long-term planning by civil authorities.� To be successful any volcano monitoring program must be based on a long-term program of basic geology, geophysical and geochemical study of the volcanic system designed to improve understanding of the system (Figure 1).� The longer the period of volcano monitoring prior to onset of an eruptive episode the better the characterisation of the behaviour and the more diagnostic and reliable is the detection of possible eruption precursors (Tilling, 2003).� Volcano monitoring networks must therefore be sufficiently robust to survive the damaging effects of explosive eruptions and suitably cost-effective to endure the changing priorities that occur during the long quiescent periods that may occur between eruptions.

The Soufri�re volcano is the only �live� (likely to erupt) volcanic centre on St. Vincent (Figure 2).� It dominates the northernmost one-third of the island (Figure 3) and has a geological record that extends as far back as 650,000 years (Heath, Turner *et al.*, 1998; Rowley, 1978a).� For the past 4,000 years it has exhibited a pattern of eruptive activity that involves an alternation between explosive ejection of fragmented material causing pyroclastic flows, pyroclastic surges and ashfall and the quiet effusion of slow-moving viscous lava forming summit domes.� Before the twentieth century the potentially destructive capacity of this volcano was not fully realised.� No monitoring system was in place and scientific knowledge of the system was very limited.� This was consistent with the state of knowledge at the turn of the century; the science of volcanology was an unknown subject and the destructive potential of volcanoes such as the Soufri�re was not fully recognised.� The eruption of 1902 and subsequent events altered the perception of the volcanic hazard and led to significant improvements in the monitoring network.� It also stimulated research into the understanding of this geological phenomenon.

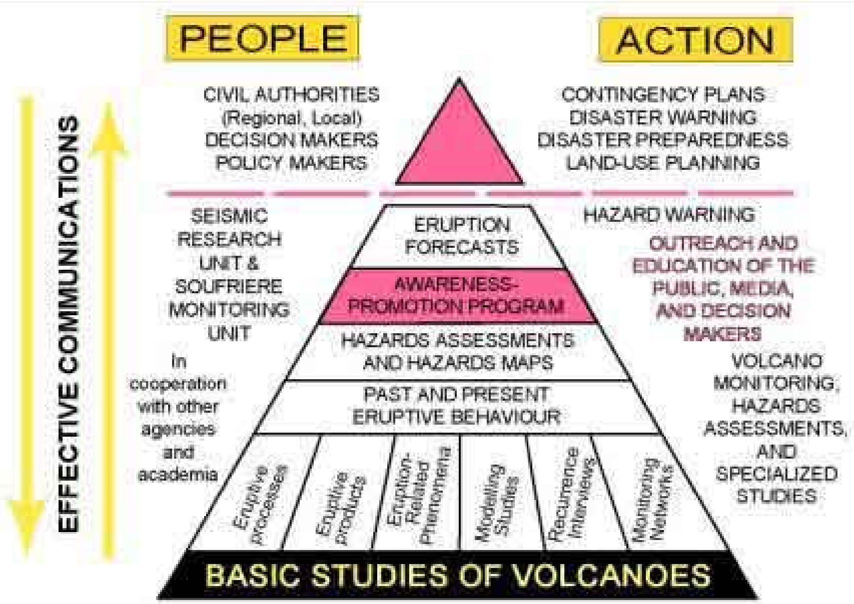

Figure 1: The key elements involved in an effective volcano monitoring and risk reduction program. The program must be built on a solid foundation of long-term basic studies of volcanic systems. The apex of the triangle is separate from the rest of the triangle to emphasize the division of primary responsibility between the scientists and the civil authorities (adapted from Tilling, 2003).

The remainder of this paper traces the development of monitoring operations associated with the Soufri�re volcano and compares the systems implemented with those that have developed elsewhere in the region.

Evolution of the volcano monitoring network on St. Vincent

<u>Pre-1950s</u>

The first description of the Soufri�re volcano is given by James Anderson (1785) who climbed to the summit in 1784.� At that time the mountain was called Morne Garu and conditions at the crater appeared from Anderson�s description to have been quite similar to that which followed the 1979 eruption.� The eruption of 1902-03 brought attention to the volcano and its capacity to cause death and destruction.� This led to a number of visits by geologists and to the first set of scientific investigations of the volcano.� J.A. Jagger (Harvard University), C.G. Curtis (USGS), T. MacDonald (a local planter) and E.O. Hovey (American Museum of Natural History) along with six porters made the first ascent of the volcano following the 1902 eruption (Hovey, 1902).� Flett (1908) gave an account of the ash that fell on Barbados from this eruption which was described in detail by Anderson and Flett (1903).� Treves (1908) also gave accounts of this eruption.� All of these initial investigations of the volcano were largely descriptive and based on eyewitness accounts of the 1902-03 eruption.

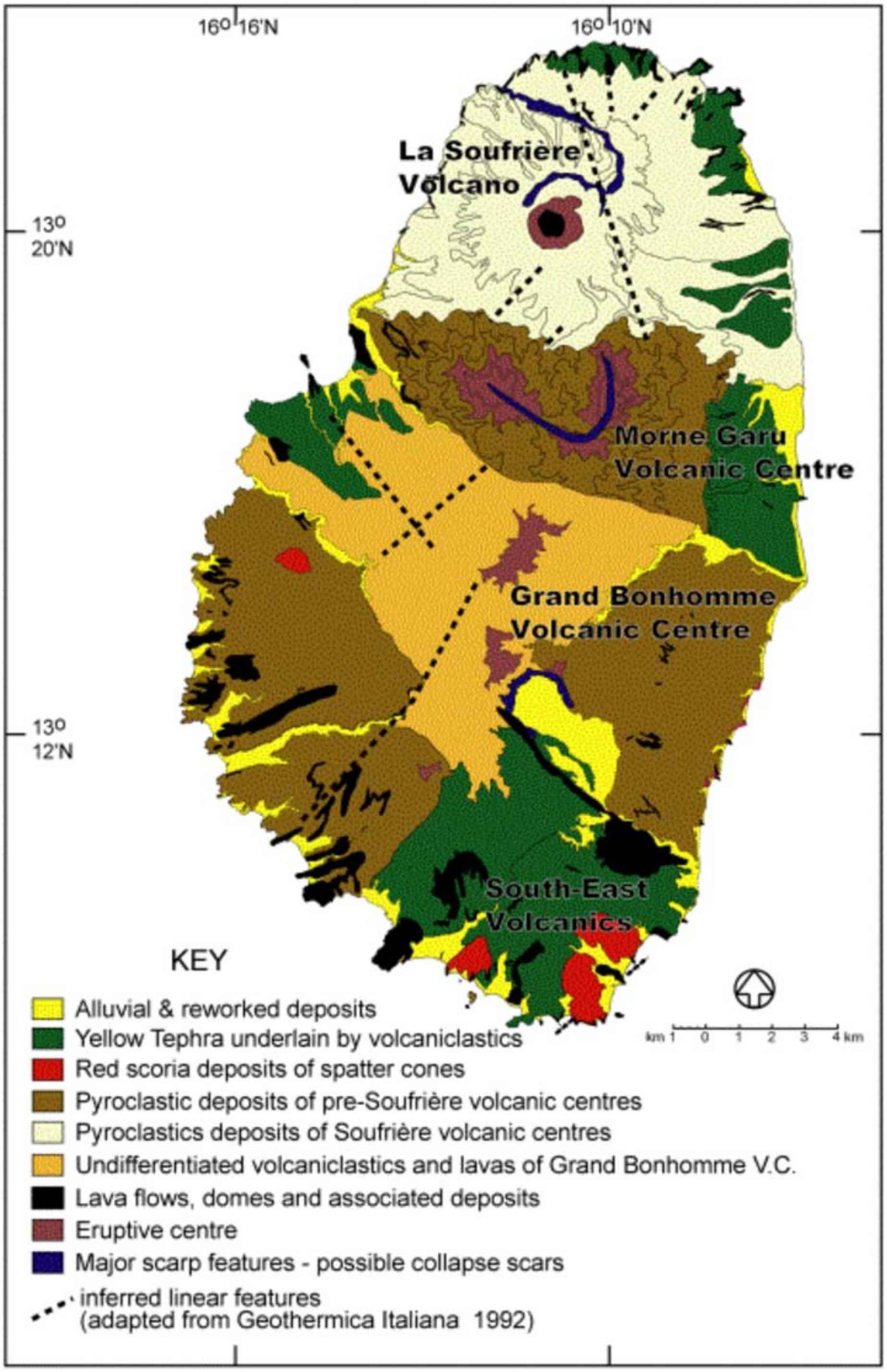

Figure 2: Geological map of St. Vincent showing the distribution of the main deposits on the island. The boundaries between geologic regions are approximate.

Figure 3: Photograph of the Soufrière volcano taken from the western or leeward side of the volcano.

From November 1945 to February 1946, a swarm of local earthquakes was followed by a rise in lake temperature to above ambient air temperature.� This led to employment of �Volcano Observers� by the Ministry of Agriculture to make regular visits into the crater to measure the air and water temperature and to report on the status of a large yellow stain in the lake which was first reported when the swarm occurred.� Monitoring of the Crater Lake temperature which began in 1946 continued more or less continuously up to the 1979 eruption when the Crater Lake was ejected (Figure 4).� The 1945-46 earthquake swarm was one of the driving forces that led to the establishment of the Seismic Research Unit, a regionally based organisation with responsibility for volcano and earthquake monitoring in the Eastern Caribbean.� Around this time, the first serious attempts to understand the geology of the volcano began with the French scientists Lacroix (1949) and Sandrea (1949) who conducted the first petrological studies on the Soufri�re volcano.� They investigated igneous cumulate blocks ejected by the volcano.

Post-1950s: (a) Instrumentation

Seismological studies at the Soufri�re volcano began in 1953 (Figure 5) with the establishment of the Seismic Research Unit. Initially changes in the volcano monitoring network was quite slow and it was not until the formation of the Seismic Research Unit in 1952 that attention was focused on improving our understanding of the volcano and on deployment of a permanent volcano monitoring operation.

� The first seismic station was an independent, short-period, vertical seismograph (SVI) which was installed at Camden Park and later moved to Maroon Hill (Figure 6).� This station was part of a regional network that extended from Trinidad to Jamaica.� It remained more or less in continuous operation up to the 1971-72 eruption when additional stations were installed.

Figure 4: A Volcano Observer from the Ministry of Agriculture taking measurements of crater lake temperatures during the 1970's. These measurements continued uninterrupted until 1969. They became very irregular after this time and ceased completely after the crater lake was ejected in the 1979 eruption.

During the 1960�s the Ministry of Agriculture continued to employ Volcano Observers (persons such as L. Gonzales, C. Harry, J. Boyea, C. De Freitas & E. Kirby), who made regular visits to the summit and reported on weather conditions, the water level, temperature and appearance of the Crater Lake and the state of gaseous emissions.� The Observers were initially paid EC$10 per month and were required to make the measurements once per month.� By 1962 this had increased to EC$20 per visit.� Unfortunately the data collected by the Volcano Observers became increasingly unreliable and by 1969 crater visits appear to have completely ceased (Aspinall *et al.*, 1973).� This meant that the increase in lake temperature and changes in water levels that must have accompanied the onset of the lava extrusion in 1971 went undetected.� The single seismograph station in operation at the time was too far away to detect the earthquakes that may have been associated with this extrusion and it was not until late 1971 due to the fortuitous visit of tourists to the summit, that the changes signalling eruptive activity was first noted.� During this eruption funds were allocated directly from the central government for volcano monitoring

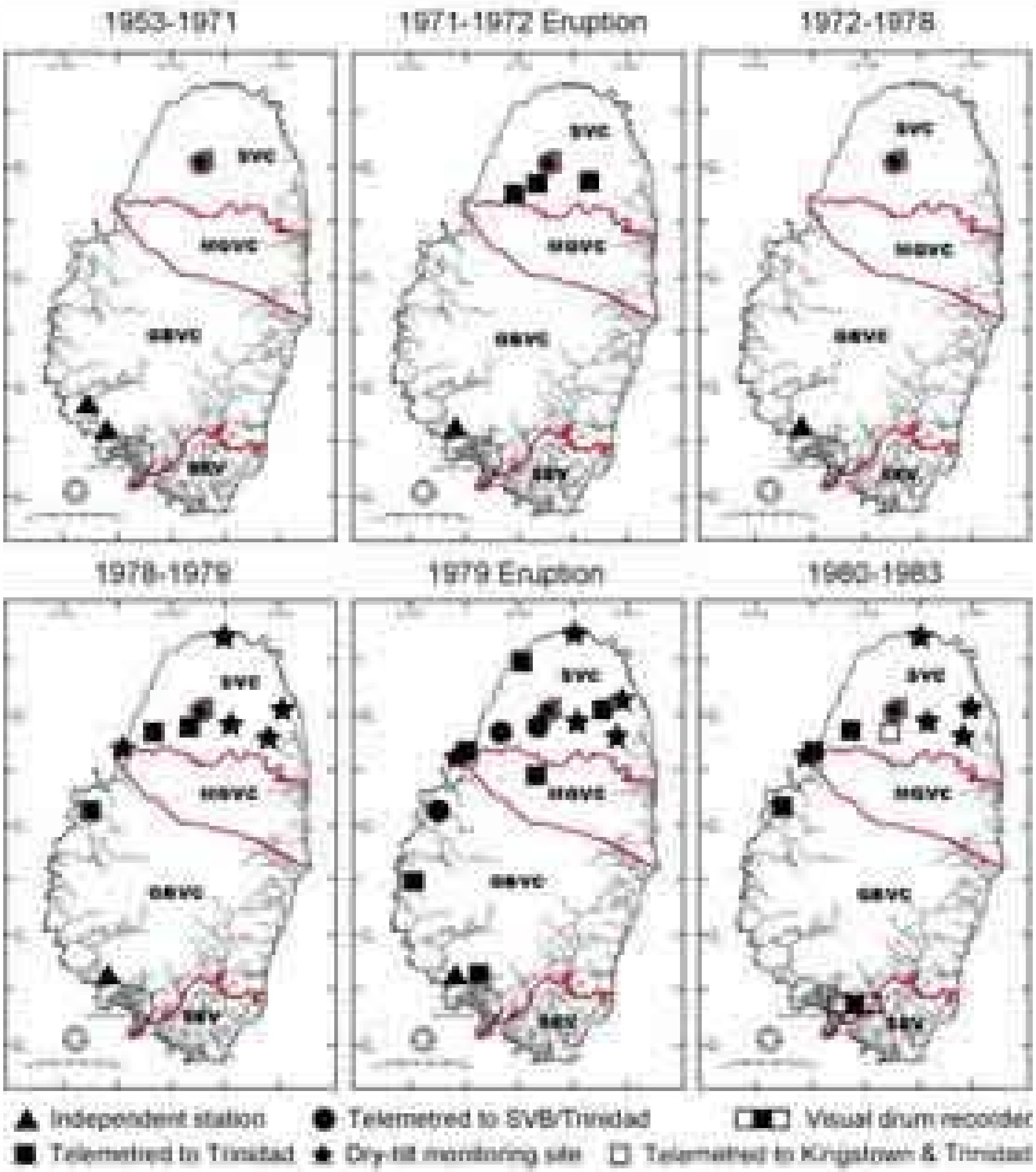

Figure 5: Distribution of the seismograph and ground deformation stations employed by the Seismic Research Unit in volcano monitoring operations in St. Vincent during the period 1953-1983. The main geological regions are labelled respectively as SEV = South East Volcanics, GBVC = Grand Bonhomme Volcanic Centre, MGVC = Morne Garu Volcanic Centre and SVC = Soufriere Volcanic Centre.

Figure 6: A Willmore portable seismograph station similar to the ones used to monitor the Soufrière volcano between 1952-1980.

operations.� These funds were designated for �Soufri�re Investigations� and came directly from the Ministry of Finance.� This was the first occasion on which local funds were specifically allocated for volcano monitoring operations in St. Vincent.

Following the 1971-72 eruption, a small observatory was constructed on the crater rim (Figure 7) to provide shelter for personnel and equipment doing work at the volcano.� The building housed a seismograph with radio, batteries, an inflatable boat, other equipment and food.� The batteries were charged by a wind-driven generator which was eventually damaged by vandals throwing rocks at the wooden propeller.� A heavy, armoured cable was transported to the summit by donkey and used to link the observatory to a device at the crater lake (200m away) that was used to measure water level and temperature (Figure 8).� Vandals broke into the building doing extensive damage to equipment and batteries and bad weather damaged the level float at the Crater Lake before the installation could be completed as intended.� The building was used thereafter to provide shelter for scientists working at the summit.� It was destroyed during the first explosions of the 1979 eruption.

In February 1977 precise levelling using the �dry tilt� method was first employed at the volcano (Figure 9).� Before this period unsuccessful attempts had been made during the 1971-72 eruption to install water-tube tiltmeters and later to measure ground deformation using optical geodimeters and portable diamagnetic-suspension instruments.� Measurements using the dry tilt method made in March and September 1978 suggested that the volcano was inflating.� Measurements made soon after the start of the explosive phase of the eruption (on 17 April 1979) indicated that a small deflation had occurred in comparison with the September 1978 results.

Around the middle of 1978 the regional telemetry network of seismograph stations reached St. Vincent and a new station was established at Belmont where the Agricultural Officer�s Quarters was used as the site for the regional telemetry relay.� This coincided with a slight increase in Crater Lake temperature which prompted the installation of two additional stations at Wallibou

Figure 7: Photograph of the observatory constructed on the crater rim of the Soufrière volcano following the 1971-72 eruption. The photograph shows the wind-dirven electric generator that provided power to recharge the batteries. The building was damaged by vandals and destroyed completely in the early stages of the 1979 eruption.

and the summit (by October 1978) to confirm the source of seismic signals being recorded at the time on the Belmont station.� The 1979 eruption prompted the installation of additional stations (initially 6 in addition to Belmont) and maintenance of a full-time observatory at the Agricultural Officer�s Quarters that later became the site of a custom build observatory in 1985.� During this eruption 100 hours of continuous volcanic tremor was recorded along with >40,000 seismic events.� Attempts were made to record explosions using still and movie cameras (Sparks *et al.*, 1979) during the eruption and the first long distance measurements to the crater rim using an electronic distance meter instrument was made.

After the 1979 eruption, four stations were maintained and all others removed as the volcano again subsided to the background level of activity common during intervening periods between eruptions.� In September 1980 the signal from the summit station was captured in Kingstown and

Figure 8a: Donkeys transporting heavy armored cable to the summit of the Soufrière volcano. The cable was laid from the observatory (Figure 7) down to the crater lake and used to relay the signal from a sensor placed there (see Figure 8b).

Figure 8b: Scientist from the Seismic Research Unit installing a water-level float and temperature sensor in the crater lake in 1974. The float was broken off by high waves soon afterwards.

Figure 9: Measurements of ground deformation being made by scientists from the Seismic Research Unit at Orange Hill on the eastern flank of the Soufrière volcano. They are using the 'dry tilt' method of monitoring changes in the size of the volcano and the measurements are being done on 17 April 1979, during the explosive phase of the eruption.

displayed on a visual recorder in the Ministry of Agriculture, Kingstown.� At the same time the seismic signals were sent to Trinidad where they were recorded and analysed continuously.

Immediately after the 1979 eruption the Seismic Research Unit proposed a project designed to improve the level of volcano monitoring on the island.� The so-called �St. Vincent Volcano Monitoring Project� (SVVMP) provided for a significant advance in the infrastructure (instrumentation and building works) used to monitor the volcano.� Most importantly, it provided for the training of two Vincentians in earth science and related disciplines and so made possible the eventual establishment of a locally staffed volcano observatory.� The government of St. Vincent and the Grenadines sought and obtained US$541,423 from the United Nations Development Programme for this project which facilitated the expansion and improvement of the volcano monitoring program at the Soufri�re volcano.

In 1987 with the return of one of the two Vincentians trained through the SVVMP, the Soufri�re Monitoring Unit was established.� From this point onwards the volcano monitoring network operated on St. Vincent became a collaborative arrangement between the Seismic Research Unit of the UWI and the Soufri�re Monitoring Unit.� Under this arrangement the seismograph stations in St. Vincent plus two in southern St. Lucia transmitted signals by VHF and UHF radio to the Belmont Observatory.� From there they were relayed to the Seismic Research Unit headquarters in St. Augustine where they were recorded on computers.� Prior to 2002 the process of transmission of seismic data from Belmont to Trinidad was complicated and consisted of the following stages:

1. From Belmont to Fort Charlotte near Kingstown by VHF radio maintained by the Soufri�re Monitoring Unit.

2. From Fort Charlotte to Arnos Vale by landline operated by Cable and Wireless (SVG) Limited.

3. From Arnos Vale to Port of Spain by microwave link operated by Cable and Wireless International.

4. From Port-of-Spain to St. Augustine by landline operated by Telecommunications Service of Trinidad and Tobago (TSTT).

This system represented the state of the art of the technology during the 1980�s when it was first established and it worked well for nearly twenty years.� However, it involved four separate segments each maintained by a different organization and therefore was prone to a number of problems.� The main problems were the expensive maintenance costs associated with it (particularly the segments operated by Cable and Wireless and TSTT for which a very high monthly rental was paid) and its vulnerability to different types of breakdown.

Advances in information and communication technologies in the late 1990�s enabled the implementation of a new system of remote monitoring in 1999 (Figure 10a).� Four seismic stations on St. Vincent (Belmont Observatory, Fancy, Wallibou Ridge and Fort Charlotte) along with two in southern St. Lucia (Sulphur Springs and Moule-a-Chique) still constitute the permanent seismic monitoring network.� They provide the foundation for the day-to-day monitoring of the Soufri�re volcano and all except Belmont are automatic stations powered by solar panels.� Data from these stations are transmitted to Belmont where a PC computer-based digital recording system record signals from the seismograph stations.� The PC is linked to the Seismic Research Unit headquarters in Trinidad through an Internet and Public Switched Telephone Network (PSTN) connection and the data is routinely transmitted and analysed by technicians at the Seismic Research Unit.� Therefore the system can communicate with Trinidad in two parallel ways.� The computer can and does automatically connects to the Internet at regular intervals and transmits data files to the Seismic Research Unit headquarters for analysis.� In addition, it is possible to interrogate the computer by modem the PSTN at any time.� Provision is made for expansion of the network in the event of an increase in the level of alert (e.g. from Green to Yellow/Orange) and for the permanent occupation of the Belmont Observatory.� The Belmont Observatory is air-conditioned and has a stand-by generator to ensure an uninterruptible power supply.� Equipment for all seismic stations are drawn from the central pool held at the Seismic Research Unit in Trinidad.� The new system has a number of advantages over the old one.

1. The new system is able to record and reproduce a more faithful representation of ground motion.� One station at the Belmont Observatory records the 3 principal axes of ground motion (N-S, E-W and vertical) and the recorded resolution of this station is more than 3 times better than in the pre-existing system.� Twelve additional local stations may be operated and the resulting resolution of these stations is also improved.

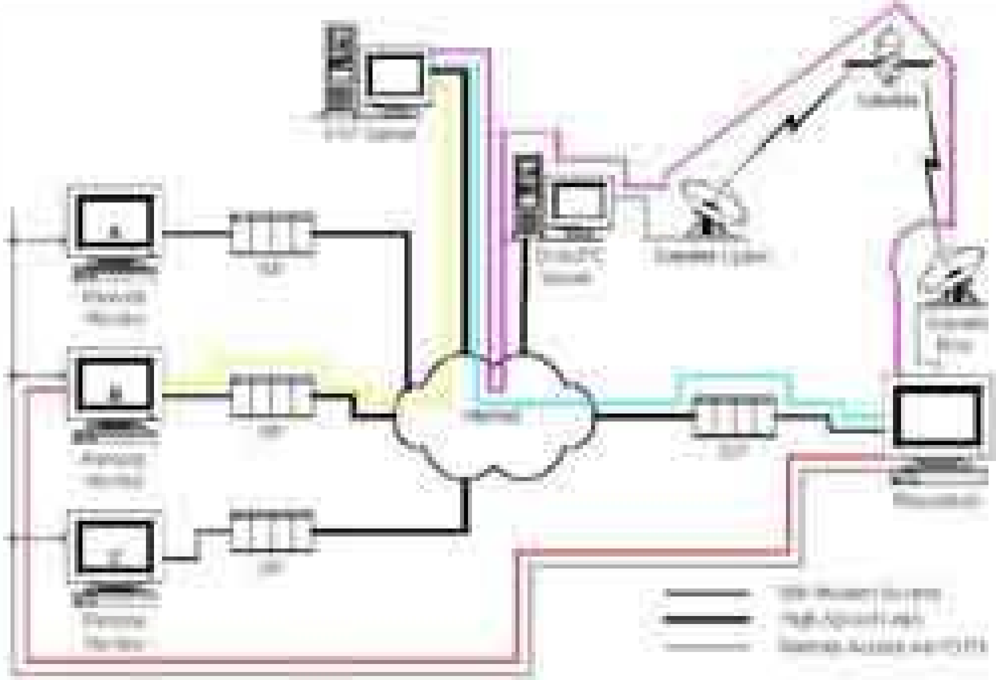

Figure 10a: Data communication architecture for the internet-based volcano monitoring and data acquisition system currently used at the Soufrière volcano.

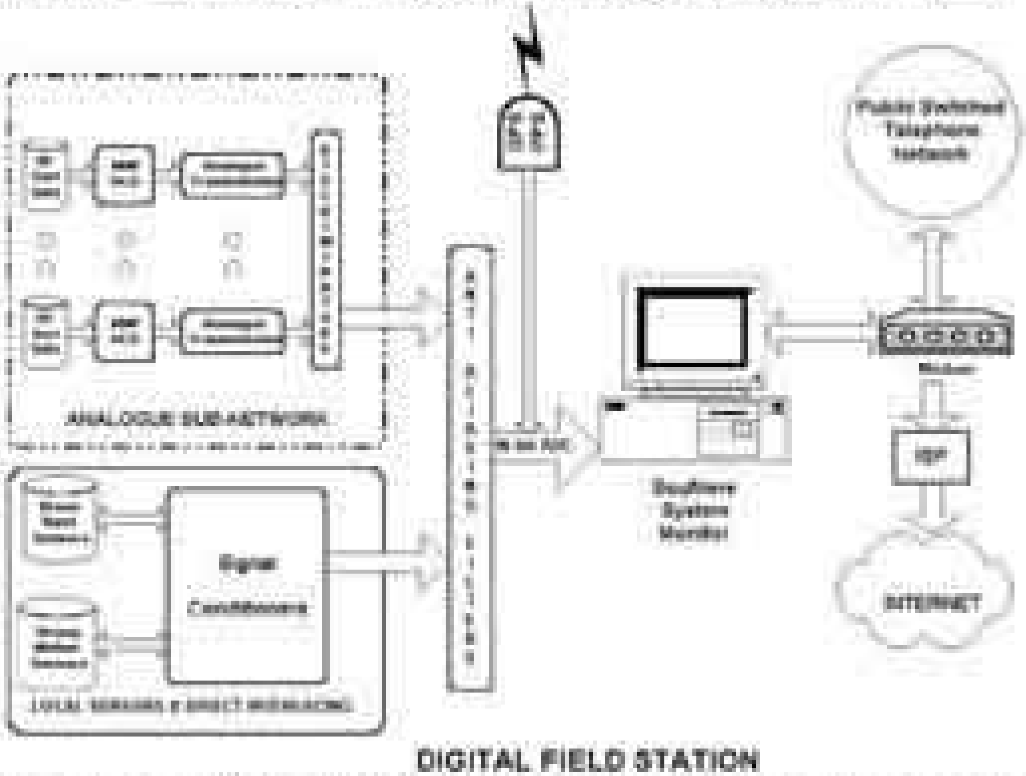

Figure 10b: The configuration of a digital field station similar to the one operated at the Belmont Observatory.

2. Data is now available in computer format both in St. Vincent and in Trinidad.� This will be particularly valuable at times of increased activity when it becomes necessary to transfer the full data analysis system from St. Augustine to Belmont very rapidly.

3. The system is easy to reconfigure to accommodate changes in activity levels.� It is much less prone to breakdowns and is more maintainable.

4. The system is much less expensive to operate. Prior to the use of an internet-based system the Seismic Research Unit paid Cable and Wireless and TSTT a total of over TT$11,000 per month to rent microwave and telephone links between Belmont and St. Augustine.� Savings on the first two months alone was sufficient to cover the initial capital costs of purchasing computer and related equipment for Belmont.

In 2001, the ground deformation network was also improved with establishment of a GPS (Global Positioning System) network to augment the pre-existing dry-tilt sites (Figure 11).� Both network consists of a number of sites where regular but not continuous measurements are made by staff members of the Seismic Research Unit in collaboration with the Soufri�re Monitoring Unit.� No equipment is left permanently at any of these locations other than benchmarks[1] similar to those used by surveyors.� These consist of short pins made of stainless steel which is either one half inch or one inch in diameter.� These pins are glued or cemented into the ground and their locations are remeasured periodically using Global Positioning System and precise levelling techniques.� The frequency of measurements depends on the level of activity at the volcano.� These measurements enable monitoring scientists to determine whether there are any changes in the size of the volcano.

A number of factors have contributed to the development and deployment of the St. Vincent volcano monitoring network.� Proximity of monitoring sites to the volcano was a key factor in determining station locations.� To effectively monitor the volcano, seismic stations had to be located in southern St. Lucia as well as on St. Vincent.� Although a seismic network confined to the island may be effective during an eruption, the signs of a new eruption after a long period of quiescence is more likely to originate from a deeper source and would require a seismic network with a wider aperture than one limited to a single island.� Contribution to a regional unit that maintains a regional network of seismograph stations is therefore essential for island-arc volcanoes such as the Soufri�re volcano.� The choice of station locations was also affected by the dual objectives of the seismograph network i.e. the detection of volcanic and tectonic earthquakes.

A key consideration in the deployment of monitoring stations was the need for equipment deployed in remote locations to be accessible for maintenance and radio transmission and free from seismic background noise.� In addition, attempts were made to minimise the risk of vandalism by concealing sites as much as possible.� Experience has shown that remote stations are more likely to be tampered with if they are easily accessible and visible to the public.� Budgetary limitations was a major consideration since the Seismic Unit have at times had to

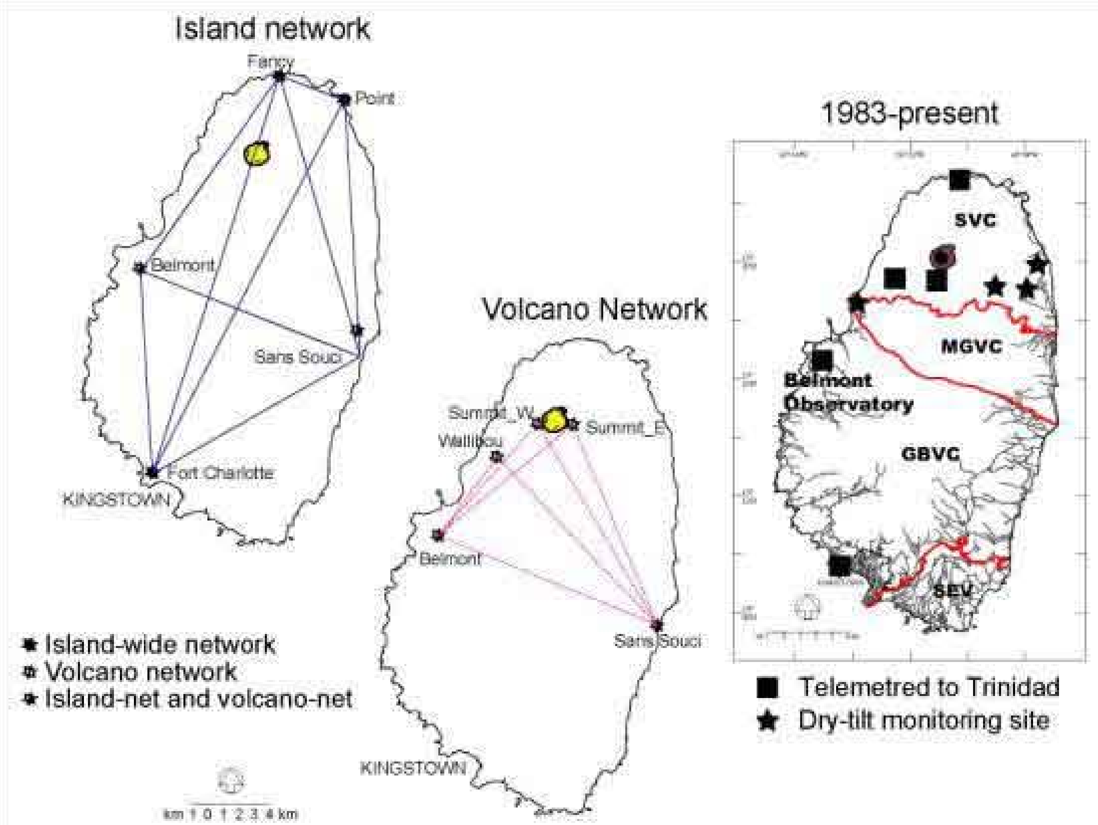

Figure 11: The seismograph and ground deformation networks operated by the Seismic Research Unit in collaboration with the Soufrière Monitoring Unit at the Soufrière Volcano.

function with a modest and fluctuating budget.� It was therefore necessary to keep maintenance costs to a minimum.� Finally the network was designed so that it could be expanded at short notice during periods of elevated activity and that all measurements could be completed in minimal time and with as low risk as possible to monitoring personnel.

Post 1950s: (b) Geological investigations

The existence of a regional volcano monitoring agency from the 1950s onwards gave impetus to geological investigations of the volcano and a significant amount of geological work was undertaken after this period.� Lewis (1964; 1965; 1969; 1970; 1973a; 1973b) continued the examination of cumulate blocks ejected by the volcano which was initiated by Lacroix (1949) and Sapper (1903) and did a comprehensive investigation of their properties.� Macgregor (1952) examined calcareous blocks of sedimentary origin that were found on the volcano.� Rowley (1978a), Graham and Thirlwall (1981) and Heath *et al*. (1997; 1998; 1998) examined aspects of the petrology and geochemistry of the volcano while Sigurdsson (1977) and Shepherd and Sigurdsson (1978) investigated the chemistry and heat absorption properties of the pre-1979 crater lake.

Geological investigation of the thick sequence of ashfall deposits that cover the entire island and which originated from Pre-Historic eruptions of the Soufri�re volcano was initiated by Hay (1959b) and continued by Rowley (1978b).� More recent deposits from the volcano have also been studied by various workers including Hay (1959a), Rowley (1978a), Carey and Sigurdsson (1978), Fiske and Sigurdsson (1982) as well as Sparks and Wilson (1982), Heath (1997) and Robertson (1992).

Surveillance of the volcano has resulted in more detailed scientific descriptions of eruptive activity as monitoring scientists were on island during the course of these events.� The 1971 eruption is dealt with by Aspinall *et al*. (1972), Tomblin *et al*. (1972), Baker (Baker, 1972), Aspinall *et al*. (1973), Sigurdsson (1977) and Shepherd and Sigurdsson (1978).� Similarly the 1979 eruption is covered thoroughly by Shepherd *et al*. (1979), Michel (1980), Graham and Thirlwall (1981), Fiske and Sigurdsson (1982), Shepherd and Sigurdsson (1982), Huppert *et al*. (1982), Sparks and Wilson (1982), Fiske (1984) and Fiske and Shepherd (1990).

Increasing concerns regarding the hazards posed by the volcano have led to a number of studies that attempt to determine eruptive patterns, premonitory signs and potential hazard zones.� Aspinall *et al.* (1973) and Robertson (1995) suggested cyclical patterns of eruptive activity and an explosive eruption frequency of about 90-100 years.� Carey and Sigurdsson (1978), Graham and Thirlwall (1981) and Shepherd and Sigurdsson (1982) have all suggested different mechanisms to explain eruptive activity at the volcano while Shepherd and Aspinall (1982) and Shepherd (1989) have examined the types of premonitory signs expected from future eruptions.� Robertson (1992; 1995) presented an assessment of the hazard and risk associated with future eruptions.

Roles and responsibilities

The volcano monitoring program on St. Vincent is a collaborative effort between the locally-based Soufri�re Monitoring Unit and the regionally-based Seismic Research Unit.� Each organisation has specific roles and responsibilities and work in tandem to ensure that a reliable early-warning system is in place at the volcano.

<u>The Soufri�re Monitoring Unit</u>

This unit is based at the Ministry of Agriculture and is headed by a trained Geologist.� It employs two technicians and a driver and has a recurrent budget of about 68,000 EC$.� The Unit is responsible for undertaking the following activities.

Routine maintenance of monitoring equipment:� This is the main element of the day-to-day duties of Unit.� This aspect of its operations is concerned mainly with keeping the four permanent seismograph stations in good condition. Routine tasks include such activities as topping up batteries with distilled water, cleaning solar panels and clearing overgrowth from remote monitoring sites.� At Belmont the Unit ensures that the electricity and telephone systems are in good working condition so that the equipment stored there can operate uninterrupted.� Monitoring sites used for ground deformation measurement has to be cleared periodically to ensure that the benchmarks do not become completely buried.

Visits to the crater rim:� Regular visits are made to the summit of the volcano and a record kept of the physical conditions in the crater and surroundings.� Any visible changes are sent to the Seismic Research Unit by e-mail so that advice can be obtained on further action that may be necessary.

Support for scientists in the field:� Local staff provides assistance and guidance to staff from the Seismic Unit whenever they are engaged in official business in St. Vincent.� This may involve assistance with the maintenance and installation of seismic monitoring equipment, sampling of volcanic gases and occupation of ground deformation sites.

The Seismic Research Unit

The Seismic Research Unit is primarily funded by the governments of Trinidad and Tobago, Grenada, St. Vincent and the Grenadines, Barbados, St. Lucia, Dominica, Montserrat, St. Kitts-Nevis, Antigua-Barbuda and the British Virgin Islands. Additional funding is provided on an ad hoc basis by a number of external agencies and private companies for expenditure on specific projects.� The Unit has a staff complement of 16 (9 scientific staff and 7 technical and support staff) and has a recurrent budget of about 1 million Eastern Caribbean dollars.� The Seismic Research Unit provides essential advice and support to the Soufri�re Monitoring Unit.� It maintains a pool of equipment ready for rapid deployment in the event of increased volcanic activity; provides essential spares for seismic equipment; undertake major repairs and installation of monitoring equipment and has overall responsibility for seismic and volcano monitoring operations in the island.� Should there be an increase in volcanic activity, the Unit will provide equipment and personnel to manage the Belmont Observatory on a full-time 24-hour basis.�

Discussion

The �St. Vincent model� for volcano monitoring operations contrasts with other volcano monitoring operations used in the Eastern Caribbean.

- On the French islands of Martinique and Guadeloupe small to medium sized local observatories are maintained by the Intitut de Globe de Physic de Paris (the IPGP).� The Observatories form part of a set of overseas observatories operated by the IPGP in French Departments and former colonies.� The Scientist-in-Charge and all key scientific personnel are appointed by the IPGP.� Funding is provided by the French government through the IPGP whose officers are responsible for directing all aspects of the scientific work undertaken on these islands.
- On Montserrat a moderate sized Observatory (the Montserrat Volcano Observatory) is managed entirely on a contractual basis by the British Geological Survey.� A local board headed by the Governor and Chief Minister functions in an overall supervisory capacity but a UK-based Scientific Advisory Committee which is also responsible for risk and hazard assessments does supervision of the scientific work of the Observatory.� Similar to the French Observatories, funding is obtained entirely from extra-regional sources (in this case the United Kingdom) and control and direction of all operations lie essentially with the funding source.

The volcano monitoring program in St. Vincent utilises similar techniques to those applied in Guadeloupe, Martinique and Montserrat but beyond this the operations is entirely different.� The St. Vincent program is funded entirely from local and regional resources and management is either local or regional.� The Soufri�re Monitoring Unit falls under the Ministry of Agriculture and control of its operations is local.� The Seismic Research Unit is a part of the University of the West Indies and its operations are supervised through the Office of Research with provision made for direct input from island governments through a Technical Advisory Committee consisting of representatives of the contributing territories.

A significant factor in the development of the �St. Vincent model� has been the constraints on funding that is reality in the Eastern Caribbean.� Small independent nations like St. Vincent and the Grenadines require monitoring operations to be cost-effective and efficient if they are to survive.� Monitoring costs have to be kept to a minimum to ensure longevity.� As the period of quiescence between eruptive episodes lengthen, competition for limited resources will increasingly threaten the survival of any operation that is costly.� The employment of experienced specialist staff and maintenance of monitoring equipment required for an effective volcano monitoring network would prove too expensive for most countries.� Even in other regions with access to greater resources it has proven more efficient to pool staff and equipment rather than establishing single entities for each individual volcanic centre.� For example, in North and South America single volcano observatories employing about 10 professional scientists have been established to monitor comparable numbers of volcanic centres as those that exist in the region and for which the Seismic Research Unit is responsible.

Of all the volcano monitoring programs that exist in the region, only the St. Vincent model is the only one that may be regarded as truly regional.� The local Soufri�re Monitoring Unit is entirely autonomous; it has its own source of funding and has a specific role to play in volcano monitoring operations on the island.� It collaborates with a regional agency that operates a network of monitoring sites throughout the Eastern Caribbean and that is itself funded by the Eastern Caribbean island governments.� The St. Vincent volcano monitoring operation has developed in response to, and is responsive to changing circumstances at the volcano.� From its early dependence on visual observations and rudimentary scientific methods, it has evolved into an operation that utilises state of the art technology in a most cost effective manner.� It has proven its worth during two different eruptive styles and has managed to survive the long quiet period between eruptions, despite the changing economic circumstances in St. Vincent and the rest of the region.� It has shown how small islands with limited resources can cooperate to fund organizations that fulfil critical functions.� We consider that the model can be applied in other regions with similar hazards, geographic setting and limited material resources and believe that it is the template that should be used to monitor other active and potentially active volcanoes in the Commonwealth Eastern Caribbean.

References

Anderson, J. 1785. An account of Morne Garou, a mountain in the island of St. Vincent, with a description of the volcano on its summit. *Philosophical Transactions of the Royal Society of London* 75:16-31.

Anderson, T. , and J.S. Flett. 1903. Report on the eruption of the Soufri�re of St. Vincent in 1902 and on a visit to Montagne Pelee in Martinique. Part I. *Royal Society Philosophical Transacctions* Series A-200:353-553.

Aspinall, W.P., H.� Sigurdsson, and J.B. Shepherd. 1973. Eruption of the Soufri�re volcano on St. Vincent island, 1971-1972. *Science* 181:117-124.

Aspinall, W.P., H. Sigurdsson, J.B. Shepherd, H. Almorales, and P.E. Baker. 1972. Eruption of the Soufriere Volcano on St. Vincent island, 1971-72. *Smithsonian Institute for Short-Liver Phenomena*:23.

Baker, P.E. 1972. The Soufri�re volcano, St. Vincent and its 1971-72 eruption. *Journal of Earth Sciences, Leeds* 8:205-217.

Carey, S.N., and H. Sigurdsson. 1978. Deep-sea evidence for distribution of tephra from the mixed magma eruption of the Soufri�re on St. Vincent, 1902: Ash turbidites and air fall. *Geology* 6:271-274.

Fiske, R.S. 1984. Volcanologists, journalists and the concerned local public: A tale of two crises in the Eastern Caribbean. In *Studies in Geophysics: Explosive Volcanism: Inception, Evolution and Hazards*. Washington D.C.: National Academy Press.

Fiske, R.S., and J.B. Shepherd. 1982. Deformation Studies On Soufri�re, St-Vincent, Between 1977 and 1981. *Science* 216 (4550):1125-1126.

���. 1990. 12 Years of Ground-Tilt Measurements On the Soufri�re of St- Vincent, 1977-1989. *Bulletin of Volcanology* 52 (3):227-241.

Fiske, R.S., and H. Sigurdsson. 1982. Soufri�re Volcano, St-Vincent - Observations of Its 1979 Eruption From the Ground, Aircraft, and Satellites. *Science* 216 (4550):1105-1106.

Flett, J.S. 1908. Petrological notes on the products of the eruptions of May 1902, at the Soufri�re in St. Vincent. *Philosophical Transactions of the Royal Society of London* 208 (Series A):225-253.

Graham, A.M., and M.F. Thirlwall. 1981. Petrology of the 1979 Eruption of Soufri�re Volcano, St. Vincent, Lesser Antilles. *Contributions to Mineralogy and Petrology* 76 (3):336-342.

Hay, R.L. 1959a. Formation of the crystal-rich glowing avalanche deposits of St. Vincent, B.W.I. *Journal of Geology* 67:540-562.

���. 1959b. Origin and weathering of late Pleistocene ash deposits on St. Vincent, B.W.I. *Journal of Geology* 67:65-87.

Heath, E. 1997. Genesis and evolution of calc-alkaline magmas at Soufri�re volcano, Lesser Antilles arc. PhD, Institute for Environmental Sciences, Lancaster University, Lancaster.

Heath, E., R. MacDonald, H. Belkin, C. Hawkesworth, and H. Sigurdsson. 1998. Magmagenesis at Soufri�re Volcano, St Vincent, Lesser Antilles arc. *Journal of Petrology* 39 (10):1721-1764.

Heath, E., S.P. Turner, R. Macdonald, C.J. Hawkesworth, and P. van Calsteren. 1998. Long magma residence times at an island are volcano (Soufri�re, St. Vincent) in the Lesser Antilles: evidence from U-238-Th-230 isochron dating. *Earth and Planetary Science Letters* 160 (1-2):49-63.

Hovey, E.O. 1902. Martinique and St. Vincent: A preliminary report upon the eruptions of 1902. *Am. Mus. Nat. History Bull.* 16:333-372.

Huppert, H.E., J.B. Shepherd, H. Sigurdsson, and R.S.J. Sparks. 1982. On Lava Dome Growth, With Application to the 1979 Lava Extrusion of the Soufri�re of St-Vincent. *Journal of Volcanology and Geothermal Research* 14 (3-4):199-222.

Lacroix, A. 1949. Sur des enclaves endopolygenes de Saint Vincent. *Bulletin De La Societe Mineral. Crist.* 72:571-590.

Lewis, J.F. 1964. Mineralogical and petrological studies of plutonic blocks from the Soufri�re volcano, St. Vincent, B.W.I. D. Phil, University of Oxford.

���. 1965. The origin of the ejected plutonic blocks of the Soufri�re, St. Vincent (abstract). Paper read at Transactions of the 4th Caribbean Geological Conference, 1968, at Trinidad.

���. 1969. Composition, Physical Properties and Origin of Sodic Anorthites from the Ejected Plutonic Blocks of the Soufri�re Volcano, St. Vincent, West Indies. *Contributions to Mineralogy and Petrology* 21:272-294.

���. 1970. Chemical composition and physical properties of magnetite from the ejected plutonic blocks of the Soufriere volcano, St. Vincent, West Indies. *American Mineralogist* 55:793-807.

���. 1973a. Mineralogy of the Ejected Plutonic Blocks of the Soufri�re Volcano, St. Vincent: Olivine, Pyroxene, Amphibole and Magnetite Paragenesis. *Contributions to Mineralogy and Petrology* 38:197-220.

���. 1973b. Petrology of the ejected plutonic blocks of the Soufri�re volcano, St. Vincent, West Indies. *Journal of Petrology* 14 (1):81-112.

Macgregor, A.G. 1952. Eruptive Mechanism: Mt. Pelee, the Soufri�re of St. Vincent and the Valley of Ten Thousand Smokes. *Bulletin of Volcanology* 12:49-74.

Michel, B. 1980. Geodetic measurements on Soufriere volcano - St. Vincent Island 1979: Institut de Physique du Glove de Paris.

Robertson, R.E.A. 1992. Volcanic Hazard and Risk Assessment of the Soufri�re Volcano, St. Vincent, West Indies. MPhil, Earth Sciences, The University of Leeds, Leeds.

���. 1995. An Assessment of the Risk From Future Eruptions of the Soufri�re Volcano of St. Vincent, West-Indies. *Natural Hazards* 11 (2):163-191.

Rowley, K.C. 1978a. Stratigraphic and geochemical studies of Soufri�re volcano, St. Vincent, West Indies. PhD, Seismic Research Unit, University of the West Indies, St. Augustine.

���. 1978b. Late Pleistocene pyroclastic deposits of Soufri�re Volcano, St. Vincent, W.I. *Geological Society of America Bulletin* 89:825-835.

Sandrea, A. 1949. Les enclaves calcaires de laves de Saint-Vincent (Petites Antilles). *Bull. Soc. Franc. Miner. Crist.* 72:374-387.

Sapper, K. 1903. A report on a visit to St. Vincent.

Shepherd, J. B., K.C. Rowley, W.P. Aspinall, J. Pereira, H. Sigurdsson, R.S. Fiske, and J.F. Tomblin. 1979. Ground and low-level observations of explosive activity at Soufriere volcano, April-May 1979. *EOS, Transactions of the American Geophysical Union* 60:832.

Shepherd, J. B., and H. Sigurdsson. 1978. The Soufriere Crater Lake as a calorimeter. *Nature* 271:344-345.

���. 1982. Mechanism of the 1979 Explosive Eruption of Soufri�re-Volcano, St-Vincent. *Journal of Volcanology and Geothermal Research* 13 (1-2):119-130.

Shepherd, J.B. 1989. Eruptions, eruption precursors and related phenomena in the Lesser Antilles. In *Volcanic Hazards: IAVCEI Proceedings in Volcanology 1*, edited by J. H. Latter. Berlin Heidelberg: Springer-Verlag.

Shepherd, J.B., and W.P. Aspinall. 1982. Seismological Studies of the Soufri�re of St-Vincent, 1953-79 - Implications For Volcanic Surveillance in the Lesser Antilles. *Journal of Volcanology and Geothermal Research* 12 (1-2):37-55.

Sigurdsson, H. 1977. Chemistry of the crater lake during the 1971-72 Soufri�re eruption. *Journal of Volcanology and Geothermal Research* 2:165-186.

Sparks, R.S.J., and L. Wilson. 1982. Explosive Volcanic-Eruptions .5. Observations of Plume Dynamics During the 1979 Soufri�re Eruption, St Vincent. *Geophysical Journal of the Royal Astronomical Society* 69 (2):551-570.

Sparks, R.S.J., L. Wilson, J. Shepherd, W.P. Aspinall, and H. Sigurdsson. 1979. Volcanic plume dynamics: Analysis of film from the 1979 eruption of the Soufriere, St. Vincent (West Indies). Paper read at I.U.G.G. Symposium on Explosive Volcanism, at Canberra, Australia.

Tilling, R.I. 2003. Volcano Monitoring and Eruption Warnings. In *Early Warning Systems for Natural Disaster Reduction*, edited by Z. J. and A. N. Kuppers. Berlin Heidelbery New York: Springer.

Tomblin, J.F., H. Sigurdsson, and W.P. Aspinall. 1972. Activity at the Soufriere volcano, St. Vincent, West Indies, between October 21 - November 15, 1971. *Nature* 235:157-158.

Treves, F. 1908. The day the earth stood still. In *Cradle of the Deep*: Bart.

[1] A term used to refer to permanent markers embedded in the ground by surveyors for marking their locations on the ground.