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Pyroclastic flows generated by gravitational instability of the 1996-97 lava dome of Soufriere Hills Volcano, Montserrat

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Abstract Numerous pyroclastic flows were produced during 1996-97 by collapse of the growing andesitic lava dome at Soufriere Hills Volcano, Montserrat. Measured deposit volumes from these flows range from 0.2 to 9 x 10^6 m^3. Flows range from discrete, single pulse events to sustained large scale dome collapse events. Flows entered the sea on the eastern and southern coasts, depositing large fans of material at the coast. Small runout distance (<1 km) flows had average flow front velocities in the order of 3-10 m/s while flow fronts of the larger runout distance flows (up to 6.5 km) advanced in the order of 15-30 m/s. Many flows were locally highly erosive. Field relations show that development of the fine grained ash cloud surge component was enhanced during the larger sustained events. Periods of elevated pyroclastic flow productivity and sustained dome collapse events are linked to pulses of high magma extrusion rates.

Introduction

The current eruption at Soufriere Hills Volcano, Montserrat, began on 18 July 1995 and by mid November 1995 an andesitic lava dome had started to grow within English's Crater (Fig 1). Rockfalls produced by gravitationally unstable or actively growing areas of the dome have been characteristic of the activity since extrusion first began. The first pyroclastic flows occurred in late March 1996 when the size of the dome (6.35 x 10^6 m^3) was such that collapsing material began to spill out of the open, eastern side of the crater into the upper reaches of the Tar River valley. These pyroclastic flows comprise a basal avalanche of blocks and ash and an overriding dilute ash cloud surge component derived by elutriation from the underlying unit. In all but the smallest flows, these ash cloud surges have a significant lateral component of motion. Upper, buoyant portions of the ash cloud surge dominated by thermally driven convection produce lofting ash plumes along the flow path which rise a few hundred metres to several kilometres. Such flows produced by non-explosive collapse of domes are commonly referred to as 'Merapi type' flows. This paper describes features of the pyroclastic flows generated by gravitational dome collapse up to 25 December 1997. Direct measurements of velocities, temperatures, and volumes were made. In particular we document observations on the derivation of the ash cloud surge component, the behaviour of the flows as they entered the sea and the extensive erosion caused by the passage of the flows. Pyroclastic flows formed by fountain collapse during Vulcanian explosions are not considered here.

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Overview of Pyroclastic Flow Activity

Pyroclastic flows at Montserrat are distinguished as (i) discrete events; where the material is shed as one pulse, which can be categorised in terms of runout distance or (ii) as sustained events; where a significant portion of the dome collapses incrementally over a period of 20 mins - 4 hours. During 1996-97 discrete events produced small runout distance flows (<1 km) up to several times a day and larger events (up to 3km) on average a few times a month. Sustained collapses occurred less frequently, during these events pyroclastic flows were generated continuously or semi-continuously building up to a distinct climax, during which the largest flows were produced and thereafter waning. Material collapsed incrementally, producing scoop shaped scars into the dome. Pyroclastic flows produced during the sustained collapse events generally had longer runout distances (3 - 6.5 km) although some individual pulses may have been small.

Between March and June 1996 all the pyroclastic flows in the Tar River valley were moderate (< 3 km), discrete events. On 12 May 1996 the flows reached the sea for the first time, 2.7 km from dome, building a small fan at the coast. Between late July and mid September 1996 a series of four sustained dome collapse events occurred, which produced pyroclastic flows, many of which travelled over 3km but which were still confined to the Tar River valley. During this period the small pyroclastic fan created by the May 1996 flows (Fig 1) was enlarged so that by early September it extended 400 m from the shoreline and had a width of ~ 1 km along the coast. A large sustained collapse on 17 September 1996 with an eight hour period of semi-continuous pyroclastic flow activity was followed by an explosive vertical eruption (*Robertson et al. 1998*). The pyroclastic flows produced were the largest that had occurred, spilling out of the lower part of the valley on both its northern and southern margins. Significant collapses down the Tar River valley occurred again in mid December 1996 and January 1997.

During late March and early April, 1997 sustained collapses occurred over the degraded Galway's Wall producing pyroclastic flows up to 4 km down the White River valley. Particularly rapid growth localised on the northern sector of the dome in May and June produced flows which overtopped the crater wall to the north first travelling down Tuitts and then Mosquito Ghaut. Flows also travelled west down Fort Ghaut and into Plymouth during June 1997. A large sustained collapse event on 25 June 1997 travelled 6.5 km down Mosquito Ghaut reaching within 50 m of the sea near the airport. During this event a portion of the upper, ash cloud surge detached from the parent flow at a prominent bend in the flow path and travelled westwards down the Belham valley to Cork Hill (Fig 1).

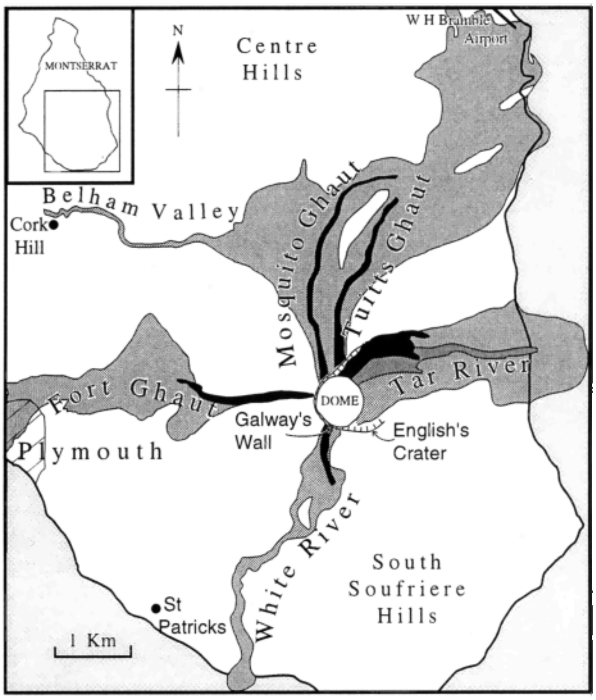

Figure 1. The distribution and extent of pyroclastic flow deposits formed in 1996 - 1997 (up to 25 December 1997). The three deposits shown in the Tar River Valley emplaced: 3 April (solid), 12 May (mod stipple) and 17 September 1996 (stipple). White River : February /March 1997 (solid) and April to November 1997 (stipple). Mosquito Ghaut: 17 June 1997 (solid). Tuitts Ghaut: June 5 1997 (solid). Large stippled area to N and NE are the flows deposits of 25 June and 21 September 1997. Fort Ghaut:: 17 June (solid) and 3 August 1997 (stipple). The extent of flows includes both the basal avalanche and the dilute surge portions.

A further large sustained collapse event produced pyroclastic flows which travelled down Fort Ghaut, destroying much of Plymouth on 3 August 1997. This event was followed by a phase of explosive activity (3 - 10 August). Large dome collapse flows occurred down Tuitts Ghaut on 21 September 1997, covering a wide area across the NE flanks and impacting the airport. This mass unloading of the dome initiated a phase of 75 Vulcanian explosions over the next month. Renewed growth focused on the southern side of the dome generating two major collapses down the White River valley which occurred in early November 1997. The small fan at the end of the White River valley was extended during this time so that it is currently 1.5 km wide along the shore and protrudes 500m into the sea.

Volumes of the flow deposits have been estimated by surveying the collapse scars as well as the deposits. For discrete events, such as the 12 May 1996 flow, deposit volumes were in the range of 0.2 x $10^6 m^3$ dense rock equivalent (DRE) while sustained collapses shed between 1 - 9 x $10^6 m^3$ (DRE) material from the dome. The total accumulated volume of deposits is 125 x $10^6 m^3$ (DRE) which is roughly half of the total extruded volume (246 million) as of 25 December 1997. Weekly running average extrusion rates are compared with cumulative pyroclastic flow deposit volumes (Fig. 2). Although discrete events have occurred regularly through the eruption, these only account for a small component of the volume and were associated with periods of low to average extrusion rates (1-3 $m^3 s^{-1}$). Sustained dome collapse events however, were generally associated with periods of elevated extrusion rate in the range 4-10 $m^3 s^{-1}$, both prior to and immediately after the collapses. The last four sustained dome collapses: 25 June, 21 September, and 4 / 6 November 1997, have involved volumes of 4.2, 8, and 18 million cubic metres respectively. The maximum volume being shed in any one event has increased with increasing average extrusion rates.

Observations of the Flows

Initiation

The initiation of the pyroclastic flows was typically associated with non-explosive, gravitational collapse of unstable dome material, although the process by which the cascading rockfall debris transforms over a few tens of metres into a coherent pyroclastic flow is poorly understood. In a few cases the generation of rockfalls and pyroclastic flows was associated with small impulsive 'rockbursts' from active faces of the dome especially during periods where growth was concentrated in a localised area. Minor, superficial explosions also occurred from source areas immediately after the shedding of material, these subsequently fed further flows which were pulsatory in nature. Some flows were triggered by long-period (LP) earthquakes and associated with ash and gas venting that preceded the generation of the flows by 10-20s. LP earthquakes are considered to be an inherent process in the generation of the rockfalls by pressurization from within the dome but they may also trigger rockfalls and pyroclastic flows by shaking the dome.

Flow Behaviour

The flow front of the ash cloud surges characteristically developed wedge shaped fronts with a ground hugging nose and a lobe and cleft type morphology in the order of a few metres high (Fig 3). This morphology was intermittently disrupted by material, including large blocks, from within and behind the flow head being ejected forward. Velocity variations between the body of the ash cloud surge and the basal avalanche unit allowed brief

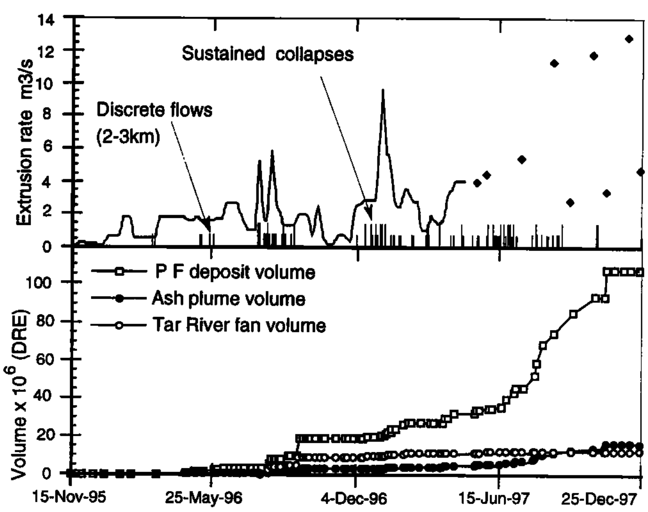

Figure 2 .Weekly running average dome extrusion rate (solid line, data points are given where volume estimates are spaced at more than 1 month) compared with cumulative pyroclastic flow deposit volume, Tar River fan volume and estimated volume of lofted ash plumes. Periods of discrete pyroclastic flow activity (short bars) and sustained collapse events (long bars) are shown.

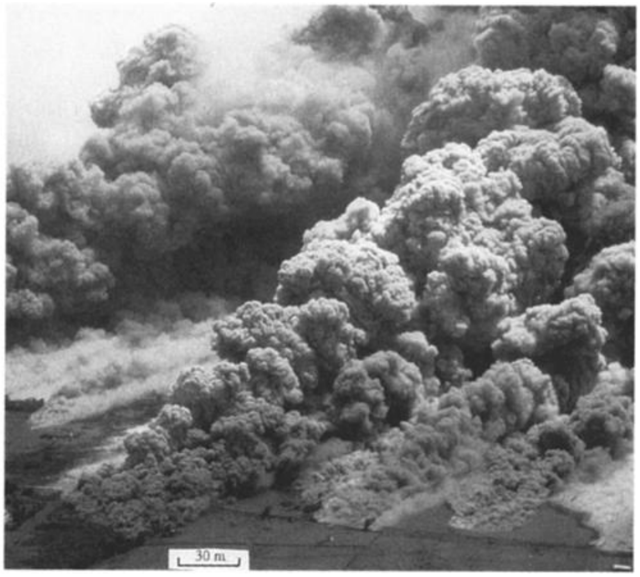

Figure 3 Pyroclastic flow at 13:17 hrs on 25 June 1997 in Spanish Point approx 1 km SSW of WH Bramble airport.

glimpses of the lower block-rich component as they accelerated over steeper portions of the flow path. However for much of the time the basal avalanches were hidden by the dilute ash so that one could not easily discern the exact behaviour of the coarse debris. Although the basal avalanche component was strongly topographically controlled they could occasionally be seen to have appreciable superelevation effects at bends in flow paths. A distinctive feature of many flows was the highly variable rates of flow front advance often of stop-start nature, varying from 0 to 10 m/s in 30 seconds for an individual flow. Elsewhere, such behaviour has been considered a function of either topography (*Hoblitt, 1986, Levine and Keiffer, 1991*) or non-linear mixing processes at the flow head (*Huppert et al. 1986*): another possible cause at Montserrat is the pulsatory nature of flow generation. During periods of continuous or semi-continuous pyroclastic flow activity later pulses supply parts of flows initiated earlier, occasionally distinct high velocity pulses completely overtake or engulf earlier, slower moving parts. Initial estimates of average flow front velocities of the discrete flows are in the order of 3-10 m/s for < 1km runout flows and 5 - 20 m/s for 3 km runout flows. Locally, the fronts of some of the larger flows advance as fast as 60 m/s.

Movement of Ash Cloud Surges Across the Sea

Good visual observations were made of the 12 May 1996 flow as it travelled over the sea. The surge component detached from the basal avalanche, travelled across the water surface and developed into large lobes each up to 50 m wide. The flow front velocity noticeably accelerated from 8-15 m/s as it approached the water to a maximum velocity of 25 m/s before it waned and came to rest approximately 200 m offshore. The dense basal portion of the flow entered the sea but dark, sediment laden clouds within the water, obscured observations. Boiling water and explosive sediment-rich fountains of the order ~10 m high occurred near the margin of the new pyroclastic fan. Mushroom shaped lofting ash plumes formed above the distal end of the flow and these were followed by columns of dense steam rising several hundred metres. Ash fallout from these clouds typically occurs as accretionary lapilli ~ 2 mm in diameter.

Lofting Ash Plumes

Vigorously convecting ash plumes were generated from the larger pyroclastic flows which frequently rose to heights of several thousand metres. Those formed during sustained collapses frequently reached as high as ~ 10 km. The lofting ash plumes develop progressively along the entire length of the flow but tend to form protuberances which rise as discrete pulses. Vigorous pulses are produced above breaks in slope such as the base of the Galways Wall where dome material cascaded into the Soufriere region and air entrainment was enhanced. Ascent velocities for lofting ash plumes typically show curved velocity profiles (*Calder et al.1997*), 3 km runout, discrete flows in May 1996 produced plumes which reached a maximum of 10 -12 m/s at heights of 300-500 m.

Temperature Measurements

Direct temperature measurements of the ash cloud surge were obtained for three pyroclastic flows in the Tar River valley using industrial temperature patches fixed to posts 1.5 m above the ground. These yielded temperatures of 99-121 ^{o}C, 99 -149 ^{o}C; and 200-250 ^{o}C respectively. Temperatures within any one flow were consistent within the brackets above for several positions on a profile running towards the valley axis. Temperature variations between flows may thus be attributed to differing temperatures of source material on the dome.

Erosion

A striking feature of the pyroclastic flows was their erosive capability. In the Tar River valley erosion has removed of all vegetation and topsoil as well as generally smoothing and rounding the topography, producing a 1 km wide denuded corridor. Eroded bedrock surfaces are conspicuous owing to the orange/brown hydrothermally altered appearance of the underlying prehistoric deposits. The side walls of ravines, constrictions and bends in valley along which the flows passed were severely scoured and striated. Measurements indicate that in places over 5 m depth of material was removed. During the 17 September 1996 collapse, a ~50 m wide channel which could be traced the whole length of the Tar River valley, was excavated up to 30 m deep into thick accumulations of pre-September pyroclastic flow deposits. On a smaller scale, chutes are regularly carved into the base of the dome by persistent rockfalls from a localised source region. A spectacular illustration of erosion by pyroclastic flows was the incision of a gully 60 m deep and 80 m wide through the upper portions of the southern crater (Galways) wall. The gully itself was excavated in only a three hour period of pyroclastic flow generation during the 31 March 1997 sustained collapse event.

Deposits

The deposits of the pyroclastic flows are similar to those of other documented dome-collapse eruptions (*Nakada & Tositsugu, 1993, Boudon et al. 1993*). They are predominantly composed of dense, non-vesicular - microvesicular andesite (*Robertson et al. 1998*). Vesicular andesite is subordinate but has been present in increasing proportions since May 1997 and during explosive phases. The development of the ash cloud surge facies, the degree of confinement of the entire flow and the slopes on which they deposit vary with size of event. The talus apron immediately below the dome comprises amalgamated fans of lobate deposits with well defined levee and channel structures. Individual flow deposits are typically 10-20 m wide, hundreds of metres in length and are comprised predominantly of coarse, block-rich material with no distinct fine grained ash cloud surge deposit, although small lofting ash plumes were observed during their emplacement.

Discrete pyroclastic flows of moderate runout (2-3 km) were strongly confined by topography. Generally two distinct deposit facies can be identified: coarse, block-rich deposits, which are confined solely to the valley axis and are interpreted as basal avalanche deposits; and thin, more widespread fine grained block-poor ash cloud surge deposits These ash cloud surge deposits are generally limited to the sidewalls of ravines, but spread up to 100 m from the valley axis where flows swept around bends. In the lower reaches of valleys such as the White River valley, Tuitts Ghaut and early flows in Mosquito Ghaut, many of these deposits have virtually no laterally extensive ash cloud surge component.

Pyroclastic flow deposits within the Tar River valley formed by the July - September 1996 and December 1996/January 1997 collapse events had a more widespread distribution such that they were not confined to ravines. The flows deposited extensive, thin (<50 cm) fine grained ash but left only very limited coarse facies in the valley even within the central channel. These events eroded pre-collapse deposits out of the valley and carried most of the coarse material down to the fan. Likewise deposits from the large collapses down Mosquito Ghaut (25 June 1997), Fort Ghaut (3 August 1997) and Tuitts Ghaut (21 Sept. 1997) all had a similar widespread distribution of the ash cloud surge component and the volumes of material involved were such that they overflowed the Ghaut walls readily. During these events the ash cloud surge component of the flows produced was more fully developed and energetic. Vegetation knock-down directions oblique to the direction of the valley axis and observations of pyroclastic flows indicate that the ash cloud surge detaches readily at bends in ravines. The 25 June 1997 pyroclastic flow was a typical example, where the upper, finer grained dilute part of flow detached, spilled out of the upper part of Mosquito Ghaut, and crossed the watershed draining westwards into the Belham valley.

The Fans

Pyroclastic flows first reached the sea on 12 May 1996 depositing a small fan of deposits ~100 m wide at the mouth of the Tar River valley. Since then, over 30 flows have reached the Tar River fan with growth mainly occurring in large increments during the sustained collapse events (Fig 1). The Tar River fan currently (December 1997) protrudes 600 m out into the sea and is 1200 m wide along the shore its relatively straight leading edge is thought to be constrained by the submarine shelf of a paleo-fan. The volume of the fan (December 1997) is estimated at 16 x 10^6 m^3 DRE, representing almost 40% of the total cumulative pyroclastic flow deposit volume. At the fan apex, the deposits are 60 m thick and slope gently (4-6^o) down to the fan margins. Bathymetric surveys (August 1996) indicate the angle of repose of the submarine deposits is typically in the range 12-17^o, with maximum slopes on the leading edge of the fan in the range 22-27^o. By April 1997 the surface of the fan comprised numerous overlapping lobate deposits and boulder trains which radiate outwards in broad arcs from the mouth of the valley. On the shoreline, where the flows entered the sea the coarse blocks show red oxidised margins and distinctive prismatic radial joints indicative of quenching.

A fan was built at the end of the White River (4.5 km from the dome) by pyroclastic flows associated with the Vulcanian explosions in October 1997. This was enlarged by dome collapses in November 1997 with the addition of 6 x 10^6 m^3 of material.

Discussion

The pyroclastic flows were all generated from gravitational collapse of the dome. Small flows are well confined by topography whereas the larger flows produced during the sustained collapse events involve more material and often overspilled the valley walls. These flows also had better developed ash cloud surge components whereas some of the smaller discrete flows appeared to have had virtually none. The development of the ash cloud surge by fragmentation and elutriation of ash from the basal avalanche increases with flow volume, velocity and the excavation level of the collapse scar into the interior of the dome.

The runout distances of these flows can qualitatively be seen to be proportional to their volumes. However, volume discrepancies between scar size and that of the deposits in the fan suggest as much as 4 million cubic metres of material has passed over the front of the Tar River fan into the deep water beyond.

The ability of both small and large pyroclastic flows to erode as well as deposit and thereby modify the topography over which they pass has consequences for the routes taken by subsequent flows. Evidence suggests a transition exists between an erosional regime and a depositional regime which is largely dependant on slope and flow velocity. Large flows are erosive the entire length of the valleys where the average slope angle is 14-16^o and deposit predominantly where slope angles in the order of 4-6^o. Small volume flows can also be highly erosive in their upper portions but are capable of depositing coarse material on slopes of up to 20^o.

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