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A Medium-sized Seismograph Network in a Challenging Environment

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RESUMEN

Se describe la operación de las red sísmica de 30 estaciones que cubre las islas del Caribe Oriental, con centro en la Universidad de West Indies en Trinidad. La red incluye la vigilancia de 15 volcanes activos en un arco de 750 km de largo. La red tiene capacidad para detectar y localizar la mayoría de los eventos de M>2 en la región. Se describe la evolución de la red y algunas de sus estrategias de superación.

PALABRAS CLAVE: Red sísmica, Caribe Oriental, Trinidad.

ABSTRACT

Several destructive earthquakes have been recorded in the Eastern Caribbean during the last three centuries. In addition to hazards posed by earthquakes most of the islands are also at risk from volcanic eruptions. The Seismic Research Unit maintains a network of thirty seismograph stations in the Commonwealth territories of the Eastern Caribbean, to monitor and study earthquakes in the region in an effort to specify the level of seismic hazard and also to maintain a volcano surveillance and warning system. Work is also geared at specifying the level of volcanic risk in each of these territories. Over fifteen potentially active volcanic centers are distributed along the 750 km long island arc. Generally, the stations are deployed at locations which enable fairly accurate detection and location of most regional earthquakes above magnitude two. Procedures are also in place to alter the deployment to investigate volcano-related seismic crises. The effectiveness of the network depends on operational strategies and procedures and equipment that were developed at the unit.

KEY WORDS: Seismic Network, Eastern Caribbean, Trinidad.

INTRODUCTION

Like most developing countries, the small island states of the Eastern Caribbean and the livelihood of its citizens may be adversely affected if struck unprepared by a natural disaster. Over fifteen potentially active volcanoes are located in a region that has experienced some destructive earthquakes and many hurricanes. It is therefore not surprising that the Volcanological Research Department (VRD) was established in the region in the early fifties to investigate seismic and volcanic activities on the Islands.

The establishment of this institution came about after an intense earthquake sequence occurred in St Kitts in 1952. Two British scientists were summoned to investigate the events. In their report, it was recommended that a permanent regional institution be set up to monitor volcanic activity. Perhaps the main impetus behind the creation of this research institute, however, was the fact that over thirty thousand lives were lost in the volcanic eruptions which took place on Martinique and St. Vincent approximately 40 years earlier (1902).

Before 1952, there were only two continuously operated seismograph stations in the Eastern Caribbean. These were established in Martinique in 1927. A third station was installed in Guadeloupe in 1938 and another was operated in Montserrat between 1938 and 1946. After the establishment of the VRD the number of stations was increased to nine. The Volcanological Research Department evolved into the Seismic Research Unit (SRU) and the responsibility to study the frequency and distribution of occurrence of earthquakes in the region, in order to specify the level of hazard in each country was appended to its functions.

During its forty-odd years of existence the Unit has experienced many challenging episodes: volcanic eruptions, volcano-seismic crises, budgetary cuts, expansion and contraction in scale of operation and damaging earthquakes. The Lesser Antilles is a geographical area that is characterized by low land to sea surface area ratio and island distribution that is geometrically unsuitable for seismograph station placement. Throughout the period, the Unit was able to rise to the main challenges and in most cases continue to discharge its duties in an effective manner. The object of this paper is to reveal some of these challenges and discuss the measures used to overcome them.

TECTONIC SETTING AND RATE OF ACTIVITY

The Lesser Antilles island arc lies near the zone of interaction between Caribbean and North American plates (Figure 1). Seismic evidence suggests that along the arc, the North American plate is being thrust under the Caribbean plate at an average rate of approximately 2 cm per year. The active volcanoes along the arc are the manifestation of this subduction. The plane of subduction dips westward from approximately 100-150 km east of the islands where the shallowest earthquakes occur. Beneath the islands it attains a depth of 150 km and reaches the maximum depth of about 200 km at approximately 50 km west of the arc (Tomblin 1975).

Several authors have reported a change in the angle of dip in the Wadati-Benioff zone along the length of the arc (Tomblin, 1975; Dorel, 1978; McCann and Sykes 1984; Wadge and Shepherd 1984). Wadge and Shepherd further asserted that the zone is segmented about Martinique. The

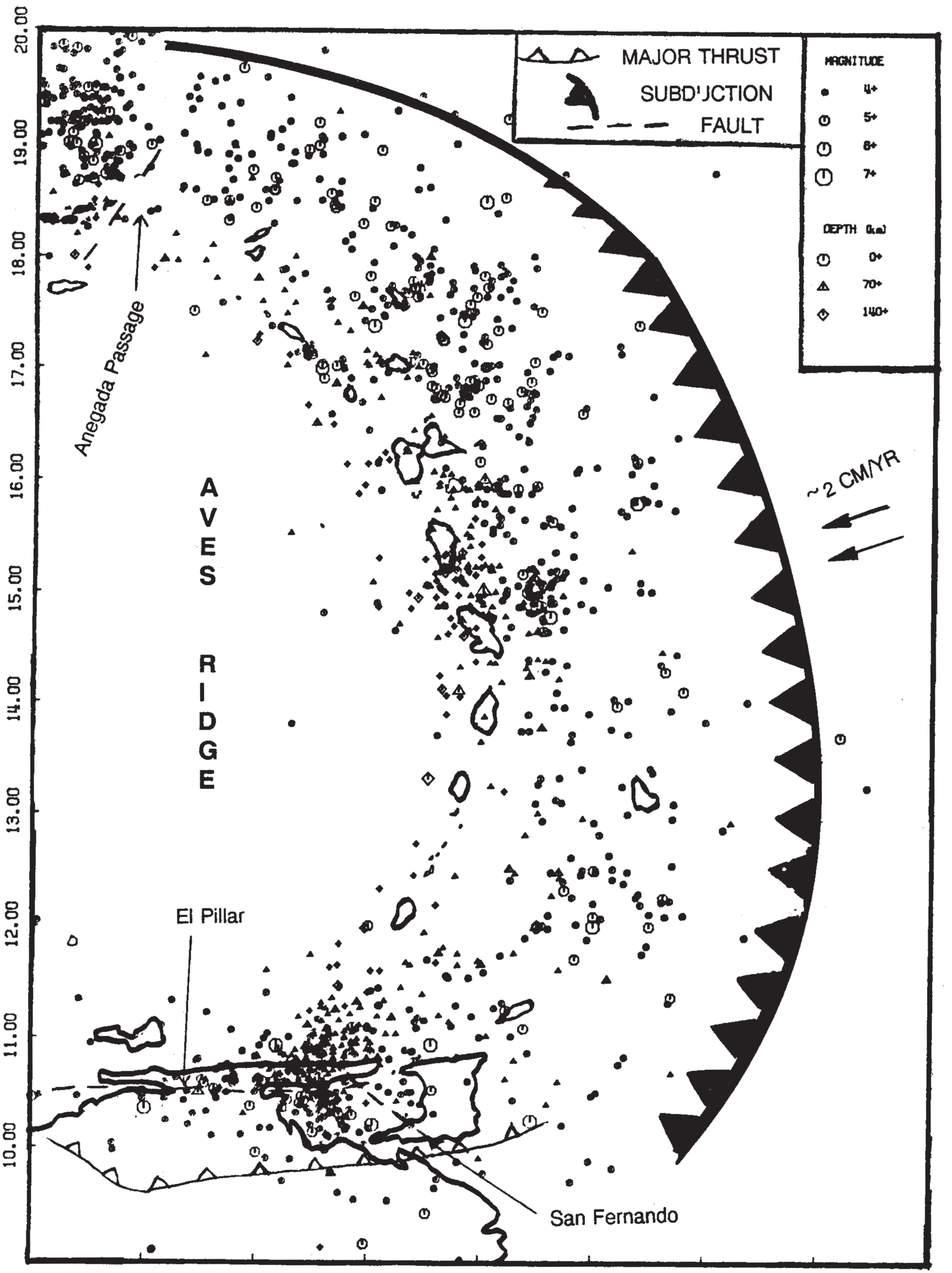


Fig. 1. Eastern Caribbean seismo-tectonics (Epicenters > Magnitude 4, (1900-1992)).

segment north of Martinique is of higher activity rate than the southern segment.

At the southern end of the arc, the dip is almost vertical. The seismo-tectonic processes at play in this area are poorly understood but it is suggested that the plate boundary is diffused and that the seismicity is characterized by the relative motion of localized faults.

Since 1650 over 15 earthquakes of MM Intensity VIII and over have occurred in the eastern Caribbean. The largest of these events occurred on February 8 1843 in the vicinity of Guadeloupe. This event was of maximum Modified Mercalli Intensity ten (MMX) and was responsible for over 5000 casualties. The largest event that occurred in the region since the establishment of the Seismic Research Unit was a moderately damaging Ms 7.5 near Antigua in October of 1974. The recurrence statistics for earthquakes of different magnitudes in the region is given in Table 1. These figures were derived by applying the Gumbel III method of hazard analysis to the data set.

Table 1

Return periods (T) and number of exceedences expected during the next 50 and 100 years for various magnitudes in the Eastern Caribbean. (Ambeh 1994).

M_s	T(Yr)	Predicted		Observed
		50 yr	100 yr	87 yr
5.0	1.7	29-30	58-59	52
5.5	2.3	22-23	44-45	40
6.0	3.4	14-15	29-30	28
6.5	6.1	8-9	16-17	18
7.0	14.7	3-4	6-7	6
7.5	73.3	0-1	1-2	2
8.0				

There are at least 15 active volcanoes along the island arc extending from Grenada in the south to Saba in the north (Figure 2). Since the mid-17th century, there have been at least 25 subaerial eruptions of which 3 have caused loss of life; 10 submarine eruptions and 10 volcano-seismic crises (Smith and Roobol 1994). The historic activity is dominated by the two Soufrières of Guadeloupe and St. Vincent and Mt. Pelée of Martinique. The pattern exhibited by these volcanoes is an eruption every few decades that affect only the volcano's immediate flanks (Smith and Roobol 1994). The eastern Caribbean islands are relatively small in comparison to the sizes of the volcanoes. In many cases the flanks of the volcano are inhabited by a high percentage of the island population. An estimated 250,000 people in the Caribbean are at risk from dangers posed by volcanoes.

With the exception of Kick 'en Jenny all of the better known volcanic eruptions that occurred in the Lesser Antilles are preceded by some type of detectable precursor (Shepherd 1989). The main precursory symptoms are increased local earthquake occurrence and higher rate of fumarolic activity. Although these phenomena often give a fair indication about the chances and possible scale of the eruption, no general rule is applicable for the entire region. Experience has also shown that each eruption/volcano-seismic crisis should be treated on its own merits, i.e. the behavioral pattern should not be arbitrarily applied to volcanoes.

Hence, the seismic monitoring network was designed to detect volcano-seismic earthquakes as soon as a sequence starts. In some parts of the Seismic Unit network, it is necessary to have a complement of spare equipment and a system in place for rapid deployment of a temporary array. It is also imperative that other programs such as volcanic history mapping and frequent reconnaissance be put in place to complement the seismic data that is collected.

SEISMOGRAPH NETWORK AND INSTRUMENTATION

The Eastern Caribbean Seismograph network consists of 32 seismograph stations distributed along the island arc as shown in Figure 3. Most of the sites were selected on the basis of being (a) close to an active volcanic center (b) accessible for maintenance and radio transmission purposes (c) free from seismic background noise and (d) free from vandalism. For transmission and maintenance purposes the stations are divided into four sub-networks as follows (Figure 4): a) Leewards, b) Dominica, c) St. Vincent/St. Lucia, d) South Windward/Trinidad and Tobago.

The analogue frequency-multiplexed (FM) telemetry method of data transmission is used throughout. Within a sub-network FM-encoded data are transmitted via VHF radio links to a central station where they are mixed and retransmitted via voice-grade leased links to the network processing center in St. Augustine, Trinidad. In sub-network (d) which is relatively close to the processing center, VHF radio links are used exclusively. A combination of VHF and telephone landline links are employed in sub-network (b).

A mixture of different designs and brands of seismograph station equipment are used in the network. The Dominica and Trinidad stations are equipped with Kinemetrics Ranger SS-1 seismometers while most of the others are equipped with Mark Products LC-4 units. Some old but serviceable Willmore MKII units are kept as spares and used occasionally. At the Network Headquarters in Trinidad there are two three-component seismometers remaining from the WWSSN project, a short period variable reluctance Benioff unit and a Sprengnether moving coil long period unit. These are still in operation.

The telemetric equipment was developed and built inhouse. The typical gain of the telemetry pair is 60 dB. Both pre-amplified and demodulated signals are lowpass filtered by second-order Butterworth filters with cutoff frequencies of 35 and 20 Hz respectively. The latter signal is further passed through a similar type fourth order anti-aliasing filter before it is digitized. Further details on these equipment can be obtained from Lynch (1990).

DATA ACQUISITION AND PROCESSING

At the processing center the demodulated data channels

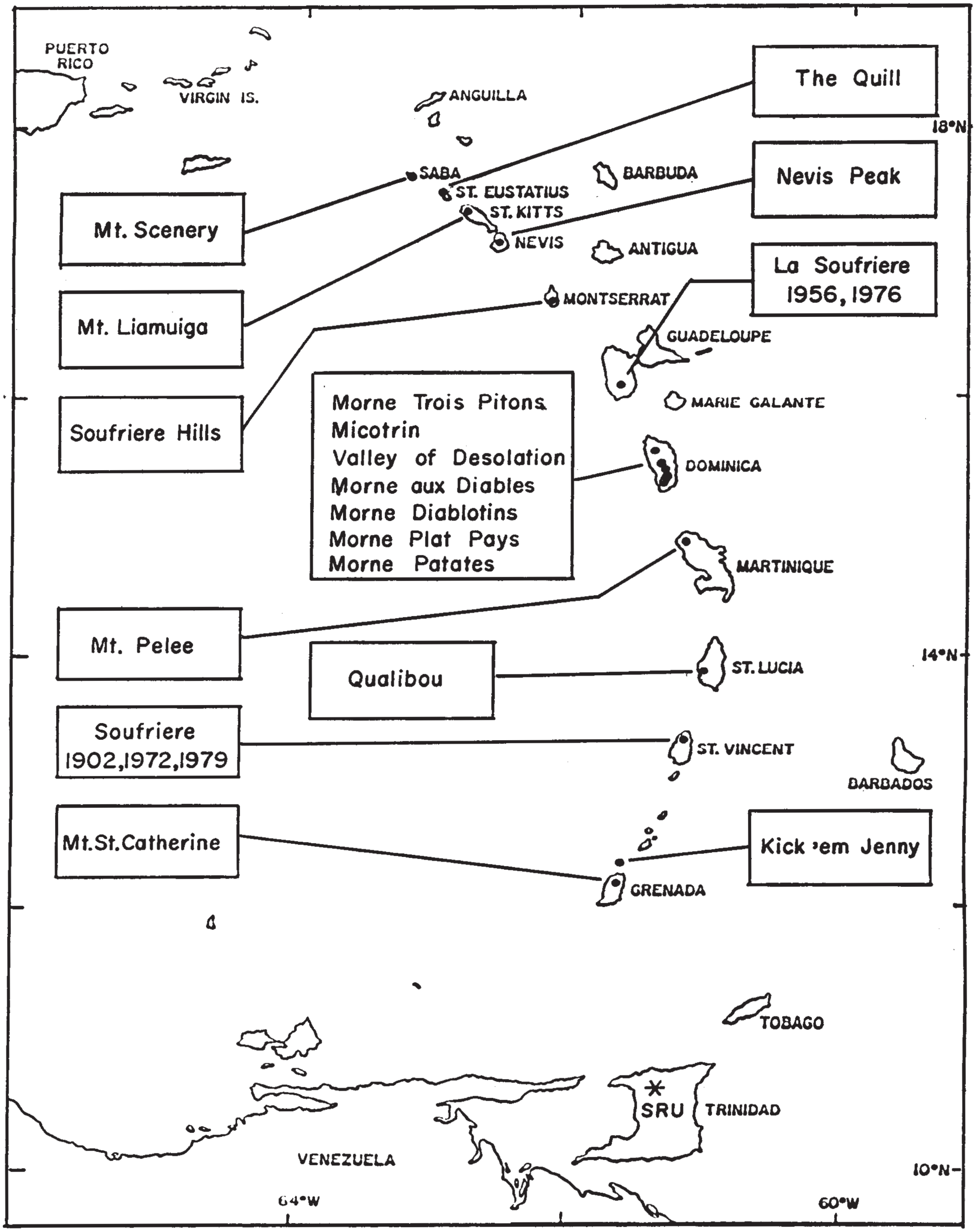


Fig. 2. Eastern Caribbean volcanoes.

are monitored with a totally automated PC-based data acquisition system. This consists of three 16-channel 12-bit digitizing system which samples at 100 Hz. Each monitoring is synchronized with signals from an absolute time source. Timing accuracy is of the order of 10 milli-second. Table 2 summarizes the main features of the monitor. Nine drum recorders are used to visually monitor the seismic activity in real time. Further analysis and processing of the data is accomplished using a family of programs that were developed in-house. The whole family including the

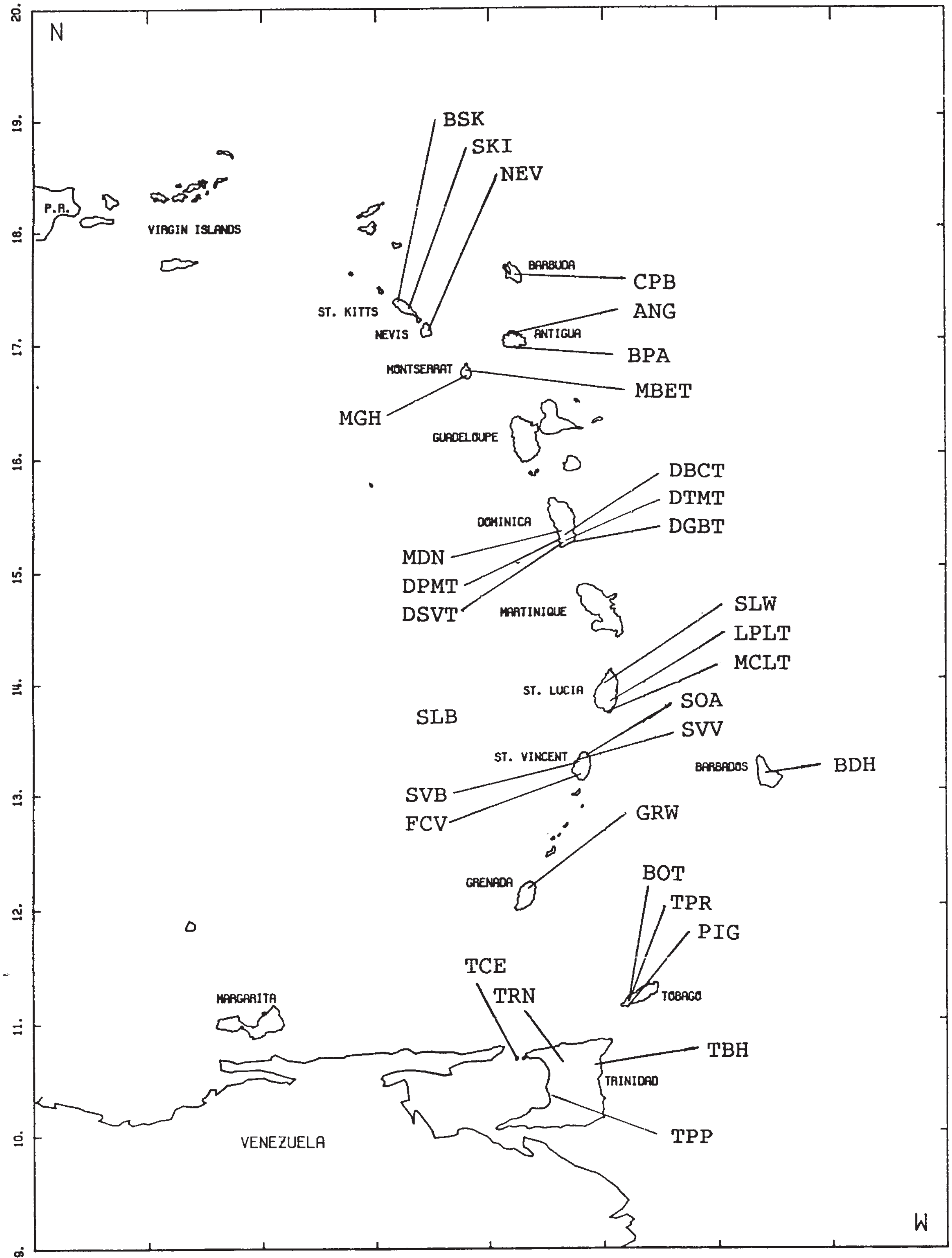


Fig. 3. Eastern Caribbean seismograph stations.

monitor constitutes what is known as the Soufrière System (Beckles *et al*, 1990). The complete package, which is PC executable, is designed to carry the major processing tasks that are typical of a medium-sized seismograph network. The block diagram in Figure 5 illustrates how the various programs of the system are related.

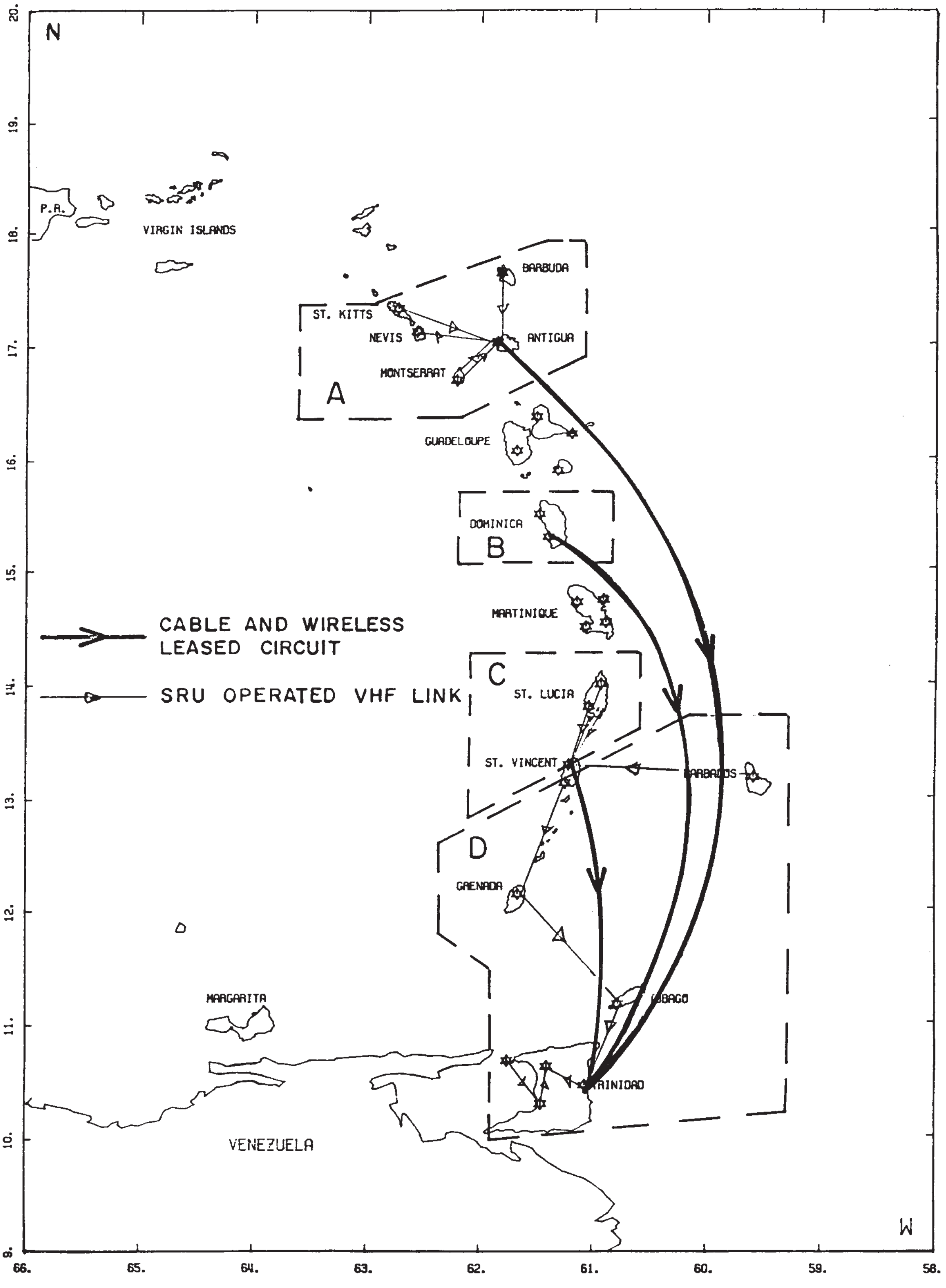
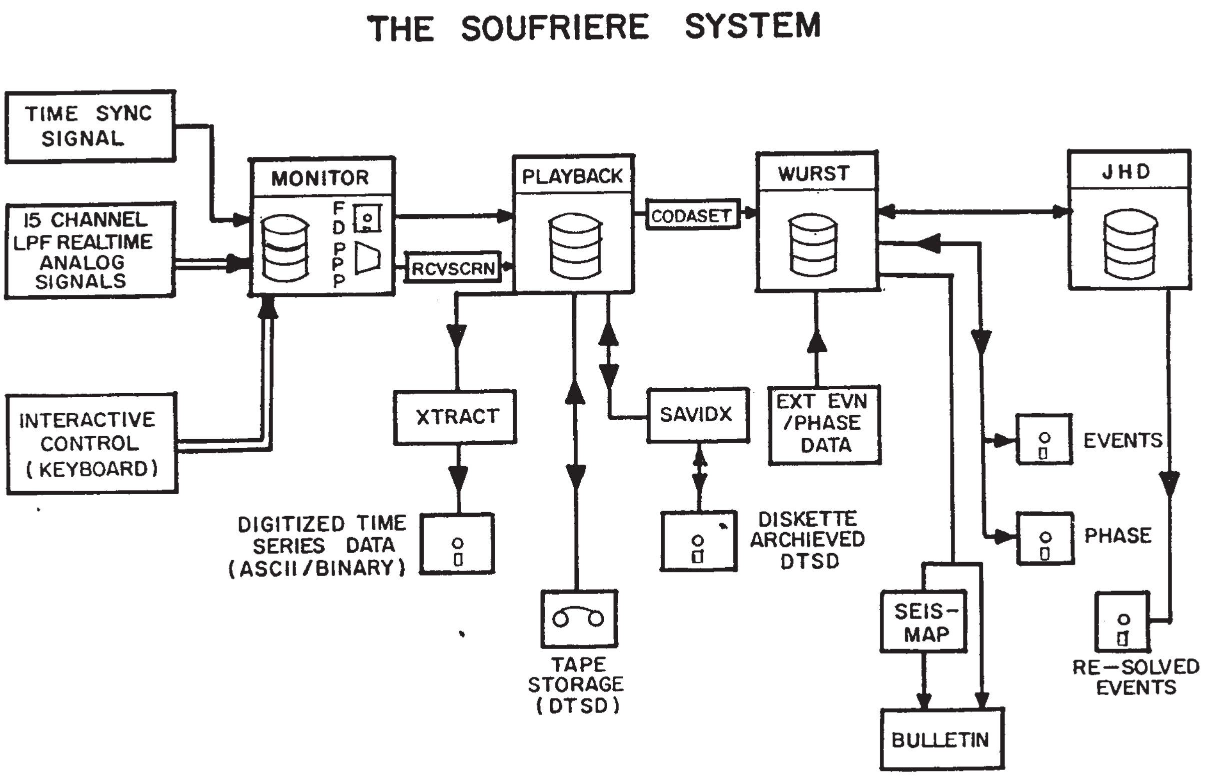


Fig. 4. Eastern Caribbean seismograph network.

OPERATIONAL CONSTRAINTS AND ADOPTED APPROACHES

The primary constraints that largely dictate how operations at the Seismic Research Unit are carried out may be identified as follows:

a) Modest and fluctuating budget.



Program	Function
Monitor	On-line seismic data collection facility.
Rcvscrn	Supervises Monitor - Playback data transfer via the Parallel Printer Port (PPP).
Playback	Inspection and analysis of digital seismograms and the production of phase arrival records.
Wurst	Hypocentral calculations/ bulletin production
Savidx	Disk/Diskette archiving of Digital seismograms.
Codaset	Used in Magnitude determination.
JHD	Joint Hypocentral Determinations.
XTRACT	Seismograms extraction from archive

Fig. 5. The Soufrière system software.

Table 2

Key features of the Soufrière systems monitor

Background data acquisition.
Triggered alarm outputs.
Multiple detection algorithms.
Continuous data capture (or trace) mode.
Event triggered detection of seismic signals.
Data retrieval without interrupting operations.
Absolute and high resolution time tagging of data.
Interactive manipulation of detection and data acquisition parameters without interrupting operations.
Tunable detection and data acquisition parameters for enhancing discrimination against noise.

b) The length of the network aperture.
c) The narrow aperture width of the network.
d) The dual monitoring that must be provided.
e) Quality and quantity of research conducted.

Modest and fluctuating budget

Although it is strongly agreed by the authorities of the territories which contribute to the running of the SRU that its services are indispensable, the financial support is well below that which is required to function properly. One factor to this is the lower rate of occurrence of destructive seismic and volcanic events compared to hurricanes and tropical storms. This breeds a sense of complacency towards seismic and volcanic awareness and preparedness. On a regular basis it is necessary for the Unit to organize special events to sensitize the relevant authorities, and to lobby for continued financial support.

To counter the restrictions of a modest budget, particularly in crisis situations, aid is sought from local, regional and international sources. Some of the more expensive capital items at the SRU such as seismometers and computers were acquired this way.

The second measure is to develop low-cost solutions to the operational problems. Examples of these are elaborated in the following sections.

The length of the network aperture

The tectonically active area in the Lesser Antilles spans an arc of length of approximately 1000 km. The active volcanoes are evenly distributed along the arc. Taking budgetary restraints into consideration, effective monitoring of such a geographical distribution of seismic and volcanic hazard must include an array of seismographs deployed along the arc with at least one instrument on each volcanic island. This design concept was adopted in early days of establishment when fully functional individual monitoring stations were operated in some of the islands.

Development of in-house equipment and systems

A minimum number of permanent stations must be maintained across the network. This is an important design parameter because the capital outlay required for each station can be large. This has a direct bearing on other factors such as the quantity and type of technical support staff needed, arrangement for tele-communication and data acquisition and processing needs.

The SRU currently maintains an array of thirty-two permanent seismograph stations. To reduce operating costs, several system components are developed and produced in house to supplement custom-made equipment. Examples of equipment and systems that are developed and produced in-house are telemetry and radio equipment, data acquisition and processing software and specialized tools to carry out maintenance and analysis of network parameters. Another effective way to achieve this end is to economize by shopping wisely. In some cases, if equipment is available from manufacturers, distributors should be avoided.

Telecommunications considerations

The cost of transmitting data over large distances (above 400 km) is very high. In 1977 when the Unit changed its operation from individually operated stations to real-time centralized data acquisition and monitoring, voice-grade data channels were used for transmission. These offered several advantages and still do, but the cost efficiency of this system has declined in recent years. Today, the cost to retain the three leased circuits used in the network is the second-largest recurring item in the budget.

The development of the Soufrière System Monitor (SSM) represented a major first step towards the design of a system that will be used to replace the dedicated leased lines. After a few years suspension, interest in executing this program has now resurged and work will be started in September. The main focus of the plan entails redesigning the SSM to operate remotely and download the data routinely via public switched telephone network.

Maintenance approach

The use of leased circuits as the data transmission backbone reduces maintenance requirements to seismograph stations and inter sub-network radio-link maintenance checks. Despite this, maintenance costs are still high because the only access to most of the islands is by air travel. An effective maintenance programme is used to optimize the number of field maintenance excursions. This program entails:

(a) Keeping a daily log of the spectral and time history characteristics of the carrier frequency of each station on each leased circuit.

(b) Checking the station channel power on the Soufrière system monitor on a regular basis. This is the power spectrum of the demodulated seismograph signal plus the noise on the circuit.

These two checks can reveal various types of problem symptoms or equipment failure. They are also useful in detecting transmission problems such as poor signal-to-noise ratio and distortion. Preventive maintenance techniques are also widely practiced. Equipment are repaired and tested rigorously before being deployed in the field. When a station is visited all of its components are checked regardless of whether they are functional or not. If a fault is developing it is corrected before it becomes fatal.

Another successful way in which the maintenance problem is tackled is by training volunteers on some of the islands to carry out minor troubleshooting and repairs to the equipment. This includes simple tasks such as replacing blown fuses, topping up batteries, radio transmitter/receiver and telemetry module adjustments or replacement. In 1990 UNESCO-ROSTRAC sponsored a training course for six Lesser Antillean nationals. It resulted in a remarkable decrease in the downtime of the stations on the islands which the participants were drawn from.

Narrow network aperture

The Caribbean seismicity map shown in Figure 1 shows that the earthquakes occur along a 200 km belt which runs roughly parallel with the island arc. The narrow aperture of the network places some restriction on the accuracy to which some earthquake hypocenters may be determined. The measures that are put in place to counteract these restraints include:

(a) development and use of good velocity models for different segments of the arc. These were derived using different methods which include refraction studies across the region and software modeling techniques using travel times.

(b) development of an interactive variant of HYPO71 hypocentral determination program that allows the user to follow changes in the location parameters while the solution is in progress. Some of these parameters may be altered interactively. For example, poor phases may be flagged or different velocity models and/or weighting functions may be tried with great ease.

Experience and judgment is a key ingredient to some earthquake hypocentral location problems. In view of this and other reasons, totally automated processing elements such as automatic phase pickers are avoided. Despite this, phases may be processed and a solution can be evaluated within 20 minutes after the occurrence of an event. With the existing station deployment and processing system most hypocenters along the arcs can be determined to accuracy of within +10 km and +20 km depth.

Another measure that is used to improve the accuracy of the solutions is the use of data from the neighboring networks (French West Indies, Puerto Rican and Venezuelan) in processing events. These data are available through bilateral agreements with these networks to exchange phase data via fax immediately after a felt event. All phase data are also exchanged on a weekly basis.

Dual nature monitoring

The permanent network layout presented in Figure 4 is inadequate for monitoring volcano-seismic activity. Occurring mostly at shallow depth, these earthquakes, unless quite intense, rarely propagate far beyond the flanks of a volcano. The strategy used to monitor these events is to deploy a temporary surveillance array as soon as a swarm is detected by the permanent network installation that is often located a few km from each volcano summit.

These temporary stations are deployed to improve the detection capability of the earthquakes and the accuracy of the locations. They are usually maintained until the abnormal activity subsides. Figures 6 through 8 show examples of some localized arrays that have been used to monitor different volcano-seismic sequences.

Crisis monitoring in St. Vincent

Figure 6a covered activities before and after the 1979 eruption of the Soufrière volcano (St. Vincent) which has always been more closely monitored than other volcanoes. Abnormal activity started several months before the eruption. Stations OHS, SVB, SVV, SLB and SSV were installed before the eruption. Stations FCV, OWIA and RSV were added after the eruption. Before and during the eruption, data were telemetered to an observatory at SVB. A fairly good correlation between increased seismic activity and the actual eruption was observed. This was used as one of the deciding factor that led to the prediction of the eruption- an action which led to the evacuation of the high-risk areas. The level of activity is currently back to normal and as a result only stations SVV, SVB, OWIA and SLB are in place to monitor the volcano. The other stations may be re-established with a few days. The telemetry data is currently being transmitted via FCV and leased-circuit transmitting terminal to Trinidad.

Crisis monitoring in Dominica and St. Kitts

The networks in Figure 6b and Figure 7 were employed in the monitoring of a swarm near the Morne Plat Pays and Mount Misery volcanoes in Dominica and St. Kitts respectively. In Dominica, the difficult terrain forced the utilization of land lines to transmit the data to stations DPMT and DSVT located along the more populated west coast. These two stations functioned as repeaters that were tied to VHF links. Seismic activity in this area started in 1986 and continued through to 1989. There is still the occasional sporadic burst of events. The government of Dominica negotiated a concession of the leased circuit tariff for this link. For this reason, coupled with the fact that there is a high density of volcanoes on the island, it was decided to maintain this array.

The St. Kitts (1988) network consisted of five stations (SEOT, BSK, SKI, SKDB and NEV), i.e. two extra stations were added within short radius from the volcano. Since it was not financially feasible to obtain an extra leased circuit, one of the extra stations was realized at the expense of one of the permanent stations of the sub-network. The second station was inconveniently accommodated onto the data channel at a carrier frequency of 3400 Hz. The full composition of the sub-network during the earthquake sequence is shown in Figure 7(b).

Crisis monitoring in Saba and Montserrat

Figures 8(a) and (b) show the networks that were used to monitor an earthquake sequence off Saba in 1992 and an ongoing sequence in Montserrat (1994) respectively. During the Saba sequence a digital tri-axial station (SABA) operating at two gain ranges was operated. It consisted of a R6000 seismometer, a six channel amplifier (3 operating at 20 dB gain and the others at 72 dB) and a portable version of the Soufrière System Monitor. The stations STMT, SABT and SEOT were installed halfway through the sequence. Again, it was necessary to suspend operation of some of the permanent installation in the Leewards sub-network to accommodate the temporary array.

The data that was collected during this sequence was of good quality and quantity. A detailed analysis of the data strongly suggested that the earthquakes were unlikely to be of volcanic origin.

The latest surveillance network is currently in operating in Montserrat (Figure 8b). It consists of four stations that are not members of the permanent network. These are MSAT, MWHT, MPLT and MSPT. The specifications of MPLT are similar to that of SABA above, but this time the bandwidth is extended towards the low frequency end, from 2.0 Hz to 1.0 Hz. The data from the array are all transmitted to MPLT where they are recorded on a SSM. Two local individuals were trained to retrieve and process the data routinely. Phase arrivals are faxed to the Unit

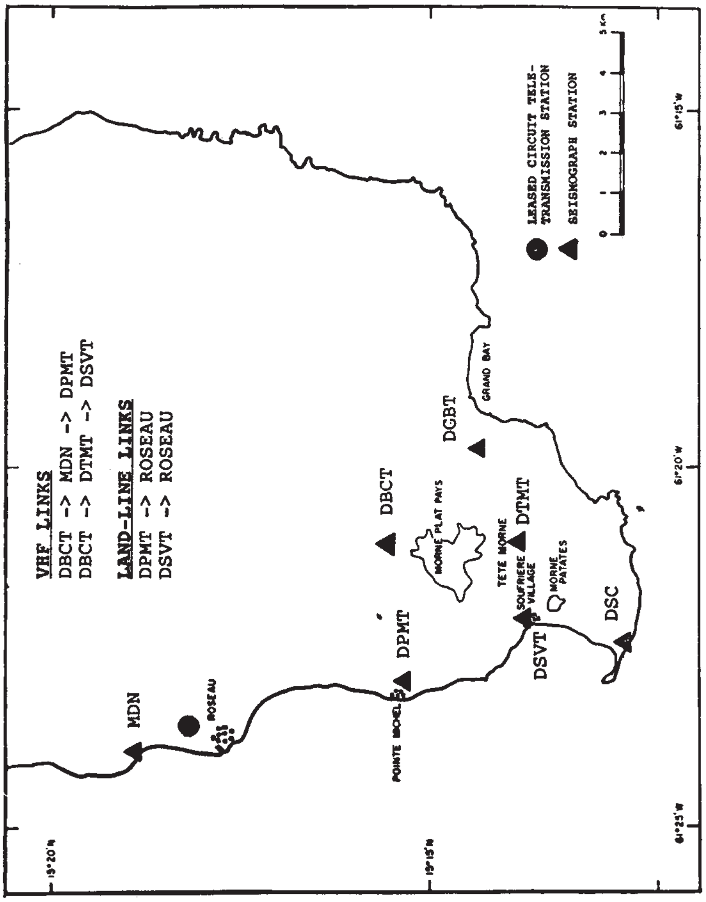
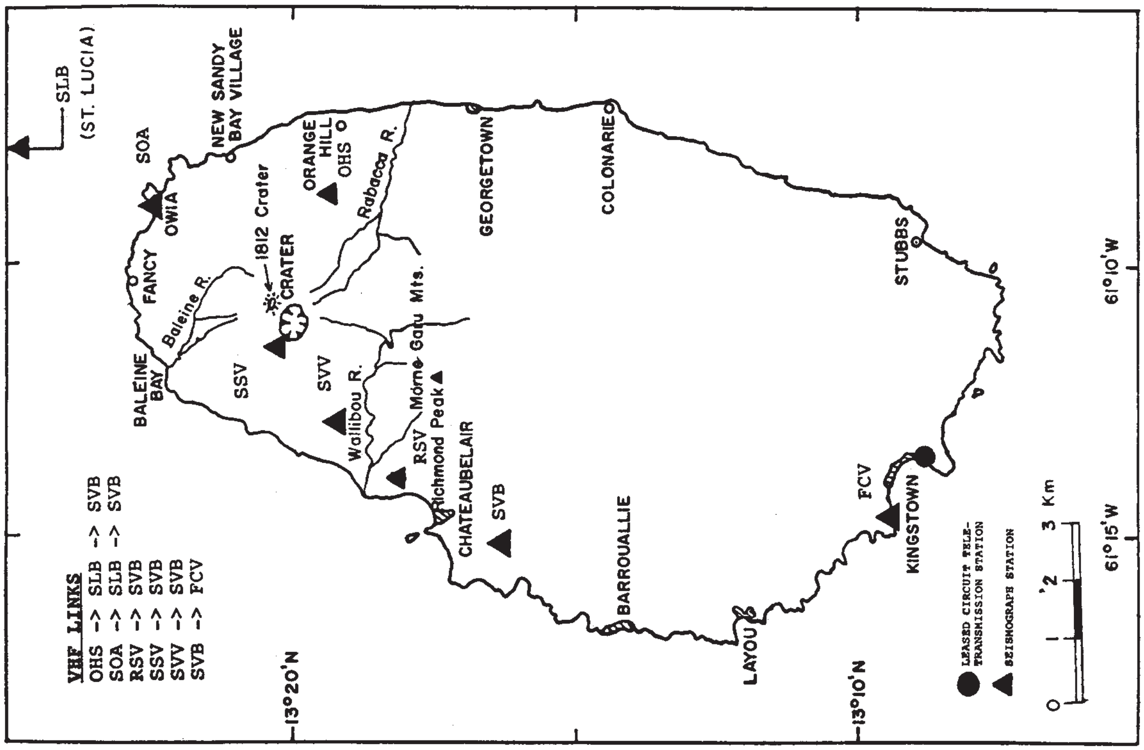


Fig. 6. Volcano surveillence networks (A) a) St. Vincent (1979)
b) Dominica (1986).



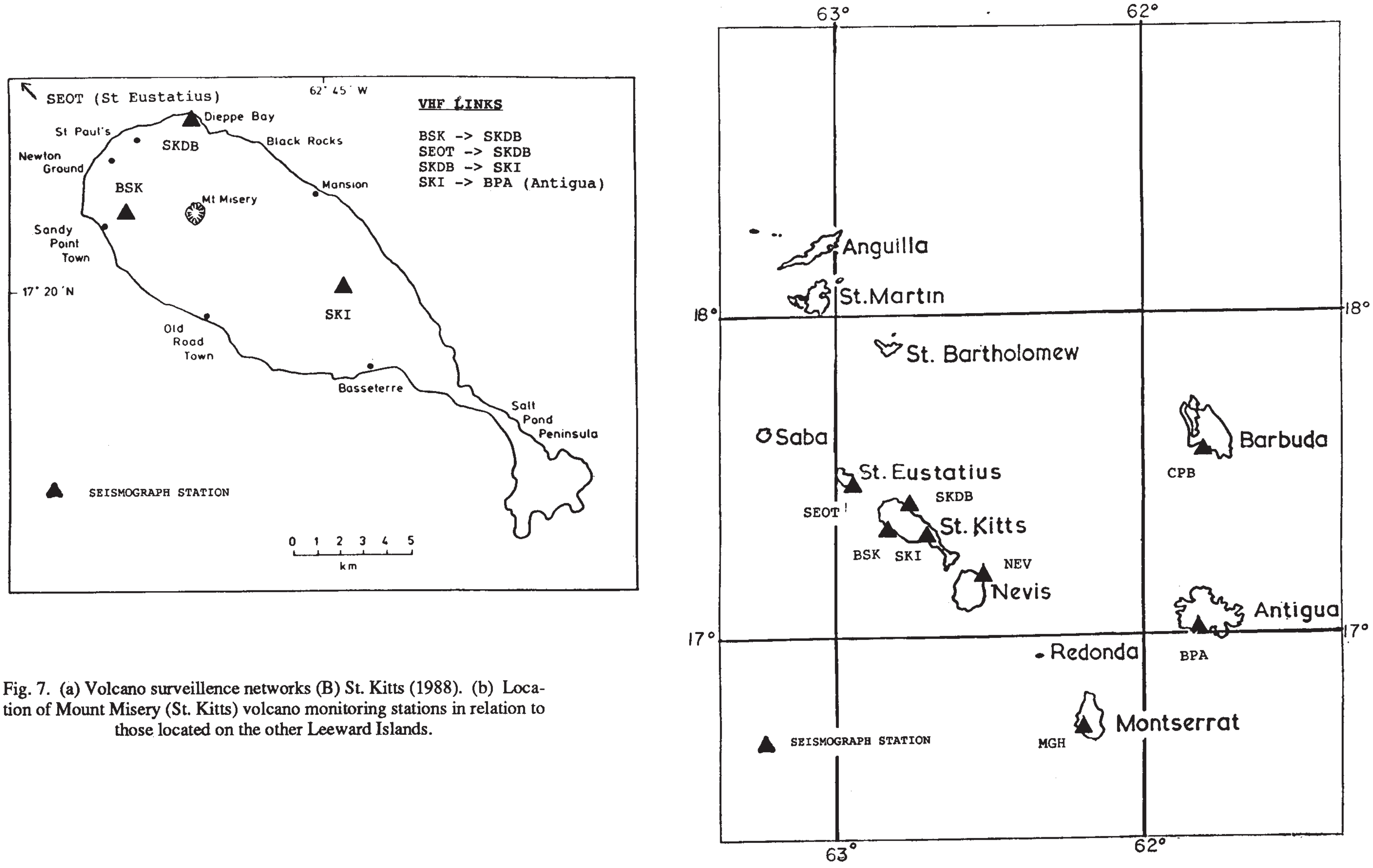


Fig. 7. (a) Volcano surveillence networks (B) St. Kitts (1988). (b) Location of Mount Misery (St. Kitts) volcano monitoring stations in relation to those located on the other Leeward Islands.

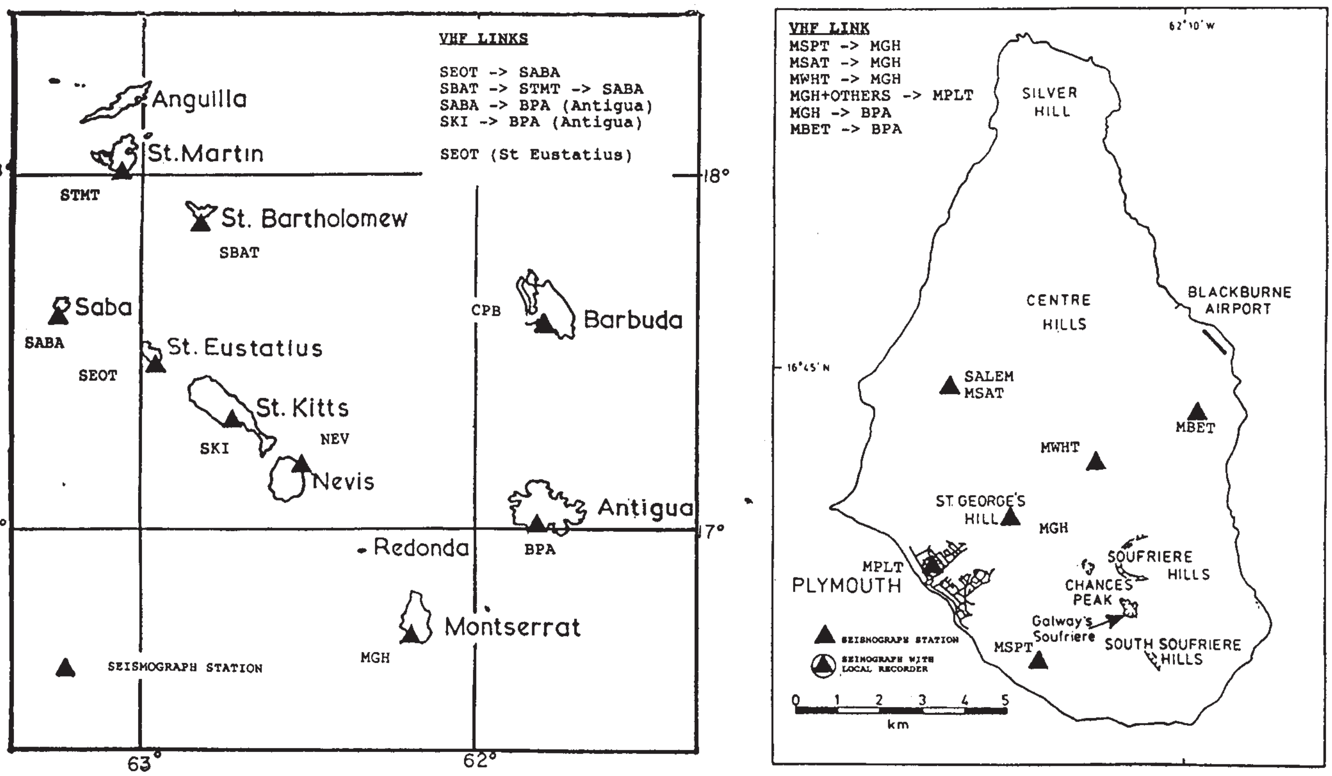


Fig. 8. Volcano surveillance networks (C) a) Saba (1992), b) Montserrat (1994).

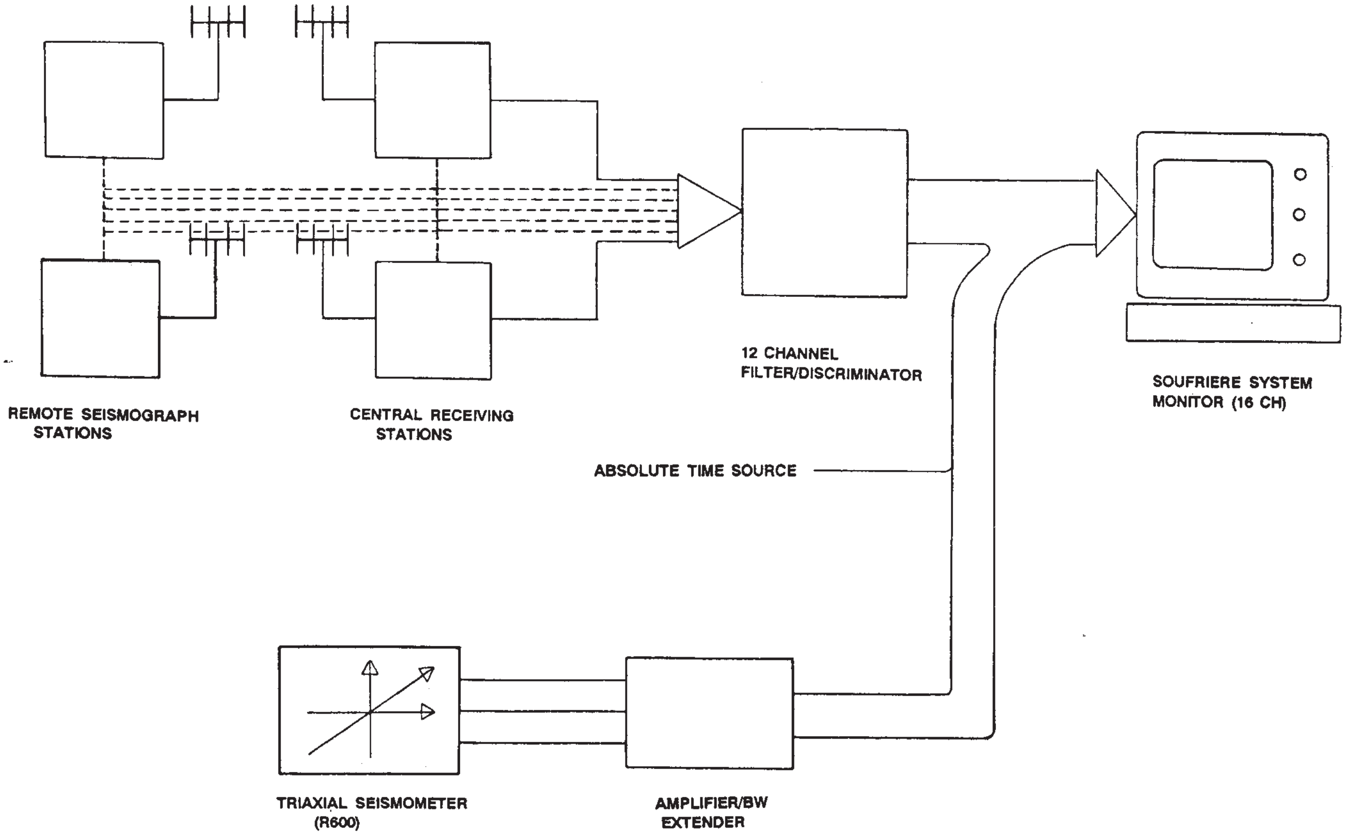


Fig. 9. Hardware configuration of portable seismograph array.

Headquarters for processing of hypocentral location while the digital seismograms are archived on diskettes and sent in batches. A block diagram of the hardware layout of the array is shown in Figure 9. It took three days to install the entire system and a week to train the local operators.

The results being obtained from the latest investigation are quite good enough to assume that all future surveillance networks will follow suit. The Soufrière System Monitor proved to be a prized tool during the last two investigations. The size of the Montserrat array is possible because of a just completed twelve channel discriminator bank which makes the entire system unusually portable. The entire system including the SSM is capable of running on 12 volts. On previous occasions it was necessary to deploy SRU staff in order to operate an array of this size. The latest developments have canceled this need and expand the time that such arrays can be operated. The latter depends on the availability of volunteers to perform routine tasks on the system.

Other volcano monitoring methods

The monitoring of volcanic earthquakes is the first line of defense in detecting abnormal volcanic activity but not the only one. Other methods of monitoring include:

a) Dry tilt measurement
b) Hot springs and lake temperature monitoring
c) Regular reconnaissance visits to detect phenomenological changes.

Baseline data have been established for the most active volcanoes. New measurements are collected whenever there are signs of renewed activity. The new and baseline data are then compared and used with the seismic data in the hazard monitoring and decision processes.

Staff and research

To execute the normal course of duties, a staff complement consisting of two geophysicists with adequate experience in earthquake seismology, a geologist/volcanologist and an electronic engineer are employed by the Seismic Research Unit. These professionals are backed by a highly trained group of technicians (5), research assistants (2) and clerical staff (2).

In earlier periods of the Units operation a higher number of staff were employed, but budgetary constraints forced a downward adjustment. This also affected the Unit's ability to attract high quality staff. Most of these changes occurred at a time when more efficient equipment and system of operation were being developed, so the remedial action was to retrain the remainder of the staff. Most of the technical training to develop and use the new systems were done in-house. The Unit, however, also makes use of regional and international courses and training opportunities from time to time.

Technological expertise and apparatus that is not available to the Unit, because of financial or other reasons, are sometimes made available through the process of institutional collaboration. Additional specialized academic expertise is obtainable through this channel or by making short term appointment. Some examples of special projects that were realized via the above measures are:

(a) Structural geological mapping in Northern Trinidad with experts from Northwestern University in the U.S.A.

(b) Operation of a broadband station at the Unit Headquarters. This station was part of an array which was installed to study the Eastern Venezuela/Trinidad region. It was done in collaboration with the Terrestrial Magnetism Department of the Carnegie Institution of Washington.

(c) Volcanic hazard mapping of Montserrat using computer simulation methods. This project was done in collaboration with staff at the Natural Environment Research Council Unit for Thematic Information Systems (NUTIS).

CONCLUSION

With modest resources it is possible to operate an effective seismograph network in a challenging setting. However, several cost cutting measures and optimization strategies will have to be employed. If the objectives are to provide volcanic surveillance and conduct investigations in order to specify volcanic and seismic hazard, it is necessary to complement the monitoring program with other methods of investigation.

The techniques and strategies employed at the SRU have led to improvements in several areas of operation and therefore to an overall boost in cost efficiency. In these days when there is a general tendency to measure performance and output in this manner the options outlined above are worthwhile to be considered.

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