PRECURSORY ACTIVITY TO THE 1995 ERUPTION OF THE SOUFRIÈRE HILLS VOLCANO, MONTSERRAT

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Introduction

The eruption of the Soufrière Hills volcano which began in July 1995 and is continuing at the present time was probably the most long-expected and clearly-signalled eruption to occur anywhere in the world in the twentieth century. The first premonitory symptoms had occurred in the late nineteenth century and there had been three near eruptions since then. In response to the clear premonitory symptoms regional scientists had taken the following actions

1. The probable effects of the eruption had been mapped out as early as the 1960's (Robson 1962) and re-mapped in great, and as it turned out accurate, detail less than ten years before the eruption began (Wadge and Isaacs 1986, 1988A, 1988B).
2. Between 1966 and 1989 successive Heads of the Seismic Research Unit at the University of the West Indies had spoken personally to each new Administrator or Governor of Montserrat and explained the situation to him.
3. Frequent warnings were published in both the scientific and the informal literature. (e.g. Powell 1937, MacGregor 1937, Perret 1939, Robson and Tomblin 1966, Shepherd et al 1971, Tomblin and Shepherd 1976, Baker 1985, Wadge and Isaacs 1986, 1988A, 1988B, LAVAS 1988, Shepherd 1989). Both Perret (1939) and Macgregor actually predicted the year when the eruption would happen with great accuracy although the basis for the prediction is not clear.
4. A three-component Wiechert seismograph was in operation in Montserrat from 1937 to 1946. It was at the time the only modern seismograph in operation in the English-speaking Caribbean.
5. A seismograph station with continuous telemetry to Trinidad was set up in Montserrat in 1980 so that the numbers of volcanic earthquakes occurring there could be carefully monitored.
6. Because of increasing volcano-seismic activity the Seismic Research Unit carried out a special study of volcanic hazard in Montserrat in 1986. Funding was provided by the Pan-Caribbean Disaster preparedness and Planning Project (PCDPPP). When the project began both chief scientists Dr (as we then was) Geoffrey Wadge and Mr. Michael Isaacs were Research Fellows at the Seismic Research Unit. By the time that the final report was published Wadge had move to a Unit at The University of Reading funded by the British National Environmental Research Council (NERC). This has lead to the curious, and spurious belief (See for example Clay et al. 1999) that the study was carried out by PCDPPP or even NERC. It was not. It was carried out by the Seismic Research Unit.
7. An equally spurious view (Clay et al 1999) has been propagated that the report was never shown to or seen by the government of Montserrat. This is also untrue. An early version of the report containing all essential conclusions was given to, and discussed with, the Permanent Secretary in the Chief Minister's office by one of us (JBS).
8. Two more stations were added in Montserrat in mid 1989. Unfortunately, both of this station and the previously-existing station were put out of action by hurricane Hugo a few months later and, for financial reasons, the network was not restored until 1992. From then until the beginning of the eruption locations of earthquakes could be mapped too.
9. A full scale volcanic eruption simulation exercise was held in Montserrat in 1985 and included a simulated evacuation (by the Royal Navy) of the part of the island which was eventually devastated by pyroclastic flows on Boxing Day 1997.

10. In 1988 a volcanic awareness seminar was held in St. Augustine Trinidad specifically to raise the level of awareness of volcanic hazards in the volcanic islands. A representative of the government of Montserrat took part in the seminar.
11. In 1990 the Seismic Research Unit mounted a training course in the maintenance of seismic monitoring equipment. It was attended by a member of the Montserrat Police Force.
12. In June 1994 a further increase in the rate of occurrence of prompted the Seismic Research Unit to add three more seismograph stations to the existing three bringing the level of monitoring up to that anywhere else in the Caribbean. The National Disaster Preparedness Coordinator and an assistant were trained how to operate the network and how and when to pass on the information gathered to Trinidad.
13. At the same time a poster presentation on volcanic awareness was mounted in the public library in Plymouth and a media conference was mounted to alert the general public to the significance of the escalating earthquake swarms. Ironically the posters and associated material were still on display when Plymouth was finally evacuated in April 1996 and are presumably still there buried under ash and mud.
14. In January 1995 when the new Emergency Operations Centre was inaugurated, the Seismic Research Unit provided three resource persons. They held a series of public lectures and shoed videos and displayed posters for a further week.
15. Finally, on the very day that the eruption began the annual conference of the Geological Society of Trinidad and Tobago was listening to a paper about the contemporary earthquake swarms in Montserrat.

Despite all of this when the eruption finally began it seems to have been totally unexpected, in Montserrat itself at least. Symptoms of this lack of awareness included the facts that:

1. All three people most closely concerned with disaster preparedness in the island– Governor, Chief Minister and Chief of Police - are on record as stating that they did not know that the island was volcanic let alone that there was a dangerous live volcano within four kilometres of the capital town and that this volcano had been showing increasingly obvious signs of an impending eruption for almost one hundred years.
2. There had been no long-term planning for a volcanic eruption at all. All of the island's essential infrastructure including electricity generation and supply, water treatment plants, port and airport as well as all government ministries and the Governor's office and of course the capital were within striking distance of the volcano.
3. Restoration of facilities following the disastrous hurricane Hugo in 1989 had completely ignored the opportunity to reduce vulnerability to volcanic activity. New buildings, including a new hospital were still being constructed as the eruption began.
4. The National Disaster Plan for 1995 (Thompson 1995) includes the statement "As Montserrat is also a volcanic island there is also the threat of a volcanic eruption". That is all it has to say about volcanoes. There are no preparedness plans and no Ministry or other government organization is given responsibility for preparing for volcanic emergencies. There is in fact considerably more planning for Exotic Animal Diseases than there is for volcanic eruptions (Thompson 1995 Appendix 10 to Annex A)

There is no doubt that part of the reason for this lack of preparedness was a deliberate wish not to think about volcanic eruptions. Some of the symptoms of this are:

1. In 1966-67 one of the more serious of the premonitory earthquake series occurred and a small team from the Seismic Research Unit was resident in Montserrat from mid-1966 to mid-1967. In early October 1966 the earthquake activity reached a severe peak and the team considered that there was a very real danger of an eruption at very short notice. The Administrator (equivalent to today's governor) was informed accordingly. We were under given strict instructions by the Administrator not to discuss what we were doing with local people. When a locally-recruited member of the team allegedly broke this rule by showing seismograph records to his friends the Administrator asked the Head of Seismic Research to dismiss him. The reason given was that any rumour that there was the slightest chance of an eruption would be "damaging to the prosperity of the island". The Administrator then gave an address to the nation downplaying the volcanic hazard and saying that "… earthquakes are not peculiar to Montserrat nor are we in any greater danger than other islands" (supporting documentation for these statements is in the files of the Seismic Research Unit).
2. In 1988 a Volcanic Assessment Seminar to which representatives from all volcanic islands, including Montserrat, were invited was held in Trinidad (LAVAS 1988). Amongst other things the delegates were told that "(recent earthquake swarms in Montserrat) … may suggest that the volcano is returning to life and there is a possibility of future eruptions within the next few decades". The response of the delegate from Montserrat was that his government "did not intend to allow the possibility of volcanic eruptions interfere with the planning process in Montserrat".
3. The following year the Government of Montserrat stopped paying its contributions to the Seismic Research Unit and no payments were made for the years from 1990 to 1995 (payments did not resume until after the eruption began)

Despite point 3 above the Seismic Research Unit continued to operate in Montserrat and in fact intensified the volcanic monitoring to a level higher than in any other island in the West Indies (apart from St. Vincent). It is certainly does not seem to be well-known in Montserrat that during the five years before the eruption when the rate of volcanic-earthquake activity was rapidly increasing the responsible authorities in Montserrat had withdrawn financial support from the only organization capable of providing it with reliable information and that, as a result, the activities of that organization had been badly impaired.

It is of course too late to correct the mistakes made in Montserrat before 1995. There are, however, lessons to be learned for the future. It is unlikely of course that the mistake of underestimating volcanic hazard will ever again be made in Montserrat – or in St. Vincent, Martinique or Guadeloupe all of which have suffered the effects of volcanic eruptions in the recent past. It would be a pity though if every island had to suffer a volcanic disaster before it began to take the volcanic threat seriously. In some of these islands volcanic awareness is very high and the population is mentally prepared for volcanic eruptions. St. Vincent, Grenada and Dominica which have all experienced recent eruptions or near eruptions are all examples. In other islands the denial syndrome which formerly existed in Montserrat is clearly still operating. A particularly worrying phenomenon is that of overseas scientists who spend very short periods of time in the West Indies and then make totally misleading statements about the levels of hazard, either overstating it or trivializing it. See Clay *et al.* (2001) for an example where volcanic and earthquake risk in a

Caribbean island is trivialized. This paper has two purposes. One is simply to set the record straight about what happened during the build up to the eruption. There has now been a complete change of volcano-monitoring personnel in Montserrat. The scientists now running the MVO have no direct knowledge of what happened before July 1995 and much of it is not in the formal literature. The official account produced by the British government (Clay and Benson 1999) is extremely misleading in some important respects, and incorrect statements in that account are beginning to find their way into the general literature. The second purpose is to try to ensure that similar errors do not happen in other eastern Caribbean countries.

The volcanic history of Montserrat

One of the reasons why there was no widespread awareness of volcanic hazard in Montserrat is that there was no long-standing tradition of volcanic eruptions in the island. All West Indians learn from a very early age of the disastrous eruptions in St. Vincent and Martinique in 1902. Until recently if they lived in any island other than St. Vincent or Martinique they also learned that "it is most unlikely to happen here". Worse than this, if they lived in islands such as Saint Lucia, Dominica or Montserrat where there are active hot-spring systems they may have been taught that the hot-springs acted as a sort of safety valve relieving the pressure on the volcano and lessening the chances of an eruption. In Montserrat itself there was a particular problem that many people did not know what a volcano was. Hot springs, known as soufrières in Montserrat, were thought to be small volcanoes themselves. Since they were such small volcanoes, they were obviously not capable of major eruptions. This error persists to the present in Saint Lucia where the hot springs near the village of Soufrière are referred to as a 'drive-in volcano' even in government literature.

The fact that volcanic eruptions are not mentioned in written histories of Montserrat is in fact a major mystery. One of the best ways of determining whether a volcano has erupted in the recent past is to look for charcoal remnants created when trees and other vegetation are carbonized by hot volcanic ash. The date at which the Carbon is formed can then be determined by a method called 14C or Carbon-14 dating. Geologists usually quote these dates as years "Before Present" or 'A BP'. To the occasional confusion of non-geologists the "present" in this case means 1952 so that a sample collected in 2002 and dated as 300A BP was in fact formed in 1652 CE (formerly referred to as AD). Here we will convert Carbon dates to Common Era dates.

The sixteenth and seventeenth centuries

In their description of the 1966-67 volcanic crisis Shepherd et al (1971) state quite clearly that "The Soufrière Hills Volcano erupted pyroclast flows as recently as 1646 +/- 54 years" The uncertainty range on this date tantalizingly straddles the date at which Montserrat was settled by Europeans which was at some time between 1631 and 1634 (Fergus 1994). Although this date was extensively quoted in later papers it was not widely accepted in the scientific world. There seem to have been two reasons for this.

1. The Carbon sample was thought to have been collected by G.R. Robson in 1952. Correct identification of volcanic charcoal requires a great deal of field experience because it is easy to confuse volcanic charcoal with charcoal created by other means like lightning strikes, forest fires and ancient hearths. Robson was the first Head of Seismic Research and

in 1952 he was a young, recent Ph.D on his first tropical field trip. This objection is in fact spurious. Robson was indeed on his first tropical field trip but he was accompanied and supervised by F.R. Wager who was Professor of Geology at Oxford University at the time and a very experienced field geologist indeed.

2. Although there were many subsequent searches for volcanic Carbon in the region where Robson and Wager found their sample nobody else ever found any of comparable age. In 1995 the most recent search had been made by Wadge and Isaacs (1988A and B) in 1986. They did not find volcanic Carbon of similar age but they did find Carbon near the same site which had been created by forest burning. On these grounds they described the 1646 date as 'suspect'.

In fairness to the authorities in Montserrat who have been seriously criticized (e.g. by Clay et al 1999) for not studying Wadge and Isaacs more carefully it should also be pointed out that that Wadge and Isaacs also estimated that the recurrence probability for pyroclastic flows at the Soufrière Hills volcano was of order 1-2% per century overall, rising to 10% per hundred years for English's crater and the region to the east. What these figures meant was that pyroclastic flows escaped from English's crater on average once every 5,000-10,000 years and affected English's crater itself only once every 1,000 years on average. Those of us who read the Wadge and Isaacs report at the time were in fact highly surprised that these probabilities were so low. We were particularly surprised that the 1646 date was not confirmed since this pushed back the date of the most recent eruptions from a few hundred years ago to 16,000 years ago. On more general grounds, such as the very youthful appearance of Castle Peak, this date seemed highly unlikely. The civil authorities who did read the reports were probably delighted that the probability of volcanic activity was so low. Elsewhere at about the same time they were being told (LAVAS 1988 and numerous personal communications) that there was a high probability of an eruption within the next few decades.

Later on when it was arguably too late, overwhelming supporting evidence for the 1646 date was found. During the early phreatic stages of the current eruption Castle Peak dome was almost totally stripped of vegetation revealing its youthful appearance even more clearly. An even more important consequence was that the rate of runoff during severe rainstorms increased considerably. Fortuitously several hurricanes and tropical storms passed over or near Montserrat in August-September 1995 and the resulting rainfall incised a number of deep gullies through the young pyroclastic deposits to the east of Castle Peak. Between then and mid 1996 when the gullies were re-buried under new pyroclastic flows five separate sets of workers collected fresh volcanic charcoal samples which were dated by two specialist laboratories in the US and UK. Supposedly the ages of these samples were published by Young et al (1996) but we have been unable to locate the original reference so the results are presented here again with acknowledgement to those who collected the data.

	AGE	Collector(s)	Group 1(> 350A BP)	Group 2 (< 350A BP)
	304	Robson and Wager		304
	200	Shepherd and Hoblitt		200
	435	Shepherd and Hoblitt	435	
	350	Devine	350	
	425	Devine	425	
	430	Wadge	430	
	320	Wadge		320
	320	Young		320
	310	Young		310
	330	Young		330
	270	Young		270
	270	Smith		270
	420	Smith	420	
	290	Smith		290
	240	Smith		240
Age (A BP)	**328**		**412**	**285**
Date (CE)	**1624**		**1540**	**1667**
S.D.	**72**		**35**	**40**

Table 1 Age dates for Montserrat volcanic Carbons. All samples collected in the Tar river Valley All samples collected September 1995 to May 1996 except Robson and Wager

The first three samples were analyzed by the National Environmental Research Council Laboratory East Kilbride, Scotland. All others by Beta Analytical Inc. in Miami Florida. The second column shows the dates of all reliable samples. These have a mean age of 328 years corresponding to an eruption date of 1624 CE +/- 72 years (1 standard deviation). The uncertainty range is wide for this type of data for which uncertainty ranges on individual samples computed in the laboratory are all less than 50 years. Elementary cluster analysis suggests that there are two clusters of dates one centred on the year 1540 (SD 35 years) and the other around the year 1667 (SD 40 years). Statistically we can be more than 95% certain that these two groups represent separate eruptions. They may in fact represent separate sequences of eruptions but the data are not sufficiently precise to be certain of this. The 1540 eruption is clearly before the European settlement but statistically we can be more than 95% certain that the 1667 eruption occurred when Montserrat was already fairly densely populated. (In 1652 the population was about 1200 and in 1678 about 3,500, Fergus (1994)). The mystery is why there are no written accounts of an eruption in Montserrat at that time. Some very vague pointers suggest that the second eruption occurred after 1673. The first maps of Montserrat were published then (See Fergus 1994 for reproductions) and they show farms on cleared land almost to the top of the Soufrière Hills. This would not be so if there had been an eruption in the previous few years. Castle Peak, which was the most recent pre-1995 dome but which was destroyed in 1997 is not shown on these maps but this is less convincing since there are other missing features too. A plaque on the side of St. Anthony's Church on Church Road says "Rebuilt in 1730." On the 1673 map St. Anthony's was shown as being on the hill overlooking Plymouth. Why and when was it moved to Church Road? Histori-

cal investigation of these points is beyond our fields of competence but may interest other participants at this conference.

Eighteenth and nineteenth centuries

There are no mentions of volcanic activity in easily accessible literature until the early nineteenth century. The first geological account of the island was by Nugent (1811) who described "Galloway's" (Galway's) soufrière in detail. It seems to have changed little between then and its destruction in December 1997. Gage's Upper soufrière was also active at this time. Montserrat is next mentioned in the scientific literature in connection with a sequence of earthquakes in the 1890's. Scientific accounts of these earthquakes and possible accompanying hot-spring activity are fragmentary and, as with the possible seventeenth century eruption, there is considerable scope for historical investigation. In the scientific literature the most extensive account is by Perret (1939). His account was written forty years after the events but he was able to interview people who remembered them. There are accounts in contemporary West Indian newspapers some of which are quoted by Robson (1964). Transcripts of all contemporary newspaper accounts are held in the archives of the Seismic Research Unit. The main difference between these earthquakes an those of the 1930's, 1960's and 1990's is that they were much more widely felt than the later earthquakes. In Montserrat the earthquakes may have begun as early as 1895 but the first period of severe earthquake activity was between April 23 and 27 1897 when a series of severe earthquakes damaged a number of buildings and caused general panic. An earthquake on April 29 1897 caused severe damage and killed four people in Guadeloupe 100 km to the southeast of Montserrat. It is still uncertain whether this earthquake was part of the same sequence as the Montserrat sequence or not (Shepherd 1992). Earthquakes in Montserrat continued until either 1900 or 1902 depending on the account. Perret (1939 p 63) refers to an increase in soufrière activity and MacGregor (1949) says that the Tar River soufrière was either created or reactivated at this time.

Twentieth century

The 1930's

The earthquakes which began in the mid-1890's continued until either 1901 or 1902. There was then a long period of apparent quiescence until 1933 when earthquakes again began to be reported felt in Montserrat. A record of the numbers of earthquakes felt was kept by Mr. T. Savage English and a copy survives in the Seismic Research Unit. English reported 3,290 felt earthquakes between March 1933 and the end of 1937. Records continued to be kept until at least 1952 but only fragments of the later records have been located so that we have complete data only up to the end of 1937. Figure 2 shows the numbers of earthquakes reported felt in Montserrat from March 1935 to December 1937. As the monthly numbers of felt earthquakes increased, activity at the hot springs also increased.

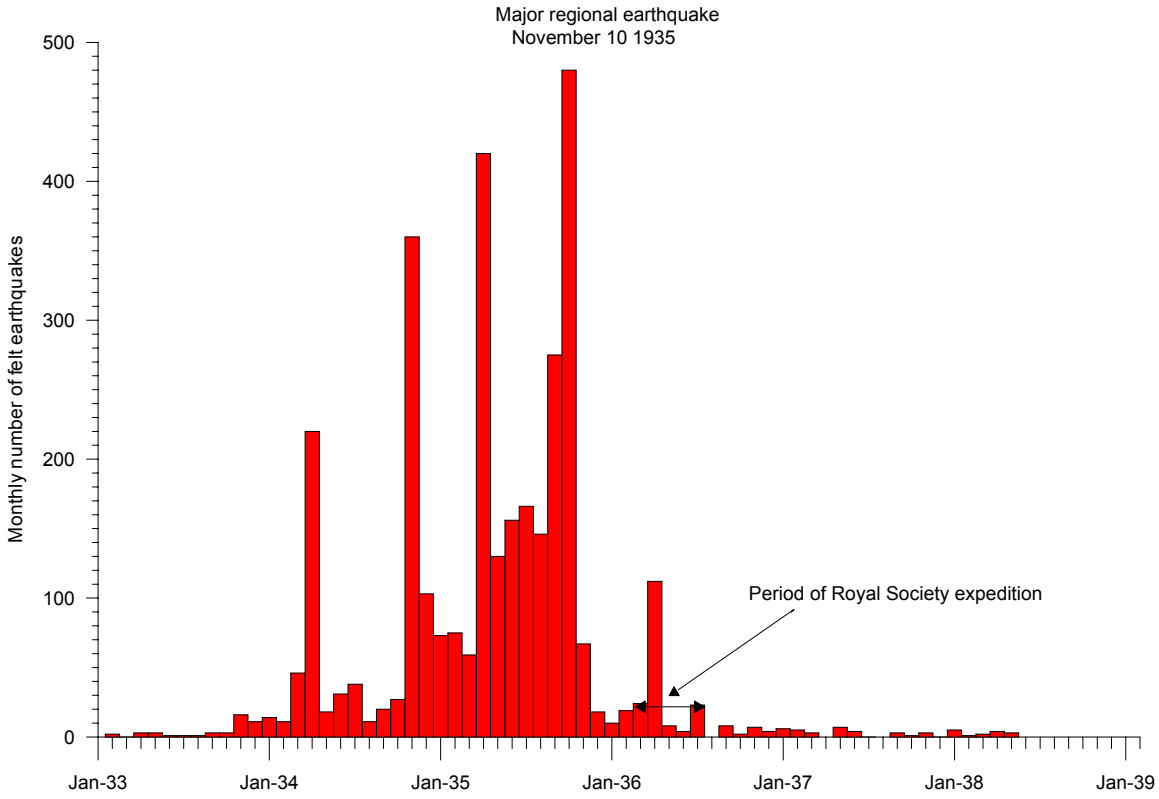

Figure 1: Felt earthquakes in Montserrat March 1933 to March 1938

The American volcanologist Frank Perret made a number of visits to Montserrat between April 1934 and April 1938 and wrote a long monograph for the Carnegie Institution (Perret 1939). Perret was an electrical engineer by training (and had been trained in the nineteenth century). Although he made careful measurements of a number of quantities, very few of these measurements are valuable today. For example he made no attempt to determine the locations or focal depths of the earthquakes or the chemical composition of the gases and fluids emitted from the soufrières. The monthly numbers of felt earthquakes increased steadily through 1933, 1934 and 1935 reaching a peak in October 1935 when 275 earthquakes were reported felt (Figure 1). In November 1935 an even greater number of earthquakes (480) was reported felt but this number includes a large tectonic earthquake at 02:27 Pm (Local Time) on November 10 1935. This was a fairly large (magnitude 6.5) tectonic (i.e. non-volcanic) earthquake which originated at a depth of about 100 km, directly below Montserrat and was recorded worldwide. This earthquake was followed by a number of strong aftershocks. Although there were no proper instrumental records. Perret recorded the earthquake and aftershocks on an instrument he called a seismeter but from his accounts it is difficult to understand what he was measuring. It seems clear from his verbal descriptions (Perret 1939 pp 50-51) however that, as well as the tectonic aftershocks, the earthquake triggered a rapid sequence of strong volcanic earthquakes. After this major tectonic earthquake the monthly numbers of felt earthquakes tailed off very rapidly. Only 73 were felt in the whole of 1937 and 15 in 1938.

The Royal Society expedition

In 1936 an expedition consisting of Dr. C.F. Powell (Physicist) and Dr. A.G. Macgregor was sent to Montserrat by the Royal Society of London to investigate the ongoing events. By the time that they reached Montserrat the crisis was in its dying stages (see figure 1). Nevertheless they produced two classic works of the volcanological literature. Macgregor (1938) produced the first detailed description of the geology of Montserrat – in fact the first detailed description of the geology of any Caribbean volcanic island – and the essential features of this description did not change until the geology itself changed in 1995-2002. For the first time in the scientific literature he identified seven major hot springs surrounding the Soufrière Hills Volcano. Powell (1938) set up a seismograph network consisting of one three-component Wiechert medium-period seismograph and seven Jaggar shock recorders

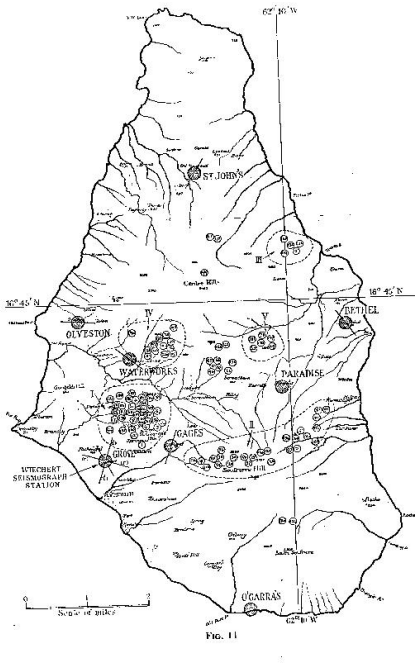

Figure 2: Powell's seismograph network. Wiechert seismograph at The Grove agricultural station on the northern edge of Plymouth. Six shock recorders at St. John's, Olveston, Bethel, Waterworks, Paradise, Gages and O'Garras. This was the first seismograph network anywhere in the West Indies and one of the first in the world designed to study volcanic earthquakes. In terms of earthquake location capacity the network is about as efficient as the current (2002) network. This network was handed over to the government of Montserrat when the Royal Society left. The Wiechert seismograph continued in operation until 1945 when it was accidentally destroyed. The Jaggar shock recorders gradually fell into disuse until the last of them stopped working in 1951. All known surviving records are held by the Seismic Research Unit but copies may still exist at the Royal Society and Bristol University.

Powell's network located about 200 local earthquakes between May 1937 and May 1938. Locations are shown as smaller circles in Figure 2. The locations showed two main centres of activity and a number of minor ones. The two main centres are the Soufrière Hills and St. George's Hill. This pattern was repeated in 1966-67.

1940's

From the time of Powell and MacGregor onwards there could be no doubt that the Soufrière Hills volcano was a live volcano in a pre-eruptive condition. Seismic and thermal activity at the Soufrière Hills never entirely ceased but the rate of earthquake activity fell back to about one or two local events per month. Two incidents during this period demonstrate the small importance placed by the authorities on these phenomena.

- In 1945 a severe earthquake swarm occurred near the Soufrière volcano in St. Vincent five islands to the south of Montserrat. The colonial authorities decided to transfer the Wiechert seismograph to St. Vincent but through careless packing it was destroyed in transit. The Jaggar shock recorders broke down one by one until the final one broke down in 1951.
- Records from the Wiechert seismographs were first read in Montserrat and then shipped back to the Royal Society for archiving. After the establishment of the Seismic Research Unit, Dr. G.R. Robson wished to analyze the records for the period 1938-1945 and requested the records from the Royal Society. Someone there decided that the postage to the West Indies for about five thousand records would be too expensive and carefully cut them into postage-stamp-sized pieces each containing a single earthquake record. This destroyed the value of the records almost completely.
- When the Seismic Research Unit was established in 1952 no seismograph station was established immediately in Montserrat. The reasons for this are unclear. We therefore know nothing about volcanic earthquakes in Montserrat between 1950 and 1965. Again, a search of local newspaper records would be useful.

The 1966-67 Crisis

In January 1966 a new Director of Agriculture assumed duties in Montserrat and resumed the practice of one of his predecessors of counting the numbers of felt earthquakes. He counted two in January and eight in February. At this stage he informed the Seismic Research Unit which installed a modern Willmore single-component short-period seismograph at The Grove agricultural station on March 22 1966. In the next 40 days the seismograph recorded 87 local earthquakes and as a result three more stations were installed in the island and a programme of ground-deformation measurements was begun. The seismograph stations transmitted their signals through the local telephone system to the central recording station at The Grove. This network continued in operation until November 1967. The main results of this investigation were that the rate of earthquake activity continued to increase until August-September 1966. Simultaneously earthquake focal depths decreased steadily, the volcano inflated significantly and the rate of heat flow from hot springs (soufrières) approximately doubled (Shepherd et al 1971). Throughout this period the Administrator (equivalent to today's Governor) was kept fully informed and he in turn kept the Commonwealth Office fully informed (see e.g. Gibbs (1966)). Amongst other things the Administrator and other key disaster preparedness personnel were provided with a sketch map showing the areas which would have to be evacuated if the volcano went into full scale eruption. It is interesting to compare this with a map showing the area which was in fact evacuated at the height of the present eruption

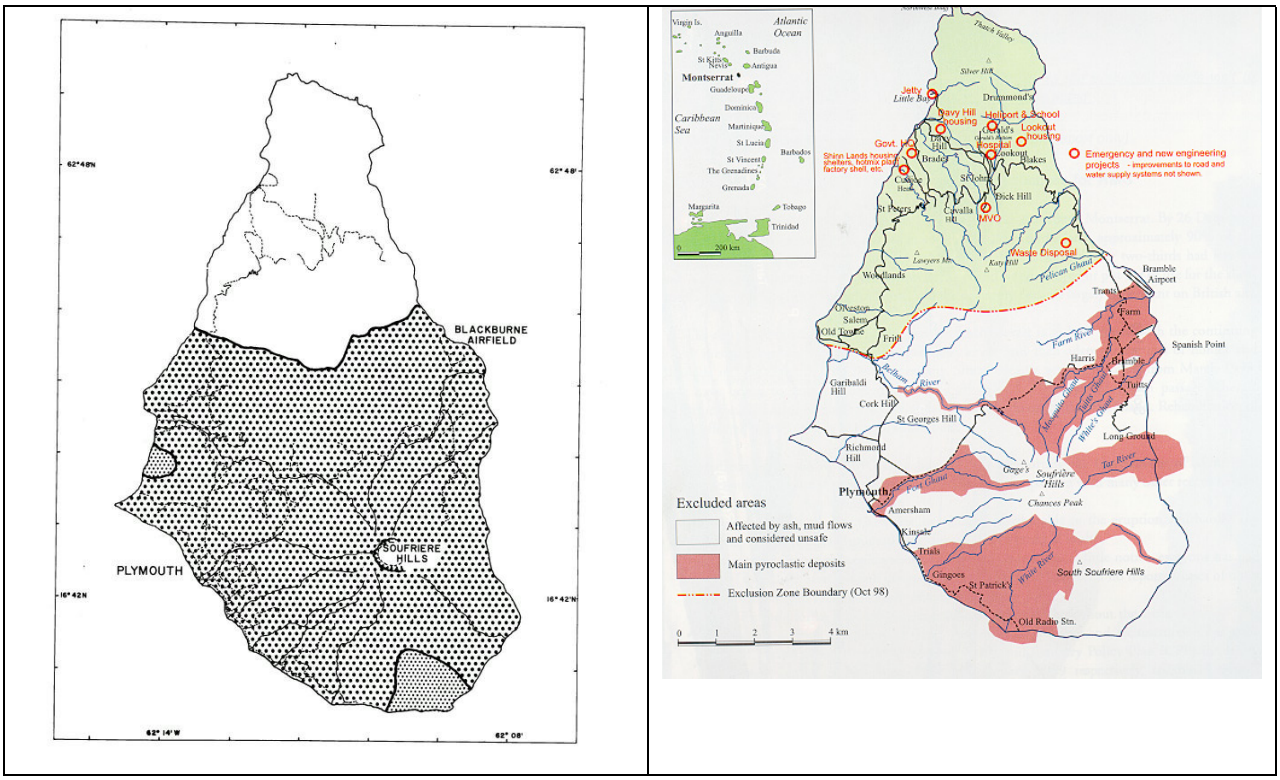

Figure 3: Risk zones in Montserrat.

Left. Hazard map from 1966 showing area (stippled) which should be evacuated in a major eruption
Right: Area which was in fact evacuated by the end of 1998. Note that in the 29 years from 1966 to 1995 development continued unchecked in the stippled region.

1967-80

After October 1966 the rate of activity in Montserrat declined steadily and in November 1967 it was thought safe to lower the level of monitoring. It is important to be clear that the earthquake sequence did not end in November 1967; in fact, more local earthquakes were recorded that month than at any time since December 1966. Activity had simply declined to a level at which it was no longer thought necessary to continue an intensive monitoring operation. From 1967 to 1980 seismograph recording in Montserrat reverted to the operation of a single, vertical component seismograph station. Until 1980 the station recorded its data locally on photographic paper where they were examined by a local station operator who was trained to recognize local earthquakes and report them to Trinidad. The intention was that whenever a build-up of local earthquakes occurred the local network could be reinforced rapidly. Montserrat never became totally seismically inactive after 1967. On average about 3-4 volcanic earthquakes were recorded each month but these never reached a crisis level. There were a number of bursts of local earthquakes during this period, notably on 15-16 August 1977 when nine local events were recorded and 31 March 1978 when 26 earthquakes occurred within less than one hour. On each of these occasions temporary seismographs were set up as quickly as possible but the burst of earthquakes

was over before they came into operation could be done and the stations were quickly withdrawn.

Countdown to Eruption

1980-1992

In 1980 the independent seismograph station at the Grove was replaced by an automatic station on St. Georges Hill. This station transmitted its signals by radio telemetry to Trinidad. This meant that data were available in real time in Trinidad so that reaction time to local events was much more rapid. The first time that this procedure was activated there was a complication which delayed matters. On 16 March 1985 a shallow earthquake of magnitude 6.2 occurred near the island of Redonda, north of Montserrat. It was followed by an enormous number of aftershocks with as many as ten or twenty earthquakes being felt each day in Montserrat, Nevis and other islands

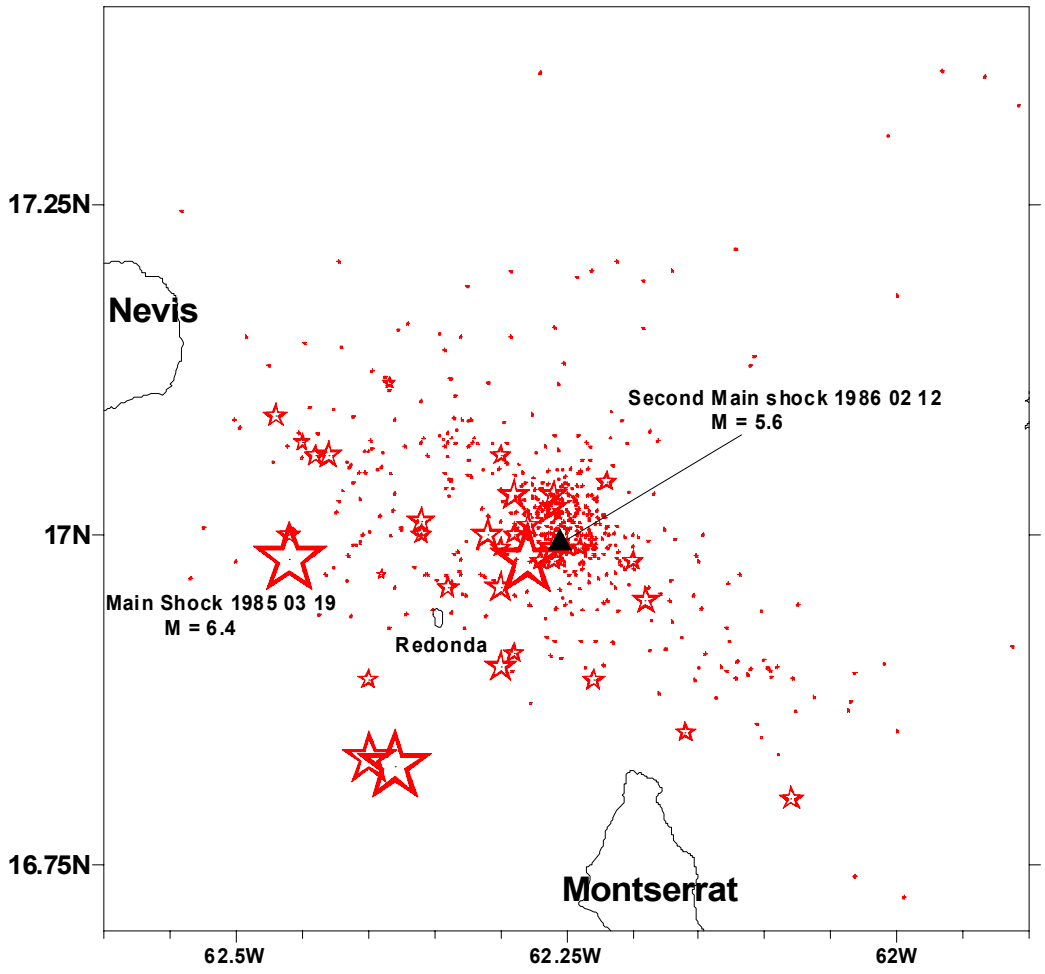

Figure 4: The Redonda earthquake sequence 1985-86

These aftershocks lasted for the rest of 1985 and had only just died away when a second earthquake of about the same magnitude occurred in almost the same place and was again followed by a large number of aftershocks. It was some months before it was realized that not all of these aftershocks were in fact aftershocks. Small numbers of the earthquakes – bursts of 1-20 at a time - were recorded only at the Montserrat seismograph station and not at the stations in other nearby islands. What appeared to have happened was that the two Redonda earthquakes had triggered local activity in Montserrat. Local Montserrat earthquakes could not reliably be distinguished from Redonda aftershocks without operating extra stations in Montserrat. After some delays caused by shortages of both money and people two extra stations were established in Montserrat in mid 1989. Unfortunately the entire network was destroyed by hurricane Hugo later in the year and the network was not restore until 1992.

1992-1995

From then onwards the countdown to eruption was steady. Figures 4 and 5 show daily and cumulative numbers of volcanic earthquakes in Montserrat between Jan 1 1992 and July 15 1995 when the first surface signs began. Throughout this period the average daily number of earthquakes was higher than at any time since 1938. In November-December 1994 the mean daily number exceeded the rate at the peak of the 1930's sequence although it appears that the earthquakes were generally of lower magnitude since a much smaller proportion was reported felt.

There is also no doubt that the earthquakes were directly associated with the Soufrière Hills Volcano. Figures 6 and 7 show the epicentres and depth-distribution of the best-recorded earthquakes. The picture is clearly that of a rapidly-increasing number of earthquakes directly below a live volcano with a known history of unrest.

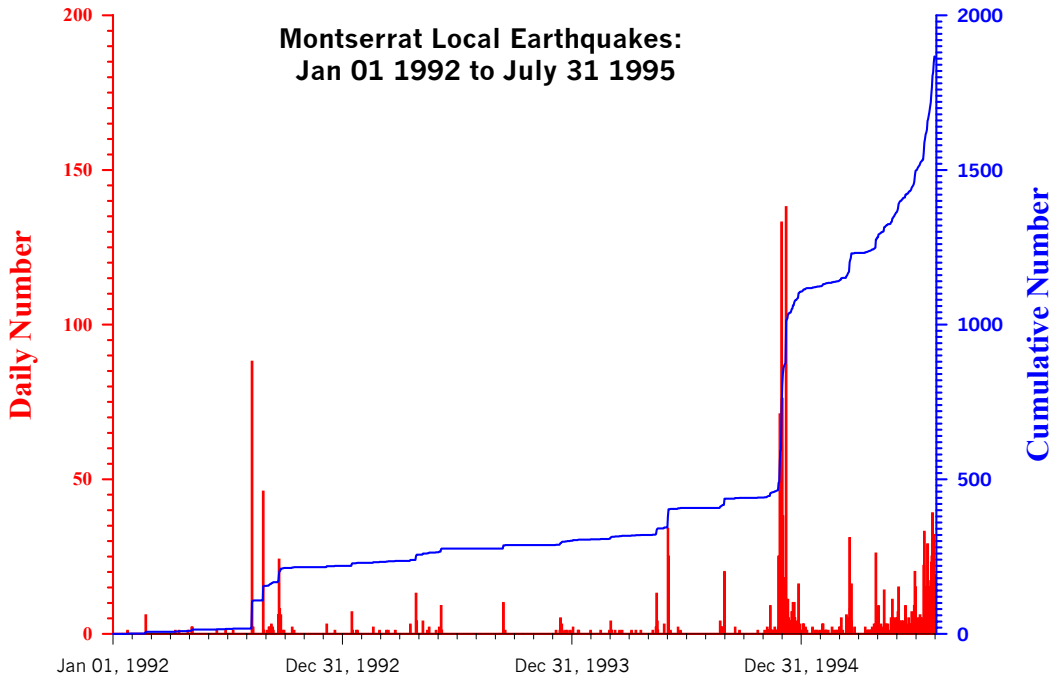

Figure 5: Daily and cumulative numbers of volcanic earthquakes in Montserrat 1992-1995

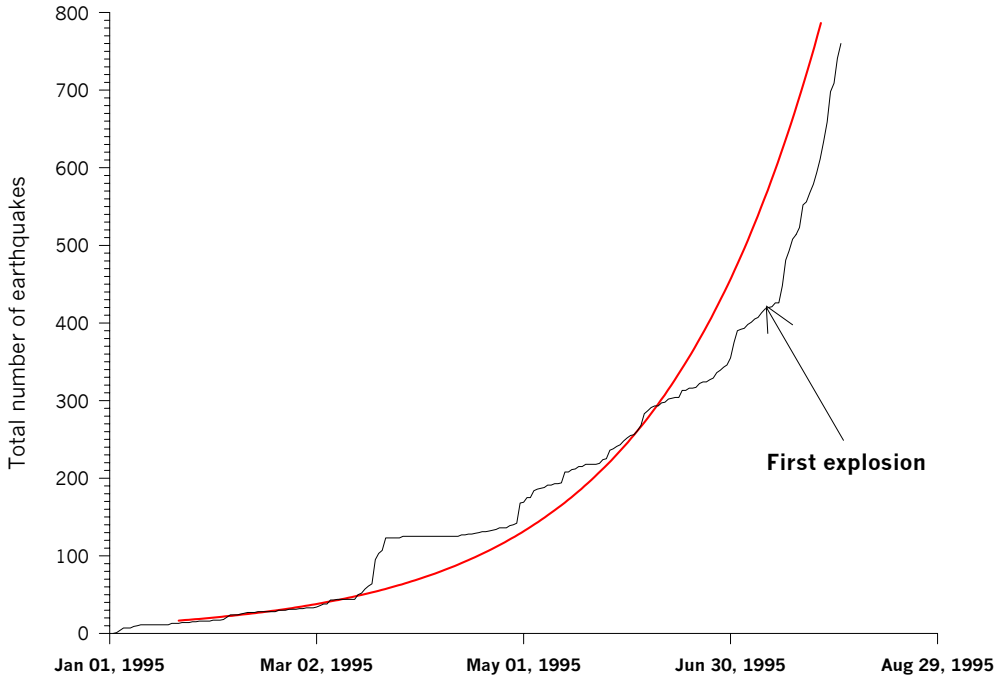

Figure 6 Detail of figure 4 showing quasi-exponential rate of earthquake activity in Montserrat during 1995

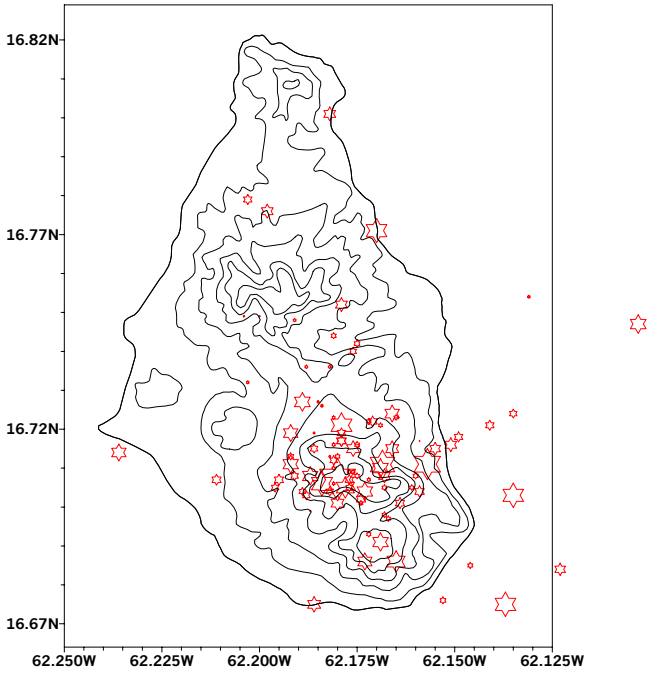

Figure 7: Epicentres of best-recorded earthquakes 1994-95

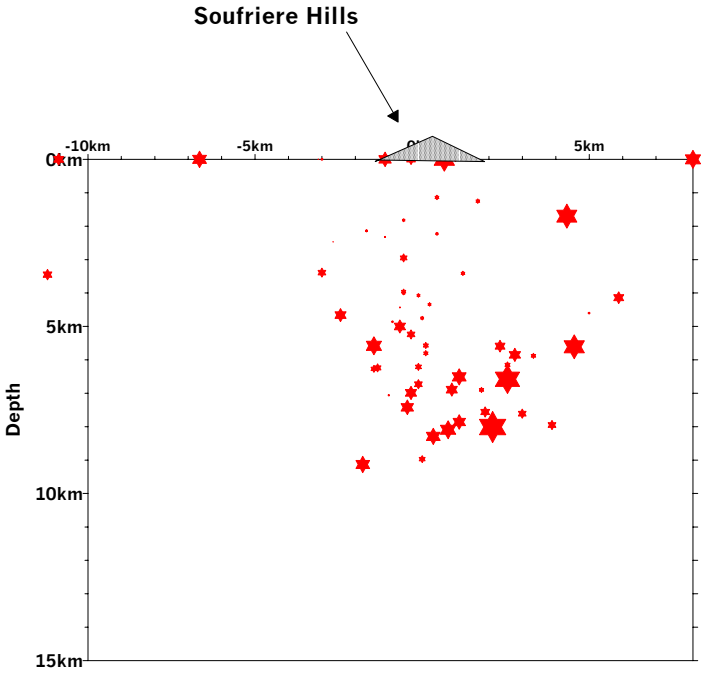

Figure 8: Depth distribution of earthquakes of figure 7

What went wrong?

The main reason for the lack of preparedness in Montserrat in 1995 was a breakdown in communications between the Seismic Research Unit and the Government of Montserrat. Contributory factors can be found on both sides. All of the information indicating that an eruption was imminent was available and all of it had in fact been communicated to the authorities in Montserrat. Unfortunately the way in which the information was communicated conveyed no sense of urgency whatsoever. It was contained in the routine quarterly report of the Seismic Research Unit for the third quarter of 1994. No attempt seems to have been made at person-to-person contact with either the Governor or Chief Minister.

Part of this was undoubtedly caused by inexperience. Before 1989 the Seismic Research Unit had only three Heads in 37 years of existence. After 1989 the University of the West Indies seemed unwilling to appoint anyone as Head and three different people acted as Head between 1992 and 1994. By 1994 there was only one person on the academic staff who had been with the Unit before 1990 and there were internal conflicts between the Acting Head and other members of staff. Almost all continuity in communication had been lost. In particular, direct communication between the Head of Seismic Research and the authorities in Montserrat had always previously been with the office of the Governor/Administrator. At some time between 1989 and 1995 contact was switched to the Chief Minister. There is no written evidence to indicate why this happened.

On the other hand it seems to be inconceivable that the Government of Montserrat, or the Governor's Office deliberately withdrew support from the Seismic Research Unit in 1990 just as the action at the Soufrière Hills was heating up. Deliberate or not, this withdrawal of support severely restricted the number of visits which the Unit's scientists could make to Montserrat and objectively this is probably the biggest single reason for the communication breakdown.

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