Vegetation damage and synchronous tephra-fall influence sediment-charged flash floods

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Introductory paragraph

Flash floods are hazardous and capable of significant infrastructure damage because they are difficult to predict; often rapid, locally erosive, and transport large sediment loads including boulders and other debris. On 20th May 2006 intense rainfall on the Caribbean island of Montserrat generated devastating flash floods and the Soufrière Hills Volcano experienced a large dome collapse. The floods had very high loads of volcanic debris (lahars), unusually high water levels and were the first to transport boulders to the shoreline of the Belham Valley. Detailed knowledge of rainfall and geomorphological change, coupled with

the precise timing of events and eyewitness accounts has enabled us to assess the relative importance of rainfall volume and intensity, volcanic debris and vegetation damage for the behaviour of this and subsequent sediment-laden floods in this setting. We conclude that rainfall intensity and volume are not the critical control on the impact of flash floods in the Belham catchment but that changing runoff behaviour (controlled by vegetation damage and tephra fall) is critically important.

Sediment-charged flash floods are hazardous and capable of significant infrastructure damage because they are a) difficult to predict; b) often rapid; c) locally erosive, and d) transport large sediment loads including boulders and other debris. Montserrat is a small island in the Lesser Antilles with a bimodal rainfall season with peaks around May and October. The eruption of the Soufrière Hills Volcano which started in July 1995 has been dominated by the extrusion of highly-viscous lava forming a series of lava domes inside the pre-existing English's Crater[1]. The eruption has been punctuated by episodes of dome-collapse and occasional vulcanian explosive activity, all of which have perturbed the upper parts of several river catchments. The catchment of the Belham River (area 12.9 km^2) drains one flank of the Soufrière Hills volcano and has tributaries draining St George's and Garibaldi hills and the Centre Hills (Fig. 1). Stream flow only occurs during, and for short periods after rainfall. Before the onset of the volcanic eruption in 1995, the catchment was densely vegetated with a diverse tropical flora and small-scale agricultural clearance. Although the climate has not detectably changed since 1995, flash floods have become a significant hazard[2].

The volcanic-dome collapse on 20th May 2006 was the second largest in the 12-year eruptive history and *c*. 115×10^6 m^3 was removed from the edifice in less than three hours with most activity taking place within 35 minutes (3; www.mvo.ms). The associated lahar activity caused more geomorphic change in the Belham Valley (Fig. 1) than observed on any other individual day since 1995. In two days (20th and 21st May) more change occurred within the valley than the cumulative total of the preceding five years (Fig. 2).

In this setting, the potential controls on flash flood behaviour are: (a) the relative timing, intensity and distribution of rainfall; (b) the timing, distribution and character of coarse volcanic debris deposition; (c) the timing, character and distribution of tephra fallout, and (d) the timing, character and spatial pattern of damage to vegetation (de-vegetation, plant mortality, leaf removal, branch breakage *etc*.). The system responds to changes in these variables by altering discharge, flow depth, channel characteristics (width, depth, form, slope, bedforms) and the deposited sediment grade. All of these have an influence on the potential hazard in the valley. Observations of events on 20th May 2006 and subsequent changes to the system, in the context of a longer term study of the Belham Valley [2, 4, 5] are used here to assess the most important variables responsible for controlling the dramatic changes observed in the mid- and lower valley and thus the important controls on the variation in character of these sediment-charged flash floods.

Methods

Data have been compiled from a continuous rainfall record, eyewitness and Montserrat Volcano Observatory (MVO) observations during 20th and 21st May, and field work (including sedimentological mapping, sampling, photographic and GPS surveying) before and after the flash floods. All of the times recorded in this paper are Montserrat Local Time (GMT-4:00). A network of tipping bucket rain gauges has been operating continuously on Montserrat since January 2001 [5] even though volcanic ash accumulation on the tipping-bucket gauges affects their operation. In May 2006, the Harris, Garibaldi Hill (GAR) and MVO North (MVN) gauges were functioning (Fig. 1) and a fixed bucket gauge at Hope provided daily totals. Volcanic activity recorded by the MVO provides timings for the eruption on May 20th 2006. Channel bed and tephra fall samples were analyzed for grain size with a Malvern Mastersizer 2000 and for composition by XRF.

The streams were not gauged, so velocity and discharge are estimated indirectly. Assuming 30 mm of rain fell over the whole catchment on the 20th May and 17 mm on the 21st May, the upper limit of runoff volume was 3.87×10^5 m^3 and 2.19×10^5 m^3 respectively.

If all of the water on the 20th ran off at a constant rate between 03:00 and 09:00 then the discharge would have been 17.9 m^3s^{-1}. Seismic data and eyewitness reports suggest the hydrograph was strongly peaked and possibly multi peaked. Peak discharge of *c*.200–300 m^3s^{-1} in the lower valley is estimated from channel cross-section data with maximum water elevation assessed from strand lines, vegetation damage and deposits, combined with velocity estimates calculated from critical shear stress for bed load transport and wavelengths of stationary wave trains.

Critical Observations

The weather on Montserrat in May 2006 was not unusual

On 20th May 2006, rainfall totals at MVN and Hope gauges (Fig. 3, 4) were 28.4 mm and 52 mm respectively and 27.4 mm fell before the GAR gauge stopped recording (intensity reached 1 mm/min). The Hope value is more representative for the catchment because the GAR gauge clogged with ash and the MVN gauge is 2.5 km further north. Relatively little rain fell after the dome collapse. After 18:30 on the 21st, 31.5 mm were recorded at Hope but only 17 mm at MVN. Spatial variation in rainfall intensity is such that individual gauges may not always record the peak intensity or maximum volume[5]. Assuming that the recorded rainfall is representative of the events, the totals and intensities on 20th and 21st May 2006 (Fig. 3a) were not exceptional for the catchment. They are comparable to many other localised convective rainfall events (representative examples shown on Fig. 4). This rainfall pattern does not explain the high flood magnitude or impact.

Very little rain fell in the preceding weeks; 1 and 1.2 mm was recorded at GAR and 7.4 and 1.4 mm at MVN on 12th and 15th May respectively. On 19th May, 3.8 mm was recorded at GAR, 0.6 mm at MVN and none at Hope. Thus exceptional flood behaviour on the 20th was not caused by unusual antecedent rainfall.

The succeeding rainy season (June to November) was also unexceptional with monthly totals not significantly different from the 2001-2007 average. Several events exceeded the daily total recorded on 20th May (e.g. Fig. 4) but the extreme flood behaviour was not repeated.

Volcanic activity on 20th May 2006

Dome collapse began at about 05:52, coinciding with peak rainfall intensity recorded at Garibaldi Hill[3]. Ash plumes drifted to the west and northwest depositing ash and lapilli (Fig. 3). Tephra fallout rate declined towards the end of the dome collapse at 09:00, although very light ash fallout continued locally until about 16:00. The ash fallout over the Belham catchment between 05:52 and 07:32 was water-saturated, and accretionary lapilli were observed at MVO between 07:32 and 08:07 implying moisture in the ash cloud[3]. The last major collapse (at *c*. 08:35) generated grey ash but later (until *c*. 16:00) distinctively red ash fell, sourced from a vent inside the crater. The thickness of the 20th May tephra deposit varied over the Belham Catchment (see Fig. 1B).

On 21st May, accretionary lapilli fell across the whole island. In the upper Belham catchment, the 21st May tephra was of the order of 10 mm thick. Data from XRD analysis of Belham catchment ash samples matched plagioclase (Ca, Na, Al and Si) as well as cristobalite (SiO_2), with no indication of any clay minerals in samples deposited in May 2006.

The fluvial events and deposits of the 20th and 21st May 2006

Some flow may have occurred in the valley between 03:08 and 04:47 on 20th May, when there was heavy rainfall (coincident with some ash venting). By 05:32, water was flowing rapidly down shallow sub-channel(s) in the lower Belham Valley and a light fall of ash was occurring (eyewitness accounts and time-stamped photographs). The sustained rainfall recorded at Garibaldi Hill from 05:48 to 06:15 was accompanied by the onset of noisy flow in the Belham Valley. Lahars were heard by MVO staff and detected on the seismic network from about 05:52. Eyewitnesses described buildings engulfed by the flowing water to roof height by *c*. 08:00 with large boulders "*bouncing downstream*" in lower reaches and the ash-laden rain "*like thick chocolate falling from my roof*". By 09:00 significant flow had ceased, with only some shallow turbid-water flow. At 13:00 the valley floor was wet but with little stream flow. Thus discharge varied rapidly through the day (Fig. 3) with peak discharge estimated at 200-300 m^3s^{-1}.

Rain fell over the whole catchment. Tephra were added to the flow by direct fallout and by entrainment in the rapid runoff. This with bed and suspended load added to the bulk discharge. The flow transported large volumes of sediment including boulders throughout the system. Sedimentary mapping indicated that the flow "bulked up" with coarse sediment in the mid-reaches by eroding up to 3 m of post-1995 deposits from the valley floor (e.g. seen at the Sappit confluence, Fig. 1). Although there was net valley floor lowering upstream of the bridge site on the 20th May, a sandy-gravel or gravely-sand bed up to a few 100 mm thick, with isolated and clusters of boulders (diameter to >1.5 m) was deposited on scour surfaces (Fig. 5).

Downstream of the old bridge site, there was aggradation across the full width of the valley floor (*c*. 200 m) on the 20th May and the channel bed aggraded by *c*. 1.5 m (decreasing downstream). A sheet of gravelly sand and sandy gravel was deposited with large numbers of boulders. The shoreline advanced seawards by up to 100 m, with at least 90 000 m^3 of new delta prism volume. The delta was strewn with woody debris and boulders. Eyewitnesses suggest that boulders arrived at distal sites late in the event and this might explain the increased noisiness of the flow. Large boulders had not previously been transported by the

Belham River to the delta. The net result of these changes was a decline in valley slope in mid- and lower sections.

At the lowest end of the Belham Valley, the valley floor was draped with up to 0.3 m of water-lain sediment with grain size distribution (d_{50} 41 μm, mean 34 μm) indistinguishable from the tephra deposits in adjacent areas. X-Ray diffraction analysis only shows primary volcanic minerals and no secondary or accessory clay in these deposits. The final waning-flood deposits in this area were distinctly red and could only have been sourced from ash fallout derived from late stage venting in the crater.

The rainfall was less intense on 21st May and less tephra fell on the Belham catchment. The catchment was covered by the veneer of tephra deposited on the previous day. The 21st flow had lower peak discharge than that on the 20th. Channel incision occurred through the mid reaches. The new channels were steep sided (Fig. 2d) and narrow by comparison with the width of the flow on the 20th. They were eroded more than 2 m through the 20th May deposits and down into older sediment. The channel depth decreased downstream (depth *c*. 0.7 m, 300-500 m from the shore) to an area of net aggradation near the coast. A sedimentary unit, up to 0.2 m thick, was deposited in parts of the lower valley.

Subsequent floods and geomorphic evolution

The Belham Valley changed further through the subsequent rainy season. During June and July the channels were described as "*worsening*" but in August they started filling and by November had been filled to pre-May 2006 levels at many downstream sites. The channels filled with gravelly-sand and sandy-gravel and the delta prograded a further *c*. 100 m. The cumulative result of the events in May-November 2006 was net shoreline progradation and net aggradation (up to 3 m) at all points below the old bridge site (illustrated by profiles, Fig.

1B). The aggradation between April 2005 and November 2006 was about the same as that in the preceding five years.

Vegetation damage in 2006

Vegetation cover affects runoff, influencing flood response time and peak discharge. It also directly controls sediment entrainment on hill slopes and channel banks. Before the eruption began in 1995, the whole Belham catchment was densely vegetated but volcanic activity had removed all vegetation from the upper 18% of the Belham catchment by end 2005. From February 2006 and particularly in April-May 2006, high volcanic emissions of HCl and frequent southerly winds, caused acid rain over the Belham catchment and this had caused widespread damage to vegetation by 20th May. On 20th May, ash fallout blanketed vegetation with increasing intensity between 05:20 and 07:32 burying low-growing plants. Very intense tephra fallout between 07:32 and 08:07 broke saplings and tree branches. Wet ash coated and adhered to leaves and this would have generated hydrochloric and sulphuric acid, accounting for the increased leaf damage over subsequent days (Fig. 2d). After the 20th May collapse, the area of the catchment over which vegetation was damaged (browned, lacking leaves) was 5.87 km^2 (45.5 % of the total area), and the area of total vegetation clearance had risen to 2.97 km^2 (23% of the total). Thus 68.5% of the catchment had no vegetation or significantly damaged vegetation. Changed wind direction and associated changes in distribution of acid rain in June allowed significant re-growth over much of the catchment (Fig. 2b and c). By the end of the year re-growth had reduced the de-vegetated area to 2.6 km^2 (20.2% of the catchment area) and there was re-growth over all of the damaged area.

Synthesis of Observations

The 20th May 2006 flow was very different from those through most of the 12 years since onset of volcanic activity. The rainfall on the 20th was similar in intensity and magnitude to that on the 17th July 2006 and less than that on 19th July 2007 (Fig. 4). Despite this similarity, the estimated flow velocities and depths suggest that the discharge was less in July 2006 and still less in July 2007. For comparison, on three days in 2004 when the rainfall was greater than that on 20th May 2006 (Fig. 4) the peak discharges were lower and the flood impact on valley morphology was far less (the total change between 2002 and 2005 was about the same as that in 2006 alone). Thus, the peak discharge on 20th May 2006 was extreme even though the rainfall was not out of the ordinary for this catchment. In none of the events before May 2006 did boulders reach the shoreline.

Given that the rainfall pattern was not unusual, other factors must have controlled the extreme flood behaviour on May 20th 2006. The relative importance of these factors is discussed here. Volcanic activity has four main impacts on catchments and flood behaviour; (a) topographic change, (b) coarse debris input to the upper catchment, (c) tephra fallout over the catchment and (d) damage to vegetation.

(a) *Topographic change* in the Belham Catchment caused directly by the magmatic and volcanic activity through 2006 was negligible on the catchment scale (only a small sub-catchment drains the volcano's flank, Fig.1) and on its own, does not account for the variation in flood behaviour. The topographic changes resulting from erosion and deposition may be more significant. These occur during runoff events with feedback between the flow and sediment movement. Rapid rill and gully development on de-vegetated and tephra-draped surfaces increases runoff efficiency (cf. 2) and development of slot channels on the 21st May influenced transport efficiency.

(b) *Coarse-grade volcanic debris* was not emplaced in the Belham catchment on the 20th May 2006, debris from the dome collapse was deposited in adjacent catchments. Coarse grade sediment from earlier volcanic events may have had an influence, but we have not been able to identify such individual sediment slugs moving down the system.

(c) *Tephra* were deposited over the whole catchment on the 20th and 21st May (Fig. 1B). Tephra fallout (i) changes infiltration rate and runoff efficiency, (ii) adds sediment to the flow increasing bulk discharge, and (iii) may alter flow rheology by changing load characteristics.

(i) Infiltration rate on newly tephra-blanketed surfaces may be reduced by up to two orders of magnitude[6] leading to greater runoff. Although the 20th May tephra fallout would have influenced infiltration, the total effect is unlikely to have been far in excess of other tephra falls in the 12 year eruptive history, therefore its influence on infiltration does not account for the extreme flood behaviour on the 20th.

The 20th May tephra blanket would have increased the runoff efficiency on the 21st May, and contributed to the tendency for channel incision. The influence of tephra on runoff decreases rapidly with time after deposition such that by June and July rainfall events with volumes and intensities similar to 20th May would have generated less runoff.

(ii) Tephra entrained from the ground and falling onto the moving water surface add bulk to floods. On days when little or no tephra fall directly onto the flowing water, suspended sediment concentration will vary with flow conditions as in other flash floods (e.g. 7-8). In contrast, on 20th May 2006, a lot of tephra fell onto the flowing water surface, injecting relatively fine-grade sediment directly into the water column. Given that the 20th May tephra thickness varied from a couple of 10s mm to 100s mm over the catchment, it must have added volume to the discharge. However the flow appears to have remained dominantly Newtonian, so it is unlikely that the sediment ever caused bulk discharge to increase more than about 25% (cf. 9). Thus, although this sediment addition may have contributed to the high peak flood discharge on the 20th May, it cannot have been the main control on discharge.

(iii) Tephra falling on flowing water adds sediment load irrespective of the capacity or competence of the flow. Grains take time to settle to the bed, thus the sediment load can be out of equilibrium with the flow and flow-bed composition. Such imposed increase in sediment load can influence flow behaviour. The proportion and composition of the ash is critical to the resultant flow behaviour because very small changes in the percent of some minerals (notably clays) can significantly alter viscosity (*e.g.* 10-11). The effect in May 2006 is difficult to quantify as the fines content of the flow is not well-represented by the deposits and we have no samples from the flow. However, the ash was predominately plagioclase and no clay minerals were detected, so the effects of fines on viscosity would have been lower than in documented in experiments with clay[10-11].

Large volumes of ash did not fall until relatively late in the runoff event (Fig. 3). Thus the early flow may have been relatively fines-poor. The final waning flow was evidently fines-rich and deposited silt across distal areas. Direct input of tephra to the flow evidently results in a very different pattern of suspended sediment concentration than in other flash floods; spikes would have been produced by the pulses in tephra fallout.

(d) *Vegetation* was damaged over an unusually large area in the weeks leading up to 20th May, whereas the increase in area of damage on the 20th was relatively small. Ash adhering to leaves increased the damage over subsequent days, but re-growth was then rapid through the year. Vegetation clearance by, for example, wildfires increases water delivery to streams, reduces slope roughness, increases runoff speed (increasing peak magnitude), increases sediment flux and reduces response time (*e.g.* 8, 12, 13). The extensive vegetation damage was a major contributor to the unusually high discharge on 20th May and during the subsequent rainy season, although rapid re-growth reduced this affect through the year.

Geomorphological feedback

Hydraulic processes, channel geometry and flow resistance are interdependent and given time, a fluvial system adjusts to maintain continuity of water and sediment flux. A channel can respond by aggrading, incising, changing width, form and slope. All these changes occurred in different parts of the Belham Valley at different times through 20th and 21st May. In a flashy system such as the Belham Valley, a state of equilibrium is difficult to achieve and the 20th May flow was an extreme disequilibrium event.

On May 20th the system responded to high runoff rate and tephra input by changing the transported grain size and channel slope, the former by movement of boulder-rich gravel down the system (such that tephra represented only a small part of the sediment load) while the latter changed by erosion, deposition and change in channel form. The relative importance of the imposed changes may be assessed simplistically by considering the stream power proportionality relationship for channels with mobile boundaries[14] stated as $QS \propto Q_s d_{50}$, where Q is channel forming discharge, S is energy gradient (approximating to channel gradient), Q_s is bed material discharge and d_{50} is the median grain size. If the volcanic sediment input was the major control one might expect the channel slope to increase, whereas, if raised discharge were more important the expected response might be sediment coarsening and slope reduction, as observed on the 20th May. There was increased boulder transport over a reduced valley slope in mid and distal reaches. Both the widespread vegetation damage and the tephra deposition caused increased discharge. Although high discharge flows occurred in June and July they did not cause so much impact as the 20th May flood, because that flood had already modified the valley for higher discharge. Subsequent smaller flows were now strongly out of equilibrium with the channel form, slope and sediment distribution, and for example the Belham River responded to the relatively smaller flows on the 21st May by channel form change cutting narrow deep channels.

We have thus provided evidence that in this setting, rainfall intensity and volume are not the critical control on the magnitude or impact of flash floods, changing runoff behaviour is. Vegetation damage was the primary control of changed runoff patterns with additional effects of tephra. These findings have important implications for hazard from sediment-charged flash floods, demonstrating that high discharge and sediment yield events may be generated without extreme rainfall.

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Figures

Fig. 1 A. Topographic map of the Belham Catchment (shaded) and adjacent areas of Montserrat with contours at 50 m intervals. The latitude and longitude are given. The ▼are rain gauge sites; the northern one is the Montserrat Water Authority gauge at Hope, and the southern one is the UEA gauge named Garibaldi. Ash thicknesses for 20th May 2006 are given in mm next to the + marking sample points. BB marks the old bridge site, s marks the confluence of the Sappit and Belham rivers, a, d and E refer to the locations of the photographs in Fig. 2.

B. Survey profiles along the centre line of the main channel of the Belham River from the old bridge site (BB on the map) to the shoreline. The main channel path did not substantially change through this period, although at peak flow additional channels became active in the lower reaches.

Fig. 2. Photographs of the Belham Valley; **A.** and **B.** are aerial views of the same reach of the upper valley at Dyer's (E on Fig. 1A) taken on the evening of the 20th May 2006 (MVO photograph; copyright NERC) and in November 2006 (photographer RH) showing the extent of tephra deposition and its later partial removal from *e.g.* roofs. The vegetation damage in May was extreme and by November significant re-growth was evident. **C.** A small house towards the lower end of the Belham Valley (A on Fig.1A) on 12th June 2006 (photographer Tina Bretton). Notice particularly the >2 m boulders against the walls that were deposited in May 2006 and the extent of vegetation damage still evident on the far valley side. **D.** View upstream at D on Fig. 1A on 23rd May 2006, (photographer SL; copyright NERC) shows the extent of vegetation damage on the hills and the channel incision into the 20th May and older deposits. The house was well above the valley floor in 1995.

Fig 3. Diagram showing the relative timing of events on 19, 20th and 21st May 2006. **A.** Cumulative rain fall data with timing of dome collapse and principle periods of tephra fall. The rainfall line for GAR terminates mid graph as the rain gauge stopped registering data. **B**. Estimated discharge. Although the timing of discharge is fairly well constrained the timing of the peaks is not and the magnitude of the peaks are estimates only. The interference of the greater peak later in the event on 20th results from the volume of noise made by the flow and the timing of boulder mobilization in the lower valley. **C**. The ash fall and vegetation damage lines are both illustrative with relative rates assessed from our eyewitness reports, and discontinuous data. The vegetation damage line includes representation of widespread damage before the dome collapse, the rapid damage on the 20th and continuation of damage after that date.

Fig . 4. A comparison of rainfall data from different rain gauges for the three days in May 2006 and for six other days for which we have been able to calculate discharge estimates to demonstrate the variations. The locations of the Hope and Garibaldi (GAR) gauges are shown on Fig. 1A and the MVO North gauge is 2.5 km north of the catchment. Although both the peak intensity (indicated by line slope) and the total rainfalls were often greater than those recorded on the 20th May 2006, the estimated discharges are all smaller (written above rainfall lines). The discharge estimates (given on right of graph in $m^3 s^{-1}$) are very approximate based on interpretation of visual observations and interpretation of deposits. The 20th May 2006 Garibaldi line terminates as the gauge stopped working on that day. The Hope gauge (dashed lines) does not record intensities and the timings at this gauge are inaccurate but the data are included for comparison of totals.

Fig. 5. Photograph of the Belham valley floor above old bridge site, showing large boulders transported by the May 20th flood and the side of the narrower channel cut after that event.

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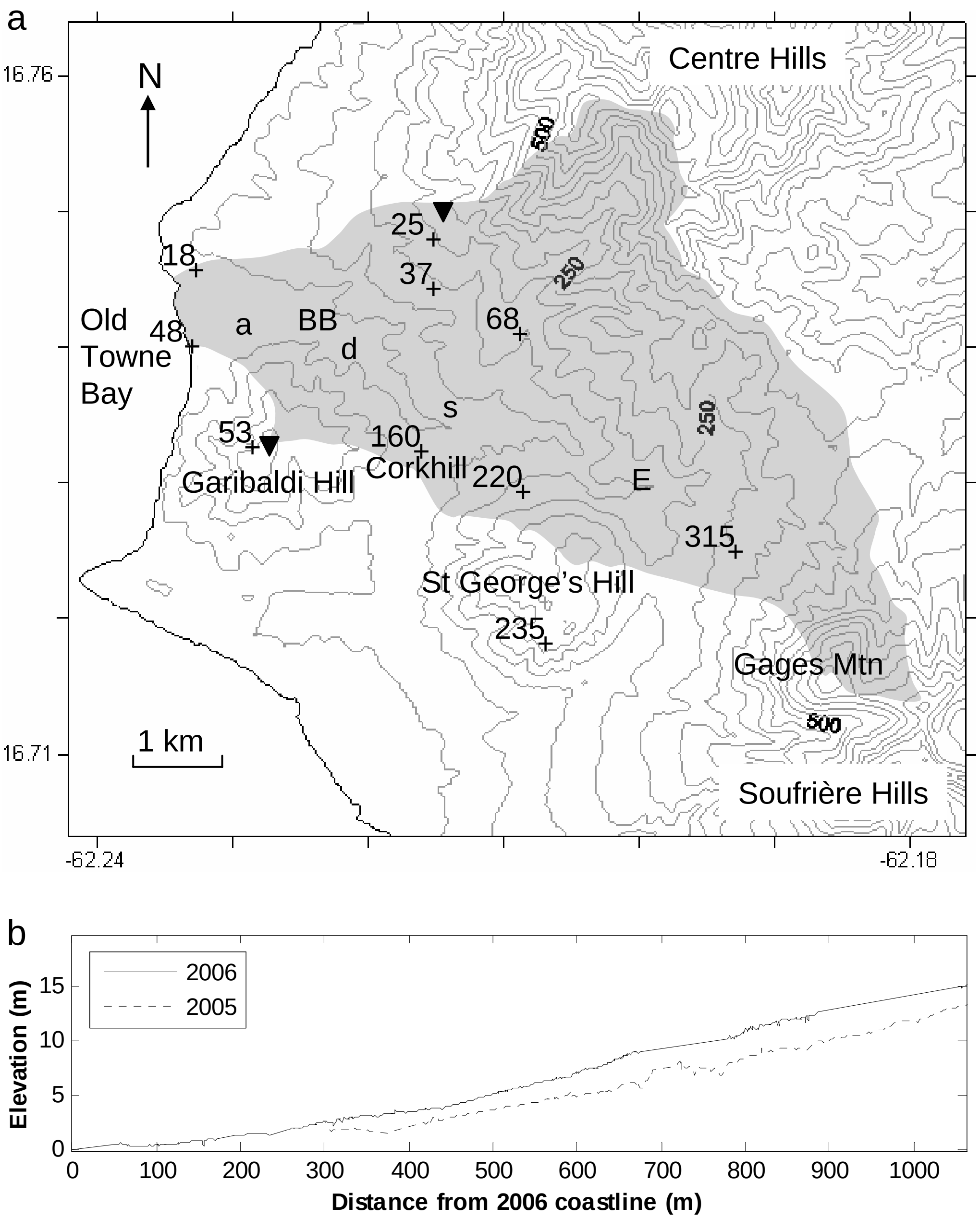
Figure 1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a
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s
53
160
Corkhill
Garibaldi Hill
220
E
315
St George's Hill
235
Gages Mtn
1 km
Soufrière Hills
b
2006
2005
Elevation (m)
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5
10
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Distance from 2006 coastline (m)

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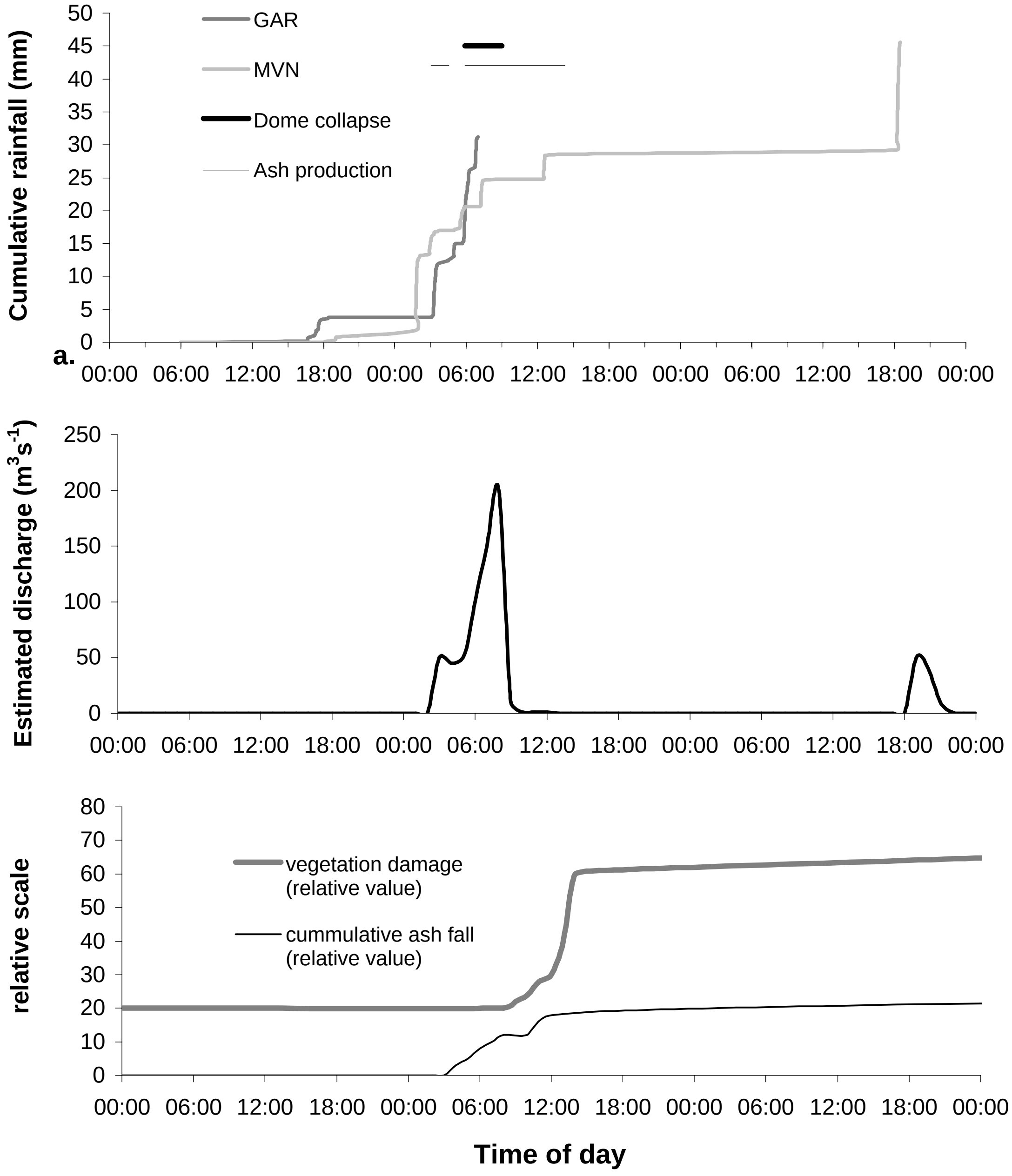
GAR
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Dome collapse
Ash production
Cumulative rainfall (mm)
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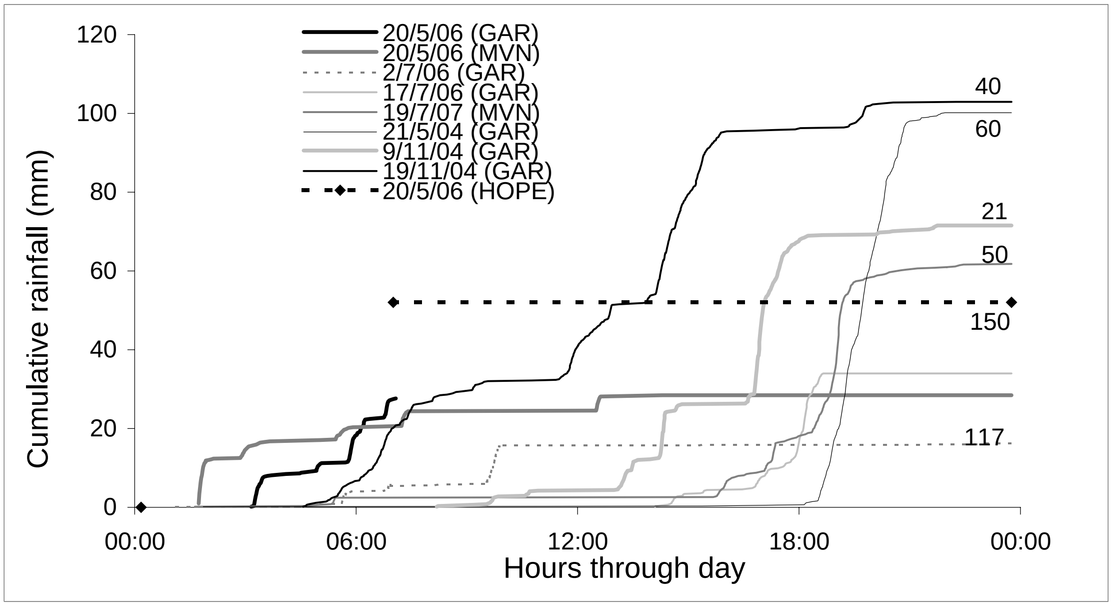
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18:00
00:00
Hours through day
20/5/06 (GAR)
20/5/06 (MVN)
2/7/06 (GAR)
17/7/06 (GAR)
19/7/07 (MVN)
21/5/04 (GAR)
9/11/04 (GAR)
19/11/04 (GAR)
20/5/06 (HOPE)
40
60
21
50
150
117

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Figure 5