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Instability and collapse of hazardous gas-pressurized lava domes

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Abstract. An important type of gravitational lava-dome failure involves significant internal gas overpressure that influences the failure process. For the first time, this paper presents a rigorous analysis of the mechanics of gas-pressurized dome failure. We develop diffusion models to calculate gas overpressures in a lava dome, and embed these pressure data into stability analyses to demonstrate how gas pressurization can initiate instability. The results bear on the mechanistic understanding of hazardous dome failures. Gas pressurization can promote deep-seated failure, and the timing of conduit pressurization can control the timing of dome collapse. Theory explains why dome collapse can be delayed for cases of oscillating effusion. Dome collapses and explosive events linked to collapse of lava domes can be hazardous. Monitoring criteria are considered to anticipate whether or not such collapses are likely to be explosive.

1. Introduction

Explosive eruptions of the Soufriere Hills volcano, Montserrat, B.W.I., directly followed major collapses of the lava dome on September 17 1996, and June 25, August 3, and September 21 1997 [*Robertson et al., 1998; Cole et al., 1998; Young et al., 1998*], indicating the presence of volatile-rich magma high in the conduit and suggesting a possible role of gas pressurization in dome instability. Tilt deformation of the edifice prior to several events confirmed shallow pressurization and indicated a coincidence of collapse with the timing of peak pressurization [*Voight et al., 1998a*]. These instances, and a number of analogous cases elsewhere [*Newhall and Melson, 1987; Sato et al., 1992; Miller, 1994; Voight et al., 1998b; Elsworth and Voight, 1995; Voight and Elsworth, 1997*], imply two types of gravitational lava dome failure - one with little or no gas overpressure, and the other with significant gas overpressure that influences the failure process [*Newhall and Voight, 1997*]. A rigorous analysis of the forces acting within gas-pressurized lava domes has not been treated previously. This paper develops diffusion models to calculate the distribution of gas overpressures in an idealized lava dome, embeds these overpressures into stability analyses, and demonstrates that gas pressurization can promote deep-seated instability. The section on theory concludes with consideration of the delayed timing of dome failure in relation to the onset of gas pressurization. A section follows on the application of the theory to the dome collapses on Montserrat. The paper concludes with a discussion on the relation of deep-seated collapse of gas-pressurized domes to the spontaneous explosive disintegration of the dome interior. Monitoring indicators of gas-pressurization as related to instability and explosivity potential are discussed.

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2. Theoretical Analyses

2.1. Failure Geometry and Stability Relations

We consider first the idealized case of a hemispherical lava dome of radius $b = 200\,m$ resting above a pressurized conduit (Fig. 1). To aid the mathematical development, the connection between dome and conduit is represented as a hemispherical cavity of radius $a = 15\,m$. The treatment is intended to be general, although the geometry and other data have been selected with a view to approximate the conditions at the Soufriere Hills volcano in Montserrat. We assume a gas pressure P_i within the cavity of 5 to 12 *MPa*, nominal values consistent with shallow high pressures indicated by ballistic blocks scattered in vent-opening explosions at the Soufriere Hills volcano, and with edifice tilt [*Robertson et al., 1998; Voight et al., 1998a*]. In modeling gas overpressure as a function of position and time, we consider both steady-flow and transient solutions for the constant pressure boundary condition, and also cases of sinusoidal pressure variation [*Carslaw and Jaeger, 1959*].

Gas pressure diffusion within the dome is controlled by the diffusion equation, $\kappa \nabla^2 \cdot p = \partial p / \partial t$, where p is the gas overpressure and κ is the gas or fluid diffusivity [*Carslaw and Jaeger, 1959*]. Steady behavior is controlled by the dome geometry, and transient behavior is additionally modulated by

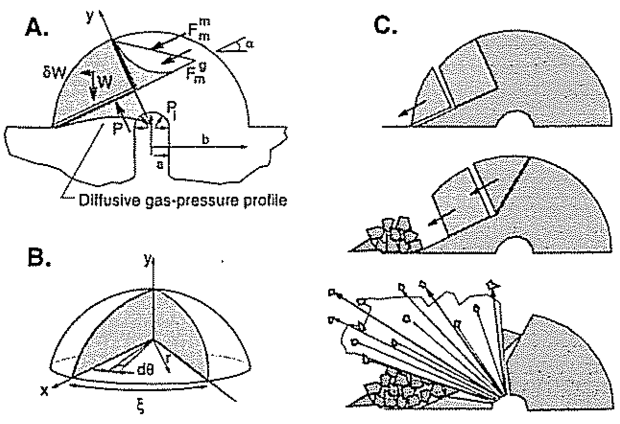
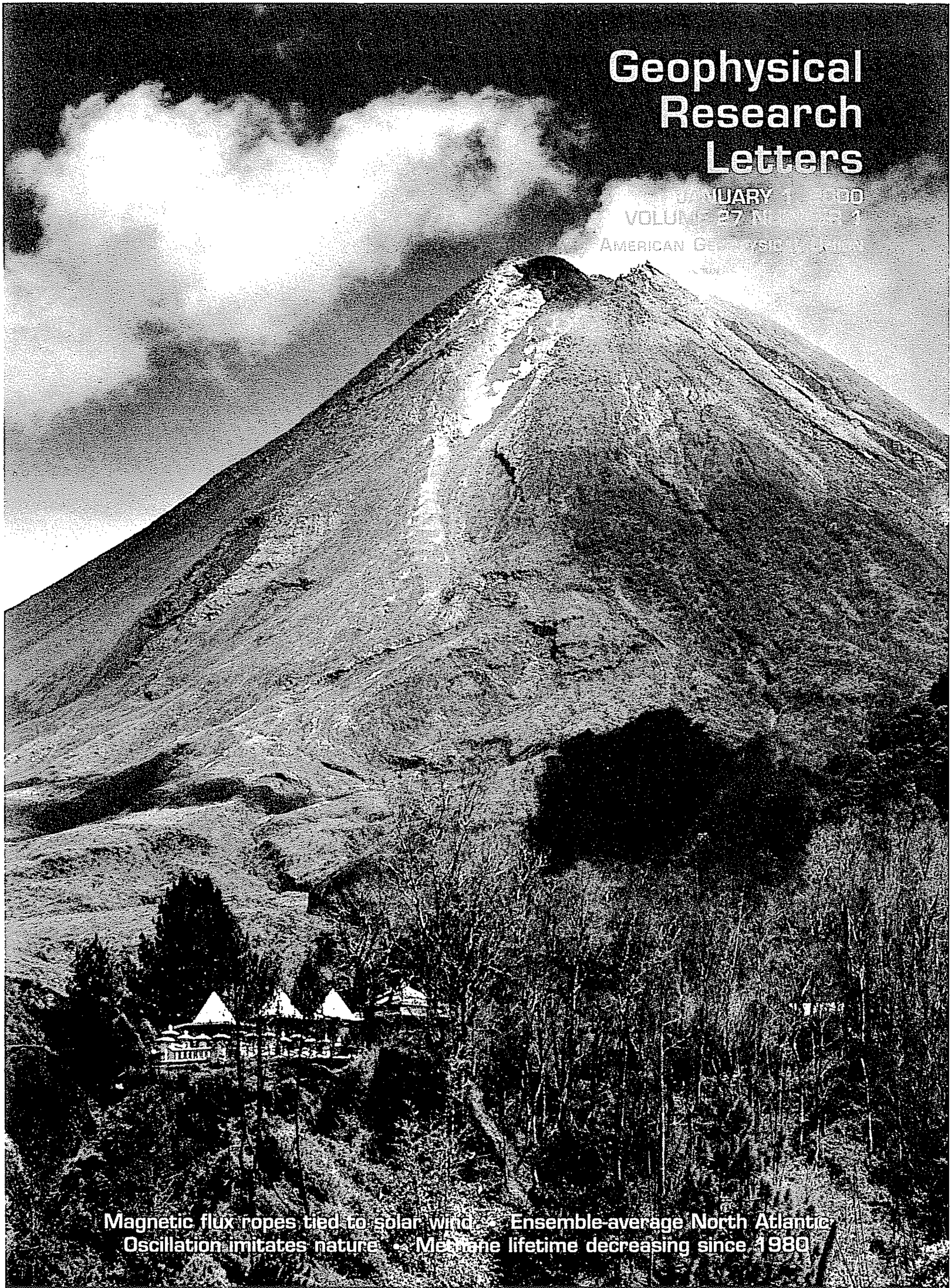


Fig. 1. Schematic views of dome collapse. (A). Section through a dome of external radius, b, subject to gas pressure, P_i, in a cavity of radius, a. The diffusive gas pressure acts on the boundaries of a failing block of weight, W. This block rests on a plane, inclined at angle, α, and is acted upon by uplift force, P, and downslope forces (F^* in text) representing gas pressures (F_m^g) or magmastatic pressures (F_m^m) acting on the block rear. (B). The three-dimensional geometry is defined by the sector angle, ξ. (C). Failure initiates with release of a toe-block, with failure retrogressing to unload the pressurized core, resulting in the potential for spontaneous disintegration or a directed explosion.



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Magnetic flux ropes tied to solar wind • Ensemble-average North Atlantic Oscillation imitates nature • Methane lifetime decreasing since 1980 the diffusion coefficient, κ. The solution of this equation determines the gas pressures acting on a potentially unstable block (Fig. 1A). Forces on any selected block surface are given by integrating the distributed gas pressures.

We define a potentially unstable, isolated block by an arbitrary basal sliding plane through the hemispherical dome, inclined at angle α (Fig. 1A). Gas uplift pressures act on this basal surface. We assume that the block can detach along a steep rear surface, on which gas pressures can act in a direction that tends to destabilize the block. The theoretical stability for a block with this geometry is less than for a block defined by a single basal plane that passes completely through the hemispherical dome. The specific geometry of this rear block surface is arbitrary, but for analytical convenience we assume that the unstable block is defined by the basal plane, and by two planes that form perpendicular bisectors with the basal plane. The two bisector planes are separated by the sector angle ξ, and thus the idealized lava dome failure is a "sector failure" (Fig. 1B). The assumed geometry is consistent with the natural development of radial fractures in growing lava domes. For this block, the ratio of resisting to disturbing forces defines stability in terms of a "factor of safety," F_s, as

$$F_s = \frac{cA + (W\cos\alpha - \delta W\sin\alpha - P)\tan\phi}{W(\sin\alpha + \delta\cos\alpha) + (4\pi F_m^* / \xi)\sin\xi/2}$$

where W is the block weight, c and ϕ represent cohesive strength and frictional angle, A is the area of the basal failure plane, δ is a horizontal pseudo-static seismic acceleration expressed as a fraction of the acceleration of gravity g, and F_m^* is the downslope force due either to "magmastatic" pressures or to diffusing gas pressures acting on the rear of a block of included sector angle ξ. Failure along the planar basal surface is assumed in order to simplify mathematical treatment for this "feasibility" analysis. The relation $F_s \leq 1$ implies failure.

2.2. Stability and Failure Surface Depth

Stability of the block is examined for a variety of loading processes, and results are presented for a lava dome of radius b = 200 m, cavity radius a = 15 m, unit weight $\gamma_r = 23.5\,kN/m^3$, diffusivity κ = 10^2-10^4 m^2/day (for a deformation modulus of $10GPa$ and a permeability of $0.1md$), cavity gas pressure P_i = 0 to 12 MPa, pseudo-static seismic accelerations of 0 to 0.1 g, cohesive strengths c of 0 to 0.5 MPa, and friction angles ϕ from 25° to 60°. Magma properties are reviewed by Dingwell [*1997*]. The calculations are given in a series of curves that represent different loadings (Figs. 2, 3). For each assumed set of loadings there exists a critical basal failure plane inclination that represents minimum stability (lowest F_s).

Factor of safety, F_s, as a function of basal failure plane inclination is noted on Fig. 2 for a variety of conditions, for material of $c = 0.5\ MPa, \phi = 25°$, unless otherwise noted, and holding κ constant at 10^3 m^2/day. If the external carapace of the dome is a purely frictional, interlocked, fractured crystalline solid ($c = 0, \phi = 60°$), exfoliation of blocks can occur on a steeply inclined surface (Fig. 2). In the absence of internal pressure and for interior strength parameters of $c = 0.1\ MPa, \phi = 45°$, failure on a less-steeply-inclined basal surface is possible, but the failure surface still does not penetrate deeply into the dome interior. However, although the actual strength properties of hot dome lava (temperature $\sim 800°\ C$) with some residual melt have not yet been fully measured, its frictional property may be much reduced. Assuming for these conditions a more cohesive and less frictional core, say $c = 0.5\ MPa, \phi = 25°$, an unpressurized dome is more stable than for the previous case. However, as internal gas pressure builds, stability is reduced on a critical failure plane inclined at about 35° to the horizontal (Fig. 2). Spalling at the block toe has a minor influence on this result, but strong shaking by volcanic earthquakes or tremor [*Voight et al. 1998a; Newhall and Voight, 1997*], back-scarp "magmastatic" pressurization by viscous extrusion from the dome core [*Elsworth and Voight, 1995*], or raising the cavity gas pressure ($P_i > 5\ MPa$), can all reduce stability of a block on a more-shallow basal surface to $F_s \approx 1$ (Fig. 2).

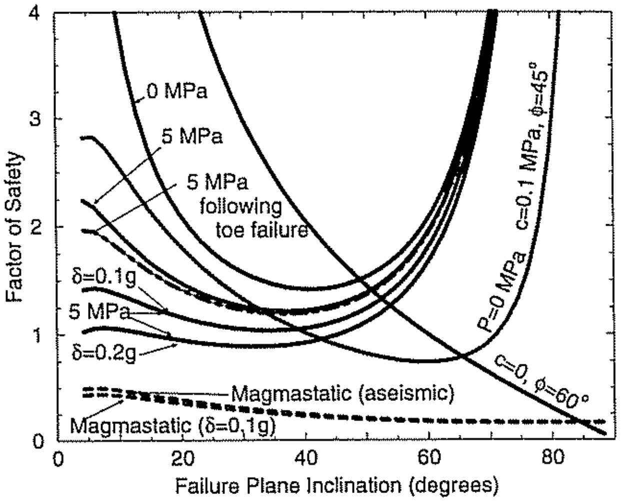

Fig. 2. Variation in factor of safety, F_s, with inclination of the failure plane, α. Results for a dome of external radius $b = 200\ m$ and cavity radius $a = 15\ m$ within material of c=0.5 MPa, ϕ=25°, unless otherwise noted. All results are for gas pressure loading of the block rear, except magmastatic shown dashed. Idealized failure plane pivots upwards from dome base. Seismic accelerations are $\delta = 0.1g$ and $\delta = 0.2g$.

Further, in these cases the sensitivity of factor of safety with failure plane inclination is reduced (i.e. the curve of F_s versus plane inclination flattens in Fig. 2), so that minor amounts of strength heteogeneity could result in critical failure surface inclinations of about 10°-20°. Thus, the combination of gas pressurization and augmentation by seismic loads can result in deep-seated failure surfaces that can approach the highly pressurized core.

The magmastatic case values in Fig. 2 (combined with a gas-pressurized basal surface) imply failure at all geometries. These cases are extreme examples in that full development of magmatic pressures along sector fractures may be unlikely in general. However the example illustrates that localized injections of magma can play an important role on stability.

2.3. Timing of Failure in Relation to Gas-Pressurization

The timing of a given failure is influenced by the migration velocity of the gas pressure pulse from the dome core (Fig. 3). Our calculations indicate that factor of safety, F_s, can decline systematically over a period of hours to days, depending primarily on the value of diffusion coefficient κ (Fig. 3). The curves in Fig. 3 assume $c = 0.5\ MPa, \phi = 25°$. The time to failure is conditioned by hydraulic/gas diffusivity, with κ of the order of 10^2 – 10^4 m^2/day capable of promoting failure (F_s < 1) within hours to days for overpressures approaching

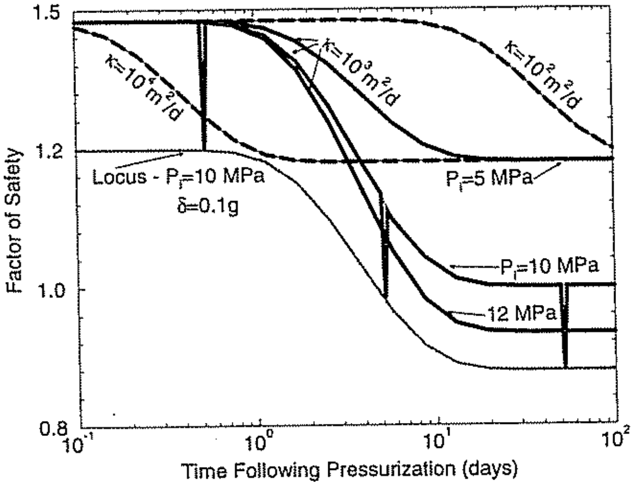

Fig. 3. Decrease in factor of safety, F_s, with time following pressurization. Results for dome with b=200 m, a=15 m and critical failure surface at $\alpha = 34°$. Cavity pressure is $5-12\,MPa$ in dome lava of fluid diffusivity $10^2 \le \kappa \le 10^4\ m^2/d$, and strength $c = 0.5\,MPa$, $\phi = 25°$. Note decrease in F_s by raising P_i. Marginal stability for $P_i = 10\,MPa$ reduces to $F_s \le 1$ for well-timed seismic loading $\delta > 0.1g$ (spikes), or increased P_i. Dotted line traces seismic-loading stability locus for $P_i = 10\,MPa$, $\delta = 0.1g$.

10 MPa (Fig. 3). Overpressures of this magnitude have been documented for lava domes [*Robertson et al.; Fink and Keiffer, 1993*].

At any given time the stability is influenced by loading conditions, such as conduit gas pressure (P_i = 5-12 MPa), and by seismic shaking, which reduces F_s momentarily as indicated by the inverted spikes in Fig. 3. The spike tips can be integrated to define a stability locus for seismic-shaking, for P_i = 10 MPa (Fig. 3). This locus illustrates that the dome can be stable - even with seismic loading - at early stages of gas pressurization, but then can become momentarily unstable (F_s < 1) with seismic shaking, in this case after about 4 days for $\kappa = 10^3\ m^2/day$.

For oscillating conduit gas pressurization, a transient pressure pulse will propagate from the core with amplitude diminishing radially from the mean applied gas pressure, and with an overprinted waveform representing the oscillating pressurization frequency, n. The overprint amplitude will diminish to 1% of the peak amplitude within one wavelength, λ, of the source with $\lambda = \sqrt{4\pi\kappa / n}$ [*Carslaw and Jaeger, 1959*]. For the nominal values of $\kappa = 10^3\ m^2/day$ and n=2 *cycles/day*, the harmonic pressure distribution further than 80 m from the pressure cavity wall will be indistinguishable from the constant application of mean internal pressure at the dome core; the non-harmonic approximations used in this work, are therefore adequate. For oscillating pressurization, the pressures indicated in Fig. 3 represent the mean internal pressure, not the peak pressure for any single oscillation.

3. Application to Dome-collapse on Montserrat

The theoretical results on stability and timing are consistent with observed major lava dome collapses at Soufriere Hills volcano on Montserrat, that have occurred hours to days after the onset of pressurization [*Voight et al., 1998a*]. Tilt and seismic data indicate that shallow conduit pressurization on Montserrat has oscillated (Fig. 4), and that a number of pressure oscillations may occur before a given major dome collapse [*Voight et al, 1998a&1999*]. The physical explanation for these oscillations is beyond the scope of this paper [*Voight et al., 1999; Denlinger and Hoblitt, 1999; Wylie, et al., 1999*], but here we are concerned with the question of why the dome did not always fail after the first significant gas pressure pulse. Our results in Fig. 3 provide a consistent answer to this question. Instability requires that a given gas-pressurization force threshold value be obtained on a critical failure surface, and a number of core pressure oscillations over a period of time may be required before the gas pressure can penetrate deeply enough into the dome to satisfy this threshold value. The time required to distribute this pressure over a given potential failure surface is a function of lava/magma diffusivity and the mean core gas pressure, about half of the peak value of a single oscillation.

The need for large core gas pressures are eased for a weaker dome, for fatigue weakening of the dome with cyclic pressurization, or with augmenting earthquake loads. For example, earthquake loads produce an instantaneous drop in factor of safety, F_s, and can promote failure provided that the "timing is right," i.e. the dome strength has been sufficiently reduced by gas-pressurization and other factors such that shaking can trigger $F_s < 1$. In addition, the average strength properties within the dome may be gradually reduced by repeated endogenous injection of relatively volatile-rich magma associated with the periods of strong oscillation [*Voight et al., 1999*]. The distribution of strength within a dome can be highly heterogeneous, and this factor too can promote deep-seated failure.

4. Discussion

Collapses of incandescent hot, gas-pressurized lava domes are hazardous because they can generate devastating pyroclastic flows and surges that reach many kilometers from the source: further, unloading of a gas-pressurized conduit as a result of dome collapse can trigger explosions involving ballistic throwout, fountain-collapse-generated pyroclastic flows, and tephra dispersal from convecting columns [*Robertson et al, 1998; Cole et al., 1998; Newhall and*

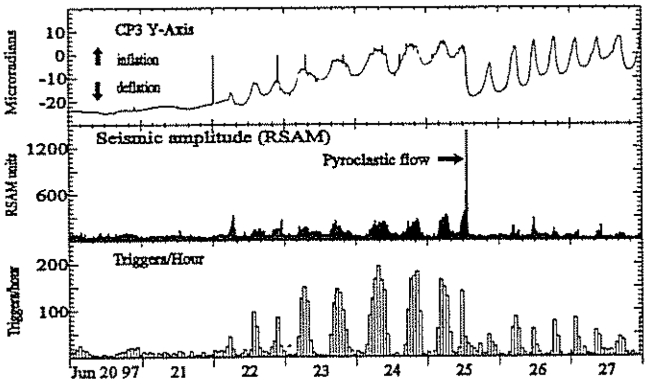

Fig. 4. Comparison of tilt time series with real-time seismic amplitude, RSAM, and triggered seismic events per hour at Soufriere Hills volcano, Montserrat. Period shown is June 20-27, 1997. Triggered events correspond to swarms of volcanic earthquakes; seismic amplitude records these earthquakes and also other events such as pyroclastic flows. Major dome collapse occurred on June 25 on the 9th pressurization cycle [*Voight et al., 1998a*], generating violent pyroclastic flows that destroyed several villages and killed 19 persons.

Melson, 1987; Fisher and Heiken, 1982]. Understanding the physics of the collapse process, as developed here, can aid volcanologists to interpret the consequences of precursory phenomena. Importantly, the possibilities of pressurized-dome collapse and likelihood of eruption explosivity can be anticipated from internal-pressure indicators such as near-vent tilt and shallow long-period or hybrid seismicity [*Voight et al., 1998a&b; Chouet, 1996*]. Likewise changing crystallinity [*Cashman, 1992*] and vesicularity of fresh lava [*Anderson and Fink, 1990*], hydrous phenocrysts lacking reaction rims [*Rutherford and Hill, 1993; Devine et al., 1998*], and minor explosions are consistent with pressurized volatile-rich magma and the attendant hazards.

In addition to pressurized volatiles diffusing through lava, pressurized gas can be trapped in vesicles. Large melt viscosities are produced by degassing of melt, and high overpressure of gas-bubbles can develop. Both viscosity and gas-bubble overpressures are greatest at small water contents typical of dome lavas [*Massol and Jaupert, 1998*]. Pressurized vesicles can violently discharge gas when lava blocks collapse, and can drive lava comminution and decompression expansion [*Sato et al., 1992; Fink and Keiffer, 1993; Fisher and Heiken, 1982; Rose et al., 1976*]. Volatile contents of recently-emplaced dome lavas have been measured, are a function of extrusion rate, and have a bearing on explosive decompression [*Anderson and Fink, 1989; Anderson et al., 1995*]. In a different sense, the pressurized vesicles may be considered as weakening-mechanisms within the bulk lava, decreasing its strength and thus its mass stability. They can partly account for some instances of explosive lava flow-front collapse far from the primary vent [*Rose et al., 1976*].

Once failure has initiated, violent spontaneous disintegration by decompressed diffused and vesicular volatiles can lead to gas-fluidized dense particulate (block-and ash) flows and/or transport of dispersed finer particles in an expanding gaseous surge [*Fink and Keiffer, 1993*]. Dome-core or shallow conduit lava decompressed by dome collapse above a critical threshold of 2-5 *MPa* can explode [*Alidibirov and Dingwell, 1996*]. We suggest that major explosions occur only if relatively deep-seated magma within the core of the dome or upper conduit is unroofed, as in this case the energy available within the volatile system is great and contains both pressurized diffusive volatiles as well as volatiles trapped in vesicles. Less energetic explosions, although still potentially dangerous, can be triggered by collapse of flow-fronts far from the vent; in this case only volatiles trapped in vesicles are available to drive the explosion.

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References

Alidibirov, M. and Dingwell, D.B., Magma fragmentation by rapid decompression, *Nature*, 380, 146-148, 1996.

Anderson, S.W. and Fink, J.H., Hydrogen-isotope evidence for extrusion mechanisms of the Mount St. Helens lava dome, *Nature*, 341, 521-523, 1989.

Anderson, S.W. and Fink, J.H., The development and distribution of surface textures at the Mount St. Helens dome, in Lava Flows and Domes, edited by J.H. Fink, Springer, Heidelberg, 25-46, 1990.

Anderson, S.W., Fink, J.H. and Rose, W.I., Mount St. Helens and Santiaguito lava domes: the effect of short-term eruption rate on surface texture and degassing processes, *J. Volc. Geotherm. Res.*, 69, 105-116, 1995.

Carslaw, H.S. and Jaeger, J.C., *Conduction of Heat in Solids*, Second Edition, Oxford University Press, Oxford, 510 p., 1959.

Cashman, K.V., Groundmass crystallization of Mount St. Helens dacite, 1980-1986: A tool for interpreting shallow magmatic processes, *Contrib. Min. Pet.*, 109, 431-449, 1992.

Chouet, B.A., Long-period volcano seismicity: its source and use in eruption forecasting, *Nature*, 380, 309-316, 1996.

Cole, P. et al., Pyroclastic flows generated by gravitational instability of the 1996-1997 lava dome of Soufriere Hills Volcano, Montserrat, *Geophys. Res. Lett.*, 25, 3425-3428, 1998.

Denlinger, R.P. and Hoblitt, R.P., Cyclic eruptive behavior of silicic volcanoes, *Geology*, 27(5), 459-462, 1999.

Devine, J.D. et al., Petrologic determination of ascent rates for the 1995-1997 Soufriere Hills Volcano andesitic magma, *Geophys. Res. Lett.*, 25(19), 3673-3676, 1998.

Dingwell, D.B., A physical description of magma relevant to explosive silicic volcanism, in *The Physics of Explosive Volcanic Eruptions*, edited by Sparks, R.S.J. and Gilbert, J., Geol. Soc. London Spec. Pub., 1997.

Elsworth, D. and Voight, B., Dike intrusion as a trigger for large earthquakes and the failure of volcano flanks, *J. Geophys. Res.*, 100(B4), 6005-6024, 1995.

Fink, J.H. and Kieffer, S.W., Estimates of pyroclastic flow velocities resulting from explosive disintegration of lava domes, *Nature*, 363, 612-614, 1993.

Fisher, R.V. and Heiken, G., Mt. Pelee, Martinique: May 8 and 20, 1902, pyroclastic flows and surges, *J. Volc. Geotherm. Res.*, 13, 362-380, 1982.

Massol, H. and Jaupart, C., Gas overpressures in lava dome eruptions, *Eos Trans. Am. Geophys. Un.* 79(45), F1001, 1998.

Miller, T., Dome growth and destruction during the 1989-1990 eruption of Redoubt volcano, *J. Volc. Geotherm. Res.*, 62, 197-212, 1994.

Newhall, C.G. and Melson, W.G., Explosive activity associated with growth of volcanic domes, *J. Volc. Geotherm. Res.*, 17, 111-131, 1987.

Newhall, C.G. and Voight, B., A survey of precursors to dome collapse, *Merapi Decade Int. Workshop II*, p. 48-49, 1997.

Robertson, R. et al., The explosive eruption of Soufriere Hills Volcano, Montserrat, West Indies, September 17, 1996, *Geophys. Res. Lett.*, 25, 3429-3433, 1998.

Rose, W.I. et al., Nuee ardente eruption from the foot of a dacite lava flow, Santiaguito Volcano, Guatemala, *Bull. Volc.*, 40, 23-28, 1976.

Rutherford, M.J. and Hill, P.M., Magma ascent rates from amphibole breakdown: an experimental study applied to the 1980-1986 Mount St. Helens eruptions, *J. Geophys. Res.*, 98, 19,667-19,685, 1993.

Sato, H., Fujii, T. and Nakada, S., Crumbling of dacite dome lava and generation of pyroclastic flows at Unzen volcano, *Nature*, 360, 664-666, 1992.

Voight, B. and Elsworth, D., Failure of volcano slopes, *Geotechnique*, 47(1), 1-31, 1997.

Voight, B. et al., Remarkable cyclic ground deformation monitored in real time on Montserrat and its use in eruption forecasting, *Geophys. Res. Lett.* 25, 3405-3408, 1998a.

Voight, B. et al., Deformation and seismic precursors to dome-collapse pyroclastic flows at Merapi volcano, Java, 1994-1998, Eos *Trans. Am. Geophys. Un.*, 79(45), F1001, 1998b.

Voight, B. et al., Magma flow instability and cyclic activity at Soufriere Hills Volcano, Montserrat, British West Indies. *Science*, 283,1138-1142, 1999.

Wylie, J.J., Voight, B., Whitehead, J.A., Instability of magma flow from volatile-dependent viscosity, *Science*, 283, 1999.

Young, S.R. et al., Overview of the eruption of Soufriere Hills Volcano, Montserrat, July 18, 1995, to December 1997, *Geophys. Res. Lett.*, 25, 3389-3393, 1998.

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