MONTSERRAT VOLCANO OBSERVATORY

GOVERNMENT OF MONTSERRAT

THE 20 MARCH, 2000, COLLAPSE OF THE NOVEMBER 1999 DOME

MVO Special Report 8

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ABSTRACT

On 20 March, 2000, an estimated 2.8 x 10^7 m^3 of dome material collapsed down the Tar River Valley. In terms of volume, for the current eruption of the Soufrière Hills Volcano, this event is second only to the Boxing Day collapse of 1997. This event removed ca. 95 % of the dome that had been growing since mid-November 1999 and was likely triggered by heavy rainfall that commenced shortly before the collapse began. Once underway, the collapse escalated over 4 hours, culminating in a sequence of small vulcanian explosions. Surges associated with the largest pyroclastic flows may have travelled about 2 km beyond the edge of the Tar River Delta.

No obvious precursory activity was apparent. It is likely that the dome was already highly pressurized or unstable and was primed for collapse for a period of many days, and the heavy rainfall provided enough of a trigger to start the collapse, possibly by eroding material off the dome and undermining the eastern talus slope. Rainfall-triggered dome collapses, which have been recognized at other dome-forming volcanoes around the world (e.g., Merapi, Indonesia), may be a previously underestimated hazard at the Soufrière Hills Volcano.

The mudflows generated by the heavy rainfall probably represent the only true debris flows from the current eruption. This means that there is still potential for large volume mudflows down all flanks of the volcano, and represents a significant hazard to the Belham valley crossing.

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1. INTRODUCTION

The first major dome collapse event since the onset of renewed dome growth in mid-November 1999 took place on the evening of 20 March 2000. This collapse lasted ~ 4 hours, and the vigour of pyroclastic flows gradually increased as the event continued, culminating in a series of small, discrete magmatic explosions. The initiation of this collapse was not related to elevated shallow seismicity, however, it directly correlated with a period of heavy rainfall experienced across the island. Dome-collapse pyroclastic flows funneled down the main channel in the Tar River Valley (TRV) to the east, whilst boulder-laden mudflows were mobilized and channeled down the Belham Valley, into Plymouth and down the north-east flanks.

The collapse removed almost (~95%) the entire November 1999 (N99) dome that had infilled the large canyon formed within the 1995-98 dome complex. This canyon had been formed by major gravitational dome collapses on 3 July 1998, 12 November 1998, 5 June 1999 and 20 July 1999. The estimated volume of the new dome immediately prior to the collapse was ~32 million m^3; the estimated volume of the collapse is therefore ~28 million m^3. In volumetric terms, the 20 March 2000 dome collapse was the second largest event of the entire Soufrière Hills eruption to date. Volumes of the N99 dome quoted in this report are relatively crude estimates (by MVO standards), as volume monitoring was hindered by the fact that the new dome grew within the Tar River - Gages canyon. It was mostly hidden by the northern lobes of the old dome and hence not visible from ground sites to the north.

This limited ground visibility, added to restricted helicopter availability, meant that surveys relied upon theodolite measurements from relatively hazardous locations (Perches Mountain and Galway's Mountain) that were only attempted when ground ash conditions were acceptable. Despite these limitations, the weeks leading up to the collapse were blessed with unusually clear weather enabling MVO staff to gather a comprehensive photographic and video archive from observation flights during this period. These data, coupled with that of the seismic networks, allowed a clear understanding of the developing N99 dome and allowed MVO to accurately forecast the likelihood of a large collapse event.

2. VISUAL OBSERVATIONS

2.1. GROWTH OF THE NOVEMBER 99 DOME PRIOR TO THE 20 MARCH COLLAPSE

In mid-November 1999 an explosion crater existed in the canyon within the 1995-98 dome, formed by over 100 small explosions in the 20-month period of no surface extrusion since March 1998. This explosion crater is believed to mark the location of the central conduit (~30-40 m diameter) that fed the entire 1995-98 dome complex. On 27 November 1999, a mound of small spines surrounded by blocky talus was first noted within this crater. Early vertical growth of this mound resulted in 3 separate growth areas within the main crater by mid-December 1999, occupying the north-west, south-west and eastern sectors [Fig. 1]. As growth continued up until mid-February 2000, the focus of growth switched intermittently between these areas; the north-west and south-west growth areas built up near-vertically whilst the eastern sector formed an elliptical shaped lobe that gradually extended eastwards over the east-sloping floor. This Eastern Lobe exhibited a steep, near-vertical, blocky leading edge that directed rockfalls down chutes eroded into its steep eastern flank.

This pattern of growth, commencing with near-vertical spines and developing into blocky, elliptical lobes, is similar to the pattern of development observed during the 1995-98 growth phase. The predominant mode of extrusion of viscous, crystalline Soufrière Hills andesite lava in that phase was as broad shear lobes directed away from the central conduit along curved shear zones that propagate away from the conduit walls. Continued extrusion along the same shear zone constructs a large structure with a convex-curved upper surface and a steep, near-vertical headwall of blocky lava. Development of a shear lobe occurs as a stack of massive lava blocks that follow a curved trajectory away from the central conduit, with summit rockfalls spilling down the active lobe headwall. Detailed studies of the first phase of dome growth indicated that shear lobe development typically takes place at an extrusion rate of 3-4 m^3/s, a rate considered to be normal for this eruption.

Between 18 February and 6 March 2000 activity was concentrated on the Eastern Lobe, stacking up in height, directing semi-continuous rockfalls in a wide swath down the eastern flanks of the N99 dome and extending its talus margin to the east down the TRV. On 26 February, good visibility allowed theodolite surveys to determine the summit of the N99 dome as ~883 m at the head of the Eastern Lobe. An observations flight on 2 March coincided with a time of very low fumarolic activity such that the N99 dome was visible, including the inactive north-west and south-west mounds, highlighting a significant chasm between the new dome and the Gages Lobe. The north-west and south-west lobes were still clearly inactive with fresh rockfalls only spilling down the flanks of the Eastern Lobe from the summit area [Fig. 2]. At the rear of this lobe was a small central depression and a large elongate boulder (~50 m long), noticeably glowing orange in daylight, that was shearing away from this zone resting atop the back of the Eastern Lobe. Observations on 6 March highlighted the extrusion of a near-vertical spine (~40 m high) occupying the central depression – this structure represented the N99 dome summit at ~930 m. In the 1995-98 phase of dome growth, the extrusion of vertical spines in the central area often signalled a significant switch in dome growth e.g., mid-May 1997.

On 9 March, further observations showed the extrusion of a large curving spine with “shark-fin” type morphology on the southern side of the new dome. This spine was growing towards the Galway’s sector and rockfalls spilled off this feature in a wide swath focussed towards the southern edge of the old crater rim. A distinct lack of rockfall activity on the eastern flanks of the Eastern Lobe was further evidence that a major switch in dome growth had occurred. The now active Southern Lobe directed fresh lava blocks down the southern flanks of the N99 dome, banking talus against the southern crater rim [Fig. 3a].

In the days leading up to the 20 March collapse, extrusion continued in this southern sector forming a broad cluster of large blocks and spines. The Southern Lobe piled up to form a broad mass of lava that grew slightly higher than the summit of the old dome (the 940 m-high north-east Buttress). By the morning of 20 March, the oversteepened flanks on the southern and southeast part of the active lobe were threatening to overspill the Galway’s Gap (~5 m vertical distance). A prominent spine (estimated 40 m high and 30 m broad) was also apparent at the rear of the Southern Lobe pointing towards the southeast flanks suggesting a slight switch in activity. This spine was near-vertical and the swath of rockfalls radiating away from the Southern Lobe had broadened with its easternmost limit extending as far as the central part of the eastern flanks. This was the last view of the N99 dome prior to the major collapse later that evening.

2.2. FIELD OBSERVATIONS OF THE COLLAPSE

Observers arrived at Jack Boy Hill at ~16:15 (all times in this report are local) in light rain and pyroclastic flows were seen to be travelling down the TRV. The plumes from these flows were not very convective or energetic and the flows were not continuous. There was a distinct waning period after separate pulsations with a lapse of ~5 min before the next flow travelled down the TRV. The runout distance of these flows was estimated to be 1-2 km down-valley and occasional flows reached as far as the Tar River Delta (TRD). This continued for over 2 hours up until ~18:30 when activity ramped up with more energetic pyroclastic flows rapidly reaching the TRD. Some of these flows entered the sea, producing small phreatic explosions visible from the observation point. The most powerful pyroclastic flows appeared to surge across the sea for a considerable distance (~1-2 km away from the fan). In the initial burst of these powerful flows, small flashes of lightning were evident and their associated ash plumes rose rapidly and near-vertically into the low cloud. Light ashfall began to drift eastwards indicating a high-level plume subjected to westerly winds at altitude. A constant, dull roaring sound was noted at this point, not unlike the roaring sound heard following previous vulcanian events in October 1997. The roaring sound seemed to be sourced from the eastern coastline and was attributed to the boiling of seawater from these more powerful flows.

Around 19:20, the largest event of the evening occurred when a very energetic pyroclastic flow surged out across the sea with accompanying flashes of white, orange and red lightning. Almost immediately after the passage of this flow, large glowing blocks were seen tumbling off the eastern flanks of the dome. Within a minute of this event, a spray of glowing ballistic blocks was ejected several hundred feet above the central part of the crater towards the east and/or northern flanks. Independent witnesses in the Old Towne area later reported seeing several small explosive events (directing ballistics to the south) from the crater area at this time. Intense thunder and lightning swiftly followed this event with a wide curtain of ash spreading across the central corridor area. Field observers at this stage (~19:35) retreated to Blakes Lookout, where light ash was already falling on arrival and ash could be seen moving across the Centre Hills and heading northwards. From this vantage point, near-continuous dull glowing was observed around the main crater area and a strong odour of chlorine was evident in the atmosphere. Thunder and lightning gradually waned over the next 10 minutes, and seismicity had returned close to background levels by 20:00 when the field party returned to MVO.

2.3. POST-COLLAPSE ACTIVITY

In the days immediately following the collapse, poor visibility and large amounts of ash in the atmosphere around the volcano prevented close inspection of the dome. Brief glimpses from ground sites suggested that the collapse had been guided by the 3 July 1998 collapse scar, funnelling all the material down the main channel on the south side of the TRV. Sporadic ash venting from within the scar and at the head of the main channel was also noted and a line of small fumarolic vents had apparently been activated across the northern flanks of the old dome. Throughout 22 March, observers from Old Towne and Bramble Airport noted periods of vigorous venting of grey ash from the western sector of the main crater near the central vent. These episodes of venting sent plumes rising to 6-7000 ft above the volcano summit, lasting several hours and coincident with tremor recorded by the seismic networks.

A clear view of the crater was not possible until 24 March when, during an observation flight at high altitude (~ 6500 ft), a window of visibility highlighted a large, empty east-facing chasm/crater within the dome [Fig. 3b]. No remnants of the N99 dome were apparent within the crater, although views of the westernmost part of the crater were minimal. No distinct changes were discerned in any of the lobes of the 1995-98 dome, except that a large slab had spalled off the south-west side of the Galway's Peak, and part of the talus material on the eastern side of the north-east Buttress had been undercut and collapsed back into the 20 March scar. The overall morphology of the dome looked remarkably similar to the period prior to emergence of the N99 dome. It was evident that the 20 March collapse had almost completely removed the N99 dome (~95% or ~28 million m^3). On the same flight, a small mound of fresh lava blocks with a large spine at its centre was seen in the location of the main vent indicating renewed growth in the collapse scar [Fig. 3b].

Further observations of the 24 March dome were not possible until 30 March when it had increased in size significantly. A prominent flat-topped lobe was evident in the eastern sector of the crater, composed of a pile of jagged slabs indicative of a relatively high extrusion rate (~5 m^3/s); a level not unexpected following a large dome collapse. Exceptional visibility on 31 March highlighted the presence of 3 large mounds of fresh lava, the largest lobe in the eastern sector seen the day before and 2 smaller mounds in the north-west and south-west sectors of the crater area. These piles were composed of blocky lava with persistent steam plumes emanating from around their margins. This morphology closely reflected the early stages of growth of the N99 dome.

Detailed theodolite and vector binocular surveys were not possible due to ashy conditions around the survey sites. Initial estimates of the 24 March dome vary between 2 million m^3 (assuming 3 m^3/s extrusion rate) and 3 million m^3 (assuming 5 m^3/s) up to 31 March 2000.

3. SEISMICITY

3.1. SEISMICITY ASSOCIATED WITH DOME GROWTH

The growth of the N99 dome was heralded by a dramatic increase in seismic activity beneath the volcano in mid-October to early November, beginning with volcano-tectonic earthquakes (M~2) at depths of ~2 km progressing to shallower low-frequency earthquake activity, culminating in a highly-energetic hybrid swarm between 3 and 8 November [Fig. 4]. This rapid progression (several days) from volcano-tectonic activity to low-frequency seismicity that preceded extrusion of the new dome in November 1999 indicates that relatively little energy was required to re-open a pathway to the surface (material in the conduit was still very hot and therefore weak).

The eastern lobe of the dome continued to grow at an average rate of 3 m^3/s (equivalent to $8x10^6$ m^3 per month) throughout the period of mid-November to early-March. This period was marked by frequent occurrence of banded tremor with variable amplitude and typically an interval of 10-12 hours between bands. Tremor bands and hybrid earthquakes share a common source and both are observed during periods of dome growth, particularly when an increase in extrusion rate occurs.

As the dome became larger, and hence more unstable, a gradual intensification of rockfall activity was expected. However, the dominant signal in the rockfall data is an underlying 3 - 4 week periodicity [Fig. 5] though later cycles in general have higher amplitudes than earlier cycles. Between 1 and 16 February rockfall activity was particularly high but no major collapse occurred and rockfall activity subsided during the latter part of February and remained low until 20 March. A corresponding increase in long-period earthquake activity also occurred during the early half of February.

3.2. SWITCH IN DOME GROWTH, 7 MARCH

An interesting sequence of events that occurred on 7 March may have been linked to a switch in dome growth from the eastern to the southern sector. At 15:39 a small swarm of volcano-tectonic earthquakes with depths of 2-3 km began. By 15:57 some of these events were looking distinctly more like hybrids and occurring at less than 2 km depth. Between 16:49 and 17:16 six large long-period earthquakes occurred. Although this marked the end of the swarm, long-period earthquake activity remained very high for the next 5 days, indicating vigorous degassing which was confirmed visually. Hybrid activity was also higher than usual for a couple of days suggesting rapid dome growth. Observations made on 9 March confirmed that growth had switched from the eastern to the southern sector of the new dome. Between 14 and 20 March long-period earthquake activity was much reduced, but still well above background levels.

One (highly speculative) interpretation of this seismic sequence is that a new batch of magma was injected into the shallow magma chamber, causing a substantial rise in fluid pressure, which was gradually transmitted throughout the shallow magmatic system. As the stress increased in the surrounding, rather weak rock, small volcano-tectonic and hybrids occurred, and as some of this excess pressure was released at the surface, quite large long-period events occurred. Higher pressure within the dome may have led to the development of new pathways for magma extrusion (and new shear faults), leading to a switch in active growth.

Many switches in dome growth from one lobe to another were observed during the 1995-1998 eruption, but no unusual seismicity was noted. Perhaps the reason that this particular switch had a distinct (though weak) seismic signature was that the volume of magma injected into the chamber (and the corresponding pressure change in the conduit) was somewhat larger than on previous occasions. Visual observations suggest that magma extrusion rate between March and May 2000 was ~ 5 m^3/s compared with ~ 3 m^3/s between mid-November 1999 and March 2000.

Following the switch in activity in early March, growth continued in the southern sector and seismicity was unremarkable until the events of the afternoon of 20 March.

3.3. SEISMICITY ASSOCIATED WITH THE 20 MARCH COLLAPSE

The escalation of the activity of 20 March, 2000 is best seen in a plot of broadband seismic amplitude data [Fig. 6].

Heavy rain began falling at Gerald's Heliport, about 10 km north of the volcano, at 15:11. At 15:37 an emergent seismic signal could be seen on the drums which rose significantly at 15:48 which prompted a scientific observation team to depart MVO for Jack Boy Hill. Due to heavy rain it was initially thought that this signal was entirely due to lahars, but after further intensification at 16:03 the relative amplitude of the signal on the 4 drum recorders suggested activity in the TRV. This was confirmed by observers at Jack Boy Hill at 16:15.

From about 16:03-17:30 the seismicity was relatively constant. Observers at Jack Boy Hill reported that larger pyroclastic flows were occurring about every 5 minutes. An underlying 5-minute periodicity is also seen in the seismic data throughout the entire collapse sequence [Fig. 6]. Throughout this period both MRYT and MLGT were clipping. Heavy rain was still falling at Jack Boy Hill at 16:24.

Between 17:30 and 18:36 the seismicity escalated by an order of magnitude, and pyroclastic flows going out to sea far beyond the at the edge of the TRD were reported corresponding to strong seismic signals at 18:21 and 18:36. Even MJHT, the least sensitive instrument on the short-period network being written to a helicorder, clipped briefly during this phase.

There then followed a brief respite until ~19:00 after which a rapid escalation again occurred. The most intense seismic signal of the entire collapse sequence was recorded at 19:23 corresponding to an explosion that ejected large glowing ballistics. All short-period instruments were clipping hard. Preliminary spectral analysis of broadband data shows that the dominant frequency during the most intense part of the collapse was ~ 2 Hz, typical of volcanic tremor [Fig. 7]. Seismicity then rapidly declined in a sequence of steps and had returned to background levels by 20:02.

This quiet period was interrupted by a further collapse phase between 01:20 and 02:30 on 21 March ['smaller collapse', Fig. 8], which was similar in intensity to the 16:03-17:30 phase of 20 March. This was a significant event in its own right but was small in comparison to the activity a few hours before. This event was probably a result of further erosion by rain, which fell throughout most of the night. Rain eventually stopped falling at Gerald's Heliport at 07:37. A total of 67.5 mm had fallen since 15:11 the previous day.

Boulder-laden lahars across the Belham Bridge were first reported at 19:40 on 20 March but these probably began as early as 16:00. Unfortunately the pyroclastic flow signals are so intense they completely mask any lahar signals that may have otherwise been recorded.

3.4. POST-COLLAPSE SEISMICITY

Since the collapse, the dominant seismicity has been the return of banded tremor with bands typically lasting 2-3 hours and occurring every 5-7 hours with variable amplitude. These bands were particularly distinct from 29 March showing a gradual onset [Fig. 8]. This activity was expected as, after such a large dome collapse, magma extrusion rate is likely to increase and banded tremor has often been seen during periods of rapid magma extrusion. From April 2-8 these tremor bands increased in amplitude and started to break down into overlapping hybrid earthquakes. On April 8 the banded nature disappeared and a continuous low-amplitude swarm of hybrid earthquakes began. At the time of writing (April 11) this swarm has now stopped and there is no apparent return of banded activity. These observations suggest that the magma extrusion rate has declined.

A particularly strong tremor band triggered the alarm at 00:30 on 25 March and a scientific observation team in Old Towne reported moderate ash venting. This tremor band subsided around 04:00. Tremor bands usually have an emergent onset and last for 1-2 hours. This tremor band had a very abrupt onset and decayed gradually. Theoretical work by *Denlinger and Hoblitt* [1999] suggests that this corresponds to an increase in magma extrusion rate. Ash venting associated with tremor bands has also been observed on other occasions at this volcano.

Relatively few discrete events have triggered the broadband acquisition system in this period. In particular, very few rockfall events have been detected, which is no surprise as there is hardly any new material left to collapse. Tremor bands have probably masked a lot of small events of all types. Most of the events that have been detected since 21 March are hybrids that triggered during times when tremor bands had broken down into overlapping hybrid events. Tremor and hybrid earthquakes share a common source, the only real difference is that tremor is a continuous rather than discrete excitation of this source.

On the morning of 27 March several rain showers occurred and heavy rain fell between 12:27 and 13:34 remobilising material in the Belham River Valley. This lahar generated an emergent seismic signal which commenced at ~12:50 and continued for about an hour [Fig. 8].

A large peak in the seismicity at 07:19 on 28 March corresponds to a M7.7 teleseism from a source near Japan [Fig. 8].

4. COLLAPSE DEPOSITS

At the time of writing, only limited observations of the deposits have been possible due to unfavourable wind and ash conditions. However, observation flights were able to confirm that pyroclastic current activity was entirely contained down the main channel and margins of the TRV. Concentrated block-and-ash flows remained within the TRV, and the surge zones from the collapse were of a similar configuration to those mapped after the 3 July 1998 collapse although not as extensive. The surge boundaries emanate from the channel margins about two-thirds of the way down valley and gradually widen out towards the coastline, although not as wide as to impact on Long Ground village.

A kinematic GPS/Binocular survey of the deposits was carried out on 30 March and accurately traced out the outline of the TRD and the extent of the surge zones [Fig. in prep]. Comparison of TRD dimensions from the 30/03/00 survey and those from the previous fan survey (16/07/98) suggests some enlargement of the delta to the north and south, but little change on its eastern margin (possible slight erosion). A fault with the vector binoculars precluded an accurate determination of fan volume; the current best estimate is that approximately 10% of the total collapse volume (i.e., ~3 million m^3) was emplaced on the subaerial part of the delta.

The TRD has not increased greatly in areal extent, however, thick flow deposits drape much of the fan. The most significant change to the fan is the presence of 3 large trenches that cut through the fan deposits and reach the water's edge. The largest is the central trench, about 5–10 m deep, and 50–80 m wide. It has an eastward trend, continuing down the same path as the main channel of the TRV [Fig. 9]. Two smaller trenches (with south-east and north-east trends) are as much as 5 m deep, 6–20 m wide and radiate away from the main channel where it meets the fan. These trenches are assumed to be the result of energetic pyroclastic flows eroding through the fan deposits in the later stages of the dome collapse.

On 25 March, courtesy of HMS Manchester, a field team landed on the south-eastern shore of the TRD and collected fresh pyroclastic deposit samples for petrological investigation. More detailed sampling was conducted on the TRD on 6 April. The northern channel created on 20 March was sampled about 100 m from the sea, where it was about 6 m wide, ~1 m high on the south bank and ~3 m high on the north bank. Depositional terraces ~1 m high occur locally within this channel. The hot block-and-ash flow deposits are veneered by a 5-15 cm-thick layer of fallout deposits generated by pyroclastic current – seawater interaction. The uppermost layer, ~10 cm thick, is dominantly composed of accretionary lapilli ranging in diameter from a few mm to 1 cm. The fallout stratigraphy is locally complex, with occasional lenses of well-sorted, crystal-rich ash, containing sparse lapilli up to 1 cm in diameter.

A traverse of the fan from the northern channel to the central channel revealed that although the entire fan was blanketed with 10-15 cm of fallout deposit, the underlying deposits exposed in the remnant beach cliff were chiefly composed of slightly warm (not hot) block-and-ash deposits from collapses of the 1995-98 dome in the period of residual volcanic activity (the majority assumed from the 3 July 1998 collapse). Fresh, hot, block-and-ash flow deposits (from 20 March) occurred, generally, 10s of metres west of the beach cliff, with shallow-angled flow fronts marking the distinct limits of the 20 March deposits. The 20 March deposits are distinctly boulder-laden, with hundreds of large sub-angular clasts, some exceeding 2 m diameter, protruding from the deposit surface. The deposits are several metres thick, and their limits should be mappable, based on the boulder-laden morphology. Boulders protruding above the surface are lacking in the older deposits at the beach cliff. However, it is likely that thin ash-cloud surge deposits generated by the 20 March block-and-ash flows may have extended over the delta to the sea, as suggested by observations of steaming along much of the perimeter of the TRD on 21 March. Stratigraphic sections examined to date are few and do not preclude the existence of such deposits over the whole delta.

Observations around the summit of the volcano suggest that there were few ballistic impacts visible, and hence the blocks thrown up by the vulcanian explosions must have either landed close to the summit or within the Tar River Valley.

Light ashfall was experienced across Montserrat, although heavy rain overnight 20/21 March washed most of the new deposits away. Ash was collected at Port Louis on Guadeloupe at 21:30 and a preliminary analysis of the ash by L'Observatoire Volcanologique de la Soufrière de Guadeloupe is given in Appendix 1.

5. SATELLITE OBSERVATIONS OF THE 20 MARCH COLLAPSE EVENT

Montserrat is imaged approximately once every 15 minutes by the Geostationary Operational Environmental Satellite GOES-8, which is situated in a geostationary orbit at an altitude of ~36000 km above the Americas (75ºW). Data are collected by the GOES Imager on board the satellite in 5 wavebands spanning the visible and infrared parts of the electromagnetic spectrum: Band 1 (0.65 μm), Band 2 (3.9 μm), Band 3 (6.7 μm), Band 4 (10.7 μm) and Band 5 (12 μm). Band 1 has a spatial resolution of 1 km whilst the other bands have a coarser footprint of 4 km except Band 3 (8 km). These images are downloaded and processed at the Hawai'i Institute of Geophysics and Planetology (HIGP) at the University of Hawai'i (UH), typically within 12-60 minutes of data collection, and incorporated into a hot spot monitoring tool accessible via the Internet and covering many volcanoes including the Soufrière Hills. A rolling archive of the latest 13 days of GOES image data is also available online; the URLs of these sites are given in Appendix 2, and links can be found on the MVO web site.

Data from GOES-8 offer some insights into activity preceding and during the March 20 event, and into the movement of the associated ash cloud in the hours and days following the eruption. Values of volcanic radiance extracted from Band 2 and Band 4 data by the UH system triggered thermal alarms on several days throughout late February and March (26/2, 7/3, 15/3, 19-20/3). The 26/2 event was probably associated with some exceptionally clear weather, but the March events seem to correlate with the progressive development of a shear lobe extruding southwards from the active N99 lava dome, first observed on March 9. A cluster of alarm events occurred on the March 19, coincident with visual observations of a new spine on the surface of this active lobe. The alarm was only triggered once on March 20 prior to the collapse, but conditions were very cloudy throughout the day.

Examination of GOES imagery collected on March 20 indicates the first appearance of an ash plume over Montserrat at around 18:15 local time (22:15 UT). Subsequent images show the appearance of two 'puffs' of ash drifting ~ESE from the island at around 18:45 (22:45 UT). Three such 'puffs' are visible in an image taken at 19:15 (23:15 UT), also drifting ~ESE [Fig. 10a]. These discrete ash clouds probably represent the products of strong ash venting or small explosive events from the collapsing dome following larger pyroclastic flows, and may correlate with the RSAM spikes observed in the build-up to the climactic explosions [Fig. 6]. Measurements from the image suggest that the individual 'puffs' are separated by a distance of ~30 km. Estimates of plume speed are difficult to ascertain without accurate knowledge of the altitude of these precursory ash clouds, but wind speeds were believed to be between 25 and 60 knots according to NOAA, increasing with altitude. A constant plume speed of 25 knots (12.9 ms^{-1}) would imply approximately 40 minutes between 'puffs', whilst a speed of 60 knots (30.8 ms^{-1}) would suggest a separation of ~16 minutes. The latter appears approximately consistent with the interval separating RSAM peaks recorded between 18:00 and 19:00 [Fig. 6].

At 19:32 (23:32 UT), shortly after the vulcanian explosions from the dome, a major eruption plume was clearly visible as it emerged through the meteorological cloud over Montserrat, and by 19:45 (23:45 UT) a lobate ash cloud measuring approximately 30-40 km (east - west) by 20 km (north - south) had developed [Fig. 10b]. One remaining 'puff' from an earlier pulse of activity was still located to the east, and the main plume was already impinging on Guadeloupe [Fig. 10b]. Information from NOAA in Washington DC indicated that the plume reached an altitude of at least 30,000 feet (~10 km), with lower level ash drifting westwards.

The lobate ash cloud observed at 19:45 displayed a small N-S oriented kink, which subsequently developed into a wave-like form drifting ~ESE evident at 20:15 (00:15 UT 21/3; Fig. 10c). This morphological change was probably due to wind shear operating on parts of the plume at different altitudes. By this time the plume was covering a large part of northern and eastern Guadeloupe, where light ashfall was reported. The distal end of the plume continued spreading eastwards and by 21:15 (01:15 UT 21/3) it had dimensions of ~100-120 km by ~40 km [Fig. 10d]. Also at this time the plume appeared to be splitting into two segments, a dense portion heading ~ESE and a smaller, more diffuse portion hanging over and to the south-east of Montserrat (possibly evaporated seawater and lower level ash). The main plume continued to spread towards the ~ESE and by 23:45 (03:45 UT 21/3) it extended ~305 km from Montserrat and was ~120 km wide. Over the next few hours the plume dispersed in the vicinity of Montserrat, with little ash evident in images after 02:46 on March 21 (06:46 UT) despite the occurrence of further pyroclastic flow signals at around 01:30. However, the main plume continued to drift over the Atlantic Ocean and by 08:45 (12:45 UT) mid-level ash (at ~15,000 ft) was still detectable around 710 km east of the volcano, with high-level ash (~30,000 ft) no longer apparent. Dense clouds over Montserrat at that time precluded the detection of any low-level ash over the island, but this was probably removed by heavy rain overnight.

No significant thermal activity has been evident in GOES imagery since the eruption to date (April 9), although the weather has been generally poor with cloud often covering the freshly exposed scar and the growing new dome within it.

6. COSPEC MEASUREMENTS

The COSPEC developed a fault in early January 2000 and was sent to Canada for repair. Hence the instrument was off-island for around 2 months until mid-March when it was returned to MVO in full working order.

COSPEC data from late 1999 show variable but generally increasing SO_2 fluxes in the weeks following the appearance of the new lava dome in November. SO_2 fluxes in late October 1999 were below 100 td^{-1}, rising to 200-400 td^{-1} in late November when renewed lava extrusion was underway. Measurements in December returned values of between ~250 and ~1500 td^{-1} with fluxes appearing to vary in accordance with cyclic bands of low amplitude tremor recorded on the seismic network. SO_2 output typically peaked shortly after the rapid decline in seismicity observed at the end of each 8-10 hour tremor cycle.

Measurements with the COSPEC recommenced on 13 March 2000, and indicated moderate SO_2 fluxes of ~450-800 td^{-1}. Seismic activity coincident with these data was relatively low and consisted largely of rockfall signals from the growing dome, with no evidence for cyclic behaviour. Although weather conditions were inclement on 20 March with widespread cloud cover, one helicopter COSPEC run was completed in the afternoon and gave an SO_2 flux of 271 td^{-1}; indicating a possible decline in SO_2 output prior to the dome collapse that evening.

Following the 20 March collapse, tremor bands similar to those recorded in late 1999 have begun to reappear, with cycles varying in intensity and duration, indicative of cyclic pressurization in the conduit. Stationary COSPEC measurements were made from the airport on 24 March, when an atypical westerly wind directed the plume towards the east. Retrieved SO_2 fluxes were low, ranging between 111 and 203 td^{-1} (although it should be noted that stationary measurements have been observed to give 30-40% lower fluxes than traverse methods), with the lowest value approximately coincident with the end of a seismic tremor band i.e., the reverse of the trend observed in late 1999. The significance of this is not yet fully understood, and hopefully will become clearer with further COSPEC measurements of SO_2 flux and seismic data analysis. However, the generally low fluxes in the aftermath of the collapse may suggest that the high-level plumbing system of the volcano is still relatively sealed with respect to SO_2, which would be consistent with the ongoing presence of rising magma in the conduit implied by seismic activity and visual observations of continued dome growth. A degree of absorption of SO_2 into a wetter hydrothermal system may also have been a contributory factor in the low observed fluxes.

7. MUDFLOWS

On 20 March 2000 heavy rainfall started at 15:11 at Gerald's heliport and continued intermittently until 07:30 the following morning. The rain was most intense at the start and decreased in intensity after 3 to 4 hours. This amount and intensity of rain produced a series of mudflows down all flanks of the volcano. During the period of intense rain large quantities of sediment from the flanks and river channels of the volcano were remobilized and transformed into a series of wet density currents that flowed down pre-existing channels and gullies. Some observers in the field witnessed one flow down the Belham Valley, and others saw mudflows from their vantage point at Jack Boy Hill. The two main areas of interest in terms of mudflows are the Belham Valley and Bramble airport, although flows also descended through Plymouth and other areas in the south of the island.

7.1. BELHAM VALLEY

The Belham Valley is the site of a pre-existing river channel and is reasonably well constrained by the topography. It has been the site of a series of mudflows over the last 4 years that are slowly infilling the valley. The recent flow from 20 March contained a large proportion (50-70%) of coarse boulders between 20 cm and 2 m in diameter. The flow overtopped the Belham Bridge by about 1 m and also deposited much debris; trees had been ripped up from further upstream and carried by the flow down the valley. From observations of the deposits, this was possibly the only ‘true debris flow’ from the current eruption (Steve Sparks, pers. comm.), previous flows being mainly hyperconcentrated stream flows with a higher concentration of fines and less capacity to transport large boulders.

At Old Road Bay there was a higher proportion of fine material. This was because the flow had started to run out of energy and could no longer support the large boulders, depositing a large proportion of them between 100 m east and 200 m west of Belham Bridge. The flows eroded three distinct channels and deposited up to 20 cm of liquid mud in the base of the channels. The flows have been gradually extending the beach westwards and the flow from 20 March added 20-30 m of sediment to the beach out to sea. The largest of the three channels was between 20-30 m across the widest point and was 1-1.5 m deep. The channels had a low sinuosity in plan form indicating that the flow still had a high sediment load when it reached the sea and was unable to form any of the characteristic features of normal stream flow (such as braiding or meandering channel forms). Erosional features such as scour zones around boulders and cobbles deposited earlier were seen; these indicate a turbulent phase of the flow when the sediment concentration was waning.

Observations of the upper channels of the Belham Valley since the collapse indicate that they are very deeply incised. The source of the boulder-rich debris is the older deposits underlying the main channel, and short, deep tributary channels near Gages Mountain. Scientists who walked up the Belham River on May 15 noted that around one mile upstream of the Bridge, a wide channel (10 m) with high walls (2 m) had been eroded through older deposits. This channel narrows and grows in height further upstream, to a width of 4 m and similar height around the point where Lee’s Ghaut meets the Belham River. It is quite likely this channel was cut by the March 20 lahars. The majority of Belham source material is probably unrelated to the 1995-present eruption.

7.2. BRAMBLE AIRPORT

The area to the south of Bramble airport forms a wide fan like deposit comprising of mudflow deposits as well as pyroclastic flow deposits from the last three years. Through this area there are two main source channels, from Tuitt's Ghaut and Paradise Ghaut located on the northern flanks of the volcano. These form a braided pattern of channels across the fan covering an area of 1-2 km^2. Concentrations of pumice form bars separating the channels.

The sediment transported to the southern end of the airport runway on 20 March was fine mud with only a small proportion of larger blocks ranging in size from 30-50 cm across (the largest of these were seen in a channel 3-4 m across). The deposit was mainly bi-modal, with the fine material making up the bulk of the deposit (70-80%), and the coarse pumice (ranging from 1 cm to 10 cm diameter) comprising 20-30% of the deposit. Arcuate bands of pumice clasts were noted illustrating the lobate form of these flows as they reach their critical thickness. This is the thickness at which they can no longer flow.

The deposits of mudflows can be very dangerous when still wet, as evidenced by two cows that had become stuck in the fresh deposits up to their mid-sections. The deposits when still wet can readily become re-liquified by any surface vibration, turning what may seem like solid mud or sand into quicksand. At the distal part of the fan the braided networks fan out into separate fingerlike lobes. None of the flows in this area were observed directly on 20 March.

7.3. MUDFLOW ACTIVITY SINCE 20 MARCH

Since 20 March there has been heavy rain fall over much of the island causing more sediment from the source areas to be mobilized into mudflows. These lack the large proportion of boulders and are better described as hyperconcentrated flows. On 1 April at 14:45 a seismic signal was recorded; this was interpreted to be a mudflow signal and observers were sent to the Belham Valley. The observers arrived at the Belham Bridge at 15:15. At this point, a weak muddy stream flow was following the channel cut by a previous mudflow on 27 March. After ten minutes a loud rushing sound was heard by the observers. This continued for 5 minutes, at which point (15:28) the flow front could be seen through the branches of the dead trees in the midst of the deposit. It was between 300 and 350 m away at this point and reached the point of observation in just over a minute giving a speed of the flow front of 3-5 ms^{-1}. Further measurements of the velocity of the mudflow during the next 20 minutes confirmed these estimates. The snout or flow front consisted of a mass of boulders and cobbles up to 0.5 m diameter that tumbled and rolled over one another. The snout passed quickly and the flow immediately following it had a laminar appearance: in areas it appeared as if large sections of the stream bed had mobilized as solid plugs in the centre of the flow.

At peak discharge the flow covered an area of 10 m across and between 0.5 to 1 m in depth. Blocks up to 50 cm were rafted along in the peak phase and later rolled and pushed along in the waning phase of the flow. During the waning phase the surface became more turbulent and at one point standing waves were seen (10 cm in amplitude). These structures are generally seen in high energy stream flows and indicates a higher energy flow with a lower sediment concentration. Boundaries across which the flow changes, from a thin high velocity flow with a placid surface to a much deeper flow with a more turbulent appearance, were noted. This boundary is defined by the Froude number, which is the ratio between the gravitational forces and the inertial forces. These boundaries are termed hydraulic jumps. The velocity of the flow decreased in the waning phase going down as far as 1 ms^{-1} at 15:55. By the time the flow reached the sea, much of the sediment had been deposited and the flow formed meandering channels, indicating a much lower sediment concentration in the flow.

8. CONCLUSIONS

a) The collapse of the November 1999 dome on 20 March 2000 was the second most voluminous event since the Soufrière Hills volcano started to erupt in July 1995, with about 28 million cubic metres of the lava dome collapsing into the sea.

b) No seismic build-up preceded the collapse, but a period of intense rainfall, starting about 30 minutes before the onset of pyroclastic flow activity implies that heavy rainfall could have triggered the collapse. A correlation of heavy rains with pyroclastic flow activity has not previously been noted during active dome growth at the Soufrière Hills volcano, but may have been a contributing factor in the 3 July 1998 collapse, and in other increased activity in smaller collapses and rockfalls.

c) The collapse was entirely directed to the east down the Tar River Valley, but relatively little deposition occurred over land. Three erosional channels were formed on the Tar River Delta, thus several pyroclastic flows were very energetic as they entered the sea. A veneer of hot block-and-ash flows covered much (but not all) of the delta. The new deposits are characterised by a boulder-studded surface, and shallowly-inclined flow lobe snouts.

d) The ash cloud from the event reached about 30,000 feet and travelled mostly to the south-east depositing ash on Guadeloupe. Light ash fall was deposited on Montserrat, but was quickly washed away by the continuing heavy rain. Heavier fallout occurred on the Tar River Delta, where ~15 cm thick deposits are characterised by accretionary lapilli (to 1 cm diameter) and local lenses of crystal and lithic-bearing ash.

e) Extensive mudflows were produced around the flanks of the volcano, with large boulders being transported over the Belham Bridge. Preliminary observations of the deposits here suggest that this may have been the first true debris flow to occur during the current Soufrière Hills eruption. The source of the lahars was not upstream deposits from the 1995-98 eruption, but rather older materials on the volcano's flanks, incorporated via deep channel incision.

f) Activity since the collapse has been characterised by cyclic tremor and ash venting accompanying renewed dome growth in the 20 March scar. On 31 March the volume of the 24 March dome was estimated at between 2 and 3 million cubic metres. Hybrid seismicity was recognised after 3 April.

APPENDIX 1 – PRELIMINARY ANALYSIS OF ASH COLLECTED IN GUADELOUPE, COURTESY OVSG.

Site sampled: Police station of Port Louis NE Guadeloupe (Grande Terre) at 21h30 local time (thus after 1h of ash fall which stopped at 22h30. Sampled was not rained on.

Thickness: 0.13 mm over 1 m^2

pH (preliminary): 6.91

Granulometry: < 63 μm 53.3 wt %

63-125 : 19.5 %

125-250 : 12.6 %

250-500: 14.4 %

500-750: 0.13 %

Lithology of unwashed 250-500 μm fraction: vitric porphyritic fresh ash. About 55 % dome andesite porphyritic dense clasts, about 10 % same but reddish oxidized (older parts of the dome), about 35 % crystals sub-angular to angular and mostly plagioclase, some amphibole, 5 % hydrothermally altered clasts.

Comments: ash is very fresh and pristine, lots of adhering fine particles and because it is very vitric but also crystal-rich and crystals are angular the ash would have been very abrasive as well as able to remelt inside jet engines. Perhaps some vesicular whiter vitric fragments (pumice?) in 500-750 fractions but very few. Need to confirm on washed sample.

APPENDIX 2. UNIVERSITY OF HAWAII GOES LINKS

Hot spot monitoring tool:

http://volcano1.pgd.hawaii.edu/goes/montserrat/latest.shtml

Image archive (latest 13 days):

http://www.pgd.hawaii.edu/~chriso/cgi-bin/imgslct.cgi

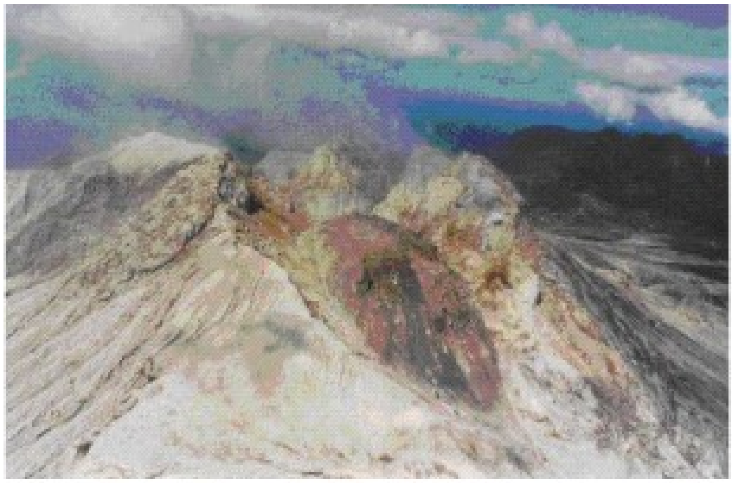

FIGURE 1: View hovering above Galways Mountain looking NW towards the 4 remaining lobes of the 1995-98 phase and the large canyon between them that was formed by the dome collapses during the 20 month interim period of no surface extrusion. Sitting at the base of the canyon (centre) are the lobes of the active November 99 dome. Chances Peak is the ash-covered peak to the left and Centre Hills are to the right. Photo taken on 16 December 99.

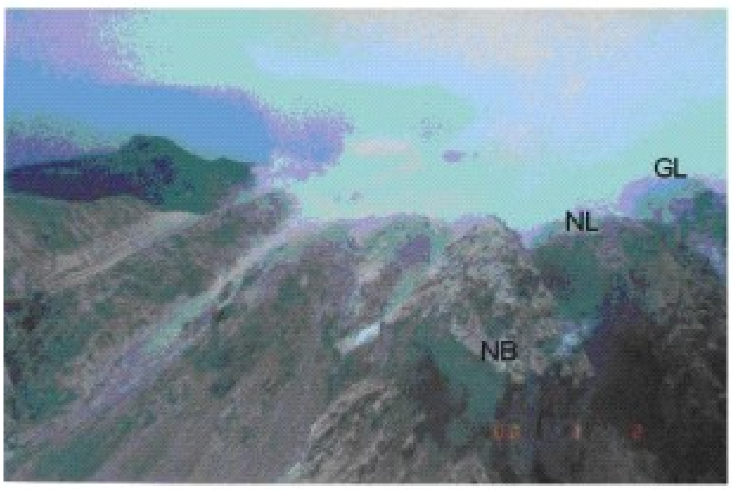

FIGURE 2: View hovering above Tar River Valley looking SW at the active Eastern Lobe (centre) with rockfalls spilling down chutes on its steep eastern face. Note the smooth curving slabs at the top of this lobe that are gradually extruding eastwards away from the main vent. To the right of this lobe is the NE Buttress (NB),Northern Lobe(NL) and the Gages Lobe(GL)of the 1995-98 dome. The Galways Peak formed in that phase is mostly hidden by steam as are the NW and SW mounds of the November 99 dome. South Soufriere Hills can be seen in the left background. Photo taken on 2 March 2000.

FIGURE 3a: View hovering near Galways Mountain looking NW at the November 99 dome (centre). The active Southern Lobe is extruding a broad cluster of slabs and spines on the southern flanks. Rockfalls can be seen spilling off the headwall of this lobe towards the fumarolic Galways Peak (to the left) and banking the talus against the southern crater rim. Note the lack of fresh rockfalls on the now-stagnated flanks of the Eastern Lobe. At this stage, the November 99 dome was close to being the summit of the entire dome complex. Photo taken on 14 March 2000.

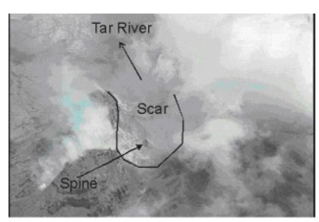

Figure 3 b. View of the dome on 24 March 2000 from approximately 6000 feet showing the outline of the scar and new spiny growth in the base of the scar.

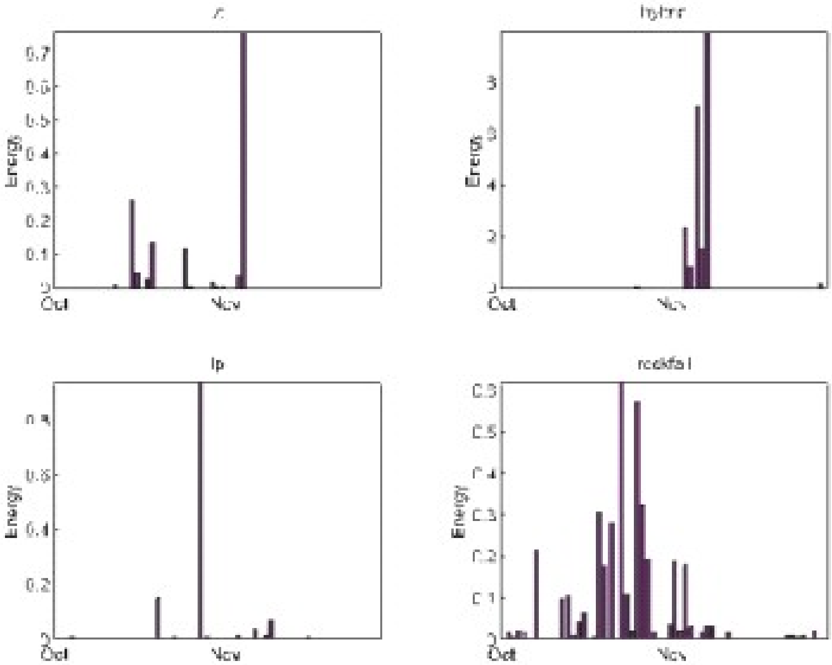

Figure 4: Cumulative energy per day for volcanic earthquakes recorded on the Windy Hill broadband seismometer from October 1, 1999 to November 30, 1999. In mid-October there was increase in volcano-tectonic earthquakes, followed by long-period earthquakes and finally a hybrid swarm from November 4-8. Calibration for MBWH may have changed during November and hence cumulative daily energy for the period December-March is shown separately.

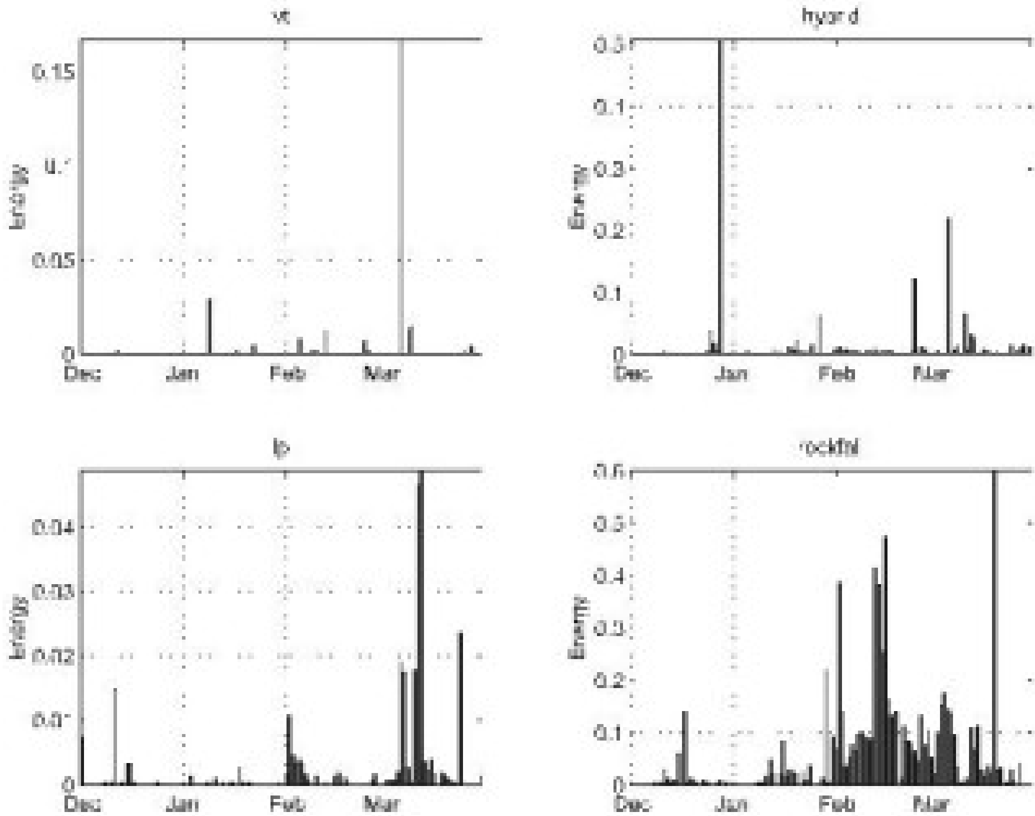

Figure 5: Cumulative energy per day for different volcanic earthquakes recorded on the Windy Hill broadband seismometer MBWH for the period December 1, 1999 to March 31, 2000.. The large spike in rockfall energy on March 20 actually goes up above 5.

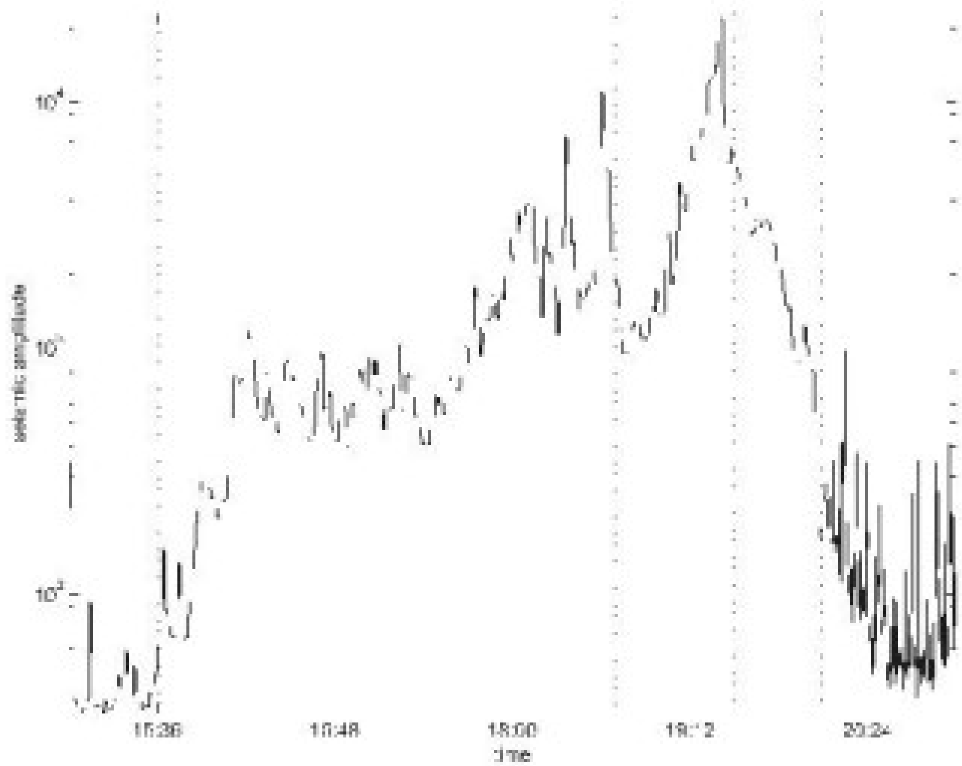

Figure 6: RMS seismic amplitude in 10-second bins for the Windy Hill broadband seismometer MBWH showing the March 20 collapse. An emergent seismic signal became noticeable at 15:37 and the collapse escalated until an explosive phase at 19:23. By 20:02 seismicity had returned to background levels. Throughout the collapse an underlying approximately 5-minute periodicity is present corresponding to individual pyroclastic flows in the Tar River Valley.

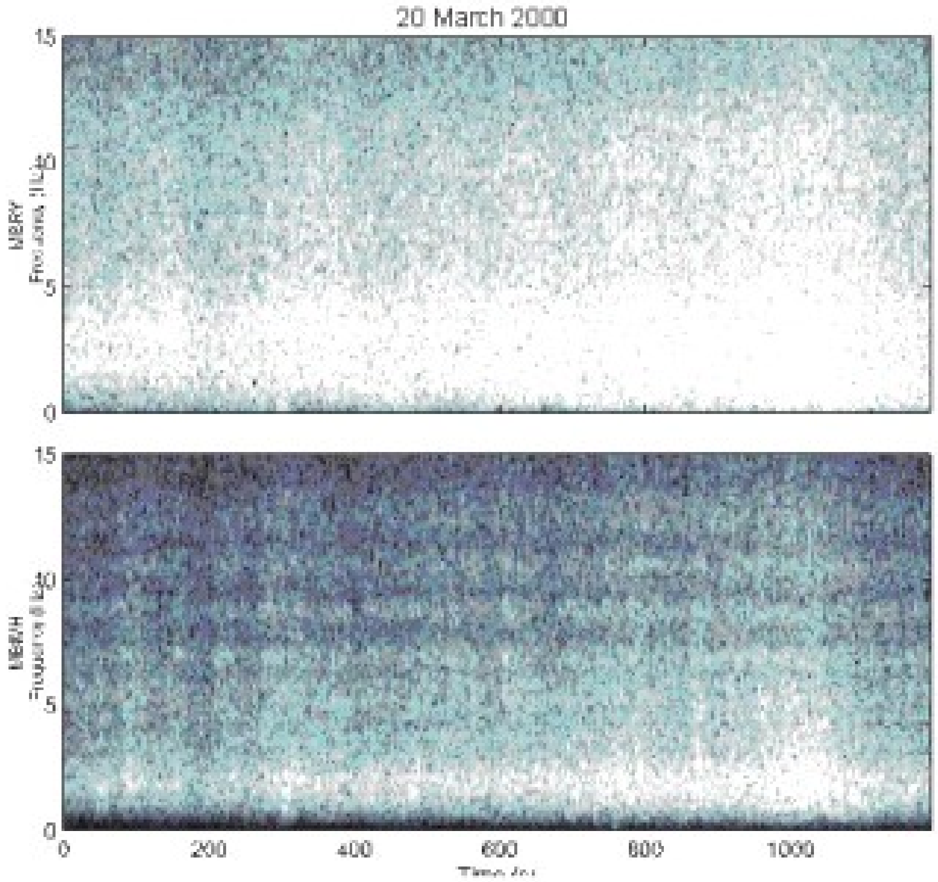

Figure 7: Spectrograms for the period 1906-1926, March 20, for Roches Yard (MBRY) and Windy Hill (MBWH) broadband seismic stations. Lighter shades indicate high signal. The spectral peak is at ~ 2 Hz, typical of volcanic tremor. The highest amplitude signal occurred at 1923.

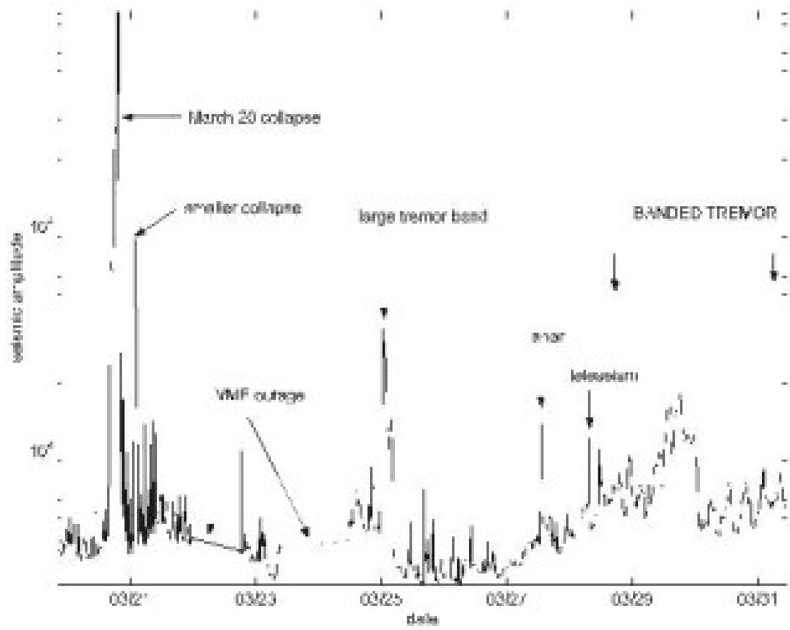

Figure 8: RMS seismic amplitude in 20-minute bins plotted for Windy Hill broadband seismometer MBWH. The collapse on March 20 was the largest event since December 26, 1997. The post-collapse period has been dominated by banded tremor with a period of 5-8 hours corresponding to ash venting. Signals from a lahar and a magnitude 7.7 earthquake near Japan were also quite prominent.

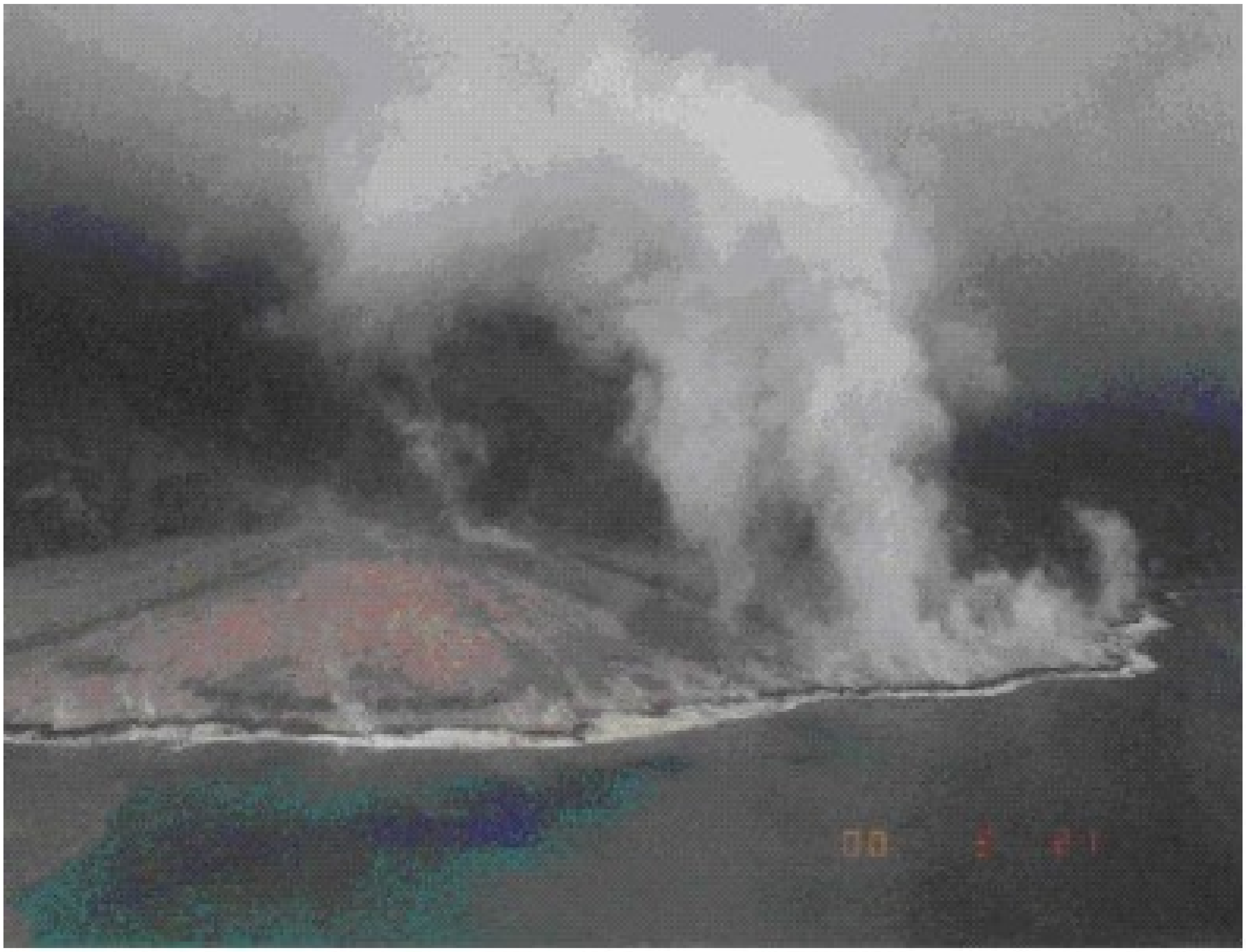

FIGURE 9: View of the Tar River Fan on the day after the 20 March collapse. Fresh block and ash flow deposits were draped across the entire fan although no major changes to its areal extent were observed. Note the wide trench (centre) cutting through the central part of the fan and the smaller southeast trending trench (to the left). Steaming was observed around the entire edge of the fan although more enhanced steaming can be seen at the point where the trench meets the shoreline.

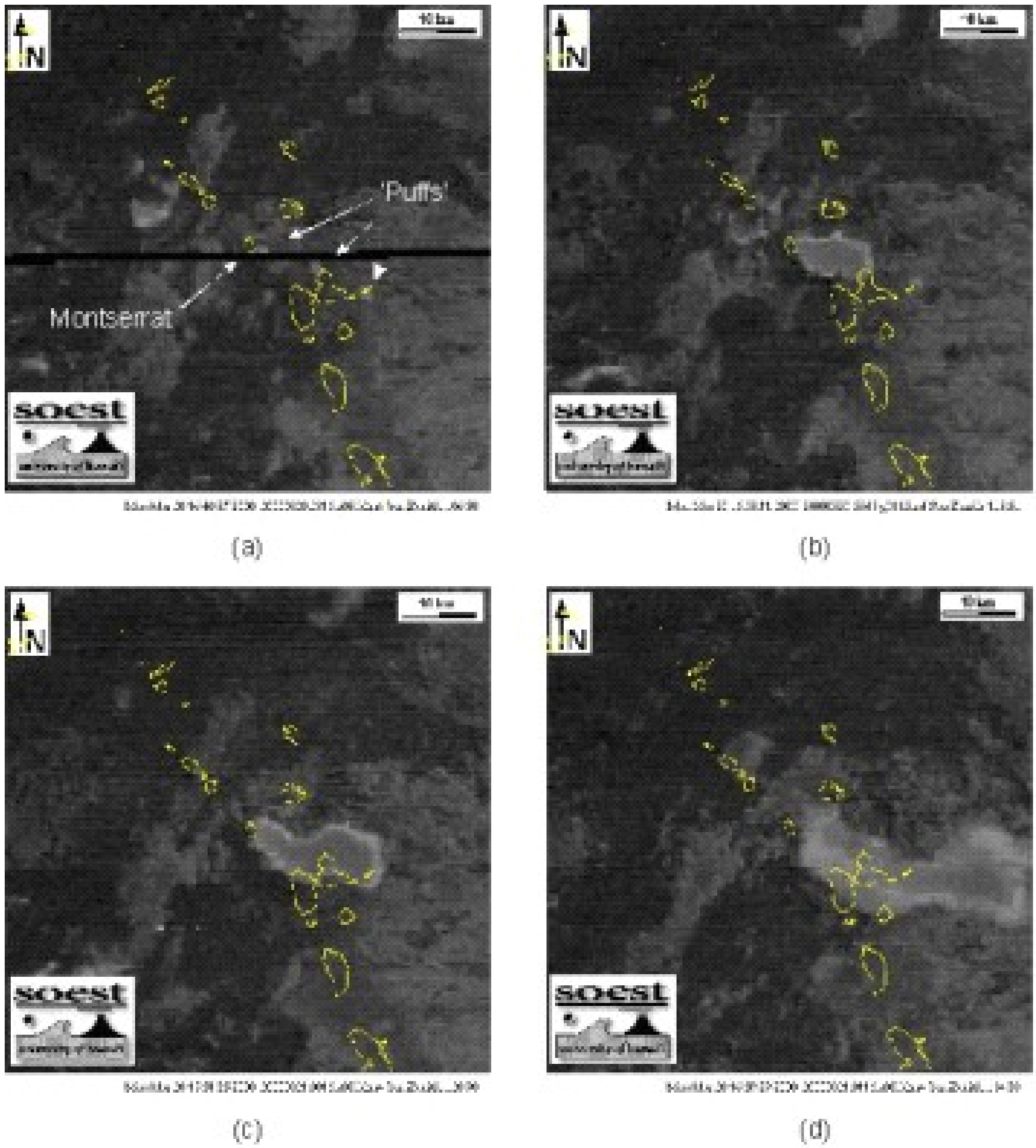

FIGURE 10: GOES images showing the development of the main eruption plume associated with the March 20th eruption. These images were processed at the Hawai'i Institute of Geophysics and Planetology (University of Hawai'i) and involve a combination of Band 2 and Band 4 GOES Imager data. (a) Three discrete ash clouds or 'puffs' visible at 1715 local time (2315 UT). There is a data gap across the middle of the image; (b) Emergence of main eruption plume at 1945 (2345 UT), note N-S oriented kink and single remaining 'puff' to ESE; (c) Wave-shaped plume spreading ~ESE at 2015 (0015 UT 21/3), over N and E Guadeloupe; (d) Continued eastward spreading of dense portion of plume at 2115 (0115 UT 21/3).