

Temperature proxy data and their significance for the understanding of pyroclastic density currents

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ABSTRACT

A major dome collapse of the Soufrière Hills volcano, Montserrat, on 26 December 1997 generated a devastating pyroclastic density current that destroyed vegetation and left a distinctive tar-like deposit on the surface. The deposit included a range of charred, mainly herbaceous angiosperm, axes and roots. Studies of reflectance of these charcoaled plants indicated mean reflectances of 0.72–1.16 for the three samples with a maximum reflectance of 1.77 recorded for all readings. These data provide minimum temperatures of the flow of 300–425 °C, consistent with organic geochemical data obtained by ¹³C solid-state nuclear magnetic resonance and gas chromatography–mass spectrometry. These temperatures have been used to calculate characteristics of the pyroclastic density current. We estimate flow front current densities near the ground of 1.8–3 kg/m³, using constraints from a mean flow speed of 90 m/s estimated from seismic data. The mean temperature of the ash component is estimated as 400–610 °C.

Keywords: pyroclastic density current, temperature, Soufrière Hills, volcano, Montserrat, charcoal.

INTRODUCTION

The eruption of the Soufrière Hills Volcano on Montserrat began on 18 July 1995 (Robertson et al., 2000). From March 1996 dome collapse generated a series of pyroclastic flows and associated ash-cloud surges (Cole et al., 1998). Many of these flowed down the Tar River Valley on the eastern flank of the volcano (Fig. 1). These flows were originally confined to the river valleys and in some cases reached the sea, where the deposits built up deltas (Cole et al., 1998). Ash-cloud surges (low concentration upper parts of flows) jumped the valley sides and destroyed vegetation and buildings (Druitt and Kokelaar, 2002). A much more energetic pyroclastic density current was generated by a major collapse of a pressurized dome on 26 December (Boxing Day) 1997. The current devastated 10 km² on the southwest flanks of the volcano, flattening buildings and destroying the vegetation.

The Boxing Day current also left a distinctive tar-like deposit on the ground surface over much of the devastated area (Sparks et al., 2002, e.g., their Fig. 18b) (Fig. 2). The term “tar” as used in the original field descriptions is a general one describing a once viscous black liquid that was derived from the destructive distillation of organic matter. It is often used to describe several distinct substances (Morf et al., 2002) and here we use the term tar-like to imply that it is used to describe its overall field appearance

and behavior rather than its precise chemical composition (see the GSA Data Repository¹). Sparks et al. (2002, p. 423) stated “Surfaces in the area between Ginkgoes Ghaut and the White River are not only scoured but also blackened. On close inspection the black color was found to be a pervasive black tar about 1–4 mm thick (Fig. 18B). The tar does not occur beneath the debris avalanche deposit, making it clear that the debris avalanche had stopped moving here before the hot density current reached the lower slopes.” The vegetation was mainly herbaceous angiosperms, and of particular interest is the physical and chemical transformation of the plants by the pyroclastic density current. Temperature estimates of surge clouds, pyroclastic flows, and their deposits were determined for three separate events. Temperature patches from the Tar River Valley yielded 99–121 °C, 99–149 °C, and 200–250 °C for the temperature of ash cloud surges from dome collapse pyroclastic flows (Cole et al., 2002). Temperatures (n = 13) were measured in the range 48–293 °C in the Boxing Day deposits 4–13 days after the event (Sparks et al., 2002). All but one of the temperature measurements were too low to char plants (Scott, 2000), and it is unlikely

¹GSA Data Repository item 2008034, description of formation of tar-like deposits, and Table DR1 (charcoal reflectance data), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

that these temperatures would be sufficient to yield a tar-like layer (see footnote 1). Three samples of the layer were collected by one of us (Sparks) and by members of the Montserrat Volcano Observatory.

Plants are commonly found charcoaled in a range of volcanic deposits (Clarkson et al., 1988; Lockley and Rice, 1990), but they have rarely been studied petrographically or used to constrain the temperature of deposits. Fossil charcoal was first recognized from coal deposits (Scott, 2000). Coals are generally studied by reflectance microscopy of polished blocks under oil. Coal petrologists recognize fundamental particles called macerals (Scott and Glasspool, 2007) that include inertinites: these are now widely believed to represent fossil charcoal (Scott, 2000; Scott and Glasspool, 2007). Inertinites are identified not only by anatomical features but also their high reflectance, a characteristic of Recent charcoal (Scott 2000). Experimental work demonstrated that reflectance of the charcoal increased with temperature (Scott, 2000). Subsequent research indicated that reflectance also increased with time (Scott and Glasspool, 2005, 2007), but stabilized after 24 h, and that it could be used to interpret the temperatures of pyroclastic block and ash deposits (Scott and Glasspool, 2005). These authors demonstrated that even if the time concerned was very short, the reflectance could provide minimum temperatures of exposure. The main focus of this report is the charcoal and its use.

MATERIAL AND METHODS

For the locations of the samples, see Figure 1; MVO is Montserrat Volcano Observatory. Sample MVO342 is the bitumen layer, surface down to 1–2 mm, from the Galways estate (location: Montserrat, 79500 44500, northeast of Morris village, just below debris avalanche front). Sample MVO444 is the bitumen layer, surface down to 1–2 mm, from the Galways estate (Montserrat, MVO location [Loc.] 22 (broadband locality, to the left of the east on estate on the map, just to the right of Germans ghaut). Sample MVO662 is the bitumen layer, surface down to 1–2 mm, from the Galways estate (location:

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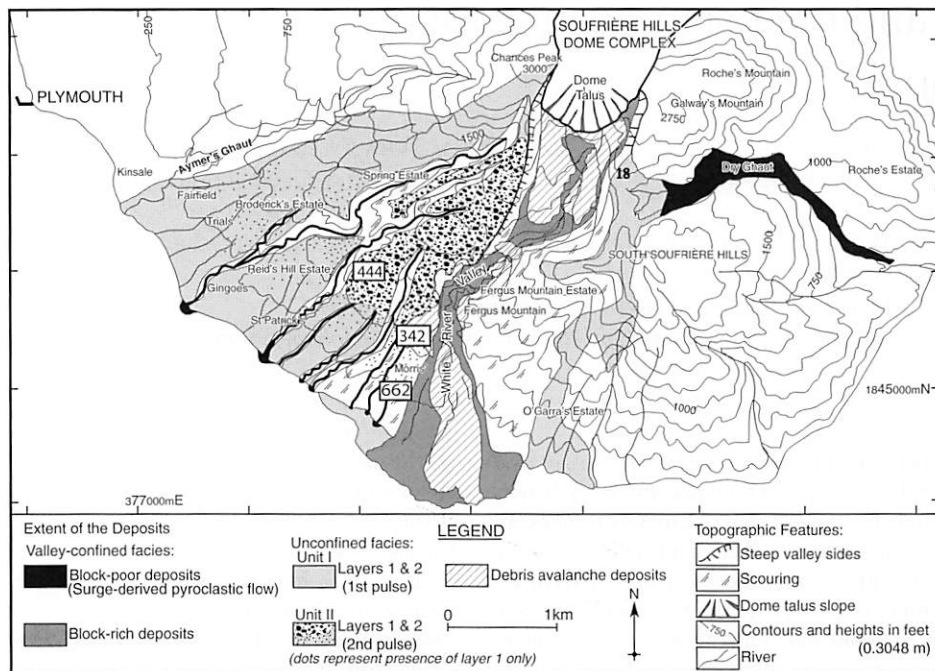


Figure 1. Map of Boxing Day flow showing position of samples.

79200 44000, near Morris village, Montserrat). The solid material (i.e., charcoal) was examined microscopically and the extractable organic materials (e.g., tar-like substances) were analyzed by organic geochemical methods.

Samples of each of the specimens were embedded in resin and wet-polished. There was no heating of the specimens that could affect the organic matter present. Polished blocks were examined using a Nikon microphot photomicroscope, fitted with a digital camera. Digital images were captured and processed using a Leica Qwin image analysis system. Reflectance was measured under oil of refractive index of 1.514, using a range of standards from silica glass (R_o 0.038) to silicon carbide (R_o 7.506), and a single wavelength of light (540 nm). Random reflectance (R_{ro}) was measured for 10 randomly selected points for each specimen in the sample and all data points from all specimens were used to obtain a mean value. Data for maximum, minimum, mean, and standard deviation were recorded for each block. Specimens were also photographed using a digital imaging system.

In addition, subsamples of all specimens were macerated in HF to release organic material and sieved at 180 μ m. Plant fragments from MVO662 were picked and embedded in resin and polished, and some specimens were mounted on stubs for scanning electron microscopy using a Hitachi S2400 scanning electron microscope.

Analysis of the organic matter in each sample was made using ^{13}C solid state nuclear magnetic resonance (NMR), and geochemical analy-

ses were also undertaken, including studies on lipids, carbohydrates, and lignin using gas chromatography–mass spectrometry (GC-MS); a detailed discussion of these findings will be published elsewhere.

RESULTS AND DISCUSSION OF TEMPERATURE

Reflectance

A full summary of the data obtained by reflectance microscopy under oil (R_o) is shown in Table DR1 (see footnote 1).

Sample MVO342 contained very small charred plants fragments, including rootlets. However, none of the material was taxonomically identifiable, although the presence of herbaceous angiosperm rootlets appears likely. Small charred rootlets yielded mean reflectance (R_o) values of 0.92 and 1.11. Small charred woody fragments yielded reflectance values of 1.28 and 1.34. The overall mean of reflectance for particles gives a value of 1.16, with a maximum mean for any particle being 1.34 and the maximum reading for any particle was 1.46.

Sample MVO444 contained the largest quantity of organic material and showed a mixture of uncharred and small charred axes. None were identifiable in reflected light. However, macerates of this sample yielded a diversity of uncharred plant and animal tissues, including angiosperm seeds and insect cuticle as well as abundant herbaceous angiosperm rootlets, some of which were charred. It is probable that this sample included plant material in the soil beneath the tar-like layer. Small plant fragments



Figure 2. Photo of tar-like layer from Galways Estate, Montserrat.

yielded mean reflectances of 0.86, 0.95, 1.07, 1.13, and 1.31. The maximum reading on any particle was 1.52 and the maximum mean value for a particle was 1.31. The overall mean for all particles was 0.97.

Sample MVO662 contained a large number of charred plants. It comprised predominantly herbaceous angiosperm axes and roots (Figs. 3B–3D) and some small wood fragments (Fig. 1A). Some of the roots showed variable reflectance in a single specimen, e.g., 0.13–0.93, indicating that the plant was not subjected to heat for any length of time. Other particles and rootlets yielded mean values of 0.29, 0.33, 0.49, 0.62, 0.85, 0.92, 1.11, 1.28, 1.34, 1.35, and 1.35, with a mean value of 0.72 and a maximum value from any particle of 1.77.

The reflectance values both within the individual specimens, within different specimens in the same sample, and between the samples, indicate that the charcoalification had not equilibrated with the temperature of the density current and was therefore subjected to the temperature possibly for only a few minutes, and certainly for less than an hour (see Scott and Glasspool, 2005). This is clearly the case in the very small rootlets. It is possible that the heat did not penetrate the soil to any extent, giving a temperature gradient. The mean of all data for all specimens was 0.86 R_o (Table DR1). Using the reflectance data from Scott and Glasspool (2005, 2007), this would yield a minimum temperature of 325 °C. In this case mean reflectance data may not be an appropriate measure of the temperature involved. However, using the maximum mean particle reflectivity, a consistent value of 1.31–1.35 is obtained. This yields a temperature of 375 °C. The maximum single value obtained was 1.77, yielding a temperature of 425 °C. These temperature estimates represent probable minimum temperature of the pyroclastic density current.

Scanning Electron Microscopy

Scanning electron microscopy shows that the plants are predominantly small herbaceous angiosperm axes and roots (Figs. 3C, 3D) that show both fibers (f) and vessels (v). The vessels

show a very distinctive pitting (p) in their walls. These roots have not been taxonomically identified. Cells show homogenization. The plants also retain their outermost epidermal layer (e). The preservation of the plants is typical of those that have been charcoaled (Scott, 2000). In particular the cell wall homogenization is distinctive of plants that have been subjected to temperatures >300–325 °C (Scott, 2000).

Organic Geochemistry

The information obtained reveals heat-mediated, destructive loss of the higher lipid homologues, combined with a concomitant release of lower molecular weight components from biomacromolecules at higher temperature. This tendency toward a selective decrease in chain length for free alkyl lipids has been observed previously (Almendros et al., 1988). In addition, the observed distributions of *n*-alkyl lipids were consistent with a mixed herbaceous angiosperm and soil origin for the organic matter in the tar-like layer. The ¹³C cross-polarization-magic angle spinning (CP/MAS) NMR data exhibit a predominant aromatic signal that maximizes at 128 ppm and is indicative of naturally charred materials (Simpson and Hatcher, 2004). These data indicate that samples were subjected to temperatures >300 °C, consistent with the reflectance data.

IMPLICATIONS FOR INTERPRETATION OF THE PYROCLASTIC DENSITY CURRENT

The organic geochemistry on the tar-like layer constrains the temperature of the mixture of the leading edge of the first pyroclastic density current to be at >300 °C, while the data on the charred plants indicate a temperature range of 325–425 °C.

Here we use these estimates to place constraints on the properties of the current. The locations of tar-like samples are close to the pathway of maximum destruction (Sparks et al., 2002). Destruction of the seismometer at St. Patrick's village gives an approximate estimate of 90 m/s for the speed for the flow front (Sparks et al., 2002). Here we consider the current as a turbulent gravity current driven by the density difference between ambient air and the mixture of hot volcanic particles and entrained air. In such currents the flow front is a region fed from the body of the flow. Entrainment of air at the front and through the upper surface of the current results in cooling of the interior of the flow and stratification of the current in temperature and particle concentration. We surmise here that the pyrolysis of the vegetation was nearly instantaneous as it was engulfed by the flow front, and thus our temperature estimates relate to the frontal flow. The highly turbulent and stratified character of such currents means that the properties of the flow front will vary considerably on a local scale and with height.

The temperature of the mixture, T_m , is related to the temperatures of the end-member components of the mixture, namely ambient air, T_a , at ~25 °C and the solid volcanic particles, T_p , through a heat balance:

$$(1-x)S_a(T_m - T_a) = xS_p(\epsilon T_p - T_m), \quad (1)$$

where x is the mass fraction of solid particles in the mixture, S_a is the heat capacity of air at constant pressure (~1020 J kg⁻¹ K⁻¹), S_p is the heat capacity of the solid particles (~790 J kg⁻¹ K⁻¹), and ϵ is an efficiency factor for heat transfer and is a measure of thermal disequilibria. Our data indicate that T_m is between 300 and 425 °C. The T_p ($T_p > T_m$) is unknown, but has an

upper limit of the magma temperature, which is ~850 °C (Murphy et al., 2000). The pyroclastic density current (PDC) was formed by the explosive disintegration of a dome that had been growing over several months, and so the fragmenting material would have included cooled regions of the dome and rock-fall talus. In addition, the PDC picked up cooled lithic clasts from the ground before reaching the site of the tar-like samples. The short time scale of flow means that only small particles will have exchanged all their heat with entrained air. The approximate size threshold is given by $\sim(\kappa\tau)^{1/2}$, where κ is the thermal diffusivity of ash ($\sim 4 \times 10^{-7}$ m² s⁻¹) and τ is time (~90 s); thus particles above ~0.6 cm will not have liberated all their heat. Because the deposits contain significant amounts of coarse clasts (Ritchie et al., 2002), the value of $\epsilon < 1.0$, but ϵ must have a value sufficiently large to provide enough heat to generate temperatures in the 300–425 °C range. A key constraint is that the mixture density cannot be less than the ambient air density or else a density current is not possible, and a buoyant plume forms instead. The current density must be significantly higher than the ambient air to provide enough negative buoyancy to drive the current at ~90 m/s.

We have used equation 1 to calculate the mass fraction x as a function of the solid particle temperature, T_p , and for mixture temperatures of 300 and 400 °C. We then calculated the mixture density as a function of T_p , assuming $\epsilon = 1$, which for the moment ignores the thermal disequilibrium problem. The mixture density, ρ_m , is approximated for dilute mixtures as $\rho_m \sim \rho_a/(1-x)$. We take the density of cold ambient air, ρ_a , to be 1.25 kg/m³ and use the ideal gas law to calculate the air density at the mixture temperature. The results (Fig. 4) show

Figure 3. Charcoaled plants from the tar-like layer MVO622, Galways Estate, Montserrat. **A:** Reflected light micrograph of woody tissue. High reflectance indicates charring. **B:** Reflected light micrograph of herbaceous rootlet. High reflectance indicates charring. **C:** Scanning electron micrograph of charred herbaceous angiosperm rootlet showing excellent three-dimensional anatomical preservation; e—epidermis. **D:** Detail of C; v—vessel, f—fiber, p—pitting in vessel wall.

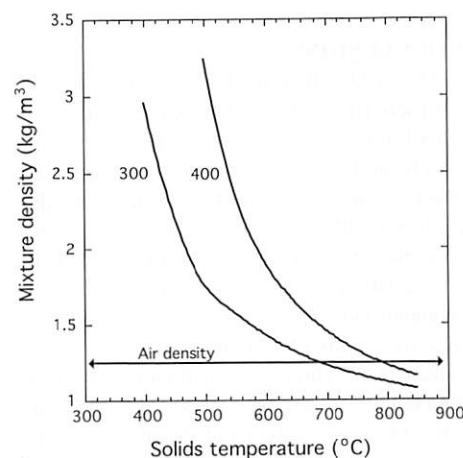
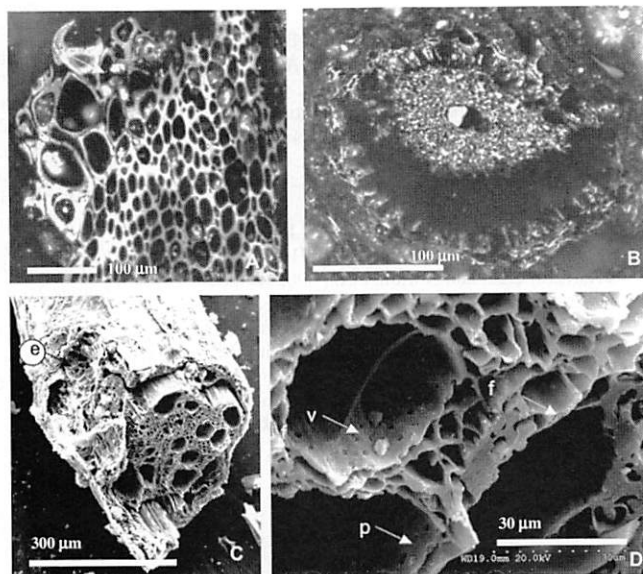


Figure 4. Flow density plotted against ash temperature in the mixture for mixture temperatures of 300 and 400 °C. Density of ambient cold air is shown as horizontal line for density of 1.25 kg/m³. Density of the current must be greater than the air density.

that if T_p is above a value of 684 °C for $T_m = 300$ °C and a value of 785 °C for $T_m = 400$ °C, then a density current could not exist. The actual mixture temperature must be even lower to make the current denser than the ambient air. We calculate the mass fraction of ash to be >0.47 and 0.55 at mixture temperatures of 300 °C and 400 °C, respectively. These values are equivalent to volumetric fractions of solid particles in the current suspension of >2.6 and 3.0×10^{-4} , assuming that the slightly vesicular and partly glassy solid particles (Ritchie et al., 2002) have a typical density of 2300 kg/m³.

The relationship between frontal velocity, v_f , current thickness, h , and density contrast with the ambient, $\Delta\rho$, is approximated by (Simpson, 1987):

$$v_f = \text{Fr}(\Delta\rho gh/\rho_a)^{1/2}, \quad (2)$$

where Fr is the Froude number. Fr is usually calculated as $\sqrt{2}$, but can be as large as 2.6 for dense non-Boussinesq fluids. Here we assume that the density differences are small enough to justify a value of Fr = 1.4. Current thickness is constrained by the distribution of deposits and damage zones at the margins of the main axis of flow (Sparks et al., 2002) such that $h < 1000$ m but $h > 300$ m. For a current of 90 m/s, Fr = 1.4, and $300 \text{ m} < h < 1000$ m, the current density is calculated in the range 1.8–3 kg/m³. In this density range the inferred temperature of the solid particle component from Figure 4 is inferred to be 400–610 °C, which is lower than the magma temperature (~850 °C). The estimated range of lower temperature for the solid particles is interpreted as the combination of thermal disequilibrium due to a component of large clasts, involvement of cooled parts of the dome in the source explosion, and entrainment of cold clasts by the flow.

CONCLUSIONS

The 1997 Boxing Day collapse of the Soufrière Hills Volcano, Montserrat, generated a pyroclastic density current that had devastating effects on the southwest flanks of the volcano. The hot ash cloud charred plants and left a distinctive tar-like layer comprising residues and condensed volatiles derived from the pyrolysis of vegetation and soil. Reflectance data on the charcoals indicate a reflectance range from 0.72 to 1.16 (means of samples) with a maximum value of 1.77. This equates to minimum charring temperatures in the range of 340–425 °C. Scanning electron microscopy of charred herbaceous angiosperms shows homogenization of cell

walls, indicating temperatures of >300 °C, and a range of organic analyses, including ¹³C solid-state NMR and GC/MS, supports temperatures >300 °C and up to 425 °C. These temperature data have been used to constrain properties of the frontal region of the pyroclastic density current. Flow densities are in the range 1.8–3 kg/m³. The solid particle component is estimated to be in the temperature range 400–610 °C. Temperatures lower than magmatic (~850 °C) are ascribed to a combination of thermal disequilibrium in the flow and the involvement of previously cooled ash and lithics in the current.

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