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Classification and idealized limit-equilibrium analyses of dome collapses at Soufrière Hills volcano, Montserrat, during growth of the first lava dome: November 1995–March 1998

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Abstract

Styles of dome collapse at Soufrière Hills volcano (SHV; November 1995–March 1998) are classified by relations between extrusion rate prior to collapse and collapse volume. Four separate modes of collapse behavior are apparent. Notably, moderate rates of extrusion are shown to result in two disparate modes of collapse: small-to-large collapses on steeply inclined failure planes that switch to collapse volumes an order of magnitude larger that cut deeply into the dome core. For constant effusion rates, this bifurcation in behavior is explained by the monotonic growth of a soft core that ultimately promotes the development of a deep-seated failure over previously favored shallow failure modes. Models are developed to test this hypothesis that first constrain magnitudes of cohesive and frictional strength with observed dome collapse morphologies and volumes. Evaluations of dome strengths confirm the important role of a soft core in promoting deep failure. A nested model representing a cohesive dome core, surrounded by a frictional rind, with constant rate of magma input, confirms the observed bifurcation in behavior, and for invariant effusive activity. Importantly, failure volumes are shown to increase by close to an order of magnitude for a few percent change in the proportion of dome core comprising cohesive material. This model is capable of replicating, a posteriori, the approximate timing of failure for both small (250 m) and large (325 m) domes. The timing and style of the 17 September 1996 and June to November 1997 collapses are honored.

Keywords: lava dome; collapse; pyroclastic flows; bifurcation

1. Introduction

The collapse of lava domes is a complex and hazardous phenomenon. Associated threats include generation of pyroclastic flows, the triggering of subsequent explosive activity that may generate

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column-collapse pyroclastic flows and widespread ashfall, and the elevated potential for lahars. Erosion of the carapace, disturbance of the talus shield providing support for dome lava, and internal dome forces, especially for the gas-infused Peléan-type domes, are important contributors to collapse. Potential mechanisms for these failures include thrust forces or mass weakness associated with an active lava lobe intrusion or extrusion (Calder et al., 2002; Watts et al., 2002; Voight et al., 2002), slope oversteepening by erosion and piping (Voight and Elsworth, 1997; Fink and Griffiths, 1998; Sparks et al., 2000), generation of fluid overpressurization of a weak underlying stratum (Lopez and Williams, 1993; Voight and Elsworth, 1997; Crowley and Zimbelman, 1997; Watters et al., 2000), the driving of thermal fractures through the brittle rind (Yamasato et al., 1998), rainwater vaporization-induced overpressurization of the outer dome (Matthews and Barclay, 2004; Simmons et al., 2004; Elsworth et al., in press), and gas overpressurization of the inner dome itself (Voight and Elsworth, 2000; Elsworth and Voight, 2001).

The andesite lava dome of Soufrière Hills volcano (SHV), Montserrat, B.W.I., evolved through several eruptive styles from November 1995 to March 1998, each associated with a particular style of dome collapse. A small overall dome volume, relatively low extrusion rate and relatively low collapse volume marked the early stage collapses of 1996. Later stage higher-volume collapses of 1997 resulted in violent explosions. Each style conforms to a systematic pattern of extrusion rate and associated collapse volume.

The following provides a classification of dome collapse styles during times of active lava effusion based on the dome volume involved. Collapse styles evolve from relatively innocuous small-to-large failures, to dangerous and potentially explosive major failures. All collapse volumes $0–4\times10^6$ m^3 Dense Rock Equivalent (DRE) are referred to as small-to-large collapses, those with volumes of $4–20\times10^6$ m^3 DRE are termed major collapses, and collapses involving greater than 20×10^6 m^3 DRE are termed gigantic collapses (after Calder et al., 2002); all subsequent volumes will be referred to in terms of DRE (Calder et al., 2002).

Behavioral signatures are identified for particular collapse styles of SHV that can aid (and indeed have aided) in risk assessments, both on Montserrat and at similar andesite domes elsewhere. These observations of collapse are supported by a simplified dual-region limit-equilibrium model of the dome. The simple first-order model incorporates a cohesive volatile-rich core encapsulated by a primarily frictional, degassed rind. Feasible rock mass strengths are defined by back analysis, to provide a consistent suite of frictional and cohesive strengths for the dual regions. The model is applied to a growing dome to define the self-organized change in collapse style as failure mode bifurcates from initial shallow surface spalling to switch to a deep-seated failure that cuts more deeply into the dome core. Importantly, this occurs as a sudden switch from shallow to deep, rather than as a progressive deepening of the initial shallow failures. This behavior is followed to define the style and approximate timing of major failures in both relatively small (r=250 m) and large (r=325 m) domes. The model is subsequently modified to incorporate retrogressive failure, an alternative mechanism for the development of major failures, in an effort to explain long-duration major collapses, e.g., the c. 9-h collapse on 17 September 1996.

2. Collapse styles

A variety of styles have been apparent in the episodic dome collapses observed at SHV in the period November 1995 to March 1998 (Watts et al., 2002; Calder et al., 2002). They have ranged from shallow, small-to-large collapses with relatively low mobility, to energetic major collapses that have spontaneously developed into long-runout pyroclastic flows. One method of classifying these failures is by collapse size, e.g., small-to-large/major/gigantic. Another classification method is to consider the relationship between collapse volume and extrusion rate. Extrusion rate and collapse volume data for 22 collapses recorded in the period 29 July 1996 to 26 December 1997 (Table 1 of Calder et al., 2002) are plotted in Fig. 1. In a general sense, extrusion rates and collapse volumes are positively correlated; larger extrusion rates result in larger volumes of unstable material being available to both drive and to participate in the collapse. Unfortunately, this simplistic observation is confounded by the presence of a small number of outlier major collapses that have occurred while preceding extrusion rates remain low.