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Magma production and growth of the lava dome of the Soufriere Hills Volcano, Montserrat, West Indies: November 1995 to December 1997

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Abstract. From November 1995 to December 1997 a total volume of 246 x 10^6 (DRE) m^3 of andesite magma erupted, partitioned into 93 x 10^6 m^3 of the dome, 125 x 10^6 m^3 of pyroclastic flow deposits and 28 x 10^6 m^3 of explosive ejecta. In the first 11 weeks magma discharge rate was low (0.5 m^3/s). From February 1996 to May 1997 discharge rates have averaged 2.1 m^3/s, but have fluctuated significantly and have increased with time. Three pulses lasting a few months can be recognised with discharge rates reaching 3 to 8 m^3/s. Short term pulsations in growth lasting a few days reach discharge rates of over 10 m^3/s and there are periods of days to a few weeks when dome growth is < 0.5 m^3/s. Discharge rate increased from May 1997 with an average rate of 7.5 m^3/s to December 1997. The observations indicate an open magmatic system.

Introduction

The Soufriere Hills Volcano, Montserrat eruption began on 18 July, 1995 (Young et al., 1998). The eruption initially consisted of phreatic explosions accompanied by seismic activity and marked ground deformation. The first unequivocal juvenile andesitic lava dome began to extrude about 15 November 1995. Dome growth has continued ever since. There have been three major periods of explosive activity on 17/18 September 1996, 3 to 10 August 1997 and 21 September to 22 October 1997 with generation of tephra fall and pumice flow deposits. This paper presents data on the volumes of juvenile erupted material from the 15 November 1995 to 25 December 1997, divided into the dome, pyroclastic flow deposits and tephra fall ejecta. Magma discharge rate has increased in vigour with time, but discharge pulsates with a range of time-scales from hours to a few months.

Methods

Volume estimates of the dome to January 1996 were made from the rim of English's Crater using compass and abney level surveys, supplemented by photographs and theodolite measurements. Estimates used simple geometries such as truncated cones with an accuracy of about 30%. From late January 1996 photographs were taken from fixed positions supplemented by photography from the crater wall and helicopter. Topographic features of known height and position were identified. Trigonometry and triangulation between photographs established scales. In August 1996 a kinematic survey method was developed to survey the dome. In this method laser ranging binoculars were used from the helicopter to measure the position of points on the dome surface. The helicopter was located by GPS relative to a fixed station on the ground. After September 1997 the photographic method was used to survey the dome from the helicopter, using the GPS to locate helicopter.

Topographic data were analysed using the Surfer software package. The programme creates a grid of x, y and z information by interpolating from adjacent data points, using kriging. Volumes were calculated either by comparing pre-dome topography with the new topography or by subtracting the results of one survey from another in areas of active growth. When the dome was obscured by cloud previous survey data or known geometrical features (such as a 33° talus slope) were used to estimate heights. Up to 17 September 1996 the pre-eruption topography of English's Crater was used. The remnant of the pre-17 September dome and crater were re-surveyed to provide the base topography for dome volume estimates after 1 October 1996. A resurvey of the base topography was made after the generation of a deep crater from explosive activity in October 1997.

The volume of pyroclastic flow deposits was determined by mapping, direct estimates of thickness and the kinematic method. New fans were created on the east and west coasts by pyroclastic flows entering the sea (*Cole et al., 1998*). The fan volumes were monitored by kinematic surveys. The pyroclastic flows generated dilute ash plumes with heights between a few hundred metres and a few kilometres. The ash fall deposits were dispersed mostly to the west. Isomass contour maps were prepared from ash collected in trays. The data were fitted by an exponential decay law (*Pyle, 1989*) to determine the total mass. Volumes of explosive eruptions ejecta were estimated from isopach maps, from calculations on the column dynamics together with estimates and eruption durations.

The dome volume estimates are subject to systematic and non-systematic errors. For the photographic method a conservative estimate is that the volumes are better than 15%

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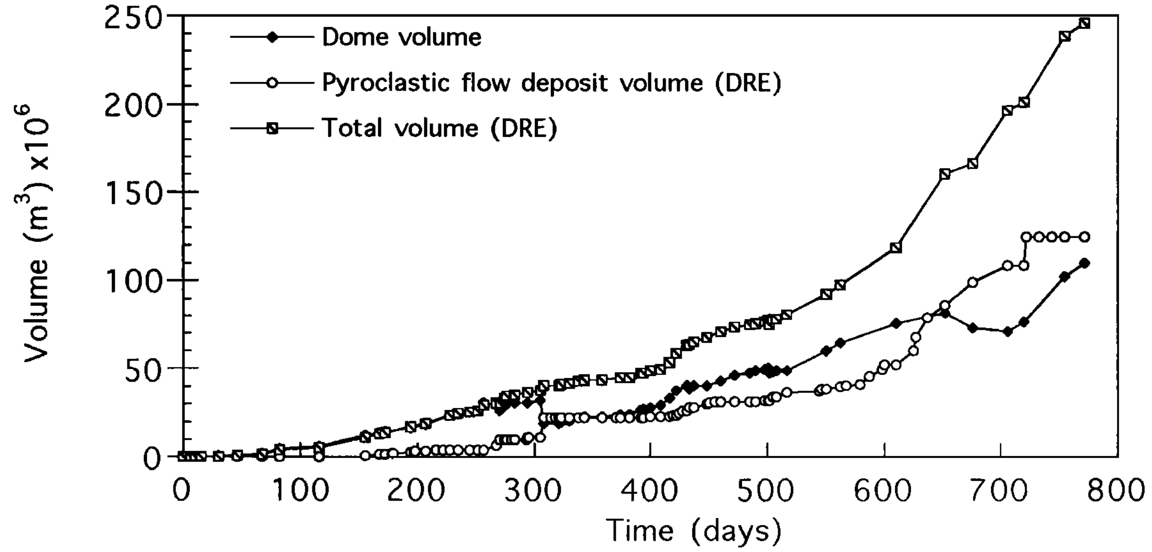

Figure 1. Variations with time of total magma production, dome volume and pyroclastic flow volume. Magma production and pyroclastic flow volumes are expressed as dense rock equivalents. Dome volume is not corrected to DRE. Time starts on 15 November 1995

accurate. For the kinematic surveys the non-systematic errors are less than 5%, with 15 to 30 well-distributed points required to produce a well-constrained result. As the dome size increased opportunities for whole dome surveys diminished and so surveys were focused on areas of active growth and the changes in volume were added incrementally. A survey of the whole dome on 17 February 1997 allowed the cumulative total volume obtained by the addition of growth increments to be compared with the volume obtained by subtracting the 17 February map from the pre-eruption topography. The dense rock equivalent volumes were respectively 41.9 and 41.0 x 10^6 m^3. Surveys have become less frequent as the dome has increased in volume, pyroclastic flows have covered larger areas and eruptive activity has escalated.

Volume Data

Various points concerning the volume data follow:

(i) Volume data are converted to dense rock equivalent using measured or estimated densities of the dome and pyroclastic flow deposits. The density of lava typically ranges from 2,100 to 2,400 kg/m^3. Dense (zero porosity) clasts have a density of 2,600 kg/m^3. The bulk density of the pyroclastic flow deposits was taken as 2000 kg/m^3.

(ii) The ash fall deposits are evaluated at 15% of the pyroclastic flow deposit volumes, based on comparison of the volume of ash fall deposits with pyroclastic flow volumes erupted between June 1996 and June 1997.

(iii) The volumes of the collapse scars formed after major episodes of pyroclastic flow formation are often larger than the volume estimates of the pyroclastic flow deposits. For example in the 17 September 1996 eruption, the scar had a volume of 11.7 x 10^6 m^3 and the total pyroclastic material was evaluated at about 6.5 x 10^6 m^3. This discrepancy is attributed mostly to pyroclastic flows entering the sea, but may also reflect some explosive cratering. We have used the scar volumes to assess pyroclastic flow production on occasions where the flows entered the sea.

(iv) The data also reflect visual observations. Some examples are cited. Volumes of the May 12 and 31 1996 pyroclastic flow deposits and estimates of pyroclastic flow production in between these dates allow a record of productivity to be integrated in. Particularly rapid periods of dome growth and times of almost no growth were observed in August and late November 1996. Visual observations allowed partitioning of volume data between particular dates and identification of rapid growth periods (29-31 July 1996) and volumes of scars formed by dome collapse.

Interpretative account of the volume data

The variation of magma production with time, dome volume and pyroclastic flow volume, including associated ash cloud tephras, are shown in Figure 1. The total magma produced as of 25 December 1997 is 246 x 10^6 m^3. Discharge rate estimates are displayed as discrete estimates using the volume difference between two successive volume determinations divided by the time interval (Figure 2a) and by calculations of 7 day and 31 day running averages up to May 1997 (Figure 2).

Initial discharge rates (~0.5 m^3/s) were low in the first 11 weeks. From 1 February 1996 to 1 May 1997 the discharge rate has averaged 2.1 m^3/s with an overall tendency for the rate to increase with time. In this period pulsations in discharge rate occur on time scales ranging from a few days to several months (Figure 2). Discrete estimates of discharge rates (Figure 2a) show large fluctuations with a general tendency to increase with time. The 31 day running average plot (Figure 2c) shows how the discharge reached a maximum (July to September 1996) declined (October-November 1996) and has been through two significant fluctuations in the first 5 months of 1997. The maxima show discharge rates in the range 3 to 8 m^3/s with periods of low activity involving discharge rates as low as 0.5 to 1.0 m^3/s. The 7 day running average plot (Figure 2b) shows shorter time-scale fluctuations with brief periods of a few days when extrusion rates in the range 7 to 12 m^3/s are observed. Examples of such periods include the 29 to 31 July 1996 and 12 to 17 August 1996. A major increase in discharge rate occurred in May 1997. Thereafter the discharge rate increased to an average of 7.5 m^3/s to 25 December 1997. After May 1997 the volume surveys became too infrequent to detect the shorter time-scale fluctuations.

There are also fluctuations in discharge rate on time-scales of hours, but these cannot be documented from the surveys.

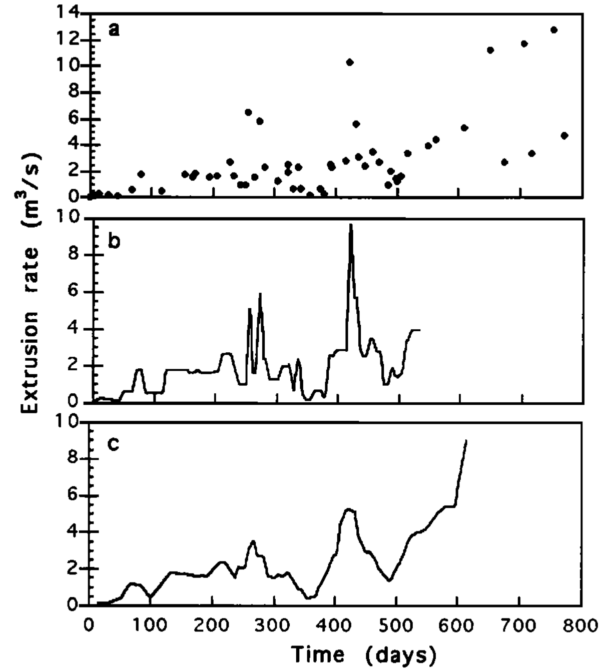

Figure 2. Extrusion rates as a function of time. (a) Discrete extrusion rate estimates; (b) 7 day running average; (c) 31 day running average. Running averages have not been extended beyond May 1997 due to larger time intervals between volume estimates after May 1997.

There have been prolonged periods in which shallow earthquake swarms lasting a few hours to a few days have alternated with aseismic periods of similar durations. Rockfall activity and visible changes of dome morphology are often pronounced during the aseismic periods and absent during the seismic swarms. Extrusion slow down or stop altogether during the shallow earthquake swarms.

Large decreases in dome volume were caused by the major collapses of the dome (Figure 1) such as on 17 September 1996 and 25 June 1997 and also by explosive eruptions in September and October 1997. The pyroclastic flow volume increases as step functions related to major short-lived phases of pyroclastic flow generation (Figure 1). There are prolonged periods lasting several days to weeks when minor pyroclastic flows are' almost continuous. The volumes of these deposits cannot be charted in detail, although the cumulative volumes are thought to be reasonably accurate.

The relation of growth pulsations to earthquake swarms is not simple. Pulses in discharge rate during 1996 in late January, late July, on appearance of the new dome on 1 October and a pulse at the beginning of November were preceded by earthquake swarms. However other pulses and increases in discharge rate were not noticeably associated with seismic swarms. The significant increase in discharge rate at the end of July 1996 was associated with the onset of major shallow earthquake swarms and marked increase in ground deformation. The pulses are preceded and followed by periods of lower than average growth and, in some cases, the dome growth slowed down substantially, as in late August 1996. Some major growth pulses are associated with vigorous pyroclastic flow activity (*Cole et al., 1998*), as exemplified by the vigorous growth and pyroclastic flow activity from July 29 to 31 1996, on the 12 August 1996, in mid-January 1997 and on the 25 June 1997. However only average growth rates (~2 m^3/s) preceded the 17 September 1996 eruption (*Robertson et al., 1998*). The focus of dome growth has switched several times. One focus of growth stagnates and a new pulse of dome occurs in another area.

Discussion

The behaviour of the Soufriere Hills dome is compared with other dome eruptions. Discharge rates are similar to other lava dome eruptions (*Newhall and Melson, 1983*) in the range of 1 to 10 m^3/s. Newhall and Melson (1983) report a mean discharge rate of 2.9 m^3/s for 67 exogeneous dome eruptions. Mount Unzen, Japan reached its peak discharge rate of about 8 m^3/s within the first few weeks of the eruption and then declined over a four year period (*Nakada, 1993*). Pulsation in dome growth is evident on Unzen: a second maximum in discharge rate of about 3m^3/s occurred 2 years into the eruption and 13 individual lobes were discharged xwith lobe extrusion often preceded by earthquake swarms. There were 20 pulses of growth at Mount St Helens between 1980 and 1986 (*Swanson et al., 1990*). Each pulse began with an accelerating period of growth and the pulses were separated by periods of quiescence lasting several weeks to a few months. Discharge rates in the pulses ranged between 1 and 40 m^3/s, but the time-averaged discharge rate was only 0.35 m^3/s. The dacitic lava dome of the Santiaguito Volcano in Guatemala has involved pulses of relatively high discharge rates (0.6 to 1.9 m^3/s) lasting a few years separated by periods of very low discharge rate (0.16 m^3/s) lasting 10 to 15 years (*Anderson et al., 1995*).

Lava dome eruptions pulsate on time-scales ranging from hours to several years. Longer time-scale pulsations (several weeks to years) may relate to deeper processes that control influx of magma from the mantle and chamber processes such as magma mixing, elastic response of the chamber walls and conduit, and ascent of gas-rich magma. Dome eruptions with lower "time-averaged" discharge rates (Mount St. Helens and Santiaguito) show more pronounced pulsations, separated by periods of low or no activity. Eruptions with higher time-averaged discharge rates, such as Soufriere Hills and Unzen, pulsate but are more continuous. Shallow level processes can cause pulsations. During the ascent of gas-rich andesite magma there are large changes in physical properties at shallow levels related to gas loss. Magma viscosity increases by several orders of magnitude and gas loss induces crystallization of the melt phase. These processes are controlled by intrinsically non-linear processes such as crystallization, gas flow through permeable magma and wallrocks, development of fracture networks, sealing of fracture and pores by precipation of hydrothermal and vapour phase minerals, and variable viscosity magma flow. Such processes can induce large excess pressures and fluctuations of pressure. Sparks (1997) has proposed that phenomena such as shallow seismicity, long period earthquakes, explosive activity in domes and pulsations in gas flux can be related to shallow level pressurisation. A wide range of time-scales are likely to be associated with crystallization kinetics, gas movement, fracturing, magma movements and mineral precipitation.

The early period of slow growth is associated with formation of large spines and highly crystalline lava. The lava was thoroughly degassed and the thicknesses of hornblende reaction rims confirm slow ascent rates (*Devine et al., 1998*). The simplest interpretation of this period is that the magma extruded until the end of January 1996 represents high viscosity degassed magma that had been infilling the conduit for several months before. The increasing flux in the first 10 months of the dome extrusion can be associated with ascent of increasingly fluid and gas-rich magma. The magma erupted in the pulses of July and August 1996 and in the 17

September 1996 explosive eruption have fresh hornblende with either very thin reaction rims or no rims (*Devine et al., 1998*). Analysis of the explosive eruption and petrological constraints (*Robertson et al., 1998; Devine et al., 1998; Barclay et al., 1998*) also indicate that undegassed magma containing between 4 and 5% water was approaching the surface in this period. Ascent of gas-rich magma to the surface can be inferred for the enhanced discharge rate in December 1996, following the decline from late October to early December 1996 and culminating in the eruption of pyroclastic flows on 19 December 1996 and January 1997.

Possible explanations for the decrease in flux in October and November 1996 and in March to mid-April 1997 are a decrease in magma driving pressure resulting in slower ascent and more degassing. Changes in column geometry and stress regime caused by the 17 September 1996 eruption and restriction of the conduit by solidification may be important factors in the decreasing flow rate. However the discharge rate picked up in 1997.

The magma discharge rate has increased with time. The driving forces for the eruption have not decayed. In a simple closed system magma chamber discharge rate decreases exponentially with time as chamber pressure drops (*Stasiuk et al., 1993*). We therefore surmise that either the magma chamber is very large so that the removal of 246 x 10^6 m^3 has not had a significant impact on the chamber pressure or it is an open system which maintains the chamber pressure by influx of new magma. The geophysical evidence does not support a very large magma chamber. The petrological evidence supports influx of mafic magma and recent magma mixing phenomena (*Murphy et al., 1998*), supporting the open-system concept with pressure being maintained high by influx of deeper basaltic magma.

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References

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

Barclay, J., Carroll, M.R. Devine, J., Gardner, J., Murphy, M. and Rutherford, M.R. Experimental phase equilbria of the Soufriere Hills magma and their constraints on pre-eruptive conditions. *Geophys. Res. Lett.*, in press, 1998.

Cole, P., Calder, E.S., Druitt, T.H., Hoblitt, R., Lejeune, A.M., Robertson, R., Smith, A.L., Stasiuk, M.V., Sparks, R.S.J., Young, S.R. and MVO Team. Pyroclastic flows generated by gravitational instability of the 1996-97 lava dome of the Soufriere Hills Volcano, Montserrat. *Geophys. Res. Lett.*, in press, 1998.

Devine, J., Rutherford, M.R. and Gardner, J. Magma ascent changes at Sourfriere Hills: hornblende reaction rim data. *Geophys. Res. Lett.*, in press, 1998.

Murphy, M., Sparks, R.S.J., Barclay, J., Carroll, M.R., Lejeune, A,M., Brewer., T.S., MacDonald, R., Black, S. and Young, S.R. The role of magma mixing in triggering the current eruption at the Soufriere Hills Volcano, Montserrat,. *Geophys. Res. Lett*, in press, 1998.

Nakada S. Lava domes and pyroclastic flows of the 1991-1992 eruption at Unzen volcano, In: Unzen Volcano: the 1990-1992 eruption, T.Yanagi, H.Okada and T. Ohta (eds.), Nishinippon and Kyushu University Press, 56-66, 1993.

Newhall, C.G. and Melson, W.G. Explosive activity associated with the growth of volcanic domes. *J. Volcanol. Geothermal Res.*, 17, 111-131, 1983.

Pyle, D.M. The thickness, volume and grain size of tephra fall deposits. *Bull. of Volcanol.* 51, 1-15., 1989.

Robertson, R., Cole, P., Sparks, R.S.J., Harford, C., Lejeune, A.M., McGuire, W., Miller, A., Murphy, M., Norton, G., Stevens, N., Young, S.R. and MVO staff. The explosive eruption of Soufriere Hills Volcano, Montserrat, 17 September, 1996. *Geophys. Res. Lett.*, in press, 1998.

Sparks, R.S.J. Cause and consequences of pressurisation in lava domes, *Earth Planet. Sci. Letter* 150, 177-189, 1997.

Stasiuk, M.V., Jaupart, C. and Sparks, R.S.J. Variations of flow rate and volume during eruption of lava. *Earth Planet. Sci. Letter.* 114, 505-516, 1993.

Swanson D.A. and Holcomb R.T. Regularities in the growth of the Mount St Helens dacite dome 1980-86, in: Lava flows and domes: Emplacement Mechanisms and Hazard Implications, J.H. Fink, (ed.), pp.3-24, Springer, Berlin, 1990.

Young, S.R.., Sparks, R.S.J., Aspinall, W.P., Lynch, L.L., Miller, A.D., Robertson, R.E.A. and Shepherd, J.B. Overview of the Soufriere Hills Volcano, Montserrat, 18 July 1995 to December 1997. *Geophys. Res. Lett., (in* press, 1998).

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