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A thermodynamical model for rainfall-triggered volcanic dome collapse

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[1] Dome-forming volcanic eruptions typically involve the slow extrusion of viscous lava onto a steep-sided volcano punctuated by collapse and the generation of hazardous pyroclastic flows. We show an unequivocal link between the onset of intense rainfall and lava dome collapse on short time scales (within a few hours) and develop a simple thermodynamical model to explain this behavior. The model is forced with rainfall observations from the Soufrière Hills Volcano, Montserrat, and suggests that when the dome is in a critical state, a minimum rainfall rate of approximately 15 mm hr^{-1} for 2–3 hr could trigge a dome collapse. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 3230 Mathematical Geophysics: Numerical solutions; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280). **Citation:** Matthews, A. J., and J. Barclay (2004), A thermodynamical model for rainfall-triggered volcanic dome collapse, *Geophys. Res. Lett.*, *31*, L05614, doi:10.1029/2003GL019310.

1. Introduction

[2] Although volcanic dome collapse and pyroclastic flows represent a significant hazard, the mechanisms behind them are poorly understood [*Calder et al.*, 2002]. Dome collapse is influenced by many variables, such as oversteepening and build up of gas, and a link between rainfall and volcanic activity has also been observed. The interaction between magma and pre-existing groundwater and surface water will usually result in the generation of steam-driven explosive activity. This phreatic or phreatomagmatic activity is well documented [*Sigurdsson*, 2000], but the more subtle relationship between intense rainfall and pre-existing hot dome material has been less clear. The coincidence of heightened volcanic (usually pyroclastic flow or explosive) activity during dome-forming eruptions with intense rainfall has been discussed on several volcanoes, e.g., Merapi [*Simmons et al.*, 2004], and Soufrière Hills Volcano (SHV), Montserrat [*Matthews et al.*, 2002; *Carn et al.*, 2004]. A statistically significant relationship has been established at Mount St. Helens [*Mastin*, 1994] for small gas-driven explosions, where volcanic activity followed rainfall by up to a few days.

2. Rainfall and Dome Collapses on Montserrat

[3] We use data from our network of tipping bucket rain gages on the SHV [*Matthews et al.*, 2002] to constrain the timings between the onset of intense rainfall episodes and the beginning of heightened activity on an extraordinarily well documented volcano [e.g., *Druitt and Kokelaar*, 2002]. In particular, recent dome collapses of the SHV on 3 July 1998, 20 March 2000 [*Carn et al.*, 2004], 29 July 2001 [*Matthews et al.*, 2002], and 14 October 2001 have all been associated with intense rainfall in the hours prior to the collapse. More generally, and including rainfall data collected by the UK Department for International Development, in the 1530-day period from 1 January 1999 to 7 February 2003, there were 46 non-contiguous days (3% of the total) on which pyroclastic flow activity was recorded (compiled from activity reports at the Montserrat Volcano Observatory http://www.mvo.ms/). However, 9 of these 46 days were heavy rainfall days, defined as a day on which more than 20 mm of rain was recorded at at least one rain gage. There were 76 heavy rain days in total. Hence, the conditional probability of observing a pyroclastic flow, given that it is a heavy rainfall day, increases by a factor of four to 12%. Therefore, there is a statistically significant (at the 99.5% level) enhancement of the probability of volcanic activity on a heavy rainfall day. If other factors were taken into account such as the stability of the dome, the strength of this link would almost certainly increase.

3. Thermodynamical Model

3.1. Physical Basis

[4] Here we present a physically based thermodynamical model that links episodes of heavy rainfall to dome collapse, and will enable predictions of dome collapse based on rainfall observations. Our observations show an interval of typically 2–5 hours between the onset of intense rainfall and volcanic activity, when it occurs. The existence of this time delay suggests a step during which rainfall interacts with the hot dome and critically destabilizes it by perturbing its thermal structure. Continued high rates of rainfall are then sufficient to allow rain water to percolate into deep fissures where a phase change to steam in a semi-enclosed volume is sufficient to shatter the carapace and trigger the collapse of an already unstable dome (Figure 1). This mechanism appears to be relevant to Merapi, where blocks on the dome flanks have been observed to be dislodged by pressure from expanding steam during intense rainfall [*Mastin*, 1994]. *Simmons et al.* [2004] provide a more

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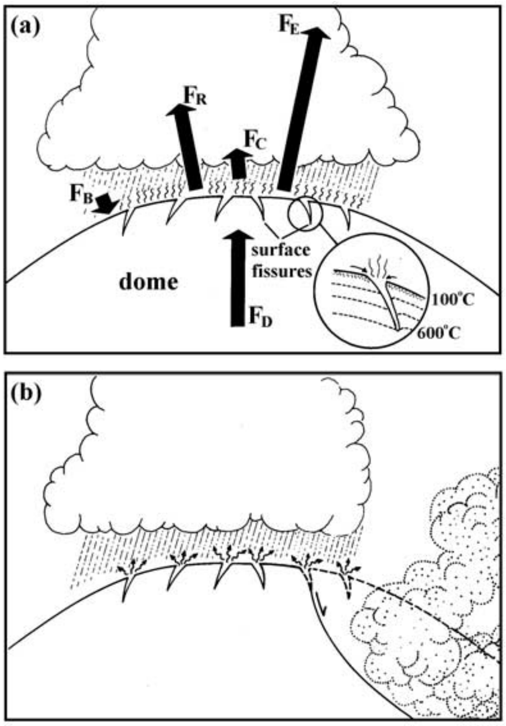

Figure 1. Schematic diagram of the thermodynamical model. (a) Fluxes of energy within and at the surface of the hot dome; diffusive heat flux F_D, surface radiative cooling F_R, convective heat flux F_C, background surface radiative warming F_B, surface latent heat flux F_E. The inset shows the detailed temperature structure at a surface fissure, and the accumulation of liquid water at the surface and percolation into surface fissures, once the surface has cooled to 100°C. (b) Vapourisation of water within the fissures into high-pressure steam, leading to dome collapse and pyroclastic flows.

comprehensive analysis of the failure process relevant to this situation.

[5] Our hypothesis is that the generation of steam and destabilization of the dome requires two sequential processes: (i) cooling of the dome surface to 100°C by the vaporization of rainwater and (ii) percolation of sufficient rain water into the dome where it vaporizes and generates sufficient pressure to shatter the cooled carapace. The temperature increases rapidly with depth and we envisage rapid vaporization of water that has percolated below the surface. The resulting steam is not then free to expand as it is impeded by liquid water in the cooler upper layer, hence the steam generates high pressures. We use a one-dimensional model of the energy fluxes through the dome and at the surface, before and during periods of intense rainfall (Figure 1a). Energy (in the form of heat) diffuses upward from the interior of the dome (F_D) and is radiated (F_R) and convected (F_C) away at the surface. This is partially offset by a background net downward flux of radiation from the atmosphere (F_B). At the onset of precipitation the evaporation of rainwater on contact with the hot surface of the dome generates a latent heat flux (F_E). The temperature tendency of the dome is calculated from the total flux divergence. With suitable initial conditions and an imposed rainfall rate, the time taken (τ_1) for the dome surface to cool to 100°C is predicted.

[6] Once this stage has been reached, subsequent rainfall is allowed to accumulate as an equivalent depth of liquid water at the surface. At each time step, a fraction of this liquid "reservoir" is evaporated to offset the diffusion of heat from below and to keep the surface temperature from exceeding 100°C. No allowance is made for rainfall runoff, which we assume to be small. Dome collapse occurs after a further time interval (τ_2), when enough liquid water has accumulated to allow percolation into surface fissures. From the ideal gas law, an instantaneous vaporization within the semi-enclosed fissures, with no change of volume, will generate pressures of up to 400 MPa, far in excess of the estimated cohesion strength of the dome rock of 1 MPa. In actuality, the vaporization process will not be instantaneous, and so the pressure generated will be less than this. However, we suggest that sufficient pressure will be generated within the carapace to destabilize the dome, initiating collapse and the generation of pyroclastic flows (Figure 1b). In predicting dome collapse it is thus the initial thermal state of the dome and the duration and intensity of the rainfall that is of critical importance.

[7] In this simple model, we neglect the advective heat flux due to degassing along fissures. This would help to both increase the temperature within the fissures, promoting the vaporization of liquid water and the generation of high pressures, and also generate high pressures directly as the upward flux of volcanic gases would be partially blocked by the liquid water in the carapace.

3.2. Model Formulation

[8] In the dome interior the vertical flux of energy can be represented as a diffusive heat flux $F_D = kdT/dz$, where $k = 2.6$ W m^{-1} K^{-1} is the thermal conductivity of the andesitic dome rock [*Spera*, 2000], T is its temperature and z is the vertical coordinate (positive upward). At the surface ($z = 0$) there are additional energy fluxes. The upward radiative flux (of infra-red radiation) is $F_R = \epsilon\sigma T_s^4$, where $\epsilon = 0.98$ is the thermal emissivity of the dome rock, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant, and T_s is the surface temperature of the dome (in Kelvin). The upward flux of heat due to convection is modeled by $F_C = C_H c_p \rho_a u(T_s - T_a)$, where $C_H = 1.1 \times 10^{-3}$ is the exchange coefficient, $c_p = 1004$ J kg^{-1} K^{-1} is the specific heat capacity at constant pressure of air, $u = 5$ m s^{-1} is the estimated surface wind speed, $T_a = 25$°C is the ambient air temperature, and ρ_a is the density of air, calculated using an average temperature $\overline{T} = (T_s + T_a)/2$ and the ideal gas law $p = \rho_a R\overline{T}$, where $p = 9.5 \times 10^4$ Pa is atmospheric pressure and $R = 287$ J kg^{-1} K^{-1} is the specific gas constant for air. The exact dependency of the convective heat flux on temperature and other parameters is open to debate [*Kesthelyi and Denlinger*, 1996], but the results and conclusions for this model are not sensitive to this. The magnitude of the convective heat flux is typically 30–40% that of the radiative heat flux. There is also a background downward flux of solar and infra-red radiation which was set to $F_B = -440$ W m^{-2}. During initial periods of rainfall, rain water evaporates on contact with the hot surface of the dome, generating a latent heat flux $F_E = \rho_w r(L + \Delta\, T_{rain} c_w)$, where $\rho_w = 1000$ kg m^{-3} is the density of water, r is the rainfall rate in m s^{-1}, $L = 2.5 \times 10^6$ J kg^{-1} is the latent heat of vaporization of water, $\Delta T_{rain} = 75$°C (assuming an initial temperature for the rain

water of 25°C and a boiling point of 100°C), and c_w = 4200 J kg^{-1} K^{-1} is the specific heat capacity of water.

[9] The temperature tendency of the dome is calculated from the total flux divergence $dT/dt = (1/\rho_r c_r)dF/dz$, where $\rho_r = 2600$ kg m^{-3} and $c_r = 1000$ J kg^{-1} K^{-1} are the density and specific heat capacity [*Couch et al.*, 2001] of the dome rock, respectively, and $F = F_D + F_R + F_C + F_B + F_E$. In the interior, this reduces to the diffusion equation $dT/dt = \kappa d^2T/dz^2$, where $\kappa = k/(\rho_r c_r) = 1.0 \times 10^{-6}$ m^2 s^{-1} is the thermal diffusivity of the dome rock. The model is discretised into levels of thickness $\Delta z = 0.02$ m, and solved by finite differences with a time step of $\Delta t = 60$ s.

3.3. Initial Conditions

[10] The model is applied to the SHV. The initial conditions for the model should be consistent with observations and other models of dome evolution. On the SHV, fresh dome rock is continuously extruded at varying rates and there is a flux of heat from below. It is therefore critical that our model provides a realistic approximation to an instantaneous dome temperature profile. There are few reported observational data that relate to the thermal structure of lava domes. Surface temperatures near 200°C have been measured by infra-red remote sensing techniques at Lascar [*Oppenheimer et al.*, 1993]. *Dzurisin et al.* [1990] used observations of changes in the dome's magnetic anomaly to infer changes in the thermal structure of the Mount St. Helens dome during periods of stagnation. This showed that even with no further thermal input the dome isotherms moved downwards at a rate of only 0.01–0.03 m day^{-1}. Theoretical models of the SHV have shown that magma ascent is essentially isothermal to the base of the dome with usually 5–15 wt% melt remaining during periods of slow dome growth [*Melnik and Sparks*, 1999]. Magma temperatures at depth [*Barclay et al.*, 1998] are of the order of 830°C and visual observations of incandescence following the removal of a meter or so of material from the surface suggest subsurface temperatures above 650°C [*Watts et al.*, 2002; *Sparks et al.*, 2000]. Hence a reasonable temperature profile should approach these observed conditions.

[11] Therefore, the temperature evolution of our model was examined in a control run with zero imposed rainfall to generate realistic initial conditions to use in the experiments with rainfall. The dome temperature was initially set to a uniform 830°C. A zero flux boundary condition was imposed at the base of the model which was set sufficiently deep to remain unaffected by surface cooling during the model integration. The large radiative (F_R) and convective (F_C) heat fluxes cooled the surface rapidly to 300°C in 5.5 hours (Figure 2a). After this stage cooling slowed and individual isotherms penetrated down into the dome at a rate consistent with the observations of *Dzurisin et al.* [1990] for Mount St. Helens. However, as the model does not include the loss and addition of material, it eventually becomes inconsistent with observations of active domes as after 15 days the surface cooled to 100°C. The model thus most closely resembles reality at the point at which the surface fluxes are no longer rapidly changing and the radiative flux has become a similar order of magnitude to the other fluxes. This situation corresponds to around t = 1 day in the model and represents a reasonable instantaneous profile for steady dome growth with the loss of some material through rockfalls offset by the emplacement of new hotter material at the base. At this stage our model has a surface temperature of 215°C and a temperature of 650°C at a depth of 0.4 m (Figure 2b), broadly consistent with observations. The actual surface and interior temperature distribution of lava domes will inevitably be more heterogeneous due to the presence of surface cracking (inset in Figure 1a) and the movements of high temperature fumarolic gases [*Dzurisin et al.*, 1990] but this represents a reasonable approximation to average conditions.

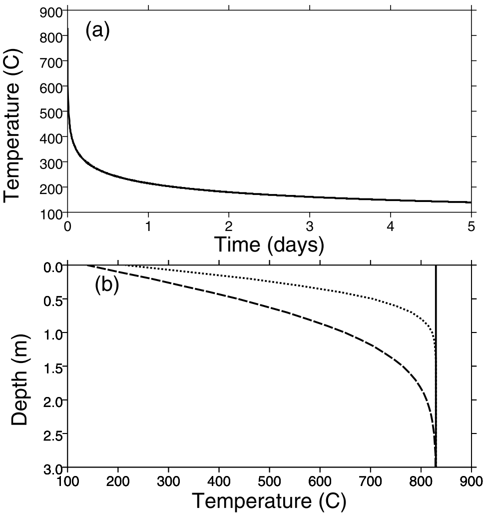

Figure 2. Model results during the control integration with no imposed rainfall. (a) Surface temperature, (b) temperature profiles at t = 0 (solid line), 1 (dotted line), 5 (dashed line) days.

3.4. Prediction of Dome Collapse

[12] The occurrence of a dome collapse or otherwise was predicted by the model by forcing it with observed rainfall from selected days, using data from our network of one-minute temporal resolution rain gages installed on and around the SHV. On 29 July 2001, a major (4.5×10^7 m^3) dome collapse occurred within hours of the onset of intense rainfall, with the daily rainfall total (85 mm) the highest since the end of the wet season 7 months before [*Matthews et al.*, 2002]. The model was initialized at 0000 local time on 29 July 2001 with the control run temperature profile described above and forced with the observed rainfall from the gage at the Montserrat Volcano Observatory, which was representative of conditions over the whole island for that day, and for the other days selected below.

[13] Early rainfall (0220–0250) cooled the surface to 130°C but surface temperatures recovered as heat diffused up from below after the rainfall ceased (Figure 3a). Several more periods of rainfall followed, each with evaporative cooling and then diffusive warming in between. At 0600 the surface temperature did cool to 100°C and liquid water began to accumulate. However, the rain stopped shortly after and the 8 mm equivalent of liquid water was quickly evaporated. At 1711 a prolonged period of intense rainfall began with 37 mm of rain falling in 2.6 hr. The surface reached 100°C by 1715 and 25 mm equivalent of liquid water had accumulated by 1815. Pyroclastic flows followed shortly after, culminating in the dome collapse at 1950, by

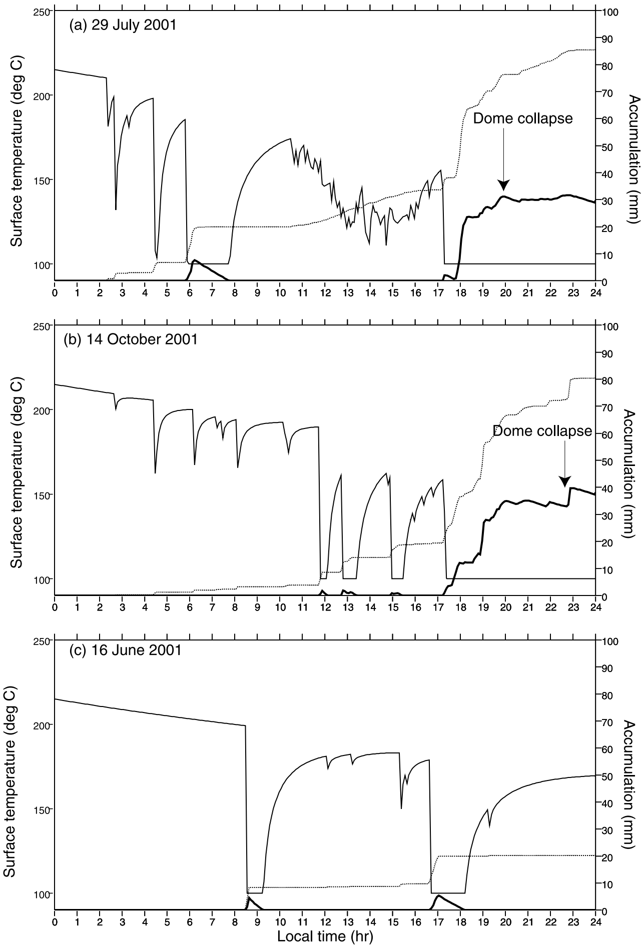

Figure 3. Surface temperature (solid line), cumulative rainfall (dotted line) and accumulated equivalent liquid water (thick line) for case studies on (a) 29 July 2001, (b) 14 October 2001, (c) 16 June 2001. The timings of dome collapse are indicated in (a) and (b).

which time 30 mm equivalent of liquid water had accumulated. In this instance τ_2 was 2.7 hours with an average rainfall rate of 14 mm hr^{-1}.

[14] The next dome collapse was on 14 October 2001. Once again, there were several intense but short-lived bursts of rainfall throughout the day, where the dome surface temperature cooled rapidly, but then partially recovered (Figure 3b). Prolonged intense rainfall began at 1716 and the surface cooled to 100°C a few minutes later. By 2000, 35 mm equivalent of liquid water had accumulated, which then remained approximately constant even though the rainfall was near to continuous, as most of the extra rainfall was evaporated to offset the diffusion of heat from below. Pyroclastic flow activity began shortly after this period of rainfall started, and the dome collapse peaked at 2245, 4.5 hr after the intense rainfall started.

[15] Finally, the model was forced with the observed rainfall from 16 June 2001. This was the only day in the 7 months preceding the 29 July 2001 collapse with a daily rainfall total above 20 mm. The dome was in a similar morphological state to 29 July at this time, and primed for collapse. Although 20 mm of rain fell in two intense bursts and the surface did cool to 100°C in the model, a maximum of only 5 mm equivalent of liquid water accumulated, which was quickly evaporated when the rain stopped (Figure 3c). This did not appear to be enough to trigger the collapse.

4. Conclusions

[16] These results and those from other SHV case studies suggest that a modeled accumulation of 20–30 mm equivalent of liquid water on the dome carapace is required to trigger a significant collapse by this mechanism, although it by no means guarantees a collapse as 88% of the observed heavy rain days did not have associated volcanic activity. Together with the results of idealized experiments using constant rainfall rates, this implies that a sustained rainfall rate of approximately 15 mm hr^{-1} is needed for 2–3 hr.

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